Government of **Western Australia**
Department of **Mines and Petroleum**

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TARGET 2017, PERTH, AUSTRALIA: ABSTRACTS

edited by
S Wyche and WK Witt

Geological Survey of
Western Australia

Government of **Western Australia**
Department of **Mines and Petroleum**

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Perth 2017

Geological Survey of Western Australia

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Cover image: Elongate salt lake on the Yilgarn Craton — part of the Moore–Monger paleovalley — here viewed from the top of Wownaminya Hill, 20 km southeast of Yalgoo, Murchison Goldfields. Photograph taken by I Zibra for the Geological Survey of Western Australia

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Welcome to Target 2017!

University Club, University of Western Australia, Perth

19–21 April 2017

This Record contains the abstracts for Target 2017. Abstracts are arranged alphabetically by author and include both oral and poster presentations.

With the first tentative indications, late last year, of a movement towards higher prices for some metalliferous commodities, there is scope for cautious optimism for those involved in the mineral industry. However, the downturn in mining was accompanied by a similar retreat from investment in minerals exploration. The result of this downturn is that fewer metal deposits have been discovered in recent years. If the first increase in commodity prices evolves into a full-scale commodity boom over the next few years, there will be few deposits to bring on stream and potential employment and income will therefore not be realized.

As a consequence, the mining industry must act now in order to find the next generation of mineral deposits that will sustain human development. Most resources extracted from the Earth today exploit near-surface deposits discovered more than 30 years ago. The outcrop/subcrop search space is being rapidly depleted of world-class deposits, leaving broad volumes of the Earth's crust unexplored. Innovation is required to aid discovery of new tier-one deposits, especially if the exploration space is to be truly broadened extending under cover. Innovation is also required to increase the discovery to investment ratio, which is at an all-time low. The program put together as part of Target 2017 focuses on all aspects of mineral exploration and provides a unique opportunity to workshop solutions to the challenges that lie ahead.

Exploration targeting is a sequential volume reduction exercise that requires multi-scale analysis from regional scale, district or camp scale, to prospect scale selection. Accordingly, the technical program showcases range of poster and oral presentation ranging in scale from greenfields regional scale through to brownfields and near-mine exploration case studies. Themes presented at the conference include conceptual innovations in mineral system analysis, futuristic exploration strategies, new and emerging exploration techniques, brownfields vectoring techniques and the role of training and precompetitive data for future exploration challenges.

With speakers and attendees from around the world, Target 2017 aims at giving you an opportunity to network with your peers in the collegial atmosphere that has developed between industry, government and academic professionals in the Australian capital for the mineral industry.

Let's shape tomorrow's exploration strategies for the future sustainability of our industry!

Thank you!

Target 2017 organising committee

Rutile as an indicator mineral in gold exploration

by

Andrea Agangi[1*], Steven M. Reddy[1], Diana Plavsa[1], Denis Fougerouse[1], Chris Clark[1], Malcolm Roberts[2] and Tim E Johnson[1]

Gold has many diverse applications, from global financial risk management to jewellery. Although the demand for this precious metal has been sustained across many decades and through fluctuating economic cycles, the discovery rate has been declining rapidly (Sykes et al., 2016). In Australia, as in other countries with mature mineral industries, many resources exposed at the Earth's surface are largely exhausted. This, combined with increased environmental sensitivities, requires new technologies that enable the efficient identification and extraction of ore deposits concealed beneath thick deposits of sediment and deeply weathered rock (Fig. 1). In this study, we explore the applicability of rutile as a pathfinder for orogenic gold deposits, which provide approximately a third of the world's reserves (Frimmel, 2008).

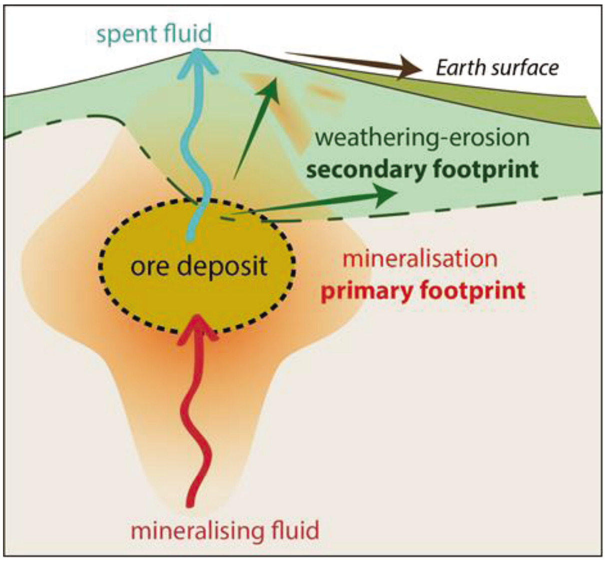

Figure 1. Conceptual model of an ore deposit and its footprint. Metal-bearing mineralising fluids leave a primary footprint in the form of characteristic minerals and elements in the rocks surrounding the ore. Dispersion of these minerals and elements related to weathering and erosion produces a secondary footprint that can be explored by means of indicator minerals

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Rutile, the most abundant polymorph of titanium dioxide (TiO_2), is a common accessory mineral in some magmatic rocks, in magmatic–hydrothermal ore systems and metamorphic rocks, where it can form as a replacement product of Ti-bearing oxides and silicates, such as ilmenite, titanite or biotite (Luvizotto and Zack, 2009). Studies of rutile associated with gold deposits (Clark and Williams-Jones, 2004) have highlighted that the concentration of some elements, such as W, Sn, V and Sb, are elevated in rutile from mineralised rocks relative to rutile in the surrounding unmineralised country rocks.

We analyse rutile from three different Precambrian terrains — the Capricorn Orogen, the Barberton Greenstone Belt and the Ashanti Belt — that share similarities in the style of mineralisation, the H_2O–CO_2 fluid and pressure–temperature conditions of formation. Samples were initially analysed by back-scattered electron diffraction (EBSD), which measures crystallographic orientation and allows rutile to be distinguished from other TiO_2 polymorphs, such as brookite and anatase. In all the samples, rutile occurs in elongate mineral aggregates oriented subparallel to the foliation that are composed of rutile needles intergrown with quartz, chlorite, carbonate and Fe(Ti)-oxide.

Rutile composition was analysed by electron microprobe and laser ablation ICP-MS. Multiple spot analyses within single grains or grain aggregates indicate strong compositional variations for several elements, most notably Nb, W, Zr and V (Fig. 2). Variations in Zr are reflected in the thermometric estimates based on Zr content in rutile (Tomkins et al., 2007) (up to 674°C at 2 kbar, with outliers up to 815°C). These estimates far exceed independent maximum temperature estimates. Incorporation of Zr as nanoscale inclusions helps explain the mismatch between Zr-in-rutile and other types of geothermometry. Therefore, the presence of Zr-bearing inclusions should be evaluated and taken into consideration when estimating the crystallisation temperature of hydrothermal rutile.

A comparison of our analyses with a large geochemical dataset of rutile from metamorphic and igneous rocks indicates that high contents of W, Sn and V are common, although not unique, in rutile from gold deposits. In contrast, Sb is higher in rutile from gold deposits when compared with unmineralised rocks. Anomalously high concentrations of Sb, as well as Au, As, Ag, V, W, Te, and Hg in orogenic gold deposits can be explained by remobilisation during metamorphism at greenschist and amphibolite facies conditions, which causes chlorite dehydration and conversion of pyrite to pyrrhotite. In these fluids, cations that have an affinity for reduced S, such as Au, As and Sb, are thought to be transported by

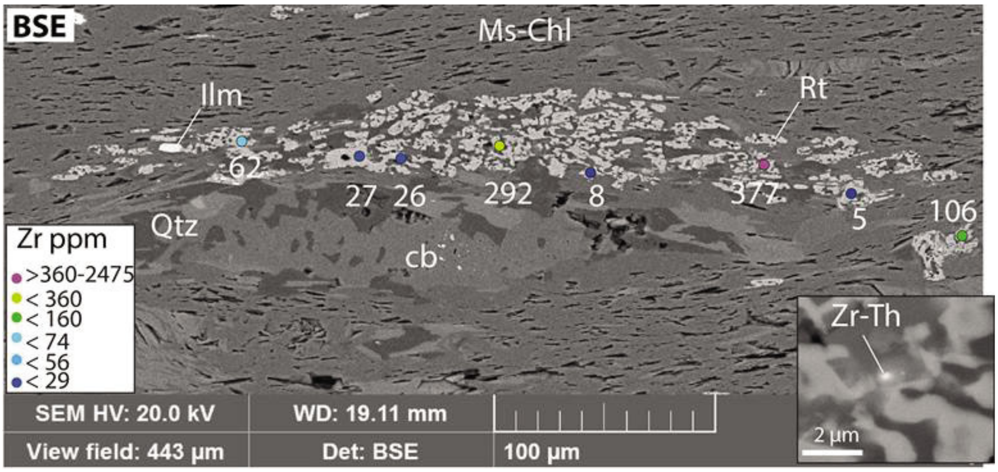

Figure 2. BSE image of rutile aggregate. Spots and numbers indicate the position and Zr content of microprobe analyses, note wide concentration variations. Nanoscale inclusions of Zr-bearing phases (inset) help explain these variations

hydrosulphide complexes such as $Au(HS)^{2-}$ and AuHS (Pokrovski et al., 2014). In addition, the occurrence of F-bearing phases in our samples, such as fluorapatite, indicates the presence of F in the mineralising fluids. Fluorine and the carbonate ion $[CO_3^{2-}]$ may have also contributed to the transport of these elements (Pokrovski et al., 2014). Our results indicate that trace element composition of rutile, primarily the Sb content, may be used as a pathfinder for gold buried beneath thick cover.

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i3DGS — Implicit 3d Time-Aware GeoStructural Simulator

by

Laurent Ailleres[1*], Mark W Jessell[2], Eric de Kemp[3], Guillaume Caumon[4], Florian Wellmann[5], Simon Lopez[6], Michael Hillier[3], Gautier Laurent[4], Gaby Courrioux[6], Ernst Schetselaar[3], Robin Armit[1], Mark Lindsay[2], Philippe Calcagno[6], Pauline Collon[4], Boyan Brodaric[3], Christelle Loiselet[6], Kate Smith-Miles[7], Peter Betts[1], Francois Bonneau[4], Sandy Cruden[1] and Steve Micklethwaite[1]

Introduction

One of the great challenges in resource exploration and geological research is to predict and represent geology in 3D. Building 3D models, even with the advent of implicit techniques, is still a highly specialised and costly task (both in time and computing resources) and often only adapted to 'simpler' basin geometries. There is currently a critical technology gap in our 3D geological modelling workflow. Current platforms only use a subset of the geological information available which makes building 3D geological models of hard-rock terranes very difficult. The integration with geophysical imaging is limited to the use of interpretative cross-sections as input data or a posteriori inversions that ignore geological data and information. Finally, uncertainty is extremely high and usually not quantified nor utilised. These three shortcomings in the modelling process conspire together to promote the production of geologically unrealistic models.

We present the preliminary development of a new open source 'Implicit 3D GeoStructural Simulator and modelling platform' (Fig. 1) that will address the entire 3D geological modelling workflow from guiding clever/efficient structural observations sampling in the field to the production of a series of consistent 3D geological models with uncertainty assessment.

i3DGS will be a modelling platform integrating all available field geological information, interpretations of geophysical datasets and allowing the creation of reference models for geophysical inversions. The platform will handle multiple-scale projects ranging from outcrops to Earth-scale systems and handle Cartesian (e.g. UTM) or geodetic projections (on a spheroid). It will be flexible enough to build groundwater, basins or more complex hard-rock models. i3DGS will be built around a core interpolation and geological simulation engine and allow automatic uncertainty modelling and export to other specialised packages for further numerical calculations (fluid flow, resource estimation, etc.).

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Preliminary results

A method has been developed (Fig. 2) to model multiple folding events. The method is time-aware (the youngest foliations are modelled first) and data driven, utilising fold axial surfaces, foliations associated with the folding event, and fold axes and intersection lineations. The fold profile is derived from structural data analysis including Fourier frequency analysis to model parasitic folds and multi-wavelength folds (Laurent et al., 2016) including in areas away from data. These advances will be incorporated with recent developments in the field of uncertainty characterisation, quantification and minimisation (Jessell et al., 2014; de la Varga and Wellmann, 2016) to provide a 3D stochastic modelling tool based on field structural information.

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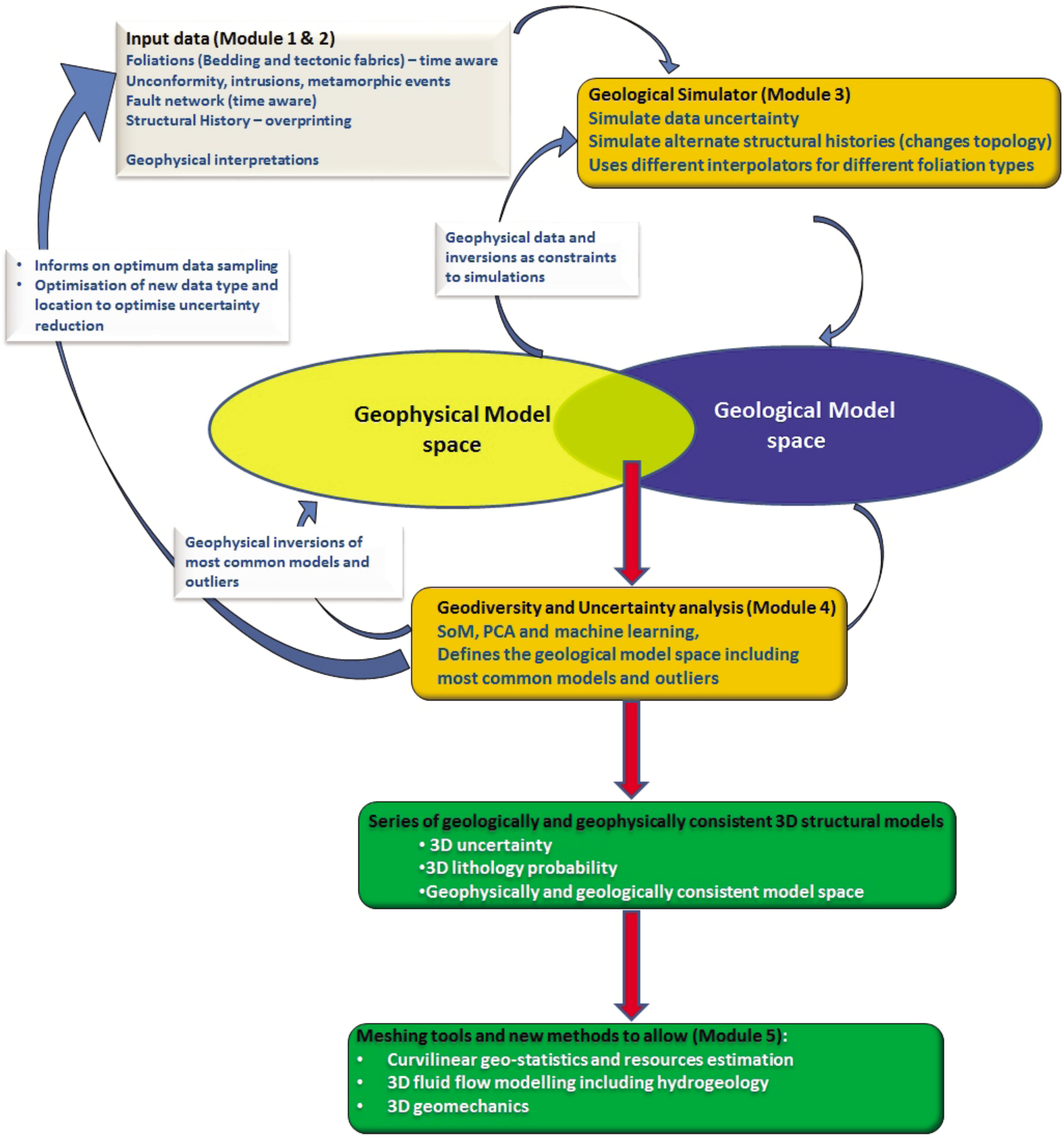

Figure 1. Proposed workflow for 3D structural modelling consistent with geological data (all types and time aware) and geophysical data

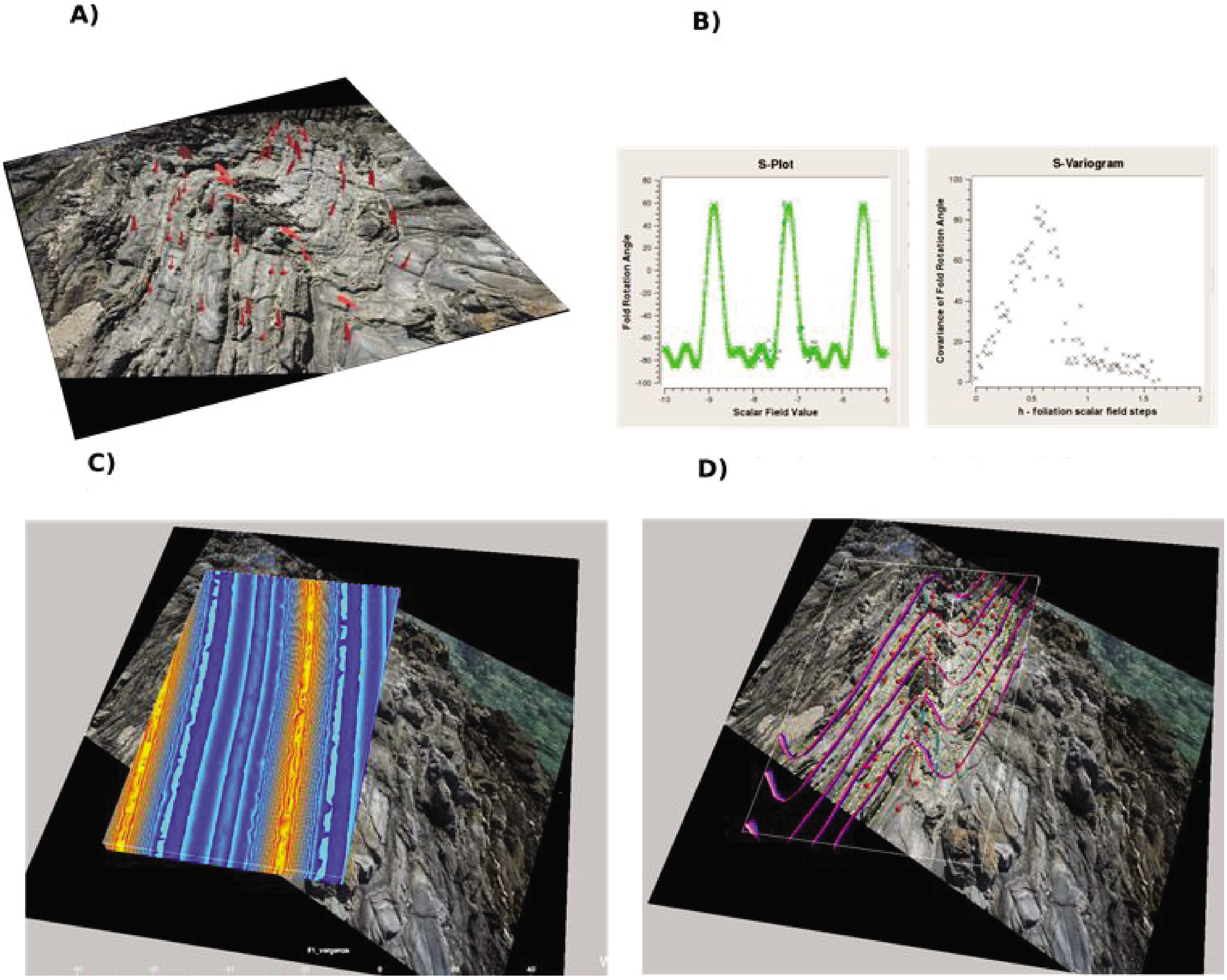

Figure 2. **Modelling poly-deformed terrane: A) Outcrop photograph and structural data representing the axial surface of a fold and bedding measurement (folded foliation). B) S-plot and S-variogram allowing to quantify the fold profile from analysis of orientation of the folded foliation (here bedding) against the modelled axial surface foliation and fold axis vector field(C). D) resulting iso-surfaces of the folded scalar field representing bedding**

Time scales and length scales in magmatic mineral systems

by

Steve Barnes[1*] and Jesse Robertson[1]

Introduction

Mineral systems are the product of multi-scale interactions of physical and chemical processes. A goal of exploration geoscientists is to reverse-engineer theses systems in order to recognise and detect the critical signals of these processes. Underpinning the science is a very simple principle: in attributing a particular effect to a particular cause, both most be operating at similar length and time scales. Thinking of mineral systems in this way allows us to arrive at some useful conclusions. We illustrate this principle first in general terms then by specific reference to magmatic Ni–Cu–PGE sulfide mineral systems.

Any major physical system can be represented on a plot of length scale vs time scale (Fig. 1). Sets of processes that make up major Earth system processes — atmospheric circulation, ocean dynamics, tectonic cycles and mineral transformations — plot along linear arrays on this diagram. The slope of each array is related to the resistance to change within the system, which is controlled by viscosity, in the case of fluid systems, or diffusivity in chemical systems. These are analagous in the sense that viscosity is a measure of the diffusivity of momentum. From fast to slow, atmospheric dynamics are limited by the viscosity of air, ocean dynamics by the viscosity of water, tectonics by the viscosity of the mantle, and mineral reactions by chemical diffusivities.

We apply this principle to magmatic processes in Figure 2, identifying a range of processes that operate from the scale of LIP-forming mantle plumes to grain-scale processes within the magma or country rock. Processes can be dividied broadly into three groups controlled by four different properties: chemical and thermal diffusivity, and magma and crust/mantle viscosity.

Application to magmatic mineral systems

Applying the scale-dependence principle, and adding a second one, that the fastest process at a given scale wins out in any competition for chemical or thermal components, we can draw some conclusions about the role of various mechanisms in ore formation. Magmatic Ni-sulfide systems require a source of sulfur from country rocks, and a number of mechanisms have been proposed, including volatile transport from pyrite breakdown in thermal aureoles, diffusion of liberated sulfur through country rock, and direct incorporation of sulfide-bearing xenoliths through stoping or wall rock spallation, followed by melting of the xenolith. Following the scaling principle, it is clear that direct melting of xenoliths is by far the fastest process (Robertson et al., 2015), although it overlaps in length–time space with the process of thermomechanical erosion of immediate footwall rocks beneath lava flows. Xenolith melting falls on the overlap between the magma viscosity and thermal diffusivity control domains, and consequently is a slower process than the flow of the assimilating magma, which falls entirely within the magma viscosity domain. Hence, it is likely that sulfidic xenoliths are liable to be transported some distance from their site of incorporation before they have time to melt and release all of their sulfides as molten sulfide liquid. Subsequent enrichment of this liquid depends on processes of chemical diffusion in the magma, one of the slower classes of process. Hence, proximity to sulfide assimilation sites is not a sufficient indication of proximity. We need multiple cycles of transport, equilibration and deposition, extending the time available for chemical diffusion, to form giant deposits such as Norilsk.

Can this type of analyses find ore deposits? The short answer is not directly, but awareness of the scaling imperative in genetic thinking greatly helps our understanding of processes in multi-scale mineral systems and helps us avoid spurious cause–effect attributions. Useful thinking about mineral systems needs to be multi-scale in time and in space.

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1 CSIRO Mineral Resources

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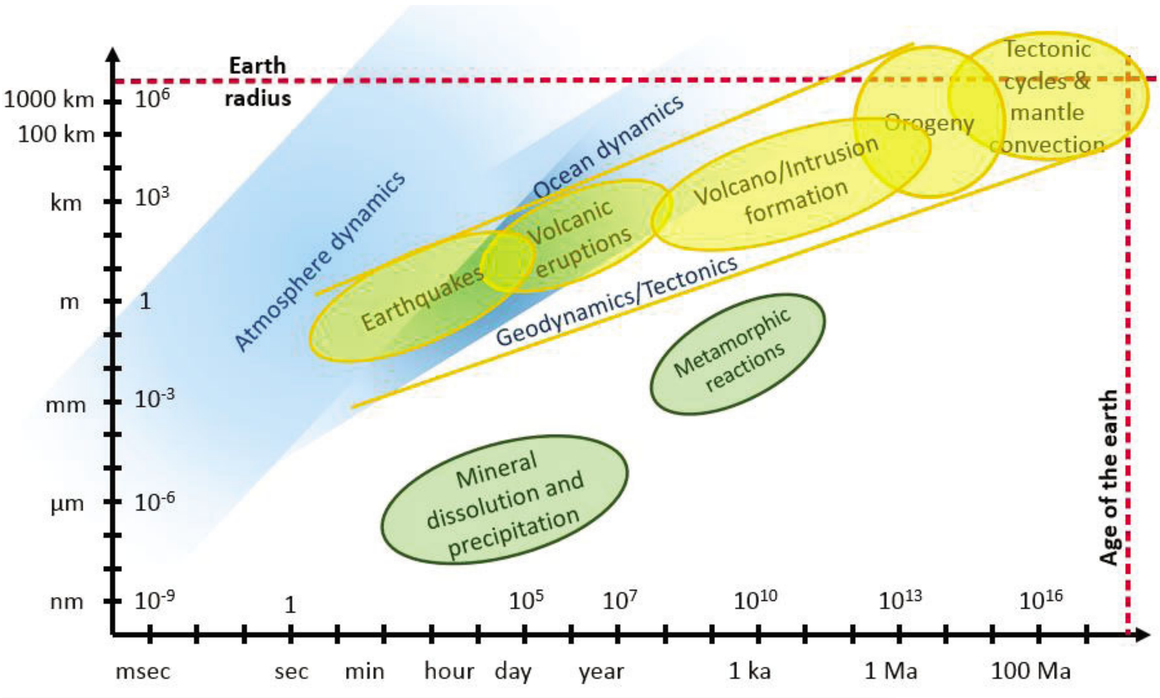

Figure 1. **Time and length scales of major Earth system processes.**

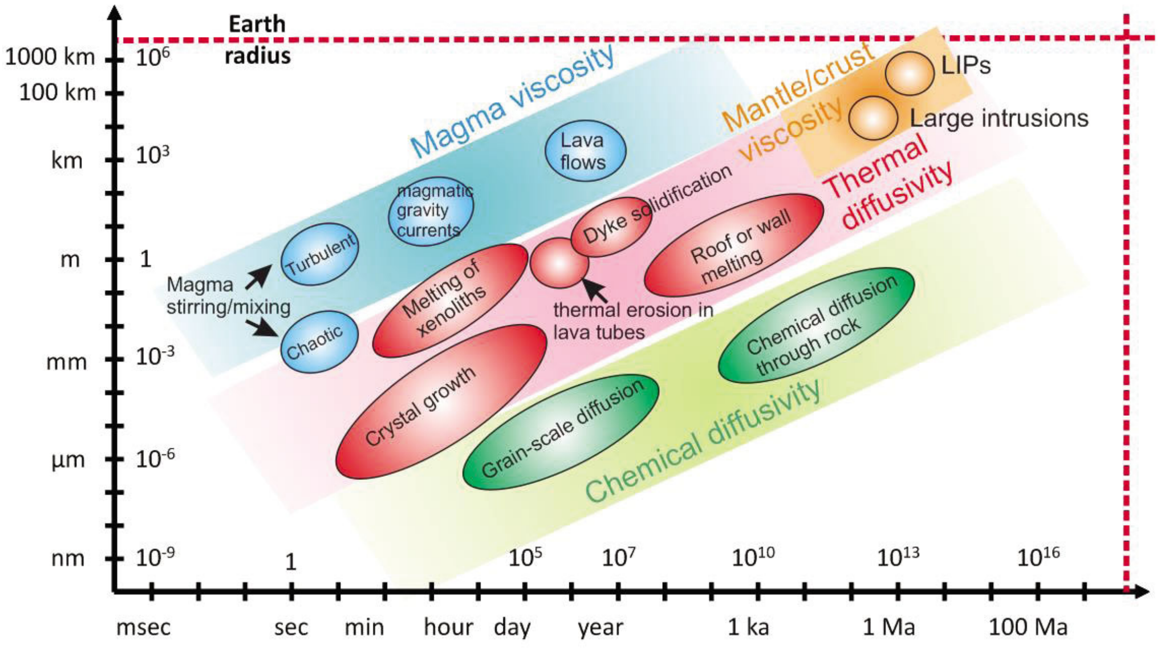

Figure 2. **Time and length scales of processes important in magmatic sulfide mineral systems**

Mappable alteration patterns linked to CO_2 metasomatism in both oxidized and reduced high grade Archean gold systems

by

Adam B Bath[1*] , John L Walshe[1] and John Miller[1]

Alteration zonation patterns and paragenetic relationships demonstrate that zones of metasomatism related to the deposition of gold are spatially larger than the deposits themselves. These alteration patterns reflect chemical gradients (e.g., redox, pH and $fCO_{2(g)}$) that occurred in gold systems, relating to the precipitation of gold along key structures. The Athena and East Repulse deposits from the St Ives Camp (Fig. 1) show evidence of these chemical gradients. Notably, the Athena deposit is dominated by reduced alteration assemblages (e.g., pyrrhotite with positive $\delta^{34}S$ values), whereas the East Repulse deposit is dominated by oxidized assemblages (e.g. anhydrite, barite and pyrite with strong negative $\delta^{34}S$ values). Despite key differences in mineralogy and isotopes, both deposits show similar alteration patterns with respect to Ti-bearing phases. Both deposits show lode-bearing rutile–ilmenite zones, peripheral ilmenite zones, outer-peripheral ilmenite–titanite +/- pyrophanite zones and an outer-most titanite-only zone in the hangingwall. Based on thermodynamic modelling, alteration assemblages in lode zones containing rutile-ilmenite equilibrated under conditions where $fCO_{2(g)}$ was highest, whereas titanite was in equilibrated under conditions where $fCO_{2(g)}$ was lower. Hence Ti-phase zonation patterns can reflect $fCO_{2(g)}$ chemical gradients, and fluids with high $fCO2_{(g)}$ are considered to be a key component of orogenic gold systems (e.g. Phillips and Evans, 2004; Goldfarb and Groves, 2015). Importantly, these $fCO_{2(g)}$ gradients are not reflected in whole rock Ti, Mn, CO_2 abundances or modal abundance of carbonate, indicating a key method to map $fCO_{2(g)}$ chemical gradients is via mapping of Ti-bearing phases.

Deposit-scale mapping of the Ti-bearing phases at the Athena Deposit shows evidence of a stacked system of shears in the footwall, with three notable ilmenite-rutile or ilmenite zones occur in the footwall, and an ilmenite-titanite +/- pyrophanite zone at approximate 900 meters away from the main deposit (Fig. 2). These zones highlight the potential to detect or track structures that cross-cut the Paringa Basalt away from the Athena deposit.

The East Repulse deposit shows rutile-bearing domains in vertically dipping granitoid dykes in the footwall of the deposit. These vertically dipping granitoid dykes are inferred to be the conduits for oxidized CO_2–SO_2 fluids (Bath et al., 2013). These fluid pathways are traceable using S-isotopes and fluorine, with pyrite with strong negative S-isotope values ($\delta^{34}S$ of <-10 per mil) evident within the footwall of the deposit and detected at depths of greater than 200 meters into the footwall of the deposit. The lode-zone contains ilmenite-rutile and pyrites that contain inclusions of gold along growth zones. These pyrites have strong negative S-isotope values ($\delta^{34}S$ of -8 per mil) and occur with fluorine-rich biotite, linking oxidized and fluorine-rich fluids to the gold event along the Repulse thrust. The East Repulse deposit contains a hanging wall with positive $\delta^{34}S$ values ($\delta^{34}S$ of 0 to +3 per mil.) within a peripheral titanite–ilmenite domain, and an outer titanite zone. The footwall of the deposit contains ilmenite–rutile, titanite and rutile–titanite domains, which is consistent with the contention that CO_2-fluids have exploited pathways within the footwall of the deposit.

Here we show that Ti-bearing phases and textural data can be accurately and relatively rapidly mapped using the SEM on diamond drill core. Recent work has demonstrated that detailed mineral mapping can be expanded and to include reverse circulation and air core chips, allowing detailed mineral mapping done at the camp-scale. These detailed data-set can be used to build maps that add to existing mineralogical/geochemical data-sets (e.g. hyperspectral and multi-element geochemistry) as well as structural and geophysical work. Detailed mineral mapping can be done on samples (i.e. 20 minutes per sample) using lab-based instruments such as the automated Tescan Intergrated Mineral Analyser (TIMA) SEM on relatively fresh material.

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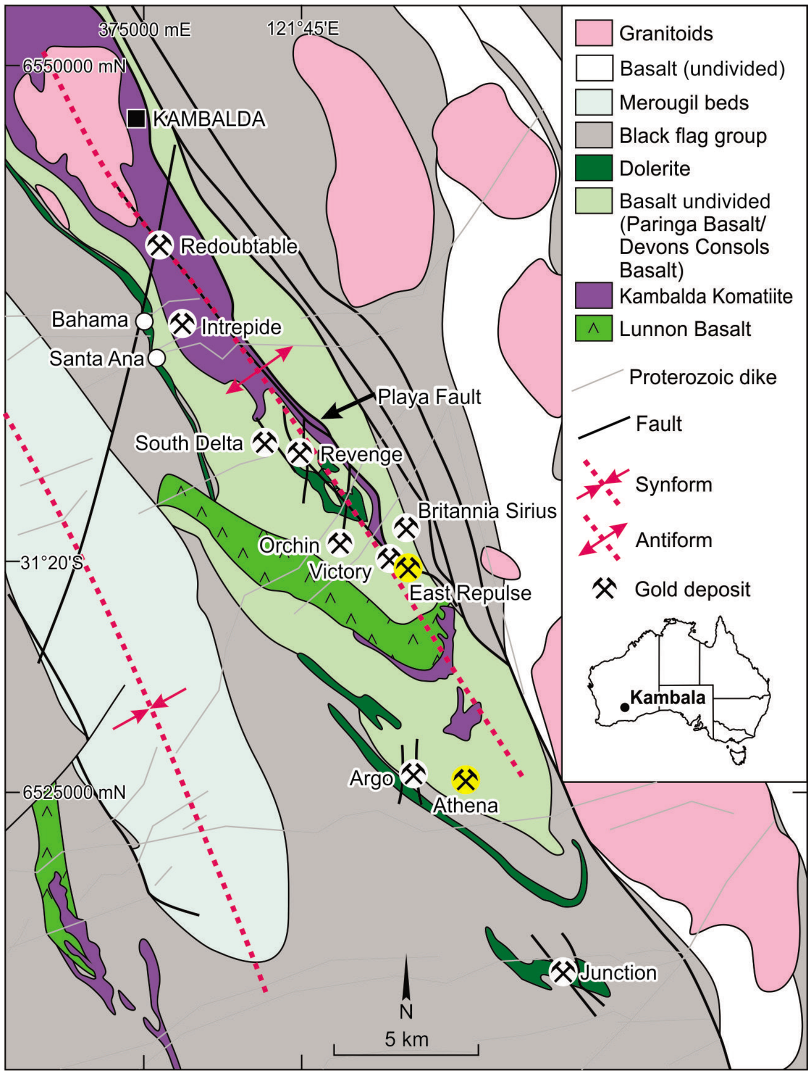

Figure 1. **Geological map of the Kambalda area showing the location of the Athena and East Repulse deposits relative to other gold deposits/prospects (modified from Neumayr et al., 2008 and <http://www.dmp.wa.gov.au>)**

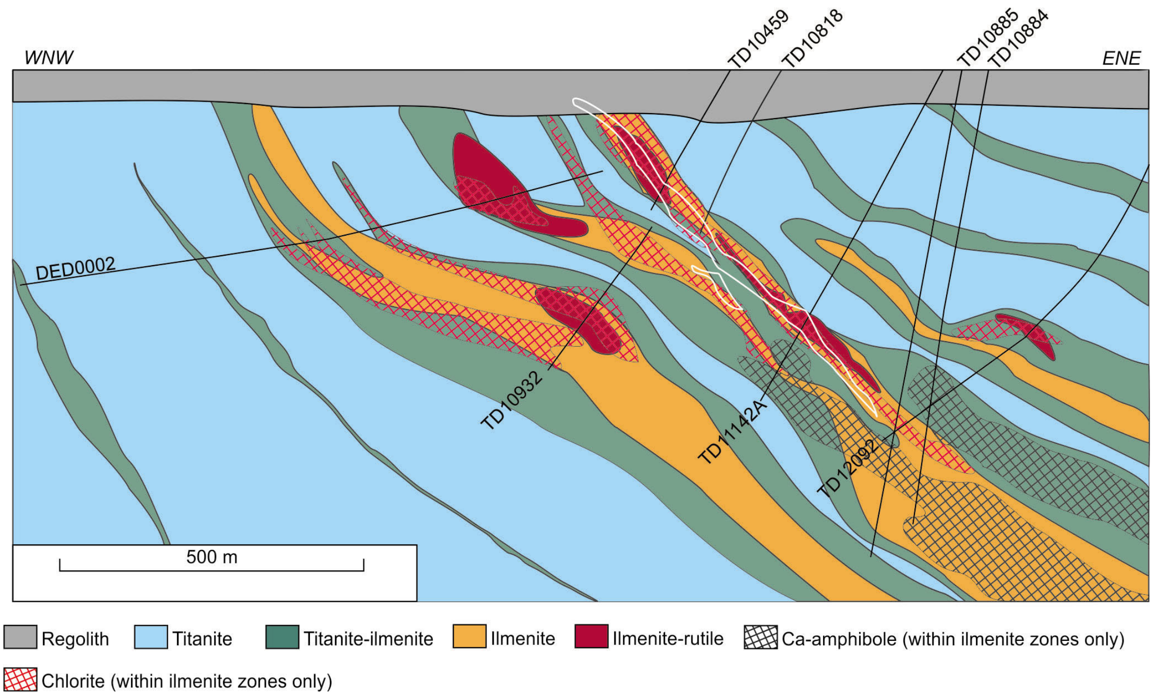

Figure 2. **East–west cross-section through the Athena deposit that also shows the distribution of Ti-phases with a single rock type (i.e. Upper Paringa Basalt).**

How semantic technology makes geodata more discoverable, more useful and more valuable

by

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Baseline geodata, such as geological, geochemical and geophysical data, is an essential pre-requisite in mineral exploration. Regional-scale geodata acquisition, for example, airborne geophysical surveying, or lithogeochemical sampling at kilometre spacing intervals, is an expensive and time-consuming process, typically costing millions of dollars. These data should ideally be freely available for access by an exploration company, but the reality is that they are sometimes difficult to obtain and can be poorly managed and stored by a GSO (Geological Survey Organisation).

Geodata will continue to grow in importance as we move into the 21st century since exploration managers and geologists will increasingly have to look in areas where deposits are concealed. However, whilst the collection of this geodata is important, it is even more important to understand and maximise the value of these data.

Semantic technology is a well-known and trusted tool used in many sectors including pharmaceutical process design and in financial prediction. Broadly speaking, semantic technologies encode meaning into content and data to enable a computer system to possess human-like reasoning, and effectively allow them to 'understand' the data they process. This makes them potentially ideal to be used in the mineral exploration sector, where prospectivity studies are typically completed following labour-intensive and time-consuming desktop studies.

Currently, only GIS-based methodologies exist in assisting with these prospectivity studies, but these are typically statistical, multivariate mathematical or neural network approaches which do not consider relationships between data. Semantic technology offers a novel approach in mineral exploration by considering the relationships between data and by using knowledge modelling that allows automated processing of data using that knowledge. This allows for a deeper understanding of the data, which can therefore be used with more confidence.

To address the dual challenge of exploring for increasingly hard to locate mineral deposits and more effectively using available geodata, we have developed a new and innovative mineral prospectivity software called IGS Xplore which uses semantic technology. IGS Xplore is a unique knowledge-based software application that examines geodata-sets using a set of well-established, non-statistical, empirically-based geological rules governing up to 50 known mineralization models worldwide, ensuring that generated mineral prospectivity areas are not theoretical constructs but are based on actual geological conditions.

The semantic technology used by IGS Xplore uses inference processes to automatically enrich geodata with geological meaning, discover new relationships between geodata and generate more comprehensive, descriptive data models. Other geological softwares lack inbuilt inference mechanisms for geological knowledge application. Furthermore, storing complex and varied datasets requires a level of interoperability and extensibility that only semantic technologies can offer. IGS Xplore also allows full traceability of prospectivity process and outcomes compared to statistical and neural analyses, which are typically 'black box' solutions. All targets and prospects identified through analyses in IGS Xplore can be confidently traced back to their origin in the geological rules.

We have recently released a series of base-metal prospectivity maps for the Ngamiland District of northwestern Botswana using free geodata available on the recently-launched Botswana Geoscience Portal, hosted by Geosoft (Fig. 1; Williams, 2016). The new prospectivity maps connect and interpret the datasets available on the Portal to bring out the potential of the data and add value. What is key about these mineral prospectivity maps is that they give industry an indication of the Greenfield opportunities in underexplored or covered terrains. Since launching in August 2016, over 800 downloads of these data from the portal have been undertaken, highlighting the interest that this area is now gaining.

Using semantic technology in mineral exploration will enable a greater understanding of favourable locations for mineral deposits using existing geodata sources to maximise the value of acquiring these data.

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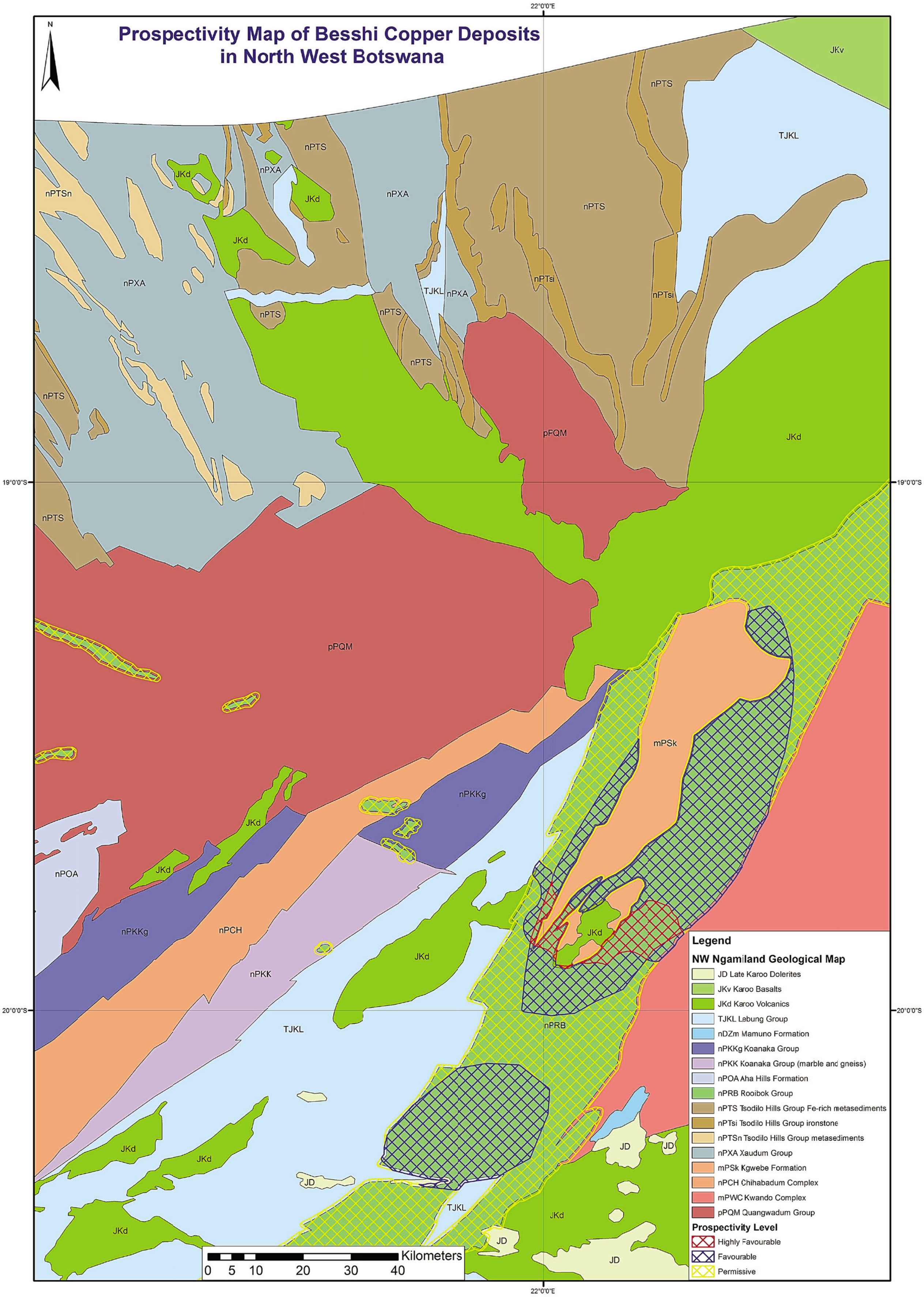

Figure 1. Prospectivity Map of Besshi Copper Deposits in North West Botswana

The OSNACA Project: Navigating in Magmato-Hydrothermal Space

by

Carl Brauhart[1]

Introduction

Multi-element geochemistry is one of the most powerful tools available to an exploration geologist, but it is also one that many skilled and seasoned practitioners struggle with. The Ore Samples Normalised to Average Crustal Abundance (OSNACA)-transform is very straightforward as far as computational geoscience goes: it can be calculated in a simple spreadsheet, but it is a very useful tool for quantifying differences between ore deposit signatures. One key advantage of the approach described here is that variations in ore-element signatures can be mapped for a single ore deposit, a whole ore-deposit class, or across all ore deposit classes.

OSNACA transform

Magmato-Hydrothermal Space (MH-Space) is a mathematical construct which, in this example, discriminates ore-signatures with 24 ore and pathfinder elements: Fe, Co, Ni, Re, Pd, Pt, Cu, Ag, Au, Zn, Cd, In, Pb, Tl, Hg, As, Sb, Bi, Te, Mo, W, Sn, La, U. These elements have been selected to characterise metal enrichment patterns in most classes of metallic ore deposit but the technique can be adapted for a greater or lesser number of variables as required. The OSNACA transform has four steps:

1. replace data below average crustal abundance (ACA) with ACA, or half the limit of detection, whichever is higher,
2. normalise to ACA or half the limit of detection, whichever is higher,
3. transform by log10 for elements with ACA <1 ppm, and logx for elements with ACA > 1ppm (rare instances of log scores greater than 6 are cut to 6), and
4. scale to a fixed distance (10 units) from the origin.

The value of x in logx is chosen such that a concentration of 100% returns a log score of 6. Average crustal abundance values are those of Rudnick and Gao (2003). For the data presented here, half the limit of detection is higher than ACA for Re (0.005 ppm) and Te (0.01 ppm).

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Data below ACA are censored in Step 1 to reduce the effect of lithological signals. If the aim of the exercise is to model all of the variation in a dataset, all available elements should be included and no censoring should be applied. However, in the case of modelling ore-element signatures, only a select suite of elements is relevant and even for these elements some of the variation in the data relates to other factors such as host rock. The aim of the OSNACA transform is to create a metric in Step 3 where all 24 elements are similarly scaled between zero and six, such that each step above zero represents a comparable enrichment above ACA. It is acknowledged that 'ore-grade' varies with geography, metallurgy, economic conditions and many other factors, but the OSNACA scores provide a universal framework with which to compare mineralised samples.

A further aim of the OSNACA Transform in Step 4 is to scale the data to a fixed distance from the origin so that the Euclidean distance between any two points is a measure of geochemical similarity. Two samples with similar ore element signatures define enrichment vectors in similar directions away from the origin (ACA) and have a small distance between points (Fig. 1).

Global example

Data from the OSNACA database have been used to create a global map of Magmato-Hydrothermal Space (Fig. 2). Any hypogene (unweathered) metal-enrichment produced by nature has a sensible position in this framework. Coloured wireframe models enclose populations of data corresponding to each major ore deposit type.

The first global view of Magmato-Hydrothermal Space shows a transition from MVT samples, through SHMS and VHMS samples to samples of Cu–Au-rich mineralisation. A second "arm" of this continuum extends away from Cu–Au-rich mineralisation through Orogenic-Au samples to the Carlin-Au sample population. These are two of the major trends identified in Magmato-Hydrothermal Space; Zn to Cu–Au and Cu–Au to Au only (Fig. 2). The majority of Epithermal samples define a population that connects these two trends by extending from Carlin-Au and Orogenic-Au across to the VHMS and SHMS sample populations. A smaller group of Cu-rich Epithermal samples overlaps with the Porphyry-Cu population.

A third major trend in MH-Space, from Ultramafic to Felsic, extends from the Magmatic Ni–Cu–PGE population through IOCG and Orogenic-Au samples to Porphyry Cu and more felsic variants of Orogenic-Au and IOCG, to Porphyry-Mo and Sn-W deposits (Fig. 2b). Most samples in this view lie along the main 'hydrothermal

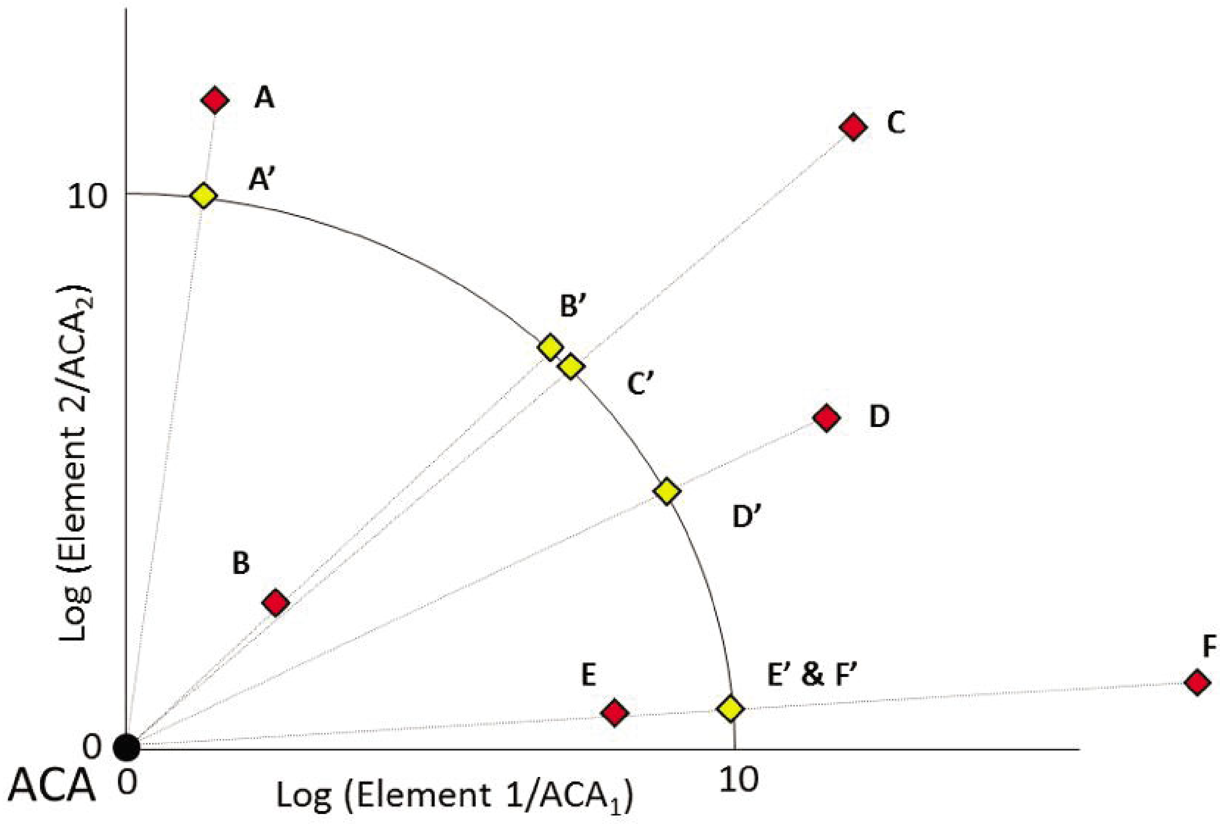

Figure 1. Schematic illustration of scaling two elements in the OSNACA-transform

plane', with ultramafic associated mineralization below and granite associated mineralization above. The main 'hydrothermal plane' contains the Zn to Cu-Au and Cu-Au to Au only trends shown in Fig. 2a, but in Fig. 2b the transition from sediment-associated to igneous-associated deposit types is more obvious.

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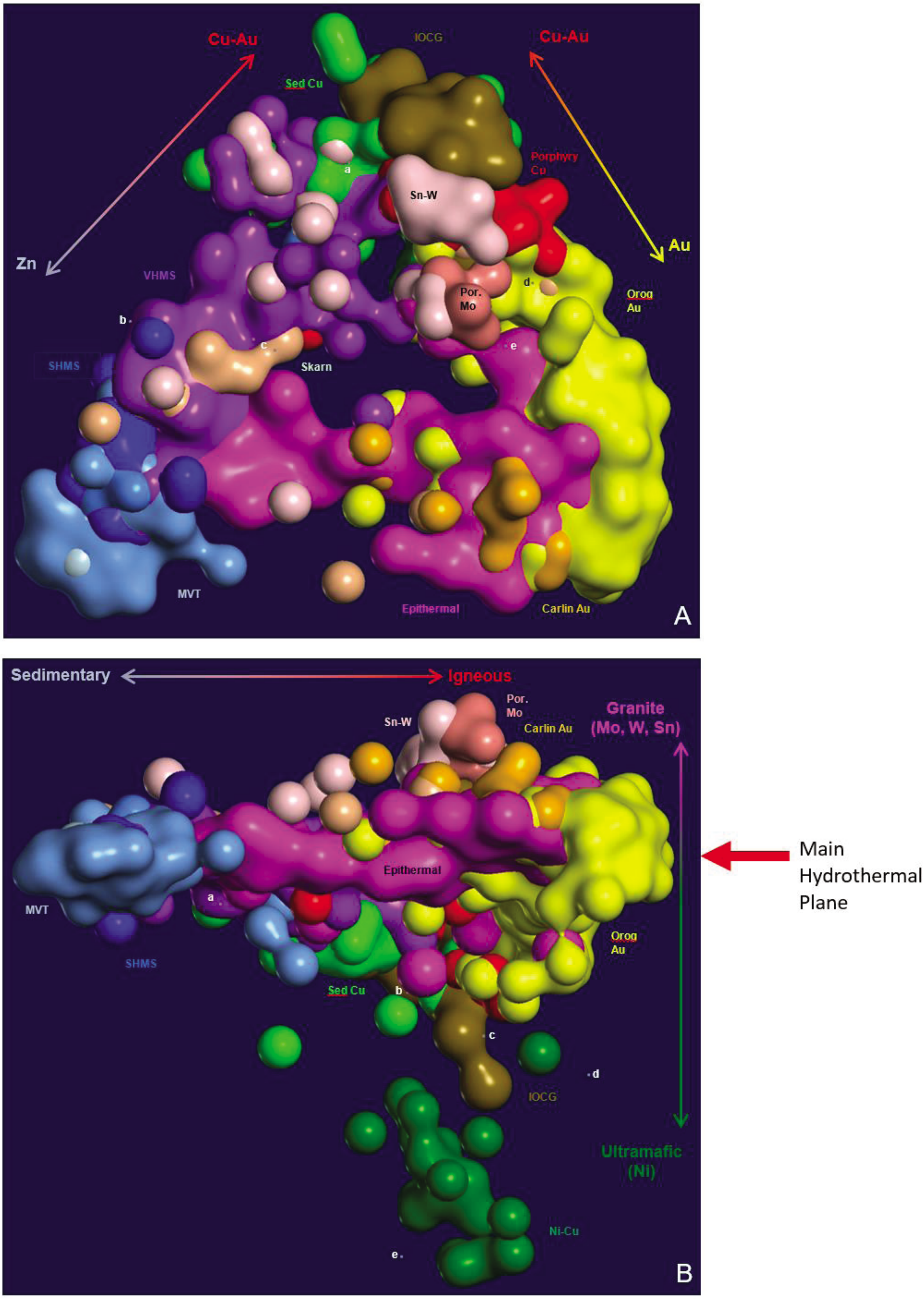

Figure 2. **Two views of Global MH-Space showing distribution of ore deposit classes**

Using potential field modelling to constrain the architecture of the Albany–Fraser Orogen

by

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Forward and inverse potential field modelling methods allow us to image lateral density and susceptibility contrasts in the crust. This is of critical importance when an understanding of lower crustal architecture is required to relate tectonic history with structurally controlled mineral systems, particularly undercover. Here we use unconstrained potential field inversion and regional, constrained gravity modelling to image the crustal structure of the east Albany–Fraser Orogen, the Proterozoic reworked margin of the Archean Yilgarn Craton that hosts the Tropicana gold deposit and the Nova–Bollinger Ni–Cu–Co deposit. Our results confirm the existence of significant unexposed lower crustal features, both along and perpendicular to the northeast strike of the Albany–Fraser Orogen.

Unconstrained potential field inversion

Unconstrained magnetic and gravity inversion provides 3D density and susceptibility property models of the subsurface that are rapid to obtain and can often be related to outcrop data. Unconstrained gravity and magnetic inversion has focussed on the Fraser Zone, host to the Nova–Bollinger deposit and target of Ni–Cu–Co exploration. Results from density models show that it is possible to image the broad geometry of the Fraser Zone, as well as internal density variations that are most likely due to changes in rock type. Magnetisation contrasts in the Fraser Zone are largely structurally controlled and susceptibility models can provide constraints on the orientation of these structues at depth.

Constrained gravity modelling

A 3D geological model of the east Albany–Fraser Orogen and southeast Yilgarn Craton margin has been constructed in GeoModeller (Fig. 1). Geological constraints on the model include an interpreted bedrock geology map, three interpreted active seismic sections (13GA-AF1/2/3; Spaggiari et al, 2014) and the Moho model obtained by passive seismic imaging methods (Sippl et al., in review). The model was tested and modified using forward and inverse gravity modelling methods. Our results show that first-order gravity anomaly data along this margin can be produced by the superposition of several features that, in addition to the dense upper crustal Fraser Zone, include a northeast trending Moho trough, a dense unit that occupies the Moho trough and a northwest trending Moho ramp beneath the Albany–Fraser Orogen (Fig. 1). These features and some of the tectonic processes that may have formed them are considered in more detail below.

An important feature of the model is the northeasterly trending Moho trough that extends along the Yilgarn Craton margin, parallel to the Albany–Fraser Orogen (Sippl et al., in review). Gravity forward modelling suggests that this Moho trough is responsible for the long wavelength gravity low observed along the margin of the Yilgarn Craton. This zone of thickened crust is interpreted to have formed during Proterozoic crustal shortening that resulted in thrusting of the middle and upper crust of the Albany–Fraser Orogen over the Yilgarn Craton and underthrusting of the Albany–Fraser Orogen lower crust beneath the Yilgarn Craton in a 'crocodile tectonics' (Meissner, 1989) process that formed a crustal scale wedge in the Yilgarn Craton.

Another feature of the model is a dense, non-reflective unit within the Moho trough, in the lower crust of the Yilgarn Craton (Murdie et al., 2014; Spaggiari et al, 2014). This dense lower crustal unit extends along the margin of the Yilgarn Craton, parallel to the Albany–Fraser Orogen and may represent an underplate emplaced into the Yilgarn Craton lower crust during Proterozoic crustal extension. It is possible that this extensional and magmatic event weakened this region of crust, making it the focus of subsequent crustal thickening.

A final feature of the model is an approximately northwesterly trending ramp in the Moho beneath the Albany–Fraser Orogen. This structure is orthogonal to the dominant northeast strike of the Albany–Fraser Orogen but parallel to the dominant strike in the Yilgarn Craton. Constraints on the Moho are quite sparse in this region, and interpretation is further complicated but the superposition of the Moho trough. Despite this, it is possible the Moho ramp is a continuation of the Ockerberry Fault system that separates the Kurnalpi and Kalgoorlie Terranes of the Yilgarn Craton.

Conclusions

- Unconstrained potential field modelling of the Fraser Zone allows us to image its broad geometry and some internal structures.

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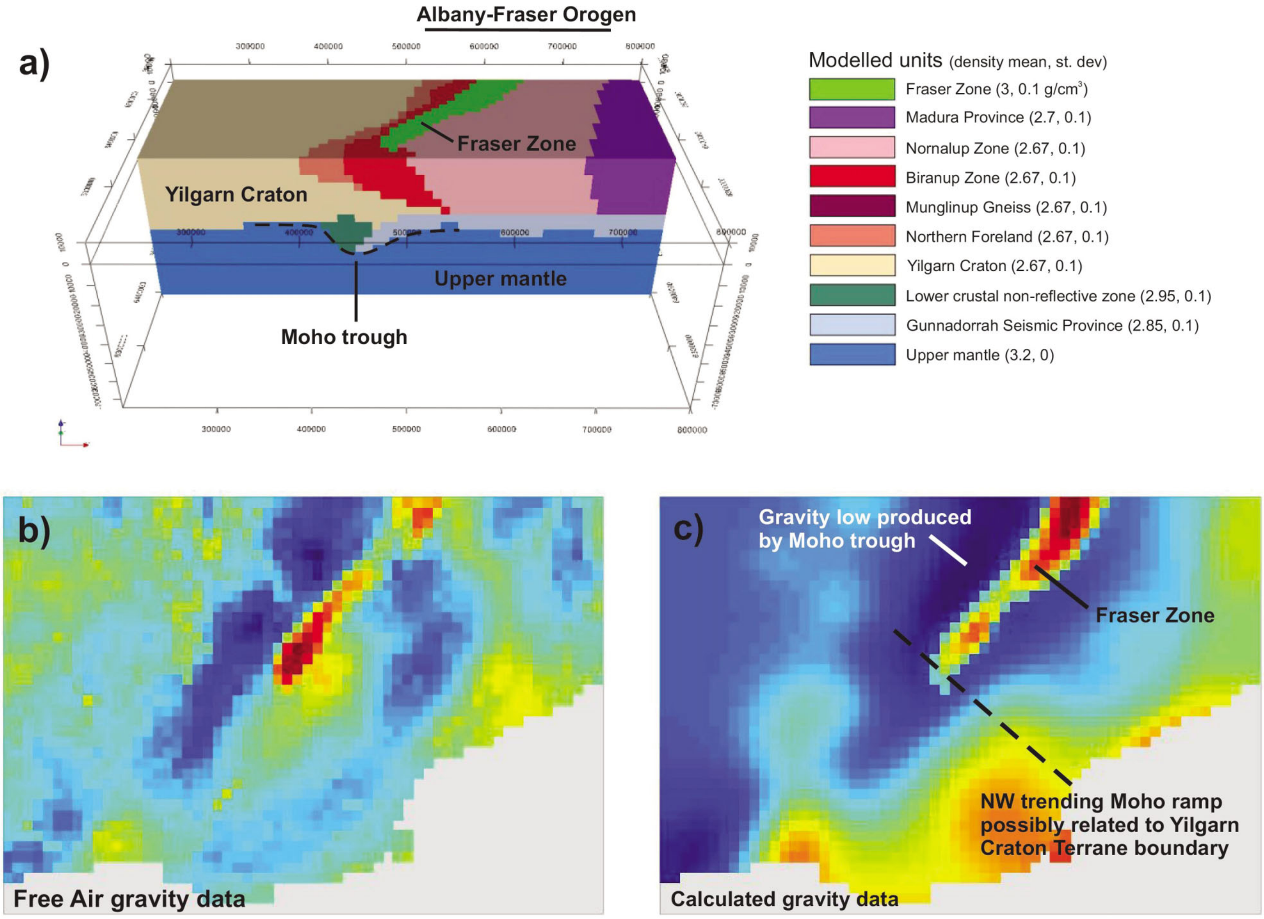

Figure 1. a) Constrained model of the southeast Yilgarn Craton and east Albany-Fraser Orogen, showing units and densities used in preliminary gravity forward modelling; b) observed free air gravity data and c) gravity calculated from preliminary model shown in a).

- Constrained forward and inverse gravity modelling allow us to image, test and modify the 3D crustal architecture of the southeast boundary of the Yilgarn Craton and the east Albany–Fraser Orogen.
- The structures and geometries determined using these methods can be used to constrain tectonic processes preserved along the margin and possibly inform future exploration.

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Creating exploration tools from data and knowledge: an example using a mineral systems analysis of nickel-sulfide prospectivity for the Eastern Goldfields Superterrane

by

L Burley[1*], P Duuring[1] and T Beardsmore[1]

The stratigraphy and nickel endowment of the Kurnalpi, Burtville and Yamarna Terranes of the Eastern Goldfields Superterrane are less well understood compared with the Kalgoorlie Terrane, which hosts some of the largest and best documented nickel deposits in Western Australia. However, the occurrence of large mafic–ultramafic belts and recently discovered nickel sulfide occurrences in these eastern terranes raises the possibility that they may be as equally prospective for large nickel sulfide deposits, and simply underexplored.

The Geological Survey of Western Australia is examining the prospectivity of the Kurnalpi, Burtville and Yamarna Terranes for komatiite-hosted nickel deposits, using a mineral systems approach (Wyborn et al., 1994; Barnes et al., 2016). There are at least 50 potential mappable geological proxies for critical mineralizing processes that could be derived from available data, of which five are considered particularly useful on the basis of their representativeness of critical elements, wide applicability at various scales of exploration, and relative ease of generation as GIS layers: (i) komatiite occurrence; (ii) whole rock MgO wt%; (iii) whole rock Mg# (defined as MgO/(MgO+FeO)); (iv) komatiite texture; and (v) komatiite volcanic facies. High Mg content and olivine-cumulate textures signal the likely presence of cumulate-rich komatiites, which are indicative of high flux magma pathways, the preferred environment for localizing nickel mineralization (Hill, 2001). Nickel mineralization is also preferentially restricted to just two of the five komatiite volcanic facies environments described by Barnes et al. (2004), making facies maps particularly important in the exploration for these deposits.

Figure 1 illustrates an example of a preliminary product combining several critical element proxies for komatiite-hosted nickel mineralizing processes in the Eastern Goldfields Superterrane, using data collected by the Geological Survey. It is clear from this initial regional-scale analysis that ultramafic rocks occur in association with large volumes of mafic igneous lithologies, indicating voluminous magmatism. Where these areas have been intensively sampled (e.g. east of Kalgoorlie; Fig. 1), the highest MgO% values correlate with mapped ultramafic rocks. A peak MgO% of 37.1% occurs near the Murrin Murrin nickel deposit, but elevated MgO% values occur in ultramafic rocks throughout all the domains. The spatial correlations between these key proxies for mineralization imply that some areas of the Kurnalpi, Burtville and Yamarna Terranes are highly prospective for komatiite-hosted nickel deposits. Work continues to develop similar maps for Mg#, komatiite texture and komatiite facies.

Another useful outcome of this work is an analysis of gaps in the availability of data. Prospectivity mapping is inherently biased towards regions of greater data density, yielding incomplete and inaccurate results. The study to date has identified 11 areas where critical data are lacking, including the greenstone belts containing the Roe Hill and Mulga Tank nickel prospects, and a small, as yet untested patch of ultramafic rocks in the northeast of the Eastern Goldfields Superterrane (Fig. 1). Ongoing work will therefore include appropriate mapping and sampling of these areas.

The development of these new GIS-based mineral systems maps should improve our understanding of the geology and potential nickel prospectivity of these potentially highly mineralized terranes, and hence help explorers to discover significant komatiite-hosted nickel deposits in this historically underappreciated part of the Eastern Goldfields Superterrane.

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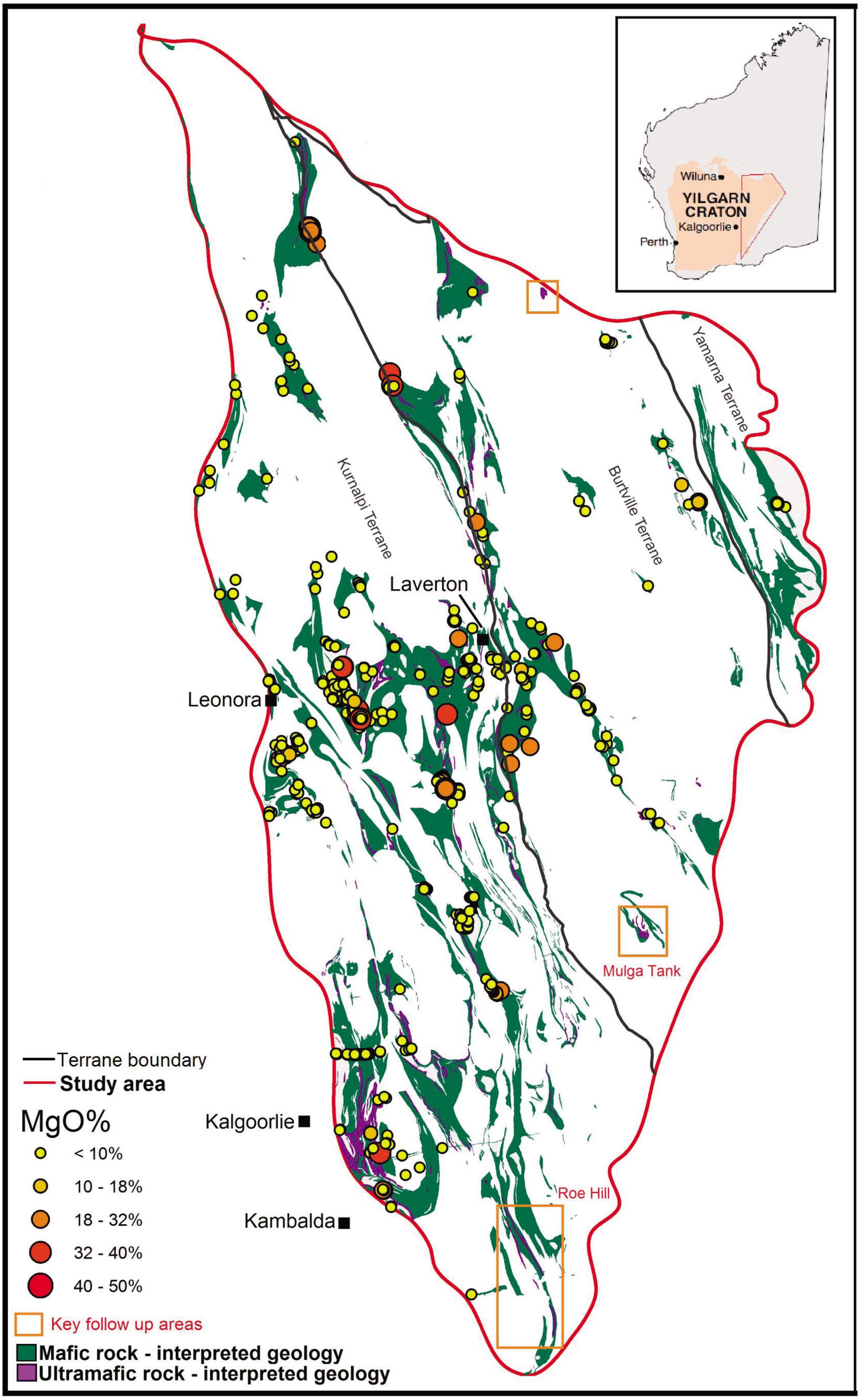

Figure 1. Mafic–ultramafic rock occurrence map for the eastern domains of the Eastern Goldfields Superterrane, with MgO% for mafic and ultramafic rocks overlain. Orange boxes depict areas for follow-up work

Thinking and targeting on the lithospheric scale, using precompetitive data

by

Ross Cayley[1]

Australia's easy-to-find giant mineral and energy deposits have already been found. They either stick out of the ground or have characteristic geophysical or geochemical signatures so that discovery did not depend on a greater systems understanding. There will be other giant deposits, but buried, cryptic, disrupted. Some will lie beneath regions no-one is currently exploring because they don't know any better...yet. Finding these, generating the confidence and knowledge to invest in exploration beneath deep cover far from regions of outcrop, requires greatly enhanced predictive capacity born of lithospheric-scale understanding. This can only come from greatly improved regional-scale data and modelling integration, and geological systems analysis. To achieve this, and for ambitions such as UNCOVER to deliver, methods for remote sensing of geology at regional scales must be deeply integrated with directly sampled data. Precompetitive geophysical and geological datasets are the key enablers in Australia. Geological interpretations (models) must be iterative, developed within the context of modern and evolving understandings of plate tectonic processes and the legacy these processes might leave in the ancient rock record. Understanding the ambiguities and limitations inherent in different data types, and understanding the nature of interplays that can operate within active geological systems is critical. The concept of scale-invariance in geology (particularly for stress-mapping) means that robust interpretations developed in discrete areas of excellent data (exposure) might be upscaled to constrain continent-scale geodynamic models, and downscaled to inform province or even mine-scale mineral systems analysis. This talk explores the complexities of such aspirations and tries to address some of the challenges, using research workflows developed in Victoria that resulted in the Lachlan Orocline concept as an example.

Precompetitive data in Australia

Precompetitive geological data in Australia has been collected routinely since the inception of Government Geological Survey organisations in the mid-19th century. From the earliest days of the gold rushes Government recognised that factual geological data collected systematically at scales much larger than any single mining claim could cover was critical for mining enterprises to succeed. The earliest investigations produced the most fundamental of all precompetitive geological data: geological maps - tools to get prospecters and land planners started, hopefully in the right place. One hundred and seventy years on, government and other research organisations still produce fundamental precompetitive geological data. Understanding of geological processes, and the quiver of tools and research organisations available to help investigate them, has expanded almost beyond the limits of imagination, but the fundamental motivation and need remains the same. Geological 'maps' now have more dimensions, but are still the staple. Today, precompetitive data and knowledge is collected by government agencies such as Geoscience Australia and State Geological Surveys, by Universities, CSIRO, and under the auspice of enablers such as AUSCOPE, the ARC and various Collaborative Research Centres. Australia's vast size, flat landscape and poor rock exposure means that acquisition of precompetitive geophysical survey data — airborne magnetics, gravity, EM, regional seismic reflection and refraction transects, MT — has been long-recognised as a priority for the continent. Work-to-date has already delivered what is probably the World's best regional-scale geophysical data coverage. Australia is also at the forefront of interpreting that data. As data continues to build, regional-scale precompetitive geophysics data will remain the go-to tool for mineral exploration under cover, and for unravelling complex geological and metallogenic histories mostly hidden. But geophysics is not the only important modern precompetitive data. Interpretation of geophysical data is only truly meaningful when underpinned by a suite of fundamental geological data — field-based observations that provide first-hand information on: lithology, geochemistry, absolute geophysical properties (eg. density, magnetic susceptibility, radioactivity), structural history, geochronology, metamorphic history, etc. Integrating such a diversity of data correctly is a challenging multidisciplinary task. And geology is a young science, evolving rapidly. Field data is collected within the context of the scientific understanding and/or technology available at the time, which means that field-based observations have a shelf-life. Emerging new understandings require new field data. This is challenging for downsized geoscientific research organisations with limited field capacities.

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The Victorian experience

Victoria showcases the value of a workflow that deeply integrates precompetitive field-based data with strategically-planned regional geophysics data to develop a highly-informed geodynamic model for the Cambrian – Devonian – the Lachlan Orocline model. The consequences and predictions arising from this model extend well beyond the small State of Victoria to encompass nearly half the Australian continent. Active throughout the Silurian, the Lachlan Orocline reworked older geology (and contained minerals systems) in Tasmania, NSW, Queensland and South Australia, including regions that are buried under younger cover and so hardly explored.

How was it possible to develop such a large-scale model from the geology of such a small State? Partly because of fortuitous geography — the Great Dividing Range swings east-west in Victoria so that the full width of deformed Early Palaeozoic Tasmanide rocks are exposed for direct study. The opportunity exists in Victoria to locate deep seismic reflection transects in areas of outcrop, where decades of detailed study have already defined rock types, identified faults and other structures, constrained timing and relationships, and developed a range of state-scale tectonic models. The Geological Survey of Victoria, collaborating with Geoscience Australia, universities, the pmd*CRC and AUSCOPE made a conscious decision to acquire crustal-scale seismic reflection profiles in these regions of greatest understanding to test existing tectonic models (e.g. the 'Selwyn Block' concept), and to allow extrapolation of well-understood surface geology into the mid- and even lower- crust. Tight geological constraints along these transects significantly reduce ambiguities inherent in interpreting seismic data by, for example, allowing faults and rock types precisely located at surface to be traced directly to depth, and by facilitating recognition and reconciliation of out-of-plane displacements (surprisingly common!) in imaged geology. The increased confidence that results creates a virtuous cycle wherby seismic data and interpretations and field data can be fed back into the reinterpretation of potential field and other datasets (eg. aeromagnetic and gravity) to deliver tightly constrained 3-dimensional models of the subsurface.

Extending the Lachlan Orocline model to the continent

Robust 3-D maps of Victoria at crustal scale significantly reduced the ambiguity of state-scale tectonic models, allowing reinterpretation of the 4th dimension — evolution through time. It became apparent that the resulting geodynamic model could be extended interstate using existing precompetitive geological and geophysical datasets. Thus the full scale of the Lachlan Orocline became apparent. 4-D numerical models of orocline formation, developed independently by researchers at Monash University, increased confidence that the Lachlan Orocline controlled evolution of the whole Tasmanides at lithospheric scale — a brand new conceptual template for predicting the location of buried mineral systems in all of Australia's eastern States, with a 3-fold+ increase in the area of potentially prospective rocks. This model thus has profound implications for understanding the mineral prospectivity of the eastern half of the Australian continent.

Surficial uranium systems in WA: genesis, prospective tracts and undiscovered endowment

by

B Chudasama[1*], A Porwal[1], S Thakur[1,2], L Muralikrishnan[1], O Kreuzer[3] and A Wilde[4]

A geochemical model of surficial uranium genesis in the 'Deserts and Xeric Shrublands' biome of Western Australia to the north of Menzies Line is developed (Fig. 1). Knowledge-driven and data-driven GIS models are used to demarcate and rank prospective tracts in the study area (Fig. 2) Finally, the number of undiscovered deposits and endowment in the prospective tracts are quantitatively estimated.

Results and conclusions

The three-stage genetic model (Fig. 1) developed in this study describes the geochemical processes involved in leaching, transportation and precipitation of uranium in near-surface oxidizing environments. It is used to identify targeting criteria and spatial proxies for surficial uranium deposits in Western Australia. A knowledge-driven FIS model, a data-driven WofE model and a data-driven NN model are used to delineate and rank prospective targets (Fig. 2). The model identifies new exploration targets in the Paterson and Musgrave regions, apart from the well-established areas in the Yilgarn Craton. Further, quantitative estimations using three independent techniques — (1) Regression models; (2) the USGS three-part assessment; and (3) Zipf's Law — analysis indicate that there about 180 kt U resources yet to be discovered in about 69 deposits at 50% confidence level.

Table 1. Quantitative estimations of surficial uranium resources

Confidence	*USGS 3 Part Assessment*		*Regression based models*		*Zipf's model*	
	kt U	*No of deposits*	*kt U*	*No of deposits*	*kt U*	*No of deposits*
90%	78	35	0	35		
50%	171	69	50	69	189	171
10%	292	123	168	123		

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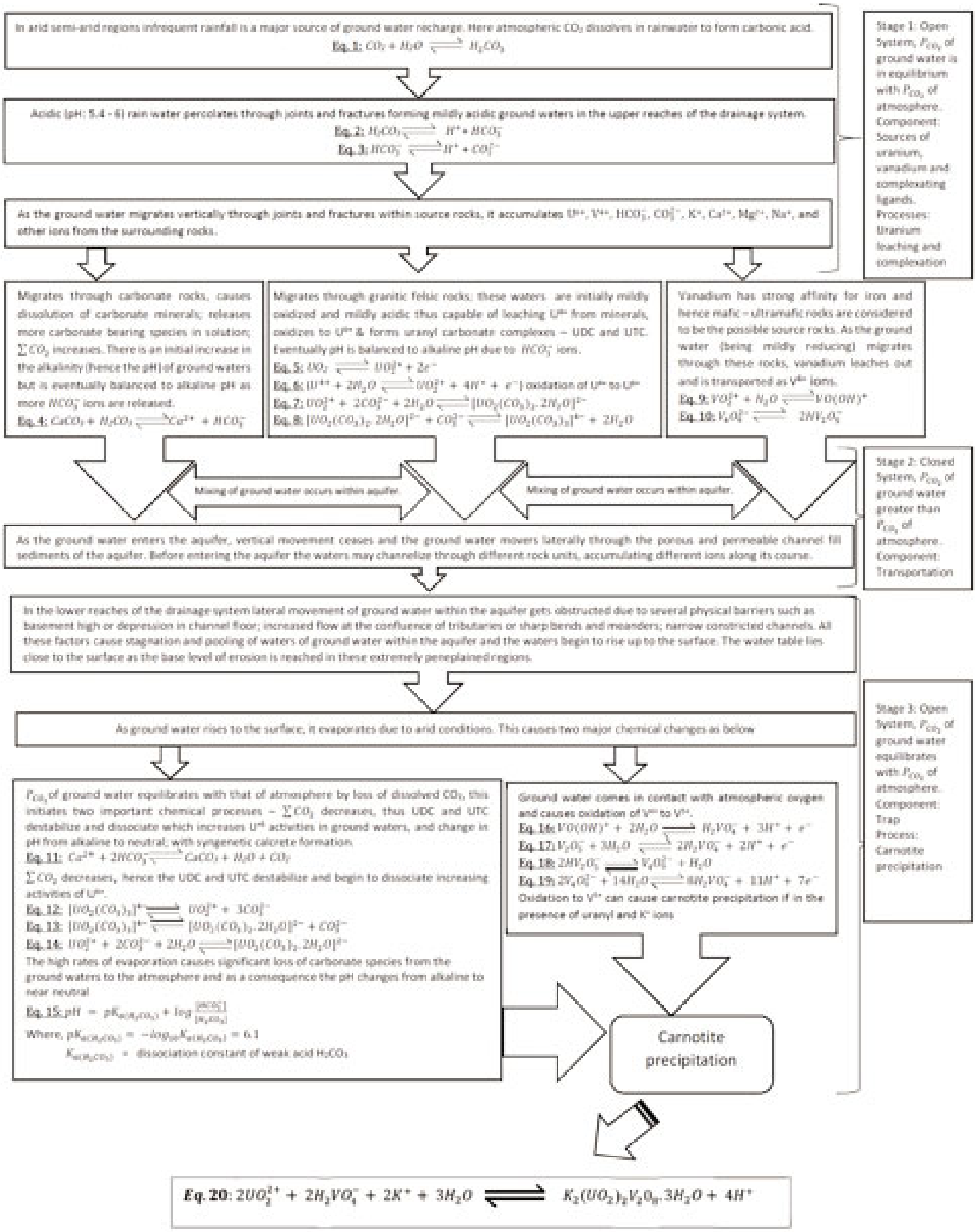

Figure 1. **Genetic model explaining critical hydrogeochemical processes that control carnotite precipitation in near surface environments of dry arid desert regions**

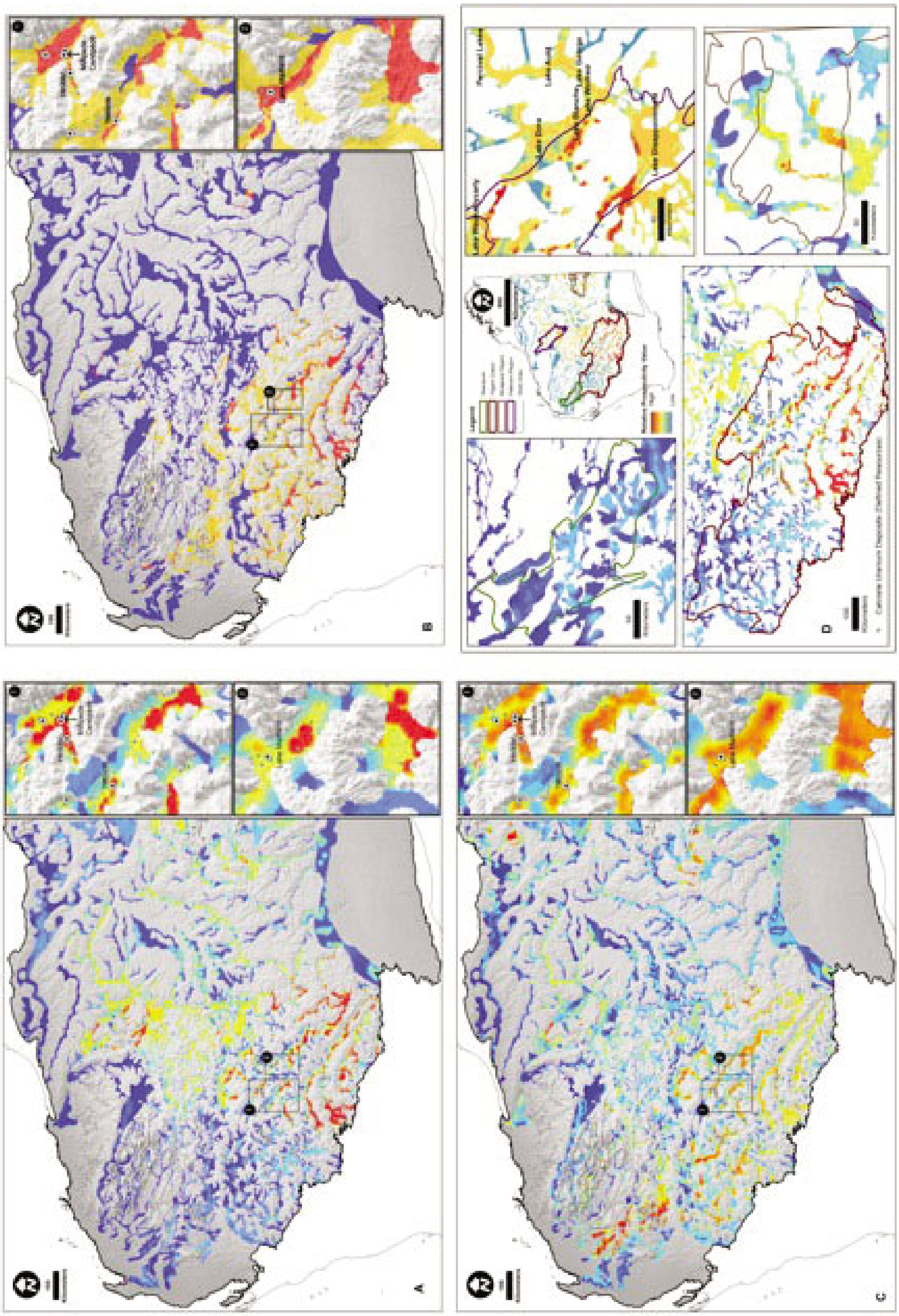

Figure 2. Prospectivity maps and exploration targets within study area in WA (prospectivity ranges from blue (low) to red (high)). A) FIS – based prospectivity map; B) WofE prospectivity map; C) Neural Network prospectivity map; D) Identified exploration targets in Paterson region and Musgrave Province

Systems Thinking for discovery: why we need a systems thinking approach to studying Mineral Systems and Ore Systems

by

Timothy Craske[1]

What is Systems Thinking?

Systems thinking is used to study interactions. It is different from simple event-orientated thinking that implies chains of cause and effect along a time line. In systems, the system behaviour emerges from its structure, that is, the flows and feedback loops, rather than any individual element or node (Fig. 1). The root causes in systems are the forces emerging from the feedback loops. Systems can exhibit feedback and balancing or reinforcing loops that may cause delays, drive growth or act as governors on system behaviour. This can sometimes produce unexpected results (emergence) that are hard or impossible to predict based on simple study of the components alone. The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe (Corning, 2002), Thus, the reductionist analytical thinking we usually use in scientific study will not work with systems. The whole becomes not merely more, but very different from the sum of its parts (Anderson, 1972). Systems Thinking is holistic thinking that is thought to be a function of the right side of the brain, rather than the left side that is the seat of logic and analytics.

The most basic structures in systems maps are termed ‘archetypes’. An archetype is a structure or or sub-system that produces the repeatable recognisable behaviour or set of behaviours in a system. Learning to identify archetypes can help us understand the workings of a system and better predict its behaviour.

To work with systems you need to properly understand the tools of systems theory. Without application of the correct thinking tools we risk assigning false causality or producing erroneous forecasts in complex systems (Fig. 2).

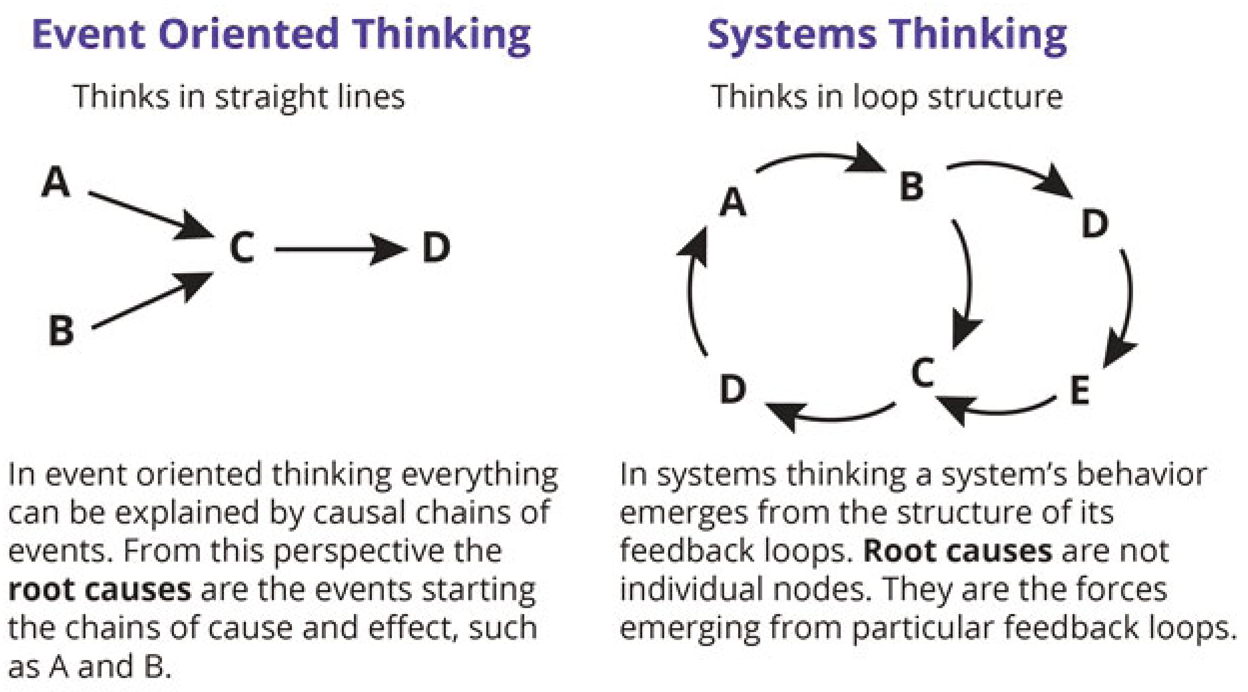

Figure 1. To understand and map Mineral Systems we need to move from event-orientated thinking to Systems Thinking. Mapping the structure and feedback loops gives us insight into the system's behaviour and potential leverage points (image source: thwink.org)

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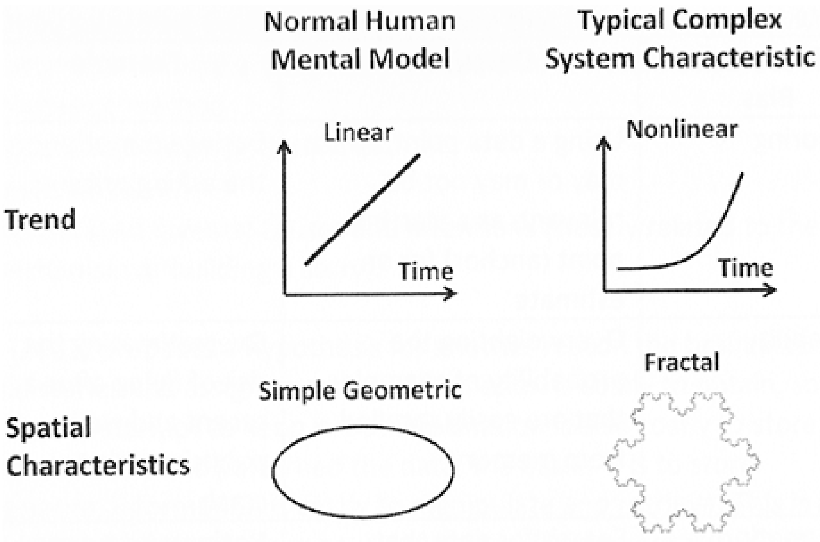

Figure 2. **Comparing normal human mental models to characteristics of typical complex systems. The snowflake geometry is governed by a simple rule, and while still having unique emergent properties, it also displays convergence (all snowflakes show fractal geometry) (after Jolly, 2015)**

One reason why emergent behaviour is hard to predict is that the number of interactions between components of a system increases exponentially with the number of components, allowing for many new and subtle types of behaviour to emerge. Emergence is often a product of particular patterns of interaction that can be mapped. It should be expected then that systems thinking can turn simple causality on its head, resulting in breakthroughs or paradigm shifts in understanding and prediction.

Why Systems Thinking is needed to understand and map Mineral Systems

Mineral Systems and ore systems are often complex and self-organising (Hronsky, 2011). As geologists and mineral explorers, it is unlikely that we will be able to truly understand complex mineral systems if we don't understand the Systems Thinking approach. Most depictions of ore systems, from petroleum systems onwards, have been largely in the form of event maps. While a tool for visualising aspects of systems, such event maps do not describe the entire system, nor emphasise important feedback loops across scales. Systems thinking allows these feedback loops and system interactions to be more fully acknowledged. We do not just want to study Mineral Systems in an academic environment, but rather we want to understand and better predict the occurrence of Ore Systems, the important wealth generating subset of Mineral Systems.

Mineral Systems are exceedingly complex multi-dimensional systems. They operate at different scales at different times and sometimes at several scales at the same time. Systems Thinking may be the key to filling the gap between regional-scale predictive targeting and prospect-scale detection targeting and unlocking ore discovery.

Mineral Systems Archetype: The Simple Magma Chamber

Ore Systems are often complex, but are made up of many simpler conceptual Systems Thinking components or system archetypes. To understand the behaviour of archetypes we can study the structure and behaviours of analogous systems archetypes from other industries including engineering and physics. By looking at different system components and examples we should be able to produce Ore Systems Maps that are useful tools to facilitate ore discovery, not simply concept infographics.

Figure 3 is an infographic that includes two simple systems maps: one for water (stock flow) into and out of a bathtub (stock), and the other a volcanic magma chamber. The other elements in the infographic illustrate the many more complexities and conceptual loops that need to be considered when studying even the simple process of magma entering, remaining in, then exiting a magma chamber: the pre-existing structures in the host environment; the confining and hydrostatic pressure and any imposed stress regime; the temperature difference between magma and host and any heat or metasomatic or physical transfer out into the country rock; the triggers for expulsion of the magma upward out of the chamber toward the surface; and the feedback loops (not shown) for changes in pressure, temperature and chemistry in the chamber and effects on crystallinity, viscosity, and stored energy in the magma chamber. Moreover, throughout the life of the system, other exterior systems such as the weather and hydrospheric systems can interact directly or indirectly with the system, for example, by eroding the volcanic edifice thereby affecting the confining pressure on the chamber. Such interactions can reinforce (reinforcing feedback loop) or balance (balancing feedback loop) the behaviour of the system, or even result in never-before-seen behaviour (emergence) such as exsolution of volatiles, explosive eruption of magma and caldera collapse.

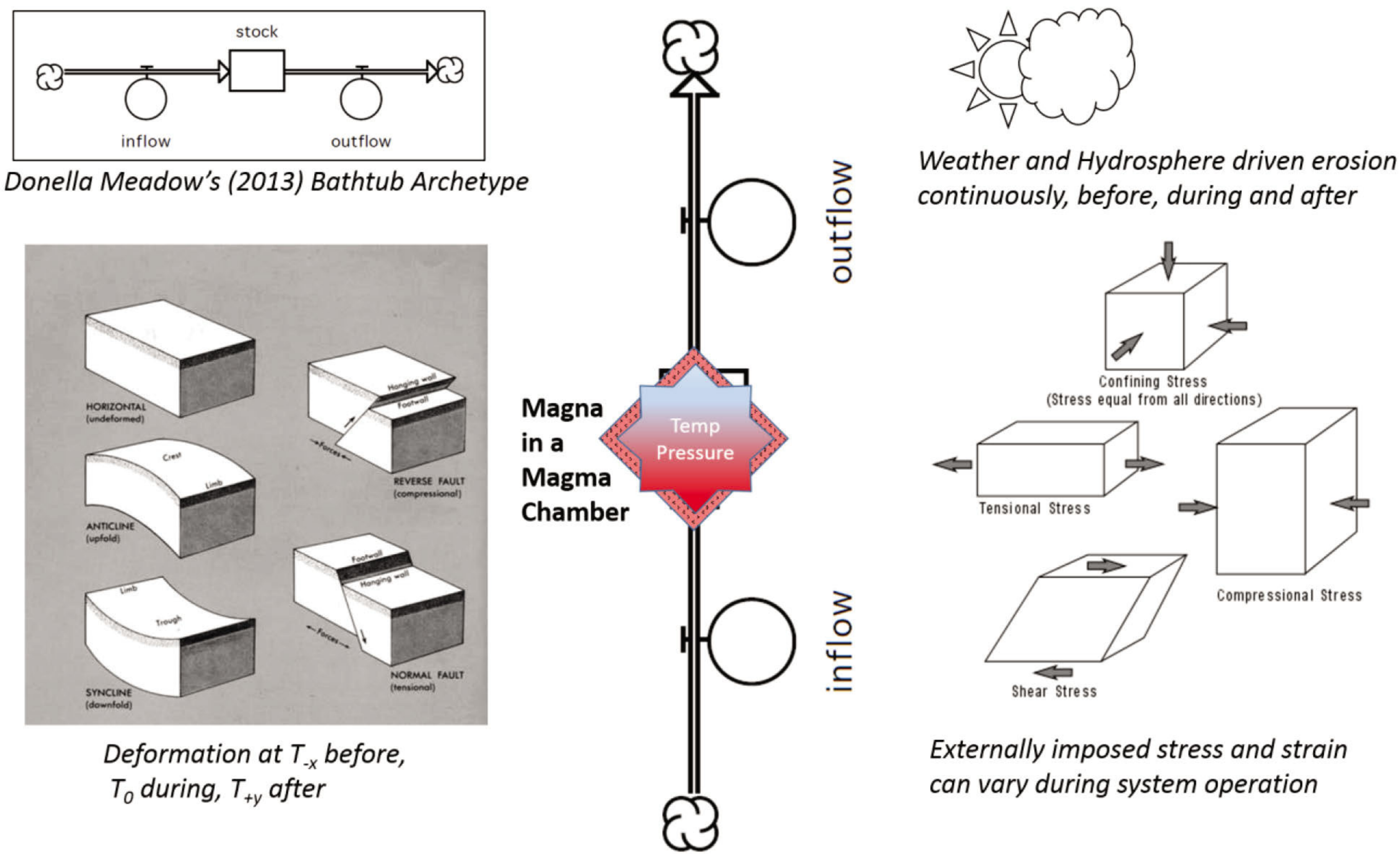

Figure 3. Geological variation of Donella Meadow's 'filling and emptying bathtub' systems (Meadows, 2008) archetype (top left) showing the many systems complexities that need to be mapped, even in simple geological systems, such as prior structures, stress, confining pressure and weather/hydrosphere-driven erosion (shown diagrammatically) when systems thinking is applied to magma entering and leaving a magma chamber, does not occur at atmospheric temperature and pressure, nor with the intervention of a human operator

Example of a Mineral Systems map: Cornish tin deposits

The Thinkercafe organisation (thinkercafe.org) has recently completed its third Thinking Skills workshop in Western Australia (Craske, 2016). One of the products from this workshop was draft Mineral Systems map for Cornish Tin Vein Deposits. This deposit type was chosen for the workshop as an example of a simple magmatic mineral system that has produced over one million tonnes of tin and two million tonnes of copper. The participants at the workshop (representatives from GA, GSSA and industry) were able to produce a draft Mineral Systems causal loop map. The map has already led to a challenging of several paradigms that apply to other Mineral Systems. Further refinement of this map will result in further insights and identification of sub-systems and Mineral System archetypes. The map will be presented as a poster at Target 2017.

Some of the preliminary findings are:

1. Humans set the boundaries of geological systems. Hence, different workers often mean different things when they talk about Mineral Systems, and should clearly state where their self-imposed boundaries lie.

2. The feedback loops can leave their own evidence in the geological record that can be identified measured and mapped.

3. Most giant mineral systems are formed within five kilometres of the Earth's surface. To ignore the role and overlap of the hydrosphere, biosphere and atmosphere systems at these levels in the upper crust is to miss important feedback loops in the system. Preservation is not necessarily the best result for an ore system as erosion, exposure and redistribution of elements are often keys to deposit economics and to exploration detection.

4. Orebodies are the output or goal of 'Ore Forming Systems'. Ore Forming Systems emerge from the behaviour of Mineral Systems over time. Similarly, going up the heirachy, Mineral Systems emerge from the actions of Geosystems (e.g. backarc basins, volcanic arcs, intracontinental basins etc.) whilst Geosystems are all part of Earth Systems. Thus, 'Ore Systems are an emergent property of Mineral Systems and can be nested within them (Camp Concept) or where they have boundaries with or overlap with other systems.'

Acknowledgements

The author would like to acknowledge all Systems to Discovery workshop participants as co-authors to this paper, including John Simmonds, Sophie Hancock, Graham Begg, Cam McCuaig, Grant Osborne, Deborah Lord, Elizabeth Amann, Mike Jones, Dave Huston, Stephan Thiel, Craig McEwan, Robbie Rowe and John Sykes.

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Regional to deposit scale 3D mineral characterisation of alteration footprints through cover

by

Tom Cudahy[1,2] and Carsten Laukamp[2]

Background

Given that accurate, spatially-comprehensive 3-dimensional mapping of alteration footprints is key to the discovery of the next generation of currently hidden economic deposits across Australia (UNCOVER), then arguably the most efficient means of obtaining this information is via visible to infrared reflectance/emission systems operating from drillcore, field, airborne and space-borne platforms. These ‘mineral mapping’ technologies, which measure only the top 1 to 100 µm of a given target’s surface, have the advantages of being: (i) physics-based, i.e. traceable, measurable and reproducible; (ii) easily validated through independent, quantitative measurements; (iii) providing spatially comprehensive, scalable coverage; (iv) are non-contact and non-destructive measurements; and (v) many process-diagnostic alteration and weathering minerals have specific spectral signatures.

One of the key challenges for the remote sensing data streams though has been removing the effects of green and dry vegetation, which can limit the seamless mapping of target mineralogy from ‘fresh rock to space’. Solutions have been developed (Rodger and Cudahy, 2009) enabling 3D mineral mapping of geology using a combination of drillcore and airborne hyperspectral data (Haest et al., 2013). However, there is currently a limited amount (<50,000 km^2) of publicly available remote (airborne) hyperspectral data across Australia (<1% coverage) for this task. As a consequence, lower quality (spectral, spatial and radiometric resolutions) but spatially comprehensive satellite-borne ASTER data has been the main spectral data type used by the exploration community to date, especially since the public release of the ASTER Version 1 (V1) geoscience maps of Australia (Cudahy, 2012; Cudahy et al., 2016).

The problem is that most of the ASTER V1 products (e.g. *AlOH Group Composition* – Fig. 1a) are strongly influenced by variable green and dry vegetation cover and thus required heavy masking to leave as residual only the vegetation-free pixels, such as across semiarid regions where annual rainfall is <300 mm. Because of this heavy masking, outside of these dry areas the ASTER V1 processing yielded much less useful geologic information. For example, the Mt Carbine area in NE Queensland (magenta box in Fig. 15c) showed <10% of the pixels with AlOH Group information. This lack of coverage was seen by explorers as detracting from the value of the ASTER V1 products, even though it was recognized that recording ‘null’ information was better than providing ‘erroneous’ information, as fieldwork is costly.

For multi-spectral data like ASTER data, it is relatively easy to unmix the contribution of green vegetation given: (i) the availability of diagnostic green vegetation spectral ASTER bands B2 (chlorophyll absorption) and B_3 (photosynthetically-active, near infrared reflectance plateau); and (ii) suitable mixing relationships. However, dry vegetation, which is a much greater cover problem compared to green vegetation for a dryland environment like Australia, in theory is not well suited for measurement using a system like ASTER. Nevertheless, approximations have been developed, including one developed by the author that is key to the generation of a suite of ASTER Version 2 (V2) mineral products developed as part of a collaborative project between CSIRO and the Queensland Geological Survey (GSQ).

This paper presents: (i) examples of the Queensland ASTER V2 mineral products; (ii) their validation (including the use of the National Geochemical Survey of Australia (NGSA); Caritat and Cooper, 2011); (iii) how they seamlessly mesh with similarly convolved/processed drillcore and airborne hyperspectral data; and iv) and how the products reveal alteration footprints through both vegetation and regolith cover.

Queensland ASTER Version 2 vegetation-unmixed products

Figure 1 compares the Queensland *AlOH Group Composition* product (maps 2200 nm absorbing minerals like kaolinite, muscovite, illite, montmorillonite) generated by V1 (no vegetation unmixing) and V2 (green and dry vegetation unmixing) processing. Cooler colours represent kaolinite (±alunite, pyrophyllite) while warmer colours are muscovite (phengite), illite, montmorillonite. The coloured dots are similarly processed NGSA spectral data (n=112) which were used to confirm an improvement in correlaton (accuracy) from V1 (R2=0.09) to V2 (R2=0.31) processing.

The effect of this vegetation unmixing on the *AlOH Group Content* product is shown in Figure 2 for the Mount Carbine area, Cape York Peninsula (Fig. 1). Note that the V1 processing yielded <10% of pixels with a

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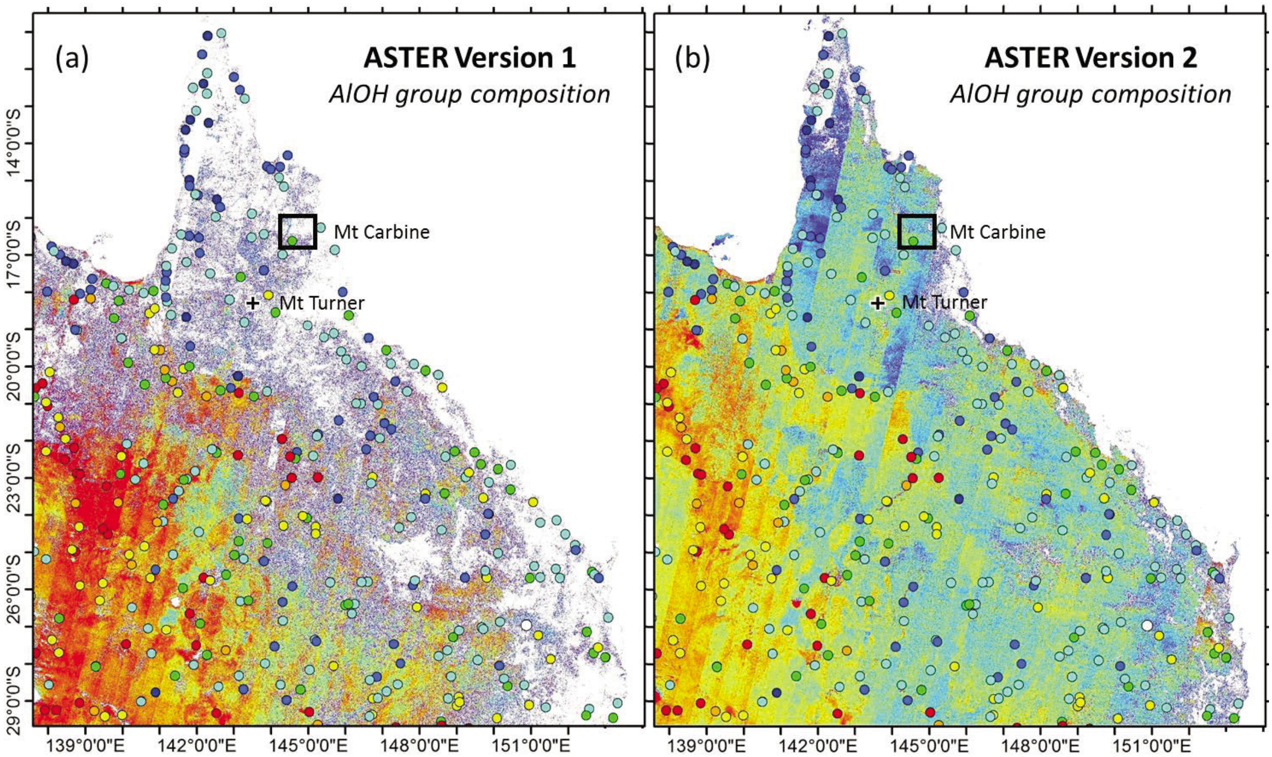

Figure 1. **ASTER AlOH Group Composition maps of Queensland together with similarly processed NGSA validation data (coloured dots). (a) Version 1 ASTER processing without vegetation unmixing. (b) Version 2 ASTER processing with vegetation unmixing. Warm colours indicate muscovite (phengite), illite, montmolrillonite) while cool colours indicate kaolin (alunite, pyrophyllite).**

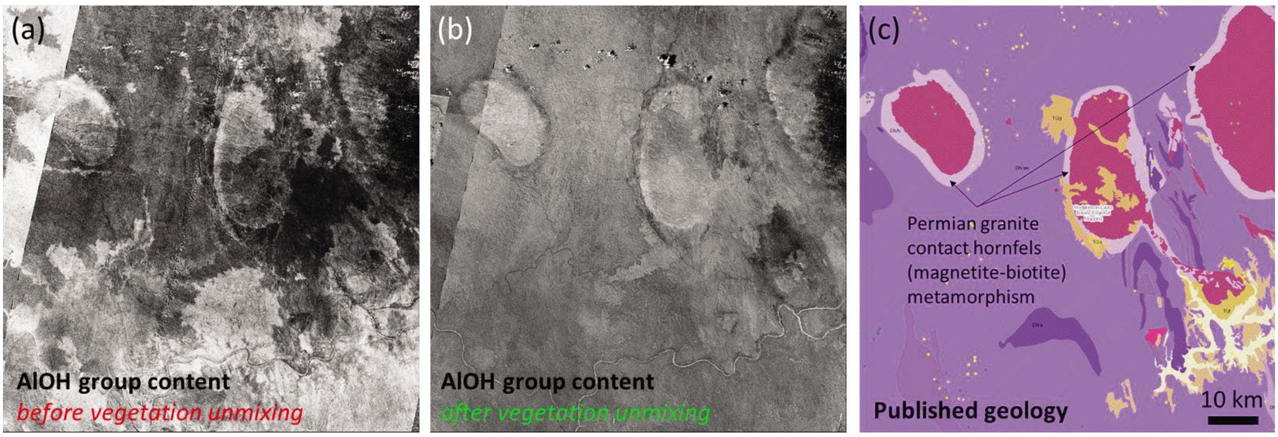

Figure 2. **ASTER AlOH Group Content mapping for the Mt Carbin area, Cape York Peninsualy (Figure 1). Scene centre approximately approximately –18.2479° latitude 143.4473° longitude. (a) Before vegetation unmixing. (b) After vegetation unmixing. (c) Published geology.**

measurable 2200 nm absorption feature, after masking. Figure 2a shows the same V1 product but without this masking, which highlights the complicating effects of variable green and dry vegetation cover. However, after V2 unmixing (Fig. 2b), the *AlOH Group Content* shows strong similarity with the published geology map (Fig. 2c), including the definition of granite plutons and their contact metamorphic aureoles. These aureoles mark zones of high temperature where the 2200 nm absorbing clay minerals in the sedimentary country rocks were transformed into minerals like biotite, thus reducing the intensity of the 2200 absorption (darker tones).

The V2 ASTER processing has resulted in (on average) ~90% of the area of Queensland now showing information for all mineral products, compared to an average <30% for V1 processing. Importantly, this increase in coverage has not come at the cost of reducing the accuracy of the extracted mineral information.

Integrated 3D mineral mapping

Published mapping (Rossiter, 1979) of the Mount Turner area near Georgetown (Fig. 1) identified a porphyry–epithermal alteration system with associated phyllic and (advanced) argillic alteration. Both the published airborne HyMap mineral mapping (Cudahy et al., 2008) and the ASTER V1 geoscience maps (Cudahy, 2012) had not shown any useful alteration information, largely because of variable vegetation cover. Here we focus on a 3D model of ASTER equivalent *AlOH Group Composition* generated from four National Virtual Core Library (NVCL) drillcores and vegetation-unmixed airborne HyMap imagery. The integrated 3D product (Fig. 3) shows a coherent spatial pattern and comprises a central, upper (proximal) zone rich in kaolin (advanced argillic alteration) and a distal outer zone relatively rich in which mica (phyllic alteration?).

The detailed spectral mineralogy interpreted from the full hyperspectral resolution NVCL drillcore data (Fig. 3b) shows the same key alteration zonation. For example, drillcore NS4 shows, at its upper levels, well-ordered kaolinite and alunite, which are diagnostic of advanced argillic alteration, together with white mica. This changes down the drillcore into dominantly white mica (phyllic alteration). The fact that information about advanced argillic versus phyllic alteration is captured at ASTER spectral resolution, despite variable vegetation and regolith cover (note the NVCL drillcores in Figure 3 started at 300 m depth because of the weathering above) is significant for exploration.

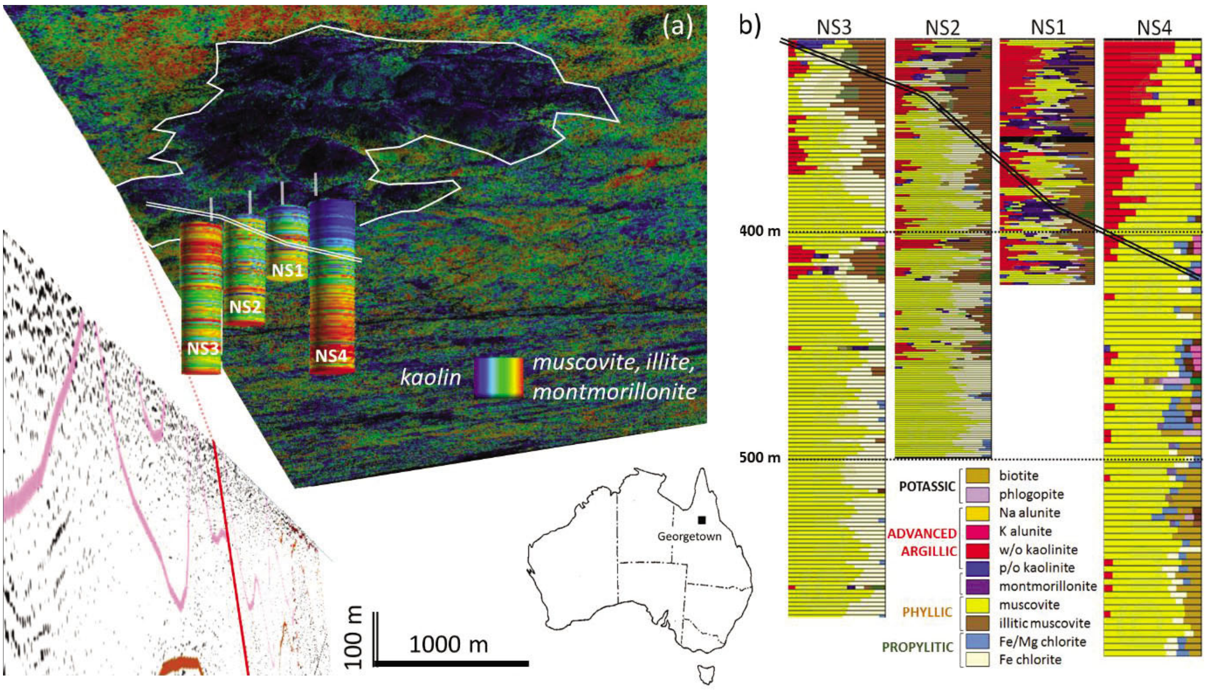

Figure 3. **3D oblique view (up from the NE) of the Mt Turner porphyry-epithermal system near Georgetown (Fig. 1). Area center is approximately -18.2479° latitude 143.4473° longitude. Surface map is airborne HyMap™ convolved to ASTER bandpass configuration and then processed to generate a vegetation-unmixed Al-clay composition map before draping over a digital elevation model. The similarly color-coded vertical pillars are drillcore HyLogger™ data which also have been convolved to ASTER bandpass configuration and the processed to generate the same Al-clay composition product. The interpreted boundary between advanced argillic and phyllic alteration zonation is shown on both the HyMap™ (single line) and HyLogger™ (double line) results. Also shown is the vertical cross-section of a seismic line with pink lines showing granite contacts and red lines showing major faults. (b) Detailed mineralogy of the four HyLogger™ drillcores shown in (a) and generated using 'The Spectral Assistant' in TSG™ software. The interpreted boundary between advanced argillic (comprises well-ordered kaolinite ± alunite) and phyllic (comprises muscovite/illite) alteration is shown by a double black line. Note that the NVCL drillcores start at fresh rock ~300 m below surface.**

Discussion/conclusions

Ideally, explorers should be able to insert their commercial-in-confidence exploration mineral information into a regional public 3D mineral framework. This would enable explorers, for example, to determine if any alteration mineral footprints recognized in their data extend beyond their exploration leases. The CSIRO–GSQ Queensland 3D Mineral Mapping project is helping to achieve this vision by creating a scalable 3D framework based on publicly derived spectral-mineral information (drillcore, field, airborne an satellite), albeit at ASTER spectral resolution, which can easily be extended nationally and globally.

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AusLAMP Victoria – illuminating lithospheric architecture for mineral systems exploration

by

Czarnota, K[1*], Duan, J[1], Taylor, D[2] and Chopping, R[1]

There is a growing appreciation that a certain range of mineral systems, such as orogenic gold, magmatic Ni and IOCG, are a consequence of geodynamic and hydrothermal processes that operate at the scale of the crust and upper mantle. It follows that exploration for these mineral systems could exploit constraints on lithospheric architecture for regional area selection. To aid industry in this task, academia, together with federal, state and territory survey organisations have embarked on the ambitious Australian Lithospheric Architecture Magnetotellurics Program (AusLAMP), which aims to collect continent-wide, long-period magnetotelluric data at a station spacing of approximately 55 km. AusLAMP results over Victoria, the first state to be covered as part this program, show that the distribution of metasomatised lithospheric mantle can be mapped by combining AusLAMP results with velocity constraints derived from passive seismic arrays. This inference has been tested using laboratory-derived conductivity depth relationships for olivine, xenolith mineralogy and bulk chemistry of Cenozoic alkaline volcanism, which samples large areas of the state. Within the mid to lower crust, strong northeast-striking conductors, which merge at depth with the aforementioned zones of conductive metasomatised mantle, display a spatial correlation with the distribution of Devonian granites and gold deposits. These spatial associations highlight potential exploration targets and suggest a yet-to-be-explored link between mantle metasomatism, gold and late crustal melting.

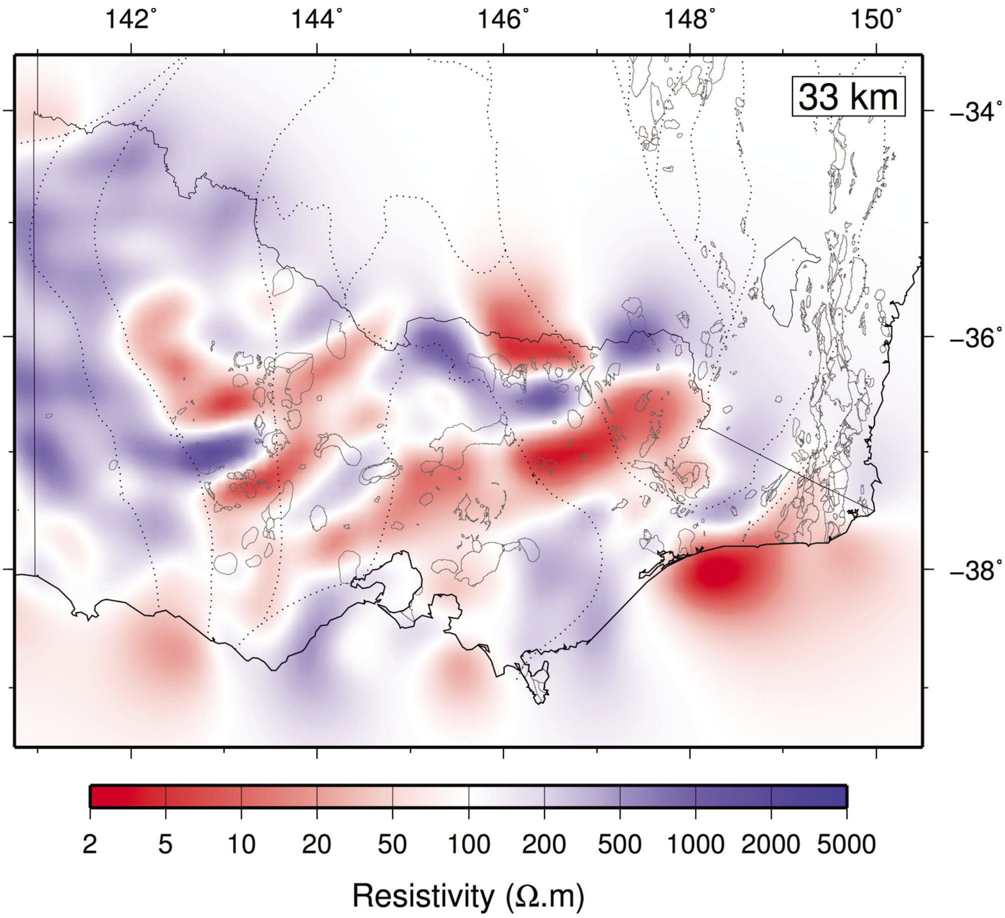

Figure 1. Map of the resistivity structure of the lower crust showing the distribution of major crustal boundaries as dotted lines and Devonian granites shown as polygons (written comm. Cayley and Liu, 2016)

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An assessment of the potential orogenic gold endowment of the Sandstone Greenstone Belt using a mineral systems framework for comparison with the Agnew Gold Camp

by

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Introduction

The Sandstone greenstone belt (Fig. 1a) covers approximately 1000 sq km of ground in the Youanmi Terrane of the Yilgarn Craton. Since the initial discovery of gold at the end of the 19th century, the belt has produced just over 1.2 Moz from surface, underground and openpit operations, far less gold per unit area than most other greenstone belts.

Unlike the Agnew gold camp (Fig. 1b), situated in the northwestern Eastern Goldfields Superterrane of the Yilgarn Craton, there is a distinct lack of research on the gold mineralisation of Sandstone. This is largely because most gold mined to date has been oxidised ore from regolith rather than solid bedrock. Due to this limited understanding, it is not clear whether significant residual mineralisation remains in lesser explored parts of the belt. This paper incorporates empirical, conceptual and quantitative methods of assessing mineral endowment (Singer, 1993; Lee and Singer, 1994; Guj et al., 2011) through comparison with the analogous Agnew gold camp, and represents a first attempt to systematically describe the geology and orogenic gold mineralisation of the Sandstone belt.

Method

Pre-existing datasets and new critical data are compiled for the Sandstone greenstone belt, which, when interrogated using the mineral systems framework (McCuaig and Hronsky, 2014; Hagemann et al., 2016; Wyman et al., 2016), define critical elements of gold mineralising systems that have been active in the belt. The drilling database provides an overview of the maturity of the exploration search space and distribution of mineralisation; field mapping and geophysical datasets are interpreted to outline geological domains and develop a greater understanding of the structure of the belt (Murdie, et al. 2015), thus defining preferential conduits for the transport of auriferous fluids from gold source to site of deposition; and deposit structure and geology provide insight into localised features controlling deposition, as well as the style and timing of mineralisation. These elements are contrasted with the Agnew gold camp, which is a mature and well-researched exploration search space. Historical production and deposit resource estimates are used in a quantitative analysis to calculate natural and residual gold endowment.

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Summary

The systems that led to gold mineralisation within the Sandstone and Agnew greenstone belts share several important characteristics. The belts are a similar size (approximately 1000 sq km) and have similar geometry due to regional scale folding from E–W compression and the complex nature of intrusion of granitic batholiths into their southern margins. They display similar mafic–ultramafic lithostratigraphic assemblages, although the Agnew belt contains more sedimentary units. Peak metamorphism occurred at approximately the same time across the belts, with the margins of the Sandstone belt and the entirety of the Agnew belt reaching amphibolite-facies metamorphic conditions. Their tectonic and gold mineralisation histories are shared from 2.72 Ga.

Trans-lithospheric structures are highlighted as pathways for auriferous fluid migration from a deep-seated, fertile gold source (e.g. Groves et al., 2016). Both the Sandstone and Agnew greenstone belts lie in close proximity to such deep-seated, domain-bounding structures: the broadly contemporaneous Youanmi Shear Zone and Ida Fault, respectively. The distribution of gold mineralisation within both belts is predominantly controlled by N–S-trending, belt-scale structures. These generally propagate along lines of weakness, such as contacts between lithologies with high competency contrasts. Mineralisation at the deposit scale is focussed by localised physical throttles and host rocks that act as chemical traps, such as anticlinoria, intersecting shear zones, cross-cutting fault structures, and fractured iron-rich host rock.

Therefore, it appears possible that the gold endowment of the exploration-immature Sandstone greenstone belt is broadly equivalent to that of the much more mature Agnew gold camp, but has not been realised due to lack of targeted exploration and drilling outside the more obvious near-surface gold anomalies under limited regolith cover.

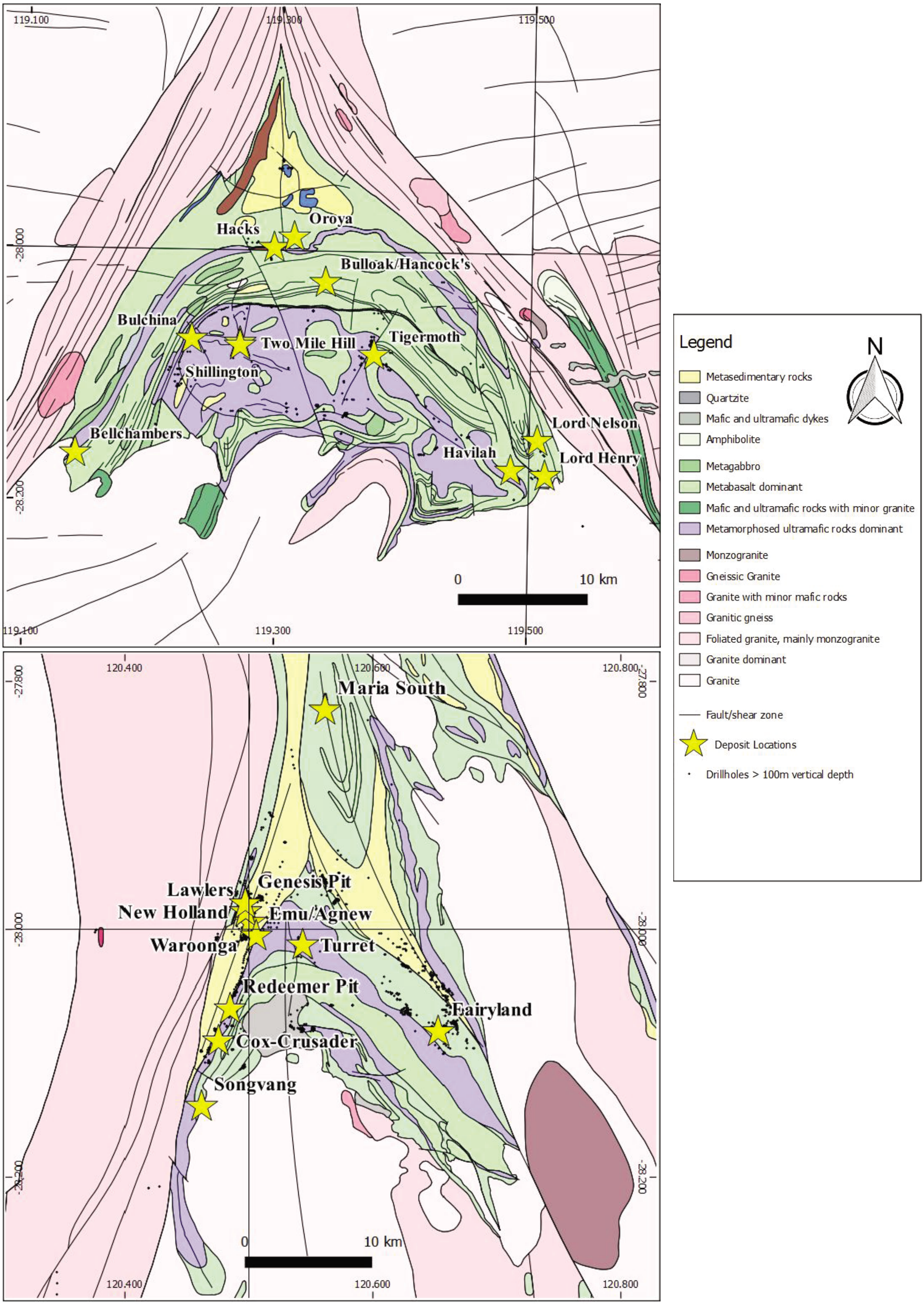

Figure 1. Comparison between the Agnew and Sandstone greenstone belts showing deposit locations and drilling below a vertical depth of 100 m: a) Sandstone greenstone belt; b) Agnew greenstone belt

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Petrophysics and exploration targeting: best practice and applications

by

Mike Dentith[1*], Cameron Adams[1] and Barry Bourne[2]

There is still much that needs to be understood about the physical properties of rocks in mineralised geological environments. This knowledge gap becomes more important as the transition to deeper exploration targets under cover occurs, with an associated greater reliance on geophysical exploration methods. Recognising and testing targets and accurately mapping the geology are equally dependent on petrophysics which constitutes a link between geologist's largely mineralogical 'view' of the Earth and the geophysicist's physics-based 'view'.

Petrophysical measurements may be made on hand specimens or in-situ via downhole logging. Measurements of density and magnetic susceptibility are most common, followed by measurements of electrical conductivity/ resistivity and induced polarisation. Remanent magnetism, which cannot be measured downhole, is easily measured but the requirement for an oriented sample means comparatively few measurements are made, and often only the intensity of the magnetism is determined. The emergence of the seismic reflection method in the minerals industry has led to an increase in the measurement of acoustic velocity.

The major challenge associated with understanding petrophysical data is not making the measurement, but rather understanding the results. The interpretation of the data is a cross disciplinary problem. Fundamentally it is necessary to understand the rock mineralogy and geochemistry to put the petrophysics in context with the geophysic results . This is hindered by behaviour in the geological environment of the main 'geophysical minerals' (Fe Oxides, metal sulphides), which is extremely complex and often not well understood in a petrophysical context, i.e. controls on magnetic properties.

All petrophysical data must be considered in the context of scale and sampling. Many properties, especially magnetism and electrical conductivity, are extremely variable even over distances of a few centimetres, and as such a few measurements from a small area are unlikely to be representative.

Cost and logistical constraints mean there are often only a handful of measurements available.

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The opportunity exists to address at least some of these problems. For example the increased use of mineralogical scanners and portable XRF instruments means quantitative measures of the geological properties of a sample are now readily available for comparison with the petrophysical measurements. Also instruments to scan core measuring both geological and petrophysical together are now available. A consequence of this is that far data volumes are now practically achievable and there are multiple measurements on the same samples. This combination of circumstances warrants a reassessment of how petrophysical data can be integrated in to the exploration targeting process.

Petrophysical Data Types

The various petrophysical properties are fundamentally different with respect to their underlying geological controls and so there is no reason they should correlate with one another. A useful way to understand the relationship between different petrophysical properties is using a schematic ternary diagram with end members categorised as 'bulk', 'grain' and 'texture' properties (Fig.1). Properties of similar types are more likely to correlate. Bulk properties are the simplest to understand because the rock properties are a weighted average of the constituent mineral properties. Density and acoustic velocity are examples of bulk properties. Grain properties, of which ferromagnetism is the best example, depend on a minority component of the rock, which may make up only a few percent of the total mineralogy. Grain properties are not only controlled by the abundance of the relevant minerals, but also their shape and size, that is, the texture of the grains. The most hard to quantify kind of physical property is the texture property, of which electrical conductivity is the best example. The overall conductivity of a particular sample is in part controlled by the amount of conductive material present (which may be only minor and may be pore water) but the main control is the texture of the rock since this is the control on whether the conductive phases form the required inter connected network. Some properties, such as electrical polarisability have both grain and textural controls.

This categorisation of physical properties is useful when interpreting the datasets. Representative sampling of bulk properties is much more likely than texture properties, for example. Also properties that plot closer together on the ternary diagram are more likely to correlate on cross plots. Regardless of particular correlations, the use of cross plots of different properties is especially useful for identifying 'anomalous' areas which may be associated with targets.

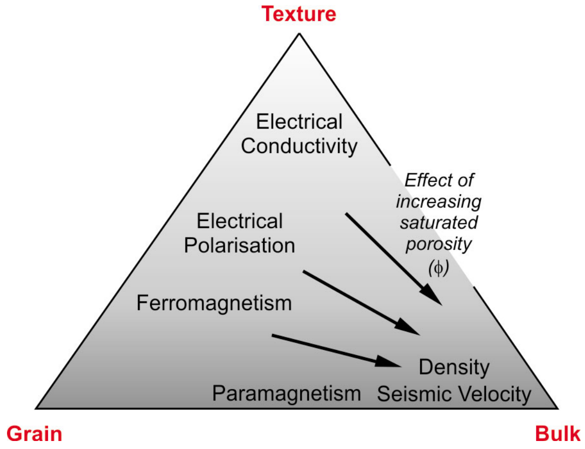

Figure 1. Ternary diagram showing the relative influence of texture, grains and aggregate effects on commonly measured petrophysical properties

Of particular use is the Henkel plot that compares susceptibility and density. This highlights serpentisation because of the associated increase in magnetism and decreases in density compared to the unaltered rock.

Presentation

An important property of petrophysical datasets is that the distributions of physical properties are almost always complex, commonly skewed and multi-modal. This is a function of the extreme variability of some properties, especially the texture properties. Even with the relatively simple bulk properties presenting data as range charts or box plots or simply in tables with average, standard deviation etc is not recommended. Individual populations of data need to be analysed accounting for such variables are geographic location, stratigraphic position and most important of all the geological context of the rocks being measured. For example rocks such as iron formations, greywackes and komatiites (Fig.1) are inherently zones/layered and so simple probability density displays are not to be expected (Fig. 2).

Not only lithology is important

Most compilations of petrophysical measurements categorise samples according to lithology. In some kinds of rocks, notably mafic/ultramafic rocks, lithology is a second control on most petrophysical properties, with alteration (serpentinisation (Fig.3), talc-carbonate alteration) being much more important. In fact, there is a general lack of systematic studies (at least published) of the petrophysical characteristics of the types of alteration commonly encountered in mineral exploration. If mineralogical/geochemical data are also collected then samples can be classified by, for example, alteration index. This kind of approach is likely to significantly advance understanding of the petrophysical properties of common geophysical targets and perhaps suggest new ones.

Another important factor, especially in sedimentary rock types, is porosity. When significant porosity is present it usually dominates the physical properties, especially electrical properties. As porosity increases the property reflects that of the sample as a whole (Fig.1). Again, analysis of the data in the context of lithology only will not lead to an understanding of the controls on physical properties.

Two studies of this type, on ultramafic rocks from greenstone terrains and on dolomitisation processes in carbonate successions hosting base metal deposits are on-going and will be presented.

Summary

The conceptual framework described above provides the basis for a work flow that can be used to analysis the increasingly large volumes of petrophysical data that are likely to become more available in the future.

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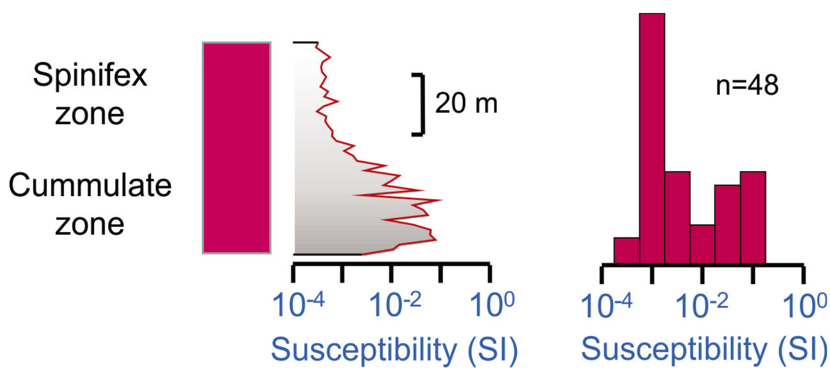

Figure 2. Susceptibility data from a single komatiite flow in the Eastern Goldfields. Simple averaging or range diagrams do not adequately represent the variation in magnetism

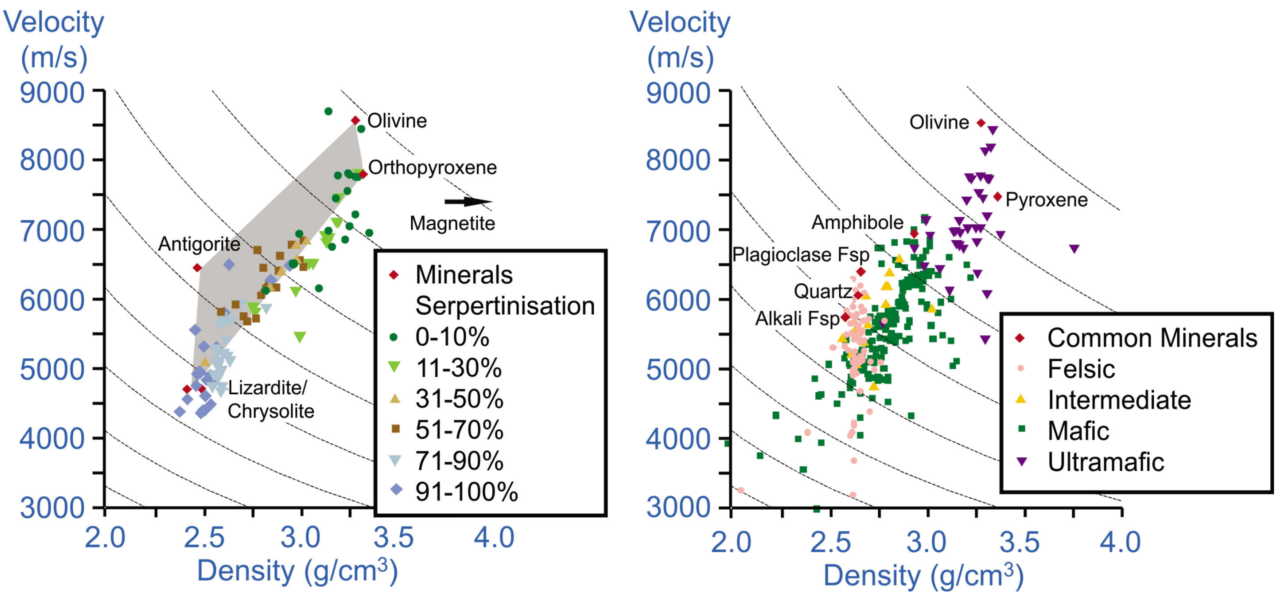

Figure 3. **Effect of serpentinisation on the seismic properties of mafic and ultramafic rocks compared to the effects of changes in lithology. The alteration has a greater influence than the change in rock type**

The spatial and temporal significance of alteration associated with gold-bearing structures in the Greater Revenge area, St Ives, Western Australia

by

Barbara M Duggan[1*], T Campbell McCuaig[2] and John M Miller[3]

A significant effort has been made to document and interpret patterns of alteration within orogenic gold systems. Many previous studies have only considered the spatial context of various alteration assemblages and not how they may be temporally related to an evolving host structural environment. This approach implicitly assumes that all significant observed alteration in the volume surrounding the deposit formed coeval with one major gold mineralisation event. A failure to integrate the spatial distribution of alteration with the structural evolution can result in misinterpretation of the data because structures that host gold deposits are commonly multiply reactivated over their history. For example, the presence of two contrasting alteration assemblages may be incorrectly identified as evidence of fluid mixing rather than two separate overprinting events.

This study focused on the Revenge deposit of the St Ives gold camp in Western Australia, with the specific goal of documenting the temporal evolution of the observed alteration assemblages and their relationship to the evolving structural framework. Importantly, this study focused only on alteration hosted by a single lithological unit, the Devon Consols Basalt (DCB), to control for any effects of lithological variability on alteration assemblages. The work completed included paragenetic mapping, lithogeochemistry and hyperspectral analysis. The spatial distribution of internal lithological variations within the DCB and each observed alteration assemblage were systematically mapped out. This work used previous structural interpretations of the area to provide context and a link to previous research.

In total, five key alteration minerals have been identified surrounding the major mineralised structures in the study area: epidote, chlorite, biotite, albite and roscoelite. Epidote, biotite and roscoelite overprint all previous stages of alteration. Chlorite and albite assemblages are observed to be coeval with epidote and biotite respectively. Pyrite is present in all assemblages except epidote. All five key alteration minerals occurred during the D_4 main gold event.

Documentation of the alteration paragenesis related to mineralisation indicates three distinct phases of gold mineralisation. The first phase overprints early pre-ore alteration, is associated with low grade gold along a WNW-trending Transfer Fault Zone and is interpreted to be syn-D_3 late basin formation. The second phase comprises albite alteration and is associated with the main mineralising event (D_4). The third and final stage is a late pervasive bleaching or veining event that overprints all previous alteration during D_5 late brittle faulting. During each phase, hematite alteration was present, indicating that three distinct hematite alteration events are related to gold mineralisation.

In summary, the observed alteration assemblages clearly represent a sequence of separate alteration events rather than the products of the mixing of two or more fluids in a single event as previously proposed. Deposit-scale targeting concepts based on the latter hypothesis therefore need to be revised. Furthermore, this study shows that using alteration patterns to target within an ore environment critically requires a detailed understanding of structural evolution and related alteration history.

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Multi-commodity, multi-scale exploration targeting using the Large Igneous Province record

by

RE Ernst[1,2*] and SM Jowitt[3]

Overview of LIPs

Large Igneous Provinces (LIPs) represent large volume (>0.1 Mkm3; frequently above >1 Mkm3), mainly mafic (–ultramafic) magmatic events of intraplate affinity that occur in both continental and oceanic settings and are typically of short duration (<1 myr) or consist of multiple short pulses over a maximum of a few 10s of myr (Bryan and Ferrari, 2013; Ernst, 2014, and references therein). Individual LIPs comprise volcanic packages (flood basalts), and a plumbing system of dyke swarms, sill complexes, layered intrusions, and crustal underplate, although erosion and deformation over time means that an individual LIP may incompletely preserve some of these components. LIP events occur at a variable rate that averages approximately every 20–30 myr (but with provisional peaks associated with supercontinent breakups) back to at least 2.5 Ga, and also continue more sparsely into the Archean due to poorer preservation (e.g. Ernst, 2014). LIPs (and associated silicic magmatism, carbonatites and kimberlites) are linked with continental breakup, regional domal uplift, global climate change including extinction events (e.g. Ernst and Youbi, 2017), and represent significant reservoirs of energy and metals that can either drive or contribute to a variety of metallogenic systems, and also affect hydrocarbon and aquifer systems.

Multi-commodity link

The relationships between LIPs and differing metallogenic systems (and also hydrocarbon and aquifer systems) can be condensed into five distinct, although partially overlapping classifications (Ernst and Jowitt, 2013; Ernst, 2014; Jowitt and Ernst, 2016):

1. LIP magmas that directly generate mineral deposits such as orthomagmatic Ni–Cu–PGE sulphides (e.g. the Noril'sk-Talnakh bodies within the 252 Ma Siberian Trap LIP) or Nb–Ta–REE and diamonds associated with often LIP-related carbonatites and kimberlites, respectively.

2. LIP magmas that provide energy, fluids, and/or metals for mineral deposit types such as native Cu, hydrothermal volcanogenic massive sulfide (VMS) and iron oxide-copper-gold (IOCG) deposits, including the world-class IOCG deposits of the Gawler Craton in Australia, with the links between IOCG deposits and LIPs also including Silicic LIPs (SLIPs). LIP magmas also act as heat sources that drive hydrocarbon source rocks to maturation or over-maturation.

3. LIP rocks (particularly sills and dykes) as barriers to fluid flow and/or as reaction zones that control mineralizing events (e.g. during the formation of some Au deposits; Phillips and Groves, 1983; Goldfarb et al., 2005), and also acting as structural traps within hydrocarbon systems, or forming impermeable barriers that control water flow and hence aquifer formation.

4. surficial effects, such as the weathering of LIP rocks to form Ni–Co laterites and Al bauxites from exposed LIP mafic-ultramafic rocks in tropical climates (e.g. Deng et al., 2010) and residual Nb, Ta, and REE laterites from LIP-associated carbonatites. This category also includes LIP-related oceanic anoxic events, OAEs), a vital stage in the generation of black shales which are hydrocarbon source rocks (Kerr, 1998; Eldrett et al., 2014) as well as important hosts for mineralisation such as a significant proportion of Pb-Zn deposits (e.g. Mudd et al., 2017).

5. indirect links between LIPs and ore deposits, where major continental breakup events linked to LIPs, and distal compression and transpression in the plate tectonic circuit can lead to the formation of orogeny-related deposits, such as Au mineralization (e.g. Bierlein and Pisarevsky, 2008; Ernst and Jowitt, 2013). In addition, because of their large volume/short duration pulses LIP events can represent 'barcode' records that can be used to reconstruct Precambrian supercontinents, enabling the tracing of metallogenic belts between presently separated but formerly contiguous crustal blocks (e.g. Ernst and Bleeker, 2010). Regional mafic dyke swarms are a key target for U–Pb dating campaigns as they tend to be better preserved than the other components (flood basalts and layered intrusions) of LIPs, and thus are more useful in building the LIP 'barcode' record for cratonic blocks (Ernst et al., 2013).

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Multi-scale exploration targeting

The relationships described above between LIPs and the generation of multiple different types of mineral, water and hydrocarbon resources are only useful to industry if exploration strategies can be developed that take advantage of the LIP record and variations in the characteristics (e.g. geochemistry) of individual LIPs. The following sections explore exploration targeting using the LIP record at three scales: Regional, Intermediate and Local.

Regional scale

Continental Reconstructions

LIP-derived information can be used in regional scale greenfields exploration for mineral resources by forming the basis for continental reconstructions that can trace metallogenic belts (and mantle lithospheric domains) from one block into greenfield areas on a formerly adjacent crustal block, as discussed above. Integrating this LIP barcode – piercing point method with paleomagnetic constraints is a key tool for continental reconstructions deep into the Precambrian, an approach that has been aided by a steadily improving global ArcGIS LIPs database.

In addition, plate boundary ore deposits (e.g. orogenic gold) can be associated with sudden changes in plate motion which can be linked with LIPs: 1) the arrival of an oceanic plateau can suddenly decelerate the motion of an oceanic plate, and 2) continental LIPs are typically associated with attempted or successful continental breakup and new ocean formation. Thus, the timing of formation of oceanic and continental LIPs represents a proxy for significant pulses of transpression or compression (and ore formation) on distal orogenic plate boundaries, and provides a LIP-based ranking of prospective events for their Au potential.

The subduction or attempted subduction of topographic anomalies associated with oceanic LIPs (e.g. potentially the lost Inca Plateau: Rosenbaum et al., 2005) can cause tectonic responses, such as the locking up or changing the angle of subduction; these processes in turn may trigger (or stop) the generation of mineral resources, such as porphyry or epithermal-type mineralisation or orogenic Au. Also, the subduction of Au-enriched LIP material (e.g. oceanic plateaus) can provide sources for Au systems.

Sea-level and seawater composition: partial control by LIPs, and metallogenic effects

All ore deposits involving seawater or modified seawater, such as sedimentary exhalative (SEDEX), iron formations, manganese, phosphate, and volcanic massive sulphide (VMS) systems are at least somewhat controlled by the composition of seawater at the time of metallogenesis. For instance, anoxic conditions produce black shales, which are a key source rock for hydrocarbons as well as significant hosts for a variety of mineral deposits, as exemplified by clastic-hosted Pb–Zn deposits (e.g. Mudd et al., 2017).

Recent research also demonstrates that LIP events can cause global warming, global cooling (even ice ages), oceanic anoxia (forming black shales as mentioned above), ocean acidification, sea level changes, toxic metal input, and variations in essential nutrient fluxes, among other impacts, producing a complex web of catastrophic environmental effects that are reflected in the seawater isotopic and trace element composition (e.g. Ernst and Youbi, 2017). More specifically, LIPs can, for instance, affect the redox state, pH, composition (i.e., the presence of trace metals such as mercury or iron), and changes in sea level. Thus, the LIP record can be used as an additional ranking criterion for a range of seawater-influenced ore deposits.

Vetting LIPs for ore potential using compositional and structural characteristics

Although LIPs can be linked with Tier-1 deposits of a variety of commodity types, the ore-bearing regions tend to be small compared to the overall extent of the LIP (which can reach millions of km2: Ernst and Jowitt, 2013). Therefore, assessing the metallogenic potential of LIPs is vital to early stage and regional exploration. For instance, Ni–Cu–PGE magmatic sulphide fertility of a LIP can be determined using lithogeochemical approaches on non-mineralized portions of the LIP (e.g. Jowitt and Ernst, 2013). More detailed geochemistry can further determine which pulses and regions of a given LIP are more prospective, enabling vectoring into such regions (e.g. Jowitt et al., 2014).

Structural aspects are also relevant. For instance, major hydrothermal ore deposits (e.g. Sb–Hg, Au–Hg, Ag–Sb, Ni–Co–As, Cu–Mo porphyry) are known to be temporally related to the Siberian Trap LIP (e.g. Pirajno et al., 2009), but are distal from the plume centre and are broadly spatially associated with a system of regional faults in Central Asia. Thus, effective targeting should integrate the known translithospheric faults (e.g. Begg et al., 2009; McCuaig et al., 2010) with the distribution of the underlying plume head (inferred from the LIP distribution). Fluid pathways that link with the magmatic underplate (at the base of the crust above the plume head) may also form key links between LIP events and metallogenesis. This is exemplified by research of Xu et al. (2014), who suggest that Cu and Pb ore deposits (up to 100 myr younger than the LIP event) could have formed from metal-rich fluids derived from the cooling underplate associated with the 260 Ma Emeishan LIP.

Rifts are also important hosts for various ore types such as SEDEX, red-bed copper, orthomagmatic Ni–Cu–PGE, VMS, and alkaline magmatism-related systems. In cases where the rift system has been obscured by erosion or deformation, it can be potentially recognized by lines of intrusions (e.g. Deccan LIP), and as the locus of a linear subswarm of dykes (e.g. Matachewan LIP) (e.g. Blanchard et al., 2017), or by associated silicic magmatism (McCuaig et al., 2010).

Intermediate scale

Proximity to plume centre (within a few hundred km)

Proximity to a paleo-plume centre (of a LIP) has implications for a variety of exploration systems. This especially applies to magmatic sulphide systems that record increased magma transport in such regions, generating higher R-factors and magmas with higher Mg# values, both of which control the tenor of any associated magmatic sulphides. The proximity to a paleo-plume centre (and therefore increased magma flux) may also influence the dynamics of magmatic systems, with more dynamic systems being able to assimilate more crustal material and crustal S, increasing the likelihood of the system reaching S-saturation and generating immiscible magmatic sulphides. These factors may also influence the generation of ferro-gabbros (with Ti–V–Fe deposits) that are also often proximal to plume centres (e.g. 260 Ma Emeishan LIP). In addition, plume proximal regions are often the locus of deep mafic–ultramafic intrusions that can be geophysically imaged, suggesting the potential presence of small ore-bearing intrusions at shallow crustal levels above (and fed from) these deeper intrusions (Blanchard et al., 2017).

In a number of cases (e.g. 66 Ma Deccan, 370 Ma Yakutsk-Vilyui LIPs) kimberlites are associated with LIPs. In such cases, the underlying mantle plume extends beneath cratons with thick lithospheric roots, producing kimberlites, in contrast to mafic melts being produced by melting of the plume beneath thinner lithosphere. The diamondiferous potential of a thick lithospheric root may also potentially be destroyed by thermal pulses associated with prior LIP/plume events (proximal to the older plume centre). This indicates that identifying the spatial and temporal relationships between LIP and kimberlite magmatism in a region can provide useful insights into whether these kimberlites would be diamondiferous or potentially barren.

Targeting 'upstream'

Tracking the movement of magmas through LIP plumbing systems is critical to magmatic sulphide exploration. The presence of 'downstream' components that are chalcophile element depleted strongly suggests deposition of these metals within magmatic sulphides 'upstream' within the same system. Chalcophile-depleted units within LIPs can therefore be used to identify areas with the potential for 'upstream' enrichment in Ni, Cu, and the PGE. It has long been suggested that the chalcophile-depleted Nadezhdinsky flood basalts of the Siberian Trap LIP are 'downstream' from the Ni–Cu–PGE-rich Noril'sk intrusions (e.g. Lightfoot and Keays, 2005). However, more recent U–Pb dating suggests that at least some of the mineralized intrusions are slightly younger than the flood basalts. Dolerite dykes that are also chalcophile element depleted can be linked to ore-bearing magma chambers 'upstream', i.e. along strike toward the mantle plume centre. Geochemistry can be used to distinguish and track specific magma batches within a sill province (e.g. of the Karoo LIP: Neumann et al., 2011), allowing targeting of those batches with 'upstream' ore potential. A more fundamental understanding of the plumbing systems and dynamics of LIPs could also improve strategies such as the targeting of magmatic structures such as chonoliths that preferentially host or are involved in the transportation of magmatic sulphides (e.g. Barnes et al., 2016).

Thermal pulse of LIP units can mobilize metals

A thermal pulse from the plume, the underplate and or the intrusive component into the crust can lead to various hydrothermal ore deposit types. For instance, the Nipissing sills (of the 2215 Ma Ungava–Nipissing LIP) intruded the Cobalt Plate region and are linked to Ag, As, Co, Ni, Bi mineralisation within the host sedimentary country rocks (e.g. Laznicka, 2010). Widespread hydrothermal vent complexes (HVCs) with massive gas release are associated with interaction between sills and volatile-rich host rocks; in the Siberian Trap LIP hundreds of such HVCs have mobilized Fe to produce magnetite ores (e.g. Svensen et al., 2009). A thermal pulse of the Bushveld intrusion (above the plume centre for the Bushveld LIP) has re-mobilized U in the region (Rasmussen et al., 2007). The original (primary) distribution of magmatic units belonging to a LIP can therefore be predictive regarding thermal pulses that potentially mobilized and concentrated metals of interest.

Local scale

A LIP context should also be useful for mineral exploration at more local scales. For instance, the criteria outlined above can be used to rank prospective individual intrusions or prospects. Also, the identification of feeder dykes within an intrusive complex can be useful for identification of high flux zones, areas with potential for dense sulphide deposition.

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The influence of geoscience integration in post-processing lithological reconstruction

by

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After running a series of increasingly integrated and constrained single domain and joint geophysical inversions integrating geology, petrophysics and geophysics, we applied tools to reconstruct lithological models from inversion results. To assess the capability of the inversions to retrieve accurate lithological models, we applied our workflow to a synthetic case study using geological field data. The comparison of the reconstructed lithological models shows that integration of geophysical and petrophysical measurements alone does not suffice to recover a realistic lithological model retaining the essential geological features. This investigation also shows that the retrieval of an accurate lithological model is possible only when statistical geological modelling and petrophysical measurements are integrated in geophysical inversion, and that the best matching models are obtained when geophysical inversions are run jointly.

Introduction

Recent advances in geophysics include improvements of the optimisation algorithms and the increase in integration efforts. However, only a few authors tackled the problem of inferring geology from geophysical inversion (see Sun and Li, 2016 and references therein). In this work we apply a method for retrieving lithologies a posteriori (in a similar fashion to Sun and Li, 2013), and compare the lithological models obtained for increasingly integrated inversions. This work builds on previous work from Giraud et al. (2017), who integrate geological, petrophysical and geophysical data in joint inversion. Here, we perform a further validation of this integrated inversion workflow through the comparison of the lithological models reconstructed from the results of increasingly integrated geophysical inversion of gravity and magnetic data.

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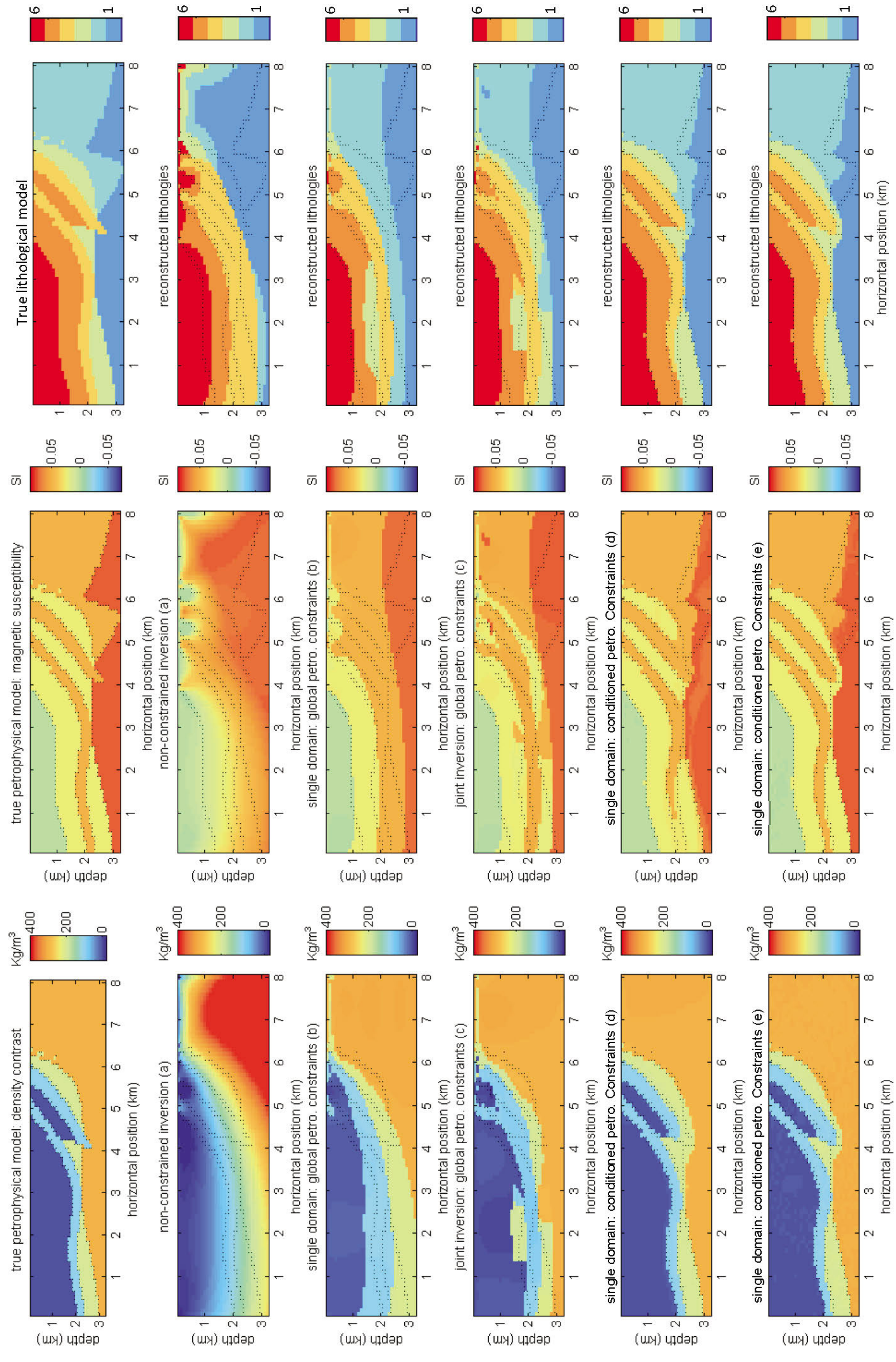
Integrated geophysical inversion and statistical geological modelling

As it accounts for uncertainties in both the input data and constraints, we formulate the inverse problem using a Bayesian inversion approach. The inverted models that we apply the lithological reconstruction to are obtained from: (a) non-constrained single domain inversion; (b) single domain inversion with petrophysical constraints; (c) joint inversion with petrophysical constraints; (d) single domain inversion with geologically conditioned petrophysical constraints (GCPC); and (e) joint inversion with GCPC. Statistical geological modelling (SGM) is obtained from a partial Monte-Carlo simulation consisting in the perturbation of orientation data (Pakyuz-Charrier et al., 2015). The petrophysical measurements are assumed to follow a normal distribution for each lithology, and are modelled using a mixture model. The conditioning of the petrophysical constraints by SGM consists in assigning weights to the normal distributions representing the petrophysical measurements using SGM. The lithological models are reconstructed by identifying, for each cell of the inverted models, the component of the mixture model with the highest relative likelihood (Sun and Li, 2013).

Synthetic case study — lithological reconstruction

The geological model we simulate is generated using geological field data from the Mansfield area, to which we added synthetic measurements to increase geological complexity. Each lithology is characterised by a specific density contrast and magnetic susceptibility. Figure 1 shows the model used for the simulations as well as the results we obtained. Inversions (a) and (b) show only mesoscale structures. The corresponding reconstructed lithological model lacks geological complexity and exhibits erroneous geometries. Inversion (c) retrieves the deepest structures more accurately. However, small-scale structures are not retrieved. Inversion (d) greatly improves the lithological model and the corresponding geology is consistent with the true model except for the most complex structures. Inversion (e) generates a lithological model whose corresponding geology is the closest to the true model in terms of retrieved lithologies and geological contacts.



true petrophysical model: density contrast
true petrophysical model: magnetic susceptibility
True lithological model
non-constrained inversion (a)
reconstructed lithologies
single domain: global petro. constraints (b)
joint inversion: global petro. constraints (c)
single domain: conditioned petro. Constraints (d)
single domain: conditioned petro. Constraints (e)
depth (km)
horizontal position (km)
Kg/m3
SI

Figure 1. (opposite) First row: true model (top row). Second through sixth rows: results for inversion (a) (second row) through (e) (sixth row). Columns from left to right: density contrast, magnetic susceptibility and lithological model. The right column shows the respective lithological model. Lithologies are labelled from 1 to 6, and their respective petrophysical properties can be identified using the true model as reference.

Conclusion and discussion

We have shown on a synthetic case that integration of geoscience disciplines in geophysical inversion is crucial for accurate lithological and geological interpretation of the inverted models. Therefore, we recommend application of lithological reconstruction only to integrated inversions, and to interpret the results with care. Future work includes the use of uncertainty to determine the ill-constrained parts of the reconstructed lithological models, and comprises applications to 3D real data case studies.

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Access to precompetitive data: what, where and how?

by

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Precompetitive geoscientific data, when made available to mineral exploration companies, has been shown to generate inward investment ranging from ratios of 3:1 to 20:1 for Australia and Canada (O'Neill, 2007; Kirkwood, 2014). For many African countries, the extent of geodata transfer between industry and government is variable and company geodata is largely missing from the government databases. In 2015, a study was undertaken to investigate barriers to corporate data delivery to African national archives from the regulation, technical implementation and compliance perspectives (Harris and Miller, 2015). In practice, company geodata is not transferred to government archives due to a combination of legislative and technical capacity insufficiencies and, crucially, a lack of trust between companies and governments. A progressive approach is proposed to improve the transfer of company geodata to relevant government agencies and to mitigate some of the barriers identified.

In addition to precompetitive data acquired on behalf of African countries as part of resource development initiatives, there are three other sources of data that contribute pieces to the geoscientific knowledge infrastructure 'puzzle'. These data categories are summarized in Table 1. Regardless of the format of historical and research data, it is theoretically possible for national archives to access and digitise these types of data as appropriate, if they are available. These are valuable components of a national archive and are incorporated into geoscience infrastructures where possible. Country level mapping from more recent EU SYSMIN and World Bank funded initiatives are available as georeferenced digital datasets, in many cases forming the foundations of geoscientific knowledge in the countries that have benefited from these programs.

Table 1. Data categories comprising a geoscientific knowledge infrastructure

Data Category	*Description*
Country level data	Regional or country scale geological mapping and geophysical surveys and interpretation products
Historical Data	Data acquired that is located predominantly in paper reports located either in national archives or in European GSOs
Research Data	Data that is located in research publications e.g. Scientific journals
Company Data	Acquired by mining companies during exploration activity, sometimes referred to as 'Dark Data' due to its inaccessibility

The final piece of the puzzle, company data, also in digital georeferenced formats, is for the most part inaccessible in most countries. When a company ceases activity on a permit, if the datasets they have acquired during exploration are not transferred to the government custodians of geoscientific data, this represents a missed opportunity for growing the national archive.

Case study: Burkina Faso

The African Mining Vision identifies knowledge infrastructure, and resources data in particular, as an imperative for countries to improve their negotiating positions when establishing extractive agreements (African Union, 2009). Geodata from relinquished permits alone would incrementally increase the area of data coverage by significant amounts over the boom and bust cycle of exploration activity.

To illustrate this point we show that, during boom to bust exploration cycle in Burkina Faso between 2007 and 2014, both the number of permits, and their combined surface area, essentially doubled during this period (Fig. 1) and that a significant amount of ground was relinquished (Burkina Faso Ministry of Mines, Quarries and Energy, 2007, 2014). The total permit area of internationally-held exploration permits in 2007 that were no longer under licence in 2014 was calculated to be all or parts of 157 permits or 5% of the total area of the country. Using published exploration expenditure data for two companies and the total exploration expenditure in Burkina Faso for the period 2007 to 2014, we make a conservative estimate of $50–100M for the value of the data associated with relinquished permits over this time period.

Based on publicly available permit data, data provided by geological survey organisations (GSOs), and reports on mining activity across Africa, Burkina Faso ranked as a mid-range country in terms of area of permits in 2015, and thus could be considered as representing a typical mining country in the African context (Harris and Miller, 2015). On that basis the total potential return to African nations of a data transfer policy for relinquished permits would easily exceed US$1B per boom to bust exploration cycle.

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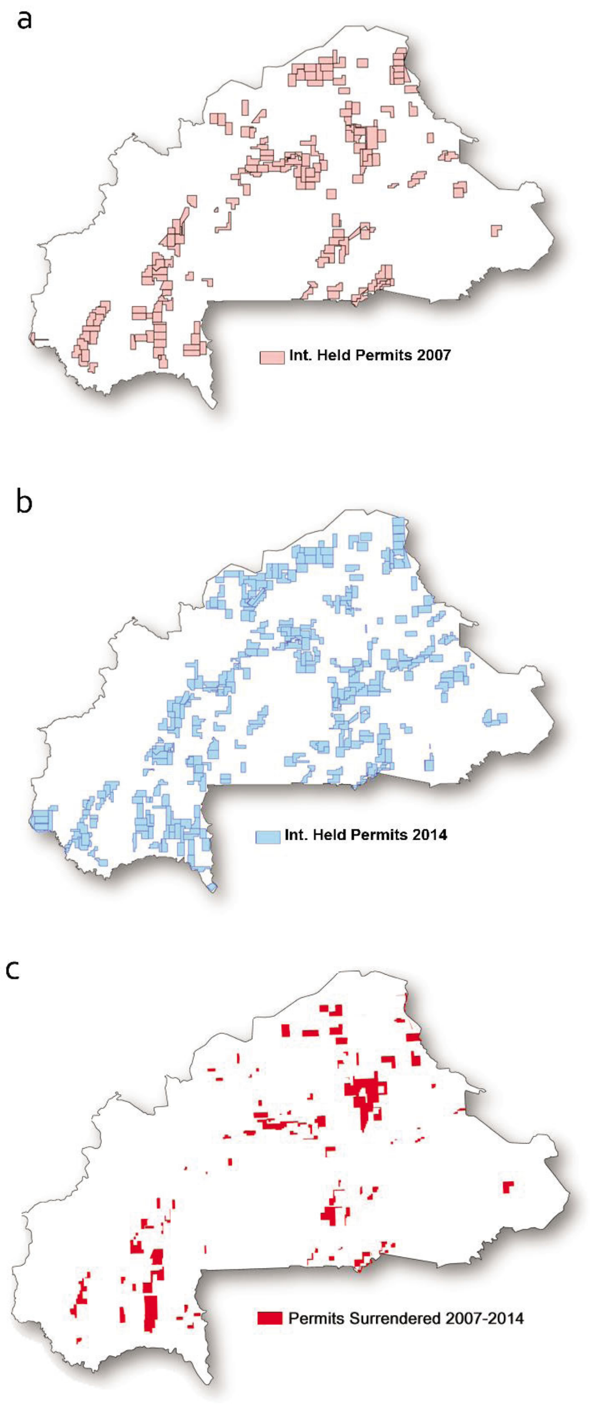

Figure 1. Evolution of exploration and mining permits held by International Companies 2007-2014 for Burkina Faso. a) Permits held by international mining companies in 2007. b) Permits held by international mining companies in 2014. c) Ground that was held by international mining companies in 2007 but was vacant ground in 2014. Source of cadastre maps: Ministry of Mines, Quarries and Energy, Department of Geology and Mining Cadastre, Burkina Faso

Precompetitive data contributing to future generations

Contributions to country development resulting from the outcomes of building a robust geoscientific knowledge infrastructure that includes company exploration data are demonstrated to benefit a broad range of stakeholders such as non-minerals government agencies (e.g. environmental ministries) and higher education institutions in addition to ministries of mines, GSOs and industry operators for whom access to geodata is a pre-condition for investment (Chindo, 2011), (Table 2).

As a first step towards a full integration of company exploration data into the geoscientific knowledge infrastructure for jurisdictions not currently archiving digital company geodata, our study explores the option of initially requiring that company data transfer to governments be specifically limited to exploration data from relinquished permits. By defining regulations for the transfer of data in this way, the entire work flow could be designed and implemented with much reduced risk to both governments and companies. This type of progressive approach is proposed to incrementally populate national geoscience archives with company geodata to ensure custodianship and access for future generations.

An initial-stage implementation of a geoscience database would meet the essential needs of end users without placing undue strain on existing human and technical resources. A schema for such a system is illustrated in Figure 3 and could simply consist of:

1. Mining legislation that refers to regulations/guidelines detailing the permit surrender process and including specific reference to raw digital data from exploration activity, the data types to be submitted data standard in formats where possible
2. A GIS meta-database for all past, pending and current permits with only past permits providing metadata on associated company data. International standards for metadata can be adapted for use here
3. A structured flat file storage of digital company data
4. A GIS template for companies to use when relinquishing permits that provides georeferenced metadata for each digital dataset
5. Online or email delivery to end users of a single GIS layer containing permits and associated metadata
6. Online or offline delivery of digital company data on request using cost recovery when necessary.

Conclusion

A robust geological knowledge infrastructure underpins effective development and management of mineral resources and contributes to a wider range of applications including strategic planning and education.

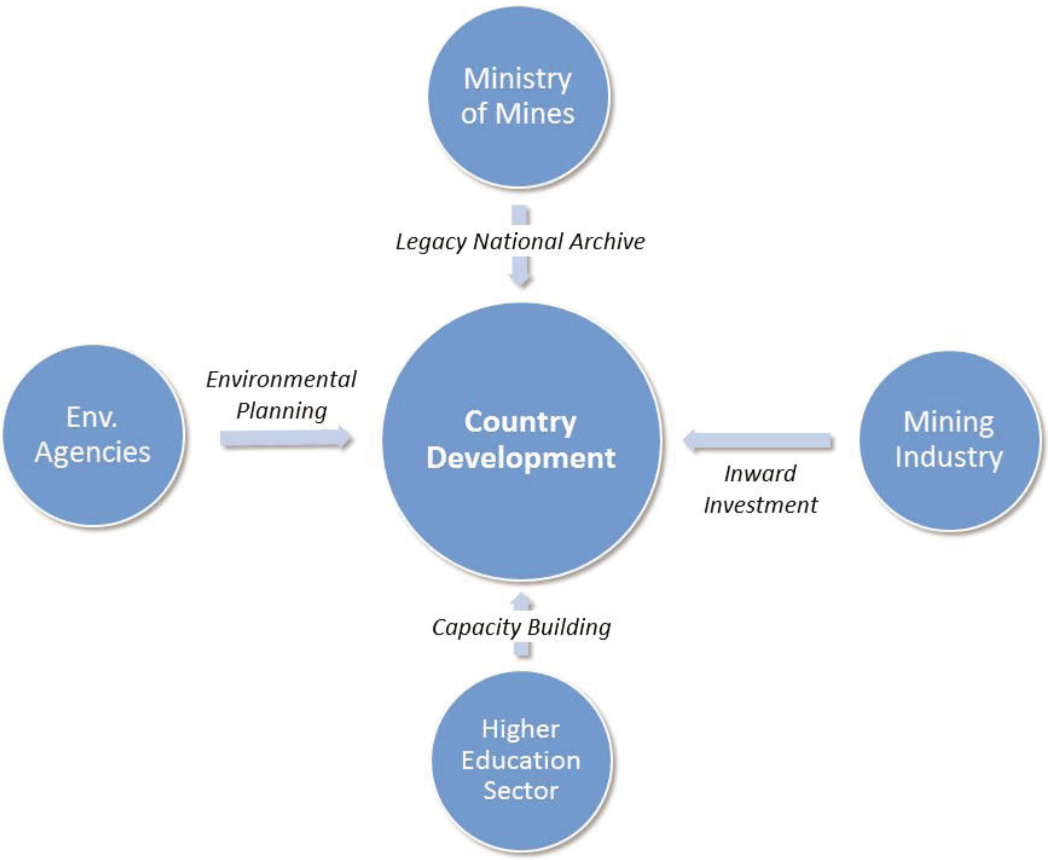

Figure 2. Illustration of the contributions to country development resulting from a robust geoscientific knowledge infrastructure that includes company exploration data

Table 2. Stakeholder benefits from the transfer of company geoscientific data to national archives

Stakeholders	*Evolution/Development*	*Stakeholder Benefits*
Mining Ministries and GSOs	GSOs become the custodians of the geoscientific infrastructure under the administration of the Mining Ministries	• Capacity building of government staff • Development of robust management systems. • Increased knowledge infrastructure improves the position of governments during resource negotiations and strategic planning
Non-mining government departments	Access to knowledge infrastructure for a broad range of applications in addition to those for which data were originally acquired	The applications of 'generic' data to domains outside the mining sector. The wide availability of the knowledge infrastructure underpins more informed decisions on environmental, agricultural and urban planning
Education	Increased availability of high resolution datasets for teaching and research projects in higher education	Improved training tools for teaching higher education students who will go on to work in government and industry
Mining Industry	Access to previously acquired company data in addition to smaller-scale precompetitive data	Reduced technical risk in successive exploration operations that can build on previous data acquisition campaigns

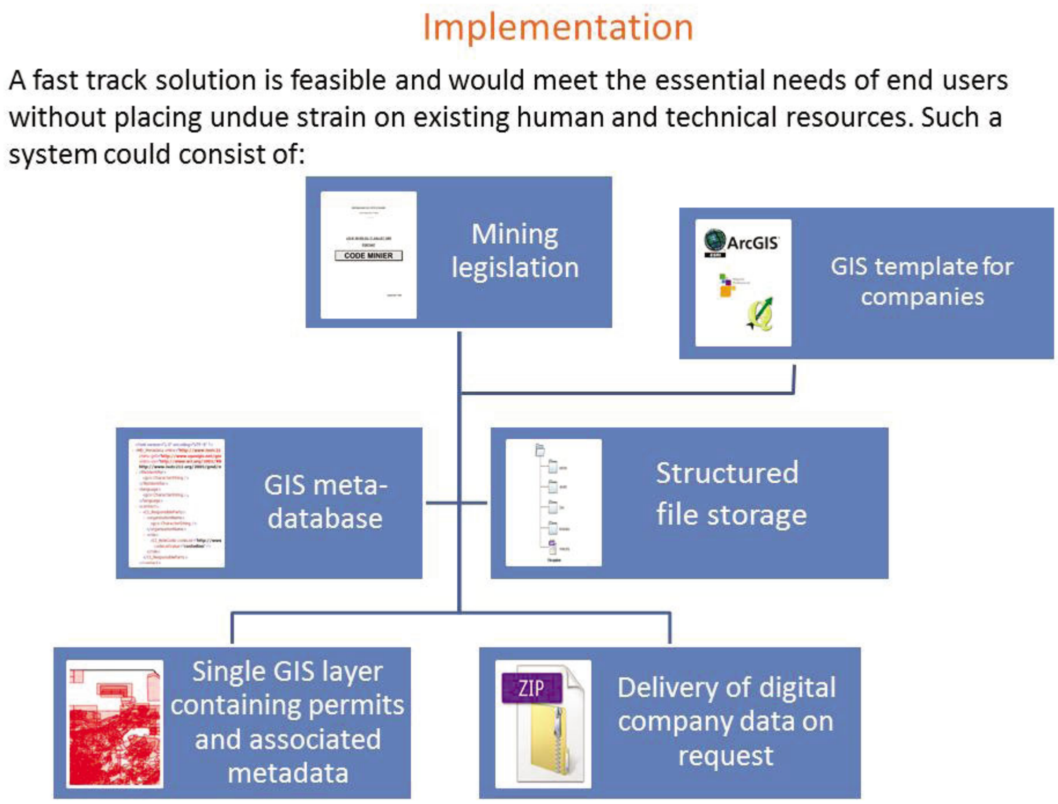

Figure 3. **Schema of an initial stage geoscience database implementation proposed for jurisdictions not currently archiving digital company geodata**

We propose a fast-tracked approach allowing early implementation via transfer of company data from relinquished permits as a first stage towards an extended company geoscientific data management initiative. This staged approach would allow transfer, archiving and maintenance systems to be established and proven before the need to ensure data confidentiality.

Geodata from relinquished permits alone would incrementally increase the area of data coverage by significant amounts over a boom and bust cycle of exploration activity. The transfer of these datasets to national archives represents equivalent data acquisition expenditure of US$1B across Africa if made available to stakeholders as publicly available data. Host countries would also see monetary benefits that are many multiples of this in the form of inward investment by industry operators benefiting from knowledge of previous work undertaken by preceding title-holders.

The effective integration of company geodata into geodatabase systems, where the data are made available to all stakeholders, would lead to a significant growth of the national archive over time with benefits from the improved accessibility of these datasets flowing to the wider community.

Future projects continuing the theme of this investigation include a targeted implementation of a geodatabase system designed to archive, manage and distribute company data for one country or for a region of cooperating countries and a data recovery project to locate and repatriate exploration data from relinquished permits acquired during the last decade.

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Deep crustal to upper mantle structures in the Superior Province, Canada — implications for exploration targeting and Archaean tectonic models

by

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Structures in the deep crust to subcontinental lithospheric mantle (SCLM) interpreted from geophysical data that are parallel and orthogonal to terrane/sub-province boundaries in the Superior Province (Canada) show a spatial relationship to large mineral deposits. These structures are difficult to reconcile with traditional models proposing systematic N to S accretion of disparate terranes (arcs, forearc basins, backarcs, small continents) through Neoarchaean subduction-related tectonic processes.

SCLM structures interpreted from seismic tomography, enhanced gravity, and long-wavelength aeromagnetic (including pseudogravity) data imply: (i) Mafic–ultramafic hosted Cr–PGE, Fe–Ti–V, Ni–Cu– (PGE) mineralization in the 'Ring of Fire' (Ontario) follows a fragmented and reassembled N–S-trending Mesoarchaean proto-craton boundary; (ii) Mineral deposits at the boundary between and within the La Grande and Opinaca subprovinces (NE Superior, Quebec) occur where major N–S faults paralleling a deep crustal structure intersect other regional structures; (iii) Major Au 'camps' in the Wawa–Abitibi subprovince in the SE Superior occur above preserved SCLM rift margins obliquely reactivated during accretion and terrane extrusion.

Geophysical interpretations and tectonic model

Previous studies of the southern Superior Province documented systematic Neoarchaean N to S accretion of terranes interpreted as oceanic plateaux and exotic oceanic and continental arcs and forearc basins; and speculated that terrane assembly was driven by subduction processes. This uniformitarian interpretation is inconsistent with regional geophysical data:

- 3D isosurface images of S-wave seismic tomographic data for the SE Superior reveal a symmetrical rift in the sub-continental lithospheric mantle (SCLM) beneath the Wawa–Abitibi Subprovince, with no evidence for 'fossil' subduction zones.
- S-wave seismic tomographic data and edges of the horizontal gradient of Bouguer gravity at different crustal depths ('gravity worms') portray structures in the SCLM and deep crust that are highly oblique to E–W-trending Neoarchaean terrane boundaries established from surface geology and aeromagnetic interpretation.
- An approximately N–S structure in the SCLM separates the Superior craton into distinct western and eastern domains (concurring with the interpretation of P-wave tomography by Frederiksen et al., 2007). A change in Hf zircon model ages from 3.5 Ga to 3.1 Ga (Lu et al., 2013) across this structure in the Wabigoon Subprovince suggests the presence of an early N–S terrane boundary preserved within ribbon-continents torn from a heterogeneous older (Superior I) craton which were reassembled between 2720 and 2690 Ma (Bédard and Harris, 2014).
- The NE Superior Province is separated into two blocks with deep SCLM keels separated by a likely mantle rift that underlies greenstone belts in the Minto Subprovince.

Taking these new geophysical data into account, a non-plate tectonic model (Bédard and Harris, 2014; Harris and Bédard, 2014) for formation and deformation of the southern Superior craton can be proposed, involving: (i) E–W assembly of an earlier, 'Superior I' craton; (ii) fragmentation of this 'Superior I' craton associated with mantle overturn or upwelling mantle plume(s), with extensive remelting of older granitoid rock; (iii) formation of juvenile rift and oceanic basins; (iv) reassembly of Superior I ribbon continents and intervening greenstone terranes and basins to the leading edge of the southwardly-drifting older N Superior /Hudson Bay terrane as a result of mantle tractions ± plume-push forces acting upon its deep lithospheric keel. NW–SE to N–S shortening/ indentation closed intracontinental rifts and caused early regional folding and ductile shearing (dominantly dextral transpression). Lateral flow subparallel to the orogen is suggested in high grade terranes. Conjugate and reverse, discrete brittle-ductile to brittle shears formed late in this event. Some regions are affected by folds with approximately N–S axial traces, cut by conjugate brittle–ductile shear zones, and early shear zones are reactivated during E–W shortening prior to intrusion of Palaeoproterozoic dykes, whose location is in part controlled by pre-existing deep crustal and SCLM discontinuities.

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Mineralization associated with reactivation of early N–S Superior I terrane boundaries and/or rifts

Cr–PGE, Fe–Ti–V, Ni–Cu–(PGE) mineralization in the 'Ring of Fire', an area of active mineral exploration in northern Ontario, is hosted by mantle derived mafic to ultramafic intrusions in the 2828–2702 Ma McFaulds Lake greenstone belt (Metsaranta & Houlé, 2013). The Ring of Fire is located on the E side of the newly identified approximately N–S boundary between two crustal blocks in Superior I, suggesting that reactivation of lithospheric-scale structures associated with this Mesoarchaean terrane boundary controlled emplacement of these ore-hosting plutons. Its location on the margin between two interpreted proto-cratons is analogous to the setting for the Bushveld Complex in South Africa interpreted from new 3D images of seismic tomographic data.

Mineral deposits, including the Roberto (Éléonore) Au deposit (one of the most significant discoveries of the past 10 years in Canada; Ravenelle et al., 2010) in the La Grande and Opinaca subprovinces in the James Bay sector of the NE Superior Province in Quebec also occur along N-S faults (i.e. orthogonal to regional structural trends), where they intersect other regional structures. The intersections also correlate with a series of local ultramafic intrusions, highlighting the trans-crustal nature of the structures and their facility as fluid conduits. N–S structures parallel a diffuse deep crustal discontinuity revealed by enhanced long wavelength pseudogravity images that also marks an E–W change in metamorphic grade. This discontinuity aligns with a N–S lithospheric-scale rift in the SCLM beneath the Minto Subprovince further northwards, imaged in 3D from seismic tomographic data. Enhanced recent high resolution aeromagnetic data for the upper crust also show that re-evaluation of some sub-province boundaries is required.

SCLM rift controls on Au mineralization in the Wawa–Abitibi

Major Au deposits in the Wawa–Abitibi Subprovince occur close to fossil SCLM rift margins, implying that SCLM discontinuities localized transcurrent to transpressional shear zones, hydrothermal fluid flow ± lamprophyre dykes and alkaline intrusions that are associated with many deposits in overlying crustal greenstone sequences.

Summary and discussion

Enhanced gravity and aeromagnetic/pseudogravity images for different crustal levels, combined with seismic tomographic images for the upper mantle, highlight previously unknown structures that are spatially related to mineralization in the Superior Province, thus providing new exploration targets.

A plume-related rift environment for formation of greenstone sequences is consistent with tectonic models for VHMS deposits in rift or incipient rift settings, as well as arc-related rifts. As in many Archaean granite-greenstone terrains, epigenetic ('orogenic' or 'lode') gold mineralization is late in the structural history, commonly localized within subsidiary shear zones associated with long-lived, lithospheric-scale structures. We provide an alternative model for the southern Superior Craton where the major late, 'orogenic' gold deposits are preferentially located along regional shear zones that track 'fossil' SCLM rift margins, which were reactivated during accretion and/or deep, approximately N–S-striking faults (i.e. at a high angle to main upper crustal trends) localized by, or produced during, structures developed during Superior I craton assembly. These early Superior I structures are preserved in deep levels of accreted crustal 'ribbon continent' blocks in the south-central Superior.

Proximity of gold deposits to our interpreted SCLM discontinuities helps explain the common association between gold mineralization and (mantle-sourced) lamprophyres as both hydrothermal fluid flow and lamprophyre emplacement may be controlled by the same lithospheric-scale faults. Structures that follow N–S Mesoarchaean terrane boundaries also likely provided conduits for ascent of mantle-derived intrusions in the 'Ring of Fire' which host Cr–PGE, Fe–Ti–V, Ni–Cu–(PGE) mineralization. There is therefore the potential for discovery of similar intrusion-related mineralization along the margins of other regional structures of this type.

Acknowledgements

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Lithospheric, 'proto-craton' controls on the intrusion of the Bushveld Complex and diamondiferous kimberlites, South Africa

by

Lyal B. Harris[1*] and Jean-François Moyen[2]

The 2.06–2.05 Ga Rustenburg Layered Suite mafic rocks of the Bushveld Complex in the northern Kaapvaal Craton, South Africa, the world's largest layered mafic intrusion, hosts PGE–Cu–Ni–rich sulphides, chromite and Fe–Ti–V oxides and is the largest PGE deposit in the world, containing half the world's resources in chromite (Groves and Bierlein, 2007). The Bushveld Complex and associated A-type anorogenic alkaline granites are generally attributed to hot-spot/mantle plume magmatism. In most previous models, ENE–WSW- to NE–SW-trending structures have been interpreted as controlling feeder dykes for the Bushveld Complex in a mid-craton setting. Seismic tomographic images of the subcontinental lithospheric mantle (SCLM) and enhanced regional gravity and gravity worms, however, suggest that the Bushveld Complex and other related mafic–ultramafic intrusions were emplaced along the NNE–SSW-trending margins to a 'proto-craton' with a deep lithospheric keel, supporting the general model for intrusion of large mafic-ultramafic complexes proposed by Begg et al. (2010) and Griffin et al. (2013). Most of South Africa's diamondiferous kimberlites are also located within this 'proto-craton', although some isolated kimberlites in younger terrains appear to have SCLM that has rifted from this early 'proto-craton'.

Previous interpretations for structures controlling Bushveld emplacement

The Kaapvaal Craton is dominated by NE–SW- to ENE–WSW-trending structures formed in the Archean and reactivated in the Proterozoic that are clearly visible in both gravity and aeromagnetic images. ENE–WSW-striking structures, especially the Thabazimbi–Murchison Lineament, a regional feature that separates the northern from southern lobes, are generally interpreted as controlling main dyke-like feeders for the Bushveld Complex and for focussing of hydrothermal fluid flow during further mineralization. It has also been suggested that the NE-striking Steelpoort fault and faults of the Thabazimbi–Murchison system may have acted as magma conduits. Modelling of gravity data and analysis of kimberlite xenoliths (Webb et al., 2011) and shear wave velocity models (Kgaswane et al., 2012) show that western and eastern lobes of the Bushveld Complex are connected at depth.

Seismic tomography of the Kaapvaal Craton

Although the Kaapvaal Craton in South Africa is a collage of low- to medium-grade Archean terranes, late Archean granitoids and sedimentary cover sequences mask terrane boundaries. Distinct terranes within the Kaapvaal Craton are not clear from previous gravity treatments nor from earlier seismic tomographic studies where data is presented in 2D vertical and horizontal slices. 3D visualization of seismic tomographic isosurfaces calculated from data described by Fishwick (2010) in our study however clearly portrays the form of the South African lithosphere, highlighting a NNE–SSW central region with a deep lithospheric keel that plunges northwards beneath the Limpopo Belt. The area east of its boundary shows no such deep keel and is interpreted as a younger Archean accreted terrane. The eastern margin of the 'proto-craton' suggested by seismic tomography is sub-parallel to deep gravity 'worms' (i.e. edges to the horizontal gradient calculated for different depths). The southwestern part of the Inyoka shear or fault system parallels the interpreted craton margin but turns away from the margin to a more northeasterly orientation in the Barberton greenstone belt. Its western margin generally coincides with N–S-trending deep gravity worms which coincide with the Colseberg lineament, a major near-vertical N–S to NNE–SSW trans-lithospheric boundary between the Witwatersrand block and western Kimberley block. A NW–SE-oriented continuation of Archean SCLM is suggested on the W side of the Colseberg lineament, possibly extending slightly beyond the mapped margin of the Kaapvaal Craton.

The Bushveld Complex occurs on the eastern margin of this central 'proto-craton', suggesting its emplacement was controlled by this lithospheric boundary. The 1915±6 Ma Trompsburg intrusion (Maier et al., 2003), a 2500 km^2 layered gabbro, troctolite, anorthosite and granite body that shares several compositional, lithological and stratigraphic features with the Bushveld Complex, also lies on the SE margin of the central deep-keeled craton. Although it is about 145 Ma younger, Maier et al. (2003)

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suggest that, as this time-span is realistic for mantle plume longevity, both intrusions may be associated with the same, long-lived mantle plume beneath the deep keel of the Kaapvaal Craton. Magma that produced Lindeques Drift and Heidelberg intrusions dated at 2055 Ma (i.e. the same age as the Bushveld Complex) by de Waal et al. (2006) north and northeast of the younger Vredefort impact structure, may have also been controlled by this mantle discontinuity. The Molopo Farms ultramafic–mafic layered intrusion on the border between Botswana and South Africa occurs on the western margin of the interpreted 'proto-craton'.

Most diamondiferous kimberlites in South Africa are located within the central 'proto-craton', consistent with its deep lithospheric keel. Some more isolated diamondiferous kimberlites in younger terrains, however, appear to occur within areas above SCLM fragments rifted from this central 'proto-craton', hence mapping these blocks provides targets for diamond exploration.

Summary and discussion

In their review of mineral deposits Groves and Bierlein (2007) contend that giant mafic–ultramafic-hosted deposits such as the Bushveld 'tend to lie towards the centre of Archean cratons, whereas smaller deposits … tend to lie closer to craton margins' and that 'thick buoyant Archean SCLM is required to support and preserve the large volumes of dense basic magma required for producing the giant deposits, hence their central cratonic position'. Seismic tomography of South Africa however illustrates that instead of being in the centre of a craton with a deep lithospheric keel, the Bushveld Complex is clearly emplaced along the margin of a proto-craton with a deep keel within the Kaapvaal Craton. Our research supports models of Begg et al. (2010) and Griffin et al. (2013) for SCLM controls on both the emplacement of large mineralized mafic-ultramafic complexes and diamondiferous kimberlites. This new geophysical interpretation will assist targeting for both PGE–Cu–Ni–Cr and diamond exploration under cover in South Africa and provides a model for exploration in other Archean cratons.

Acknowledgements

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Targeting plate-like basement conductors using airborne electromagnetic data

by

Juerg Hauser[1*], James Gunning[2] and David Annetts[1]

Understanding model robustness or uncertainty is central to understanding exploration risk and the ranking of basement conductance anomalies. One of the main obstacles to managing uncertainty when making exploration decisions is the computational requirements of quantifying model uncertainty. For uncertainty quantification we introduce a Bayesian parametric bootstrap approach, applied to a thin-plate layered earth hybrid model, as a practical compromise between an efficient deterministic inversion and a computationally expensive exhaustive search of model space. We demonstrate how the approach can be used to invert for a basement conductor and associated uncertainties using GEOTEM airborne electromagnetic data collected over the Walford Creek prospect in northwest Queensland. Recovered uncertainties reveal both the expected trade-off between model parameters and persuasive evidence of a sufficient exploration of model space.

Introduction

A primary motivation for the collection of airborne electromagnetic AEM data in a greenfield exploration context is the identification of economical basement conductors. Given an inversion of these data, economical targets are commonly identified through a qualitative interpretation of the inverted electrical resistivity distribution. Using AEM data in such a manner for the identification of exploration targets does not account for the inherent non-uniqueness of geophysical inverse problems. While iterative Bayesian techniques allow quantification of model robustness, they also demand a very large number of solutions of the forward problem when compared to a deterministic inversion. Identifying a sufficiently accurate, but computationally efficient, way to model the forward response of a basement conductor is therefore critical for a Bayesian approach to be a practical tool for the exploration of basement conductors. A well-known computationally efficient way to model the response of a plate-like basement conductor is to use a thin plate (e.g. Irvine, 1987, Witherly et al. 2003).

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Markov Chain Monte Carlo (McMC) algorithms are widely employed for the quantification of model uncertainty in geophysical inversion. They work by generating a chain of models, which are usually constructed by 'jumping' to new models that are close in some sense to the current model and then tested against the data. The sequence of models is therefore strongly correlated and the chains have to be heavily thinned (or decimated) to obtain uncorrelated samples. With the exception of truly few-parameter problems, McMC algorithms become quickly computationally too expensive for practical applications.

The major alternatives to McMC are bootstrapping techniques (e.g. Efron, 1978). These are often seen as a practical compromise between an efficient deterministic inversion and an exhaustive search of model space. Here we employ the Bayesian parametric bootstrap (e.g. Gunning et al., 2010; Hauser et al., 2015), which treats prior information on the model and its spatial correlation as implied observations and then applies the classical parametric bootstrap. It provides an adequate exploration of model space for non-pathological situations (e.g. Gunning et al. 2010; Hauser et al., 2015, 2016), while requiring many fewer forward problems solves than a comparable McMC algorithm.

The remainder of this abstract is organised as follows: first we discuss the ability of the Bayesian parametric bootstrap (BPB) to recover the main geological features of the Walford Creek prospect in northwest Queensland (Hauser et al., 2016). We will then illustrate how it facilitates the quantification of model uncertainty and explore trade-offs between model parameters, before offering some conclusions.

Walford Creek

The Walford Creek prospect in northwest Queensland is formed by a Pb–Zn–Cu–Ag mineralization associated with a series of synsedimentary pyrite horizons hosted by dolomitic sandstones and siltstones in the downthrown block to the south of the Fish River Fault (Webb and Rohrlach, 1992). The upthrown block to the north is characterized by dolomite overlying sandstone. The prospect was originally discovered by reconnaissance TEM surveys that identified the uppermost pyrite lens. Figure 1a shows the geological features (Webb and Rohrlach, 1992; Lane et al., 2000) and the survey lines of the GEOTEM airborne electromagnetic survey.

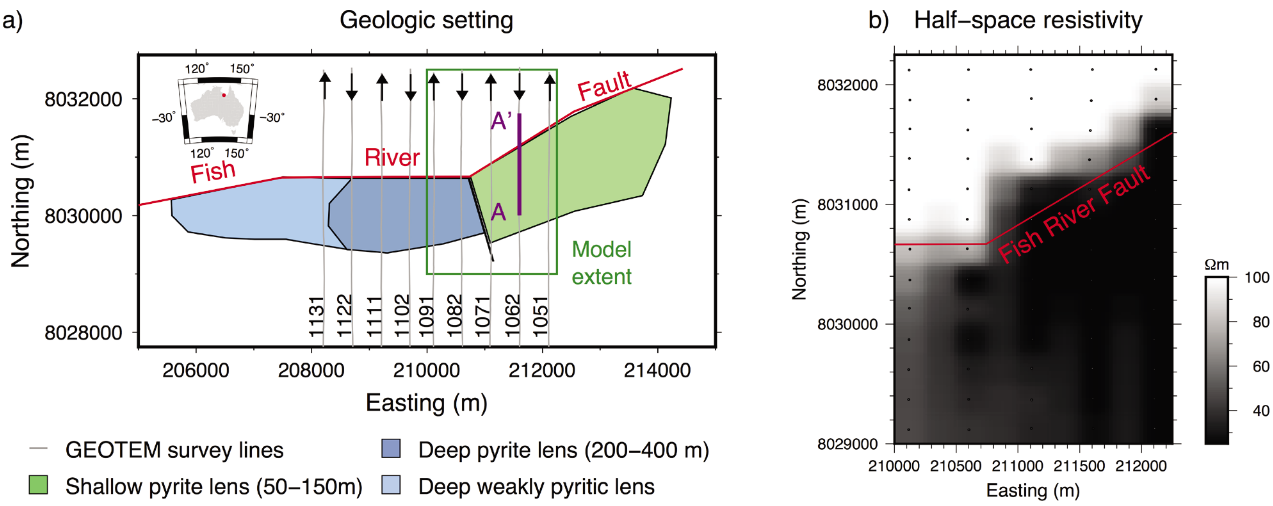

Figure 1. **a) Geologic setting for the Walford Creek deposit in northwest Queensland. For the cross-section A–A,' prior and posterior probability for uppermost pyrite lens are shown in Figure 2; b) Recovered half-space or background resistivity with the expected resistivity change across the Fish River Fault (after Hauser et al., 2016)**

The background electrical resistivity is likely to change across the Fish River Fault and there is a very thin surface cover. We expect a thin plate hybrid model to recover the Fish River Fault and the most shallow pyrite lens. The important aspect of the modelling undertaken in this study is that we seek a single thin plate representing the most shallow eastern pyrite lens in a spatially coherent model accounting for the data from multiple survey lines. This is a more comprehensive or integrated way to model the subsurface than analysing the data on a line-by-line basis (e.g. Lane et al., 2000, Macnae, 2015).

Figure 1b shows the inversion result for the background resistivity with the expected change in resistivity across the Fish River Fault. The recovered resistivity values are a consequence of the host rock and complex pattern of zones of mineralization that exist in addition to the shallowest pyrite lens. We now seek to determine the extent and conductance of the conductive (potentially most economic) part of the pyrite lens. For the cross-section A–A' highlighted in Figure 1a, Figure 2a shows the prior probability for the pyrite lens. This probability is a quantification of our belief that the pyrite lens is located to the south of the Fish River Fault dipping in a predominantly southern direction. The posterior probability in Figure 2b (the combination of our prior beliefs with the information in the GEOTEM data) shows a clear plate target with the expected decrease of probability with increasing depth and a high probability that the target is confined south of the Fish River Fault. This decrease in probability with increasing depth reflects the well-known limited depth of investigation of airborne electromagnetic systems. A scatter plot (Fig. 2c) for plate area and plate conductance shows that while plate conductance appears well resolved, there is a trade-off between plate area and plate conductance captured in the samples of the posterior distribution. The BPB has explored model space and been able to identify the two expected 'end-members', viz. a smaller plate with a higher conductance, and a larger plate with lower conductance, which can both fit the data.

An optimal 'jumping' McMC sampler for an n-dimensional multi-Gaussian distribution has an asymptotic efficiency of approximately 0.3/n (Gelman et al., 2013). For our model, with 128 model parameters, the best possible McMC sampler would therefore generate a chain of models where every ~38th model is an uncorrelated sample. For practical applications samplers rarely achieve this efficiency. In contrast to this, in the BPB an individual uncorrelated sample of the posterior distribution is obtained by an iterative non-linear solver, which seldom requires more than 10 iterations to converge.

Conclusions

Greenfield exploration is typically directed towards confirming the existence of a basement conductor with a successful drillhole. Information about the probability of intersecting such a conductor with a drillhole allows for a more targeted drilling campaign. For plate-like basement conductors, the BPB combined with a thin plate layered earth hybrid model provides an efficient way to compute these probabilities. It is a practical compromise between an exhaustive search of model space and an efficient deterministic inversion.

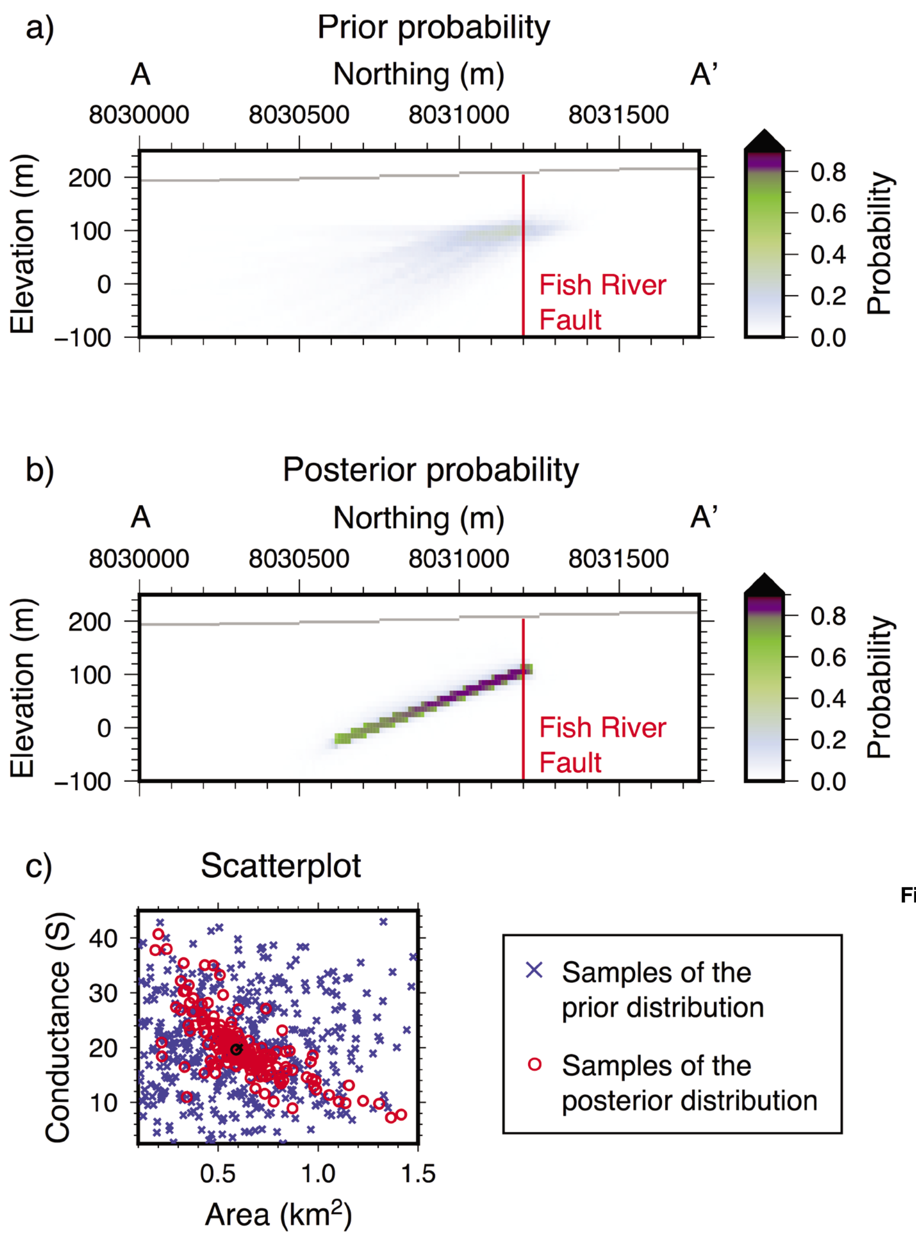

Figure 2. For the cross-section A-A' highlighted in Figure 1a, panel (a) shows the prior probability for the most shallow pyrite lens and panel (b) the corresponding posterior probability. Panel (c) shows the trade-off between plate area and plate conductance as captured by samples of the posterior distribution (after Hauser et al., 2016)

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Applications of volcanic stratigraphy to mineral exploration: examples from the Kalgoorlie Terrane

by

PC Hayman[1]

Volcanic stratigraphy of greenstone belts has important applications for mineral exploration for both structural and stratigraphic deposits. For the case of exploration for orogenic gold, it is well known that major structures, such as terrane margins, provide the first-order pathway for ore fluids from depth (Groves et al., 2003); however, distinguishing these from less important structures is often challenging. In the case of base metals, many deposit types are stratigraphically hosted (e.g. VMS, Ni-deposits) and thus an improved understanding of the stratigraphy can guide regional exploration. Two examples where volcanic stratigraphy provide insights into mineral exploration from the Yilgarn craton are presented here: the first example helps answer why the gold-rich Boulder/Bardoc structure occurs within the middle of a 'terrane', rather than at its margins, while the second example provides new ideas on correlations of, and source rocks for, 'komatiite'-hosted nickel systems.

Volcanic stratigraphy of the Kalgoorlie Terrane

The 2.7 Ga Kalgoorlie Terrane consists of several greenstone belts that are divided into a number of domains (Cassidy et al., 2006), each of which represents a structural block (Fig. 1). Recent studies by Hayman et al. (2015), using published data on stratigraphy, geochemistry and geochronology across the Kalgoorlie Terrane, as well as new data from the Agnew region, show many new correlations for the 2720–2690 Ma mafic–ultramafic stratigraphy (Fig. 2). The data show that the Kalgoorlie Terrane can be divided into two cycles. The first cycle (2720–2705 Ma) is divided into a western portion, which makes up the lower stratigraphy of the Ora Banda and Coolgardie Domains, and an eastern portion that makes up the lower stratigraphy of the Kambalda and Boorara Domains. The second cycle (2705–2690 Ma) caps both the west and east portions. There are insufficient data to extend correlations north of Agnew.

Structurally hosted deposits

Structures provide the main control for orogenic-style gold mineralisation, acting as pathways for fluids to ascend through the crust. For the exploration geologist, success is enhanced by the ability to distinguish deep-tapping structures from less important ones; however, the criteria for distinguishing these structures in most datasets are unclear.

The Kalgoorlie Terrane is one of the most Au-endowed districts in the world and includes four world class Au-deposits that lie along the Boulder–Lefroy shear zone (Weinberg et al., 2004), which runs through the middle of the Kalgoorlie Terrane far from the identified terrane boundaries. This 130 km structure merges northward into the Bardoc Tectonic Zone, and becomes diffuse and ambiguous southward (Weinberg et al., 2004). There are also several other structures within the Kalgoorlie Terrane that can be traced over great distances that are not as prospective. One technique that has been able to demonstrate the crustal-scale nature of at least part of the Boulder–Lefroy shear zone is deep seismic reflection data (Goleby et al., 1993). Stratigraphy also highlights the importance of this structure.

Cycle I volcanism is different across the Boulder–Lefroy shear zone and Bardoc tectonic zone structures. Cycle I west consists of several extrusive basaltic rocks that occur in the same order, from base to top, across the Coolgardie and Ora Banda Domains, from west of Kalgoorlie to about 400 km north at Agnew. To the east of these structures, cycle I consists of one basalt, which is known as the Lunnon Basalt in the Kambalda Domain. The structures are interpreted as basin-margin structures as they separate two different stratigraphies. Cycle II volcanism caps both cycle I west and east and has obscured the stratigraphic differences between the separate basins.

Stratigraphically hosted deposits

The Mount Keith (about 60 km N of Agnew) nickel mine is hosted in Boorara Domain greenstones and is characterised by three komatiites, comagmatic dacitic volcanism, and intercalated basalt (Beresford et al., 2004) (Fig. 2). The McFarlanes Basalt is the basal unit and is overlain by the Mount Keith Ultramafic, which is characterised by adcumulate textures, high MgO and [La/Sm]>1.5 (Fiorentini et al., 2010). Overlying this unit is the Centenary Bore Basalt, a high-Mg and high-Fe unit. The overlying Cliffs Ultramafic is a spinifex-textured komatiite with 25–30 wt.% MgO and [La/Sm] <1 that includes comagmatic dacite intrusions (Fiorentini et al., 2010). The Mount Keith Ultramafic has been interpreted as a comagmatic intrusion to the extrusive Cliffs Ultramafic, and its higher [La/Sm] content a product of contamination by syn-intrusive dacites (Fiorentini et al., 2010).

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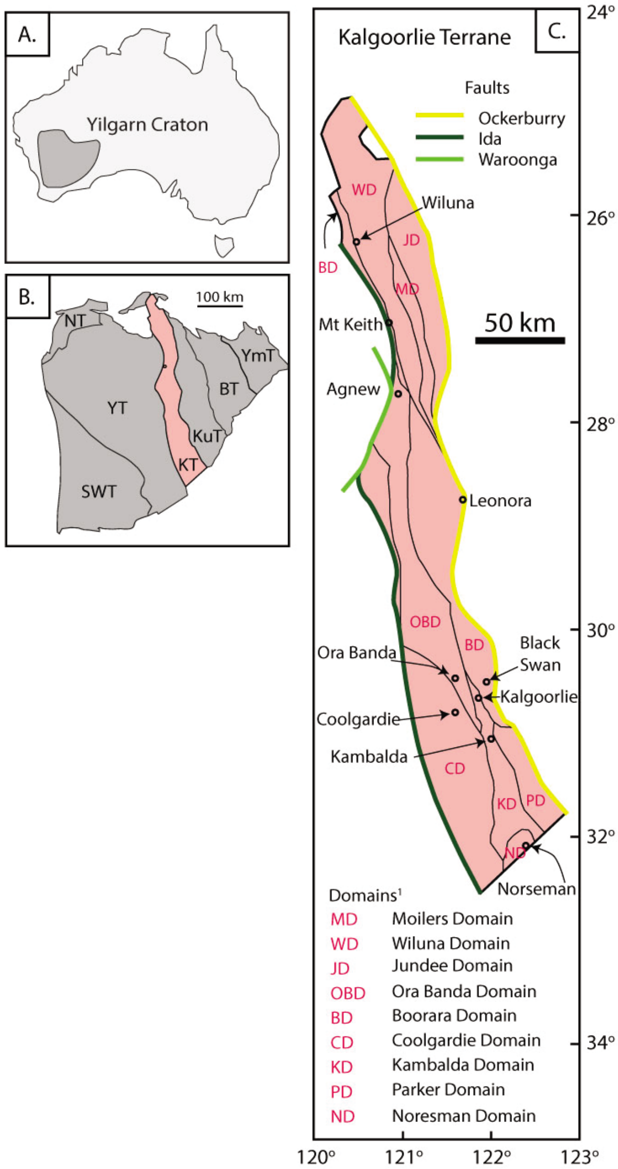

Figure 1. Location map of: A) Yilgarn craton (dark grey) within Australia, B) Kalgoorlie Terrane (KT) within the Yilgarn craton, and C) Domains within the Kalgoorlie Terrane (after Cassidy et al 2006).

An alternative origin for the Mount Keith Ultramafic was proposed by Hayman et al (2015) that is consistent with both geochemistry and geochronology (2707–2712 Ma) of Fiorentini et al. (2010), and the faulted upper contact interpretation of Gole et al. (2013), and fits well with the Agnew stratigraphy. In this alternative interpretation, the McFarlanes Basalt, Mount Keith Ultramafic, Centenary Bore and Cliffs Ultramafic are correlated with the Hickies Bore Basalt, Songvang Basalt, Never Can Tell Basalt and Agnew Komatiite, respectively. In this correlation, the Mount Keith Ultramafic correlates with the differentiated comagamatic intrusion to the Songvang extrusive (komatiitic) basalt as both have similar trace element ratios, including high [La/Sm]. High [La/Sm] content may be a result of contamination; however, the association with extrusive rocks that underlie the extrusive spinifex-textured komatiites indicate they formed earlier than the komatiites.

The implications for exploration are twofold: 1) that intrusive komatiitic basalts can be prospective for Ni-mineralisation, and 2) correlates of the Songvang Basalt (Brilliant Ultramafic: Coolgardie Domain; unnamed komatiitic basalt; Ora Banda) should be considered as potential targets for nickel mineralisation.

Conclusions

The volcanic stratigraphy of the Kalgoorlie Terrane can be used to guide exploration programs for both structurally and stratigraphically hosted mineralisation. Volcanic stratigraphy demonstrates that the portion of the stratigraphy below the regional komatiite differs on either side of the Boulder/Bardoc structures and thus a portion of the west and east formed in separate basins. As a result, the structure represents a basin margin structure (obscured by later volcanism) and this helps explain why it is associated with orogenic gold deposits. Volcanic stratigraphy also demonstrates how the Ni-mineralised Mount Keith Ultramafic correlates well with comagmatic intrusive rocks found in cycle I west volcanism across the Coolgardie and Ora Banda Domains. This correlate, as well as other comagmatic intrusions to komatiitic basalts, should be considered prospective for Ni-mineralisation.

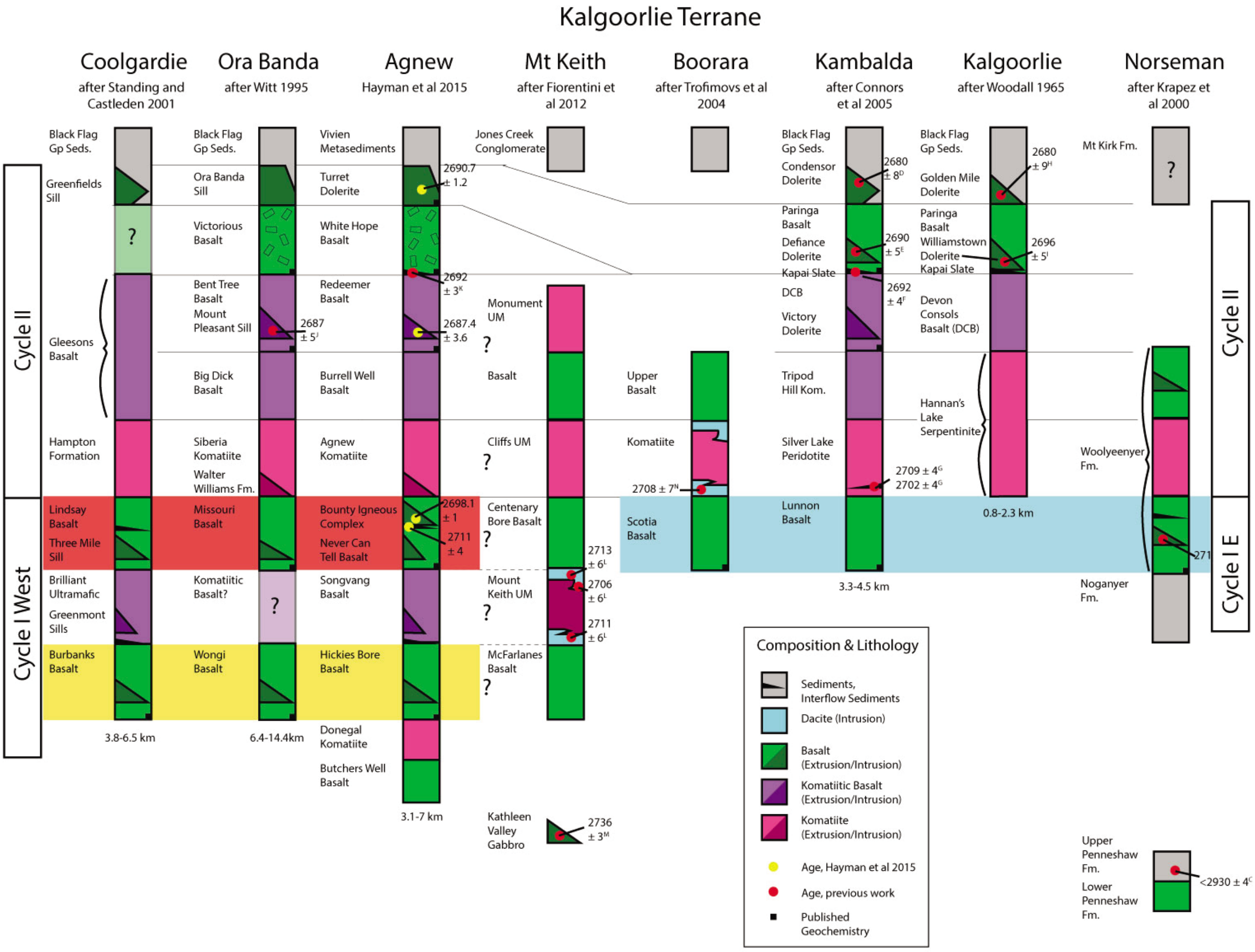

Figure 2. **Stratigraphic relationships of the principal mafic–ultramafic units of the Kalgoorlie Terrane. Vertical positions are an approximation of their relative stratigraphic positions. See text for further explanation and figure caption 14 in Hayman et al (2015).**

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Exploration targeting: toward best practice

by

Nick Hayward[1]

Area selection is one of the most important strategic decisions we make in exploration. Good targeting decisions drive substantial, even transformative, long term value creation; poor targeting decisions have high opportunity costs. Explorers need to adhere to leading practices in targeting to provide better returns on investment, given that industry failure rates for an economic discovery regardless of size are >99% (Bartrop and Guj, 2009). We need to target more effectively than ever before as we shift to new search spaces at greater depths, under transported cover, or in higher risk jurisdictions, and as escalating discovery costs and execution times mean fewer targets get tested.

A multi-scale, multi-stage approach

Targeting occurs across the entire value chain in sequential steps over time, from regional area selection (sub-province), to project generation (district, camp), to drill targeting (deposit, lens, shoot); and from Greenfield plays, to proactive third-party project evaluations, to Brownfield resource extensions. Target selection criteria and objectives vary greatly across these stages, requiring a multi-staged approach with multi-scale models; however, all stages may follow a process broadly similar to the one outlined in Figure 1.

Mineral system and targeting models

Over the last decade there have been initiatives to shift from somewhat empirical Deposit Models which targeted analogous patterns and features, to more conceptual Mineral System Models that encapsulate common ore-forming processes at deposit to lithospheric scales (e.g. McCuaig et al., 2010). The UWA Centre for Exploration Targeting has been a global leader in driving this shift. Mineral System Models link fertility (metal and fluid sources), geodynamics (transient tectonothermal event drivers), fluid conduits (structures, aquifers, aquitards), and depositional environments (metal 'scrubbers') in terms of architecture and interdependent processes. The best Mineral System Models integrate the collective knowledge of critical ore-forming processes from analogous deposits and metallogenic events at global, lithospheric and local scales, while recognising that specific deposit types are end-members of critical process spectrums. They take a more holistic approach and when feedback processes between interdependent components are considered, emergent properties may be recognized that cannot be detected by analysis of constituent parts in isolation (e.g. Self-Organized Critical System: Hronsky, 2011). Mineral System Models must also embrace Ore System Models that address economic viability and sustainability from discovery to recovery to rehabilitation.

Leading practices in targeting should adopt a balanced approach that systematically integrates both inductive and deductive reasoning, supported by increasingly sophisticated computational tools for prospectivity mapping and ranking, utilising both knowledge- and data-driven approaches. Neither conceptual nor empirical approaches work adequately on their own. The most difficult and important step, however, is to translate System concepts into effective local empirical targeting criteria that describe in a self-consistent manner the constituent processes, targeting elements, map proxies, critical evidence, application scales, interpretation products and rating criteria. It is also important to critically analyse and iteratively refine targeting efficacy against training data in analogous situations, in order to minimise false positive response rates and understand inherent model limitations and uncertainties.

Managing uncertainty

In targeting, explorers commonly interpret fragmentary evidence with unbridled optimism, blissfully unaware of our ignorance and bias, hoping for success in applying simple 2D map solutions to complex 4D problems. One of the highest uncertainties in district-scale targeting models is the prediction of high flux fluid conduits along fault corridors. Frequently explorers settle on just one target model yet early-stage targeting faces huge uncertainties, accounting for extremely high false positive rates (and low success rates) in both prediction and detection. The uncertainties may be either stochastic (missing and poor quality data) or systemic (model inadequacy, weakness and bias). With more information, uncertainty resolves into quantifiable upside and downside risk. New opportunities can be found in questioning interpretations and assumptions and challenging paradigms. Rather than shun uncertainty, leading practitioners should embrace a variety of methods to carefully manage it as an intrinsic part of the targeting process. Stochastic uncertainties can be managed with data verification, field validation, strength testing, sensitivity analysis and threshold optimisation. Systemic uncertainties can be managed with team-based scenario modelling and simulation, independent expert review, and embedded learning feedback.

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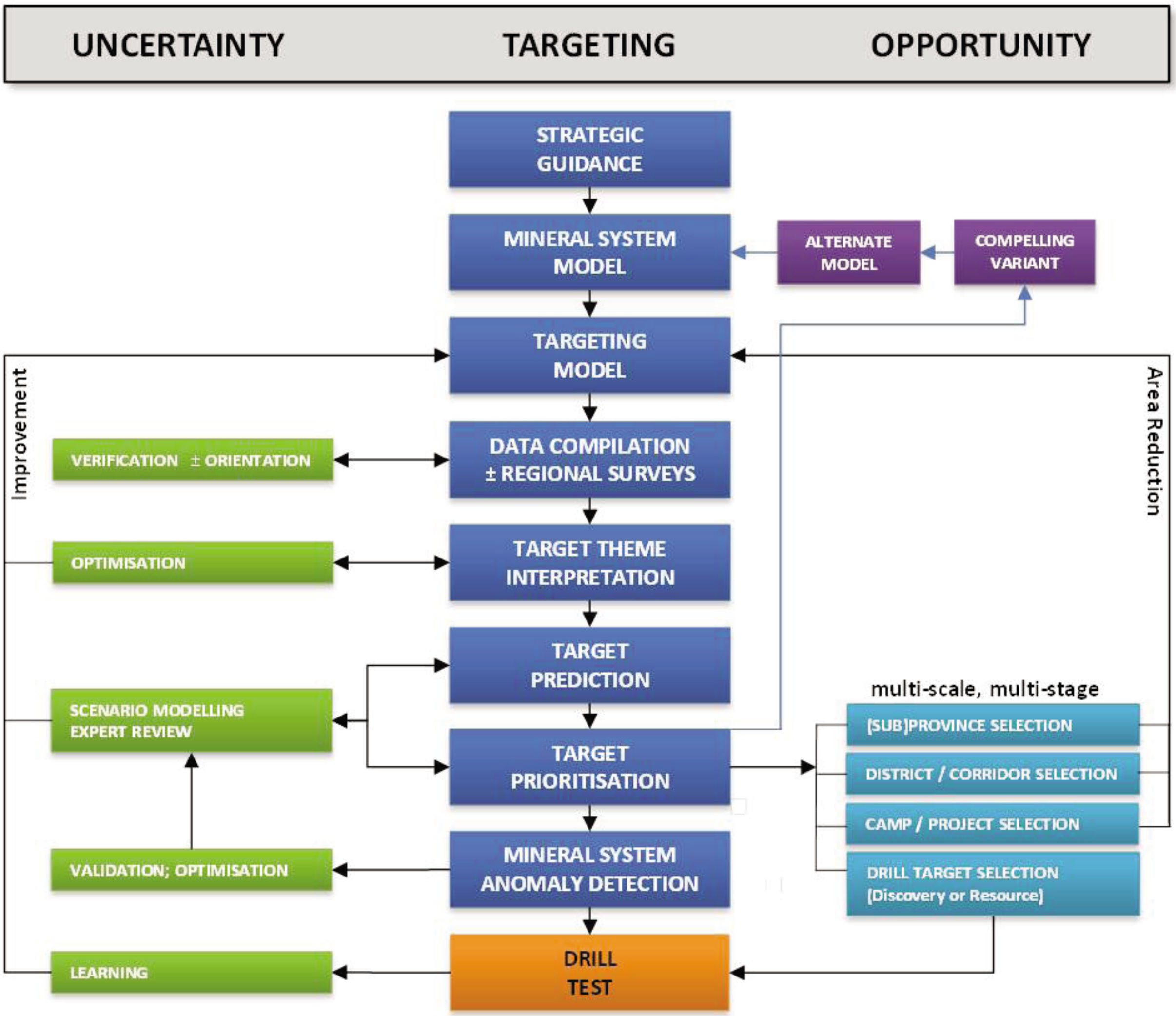

Figure 1. **A multi-scale, multi-stage, adaptive targeting process.**

Targeting prospective anomalies

Detection of evidence of a mineralised system from new geological, geochemical, and/or geophysical data is an integral part of the targeting process. Indirect evidence is derived from spatially coherent data anomalies determined to be consistent with target parameters (i.e. a prospective anomaly, as opposed to merely a data outlier). The number of anomalies detected typically greatly exceeds the number of possible economic discoveries, reflecting high false positive rates that require effective targeting practices to filter and select. There remains much room in targeting practices for improving the classification and rating of prospective anomalies, particularly in geophysics. That said, several significant discoveries have been made by drill testing anomalies that were compelling variations from an applied targeting model (e.g. Olympic Dam, Tropicana). While these discoveries are commonly considered serendipitous, the key driver for success in many of these situations was consideration of multiple working hypotheses, allowing permissiveness for a different target model.

Target prioritisation

Ranking and prioritisation of all early-stage Greenfield targets should consider three high level critical risk factors: (a) prospectivity (chances that an undiscovered economic resource exists); (b) explorability (likelihood that a discovery can be made cost-effectively with current capabilities); and (c) accessibility (likelihood that a desired interest level in the property can be secured and sustained throughout exploration and mining), based on key non-technical factors such as sovereign risk, social licence, environment restrictions, plus permitting and regulatory risks.

Several authors have proposed that target ranking should use a multiplicative probability approach (e.g. Hronsky and Groves, 2008). In practice, probabilistic methods are not very useful for early-stage targets faced with high uncertainty, missing evidence and co-dependent geological processes, where accurate probabilities cannot be meaningfully assigned. Furthermore decision makers may struggle to choose between small cumulative probabilities

(<1%) at early exploration stages. In these situations permissive quantitative ranking systems that do not penalise for missing data may serve us better. However, for more advanced-stage prospects (post-discovery of significant mineralisation), probabilistic approaches can and should be realistically applied, incorporating additional economic factors such as resource risk (size, grade, quality) and development risk (geomet, geotech, mine geometry and continuity).

Conclusions and future directions

The targeting process is multi-scale, multi-stage, non-linear and adaptive. Leading practices in targeting adopt global Mineral System Models customised for local economic viability and translated into effective local exploration targeting models for target identification, evaluation and prioritisation. It is important to manage uncertainty before managing risk in these models using a variety of embedded methods that include field validation, embedded learning, multiple working hypotheses and scenario testing in order to systematically refine targeting efficacy.

With exponential increases in data availability and machine learning capabilities, future developments in targeting practice will utilise more sophisticated 4D computational models that integrate dynamic concepts, such as process scale (space and time), efficiency (not just presence/absence), interdependency and feedback. For example, process efficiency can be modelled in terms of proxies for physico-chemical gradients (e.g. thermal and stress gradients, rheology gradients, permeability gradients, threshold barriers and chemical gradients: Eh, pH). Leading practices in exploration targeting must continue to evolve down this path in order to sustain and improve our economic discovery rates.

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National Exploration Undercover School (NExUS)

by

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The National Exploration Undercover School (NExUS) is a new initiative to provide world-class training in mineral exploration to senior undergraduates, postgraduates and early career professionals. The School is funded by the Minerals Council of Australia (MCA), and its education sub-group Minerals Tertiary Education Council (MTEC), and run by the University of Adelaide. Students from the full range of Australian Universities, along with early career staff in industry and government geological surveys applyed for entry. Numbers are limited to 30 placements so attendance at NExUS (Fig. 1) is considered competitive and prestigious.

The inaugural program started at the end of November 2016, and ran over a three-week period. NExUS is centred on addressing the four key themes identified by UNCOVER program (www.uncoverminerals.org.au) being the major knowledge areas to improve the success rate of world-class mineral system discoveries, particularly for areas of extensive and deep cover. Our intention is that the primary outcome of the program will be students who understand the challenges and opportunities of mineral exploration in Australia into the future, and have knowledge of the tools required to address these problems.

The program is a mixture of classroom, laboratory and drill core activities in the first week. NExUS is run at the new South Australia Drill Core Reference Library at the redeveloped Tonsley site in the southern suburbs of Adelaide. The Drill Core Reference Library includes a small conference room and a visualisation suite that provides students with state-of-the-art facilities and hands-on experience. The second week is held at Strathalbyn in the Adelaide Hills, and focuses on practical mineral exploration with the Deep Exploration Technologies CRC at Brukunga and in partnership with Hillgrove Resources at the Kanmantoo Copper Mine and nearby exploration targets. The final week is based on the Yorke Peninsula with Rex Minerals at the Hillside deposit and other field locations. The aim is to develop ongoing geophysical and geochemical sampling programs that will add from one year to the next.

The 2016 three-week program wrapped up mid-December but we plan to have a six month reunion in mid-2017 to reflect on the outcomes for the participants, and to build an alumni of future leaders in resource exploration. It's an exciting new program, and we look forward to reporting the outcomes and plans for moving NExUS forward in 2017.

Figure 1. The NExUS Summer School aims to provide world-class training for future explorers, <www.nexus.org.au>

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Machine learning in brownfields exploration

by

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Drilling is used for collecting high resolution geological data when prospecting for mineral resources that may be deeply buried or hidden under sedimentary cover. Samples from the drilling products are collected, from which chemical, mineralogical or physical characteristics can be measured. Measurements can also be taken from devices inserted into the drillhole cavity (during or after drilling), such as wireline logs. Data sets for individual drillholes may be composed of many different types of variables measured at a variety of different resolutions. In order to extract maximum value from these data sets, geologists would like to integrate different data types and synthesize the essential information for recognising geological features which (a) contribute to the general understanding of the local structural architecture, rock types and geological processes, and (b) predict the most likely location of economic mineral deposits.

Traditionally, geologists have interpreted drillhole data manually. However, today's large and complex data sets mean that manual interpretation is slow and the subjectivity of individual geologists may compromise the quality of the results. Increasingly, geologists are turning to automated methods of interpreting drillhole data. Machine learning (and associated fields) can provide geologists with the tools they need for rapidly extracting consistent results.

Machine learning is a very broad field. This talk will show some examples of the successful application of machine learning techniques to drillhole data. It will highlight some of the problems and limitations associated with drillhole data and discuss the importance of including spatial information when classifying rock types.

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Innovative and interpretable data analytics for mineral exploration

by

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There has been an increasing interest by the minerals industry to capitalise on recent advances in data science as the industry invests heavily in collecting and using diverse geoscientific datasets throughout exploration, extraction, and processing. The biggest challenge for the mineral explorers (greenfield or brownfield) is addressing uncertainty in geological interpretation. Understanding complex geology using sparse and diverse observations (often at varying scales) is not a trivial task, where human biases play a key role that results in highly inconsistent outcomes amongst and even within individuals. Computational algorithms can assist geological knowledge discovery through various analytical steps such as recognising patterns of interest through machine learning or statistical methods (Horrocks et al., 2015; Porwal et al., 2003). However, the geological insights by an interpreter, albeit inconsistent, that contribute to geologically feasible interpretation outcomes are hard to model for computational algorithms, especially considering highly variable existing knowledge, diverse and complex geological settings, and availability of different types of data at different scales. Our research focuses on equipping geological interpreters with new data analytics tools that use computational algorithms to minimise human biases and to improve efficiency in analysing large volumes of data; and provide workflows and interactive visualisation methods to make the algorithms interpretable by end-user geologists to allow them to incorporate their geological insights throughout the analysis workflows. This geologist-driven and computer-assisted approach is demonstrated using two studies that focus on structural interpretation at two different scales: one using downhole imagery, and the other using regional scale spatial maps.

Structural interpretation of televiewer images

Downhole televiewer images (acoustic and optical) are important datasets for structural and geotechnical analyses for the minerals industry. In these images, a planar structure appears as a sinusoidal pattern where its amplitude and phase shift represent the dip and azimuth of the structure. With image logs collected from hundreds of kilometres of drillholes a year, interpretation of structures, often in abundance and in incomplete form, is labour intensive and thus creates a significant bottleneck in data workflow. In addition, televiewer images are routinely used by two different groups within the industry: structural geologists for resource evaluation and geotechnical engineers for mine stability analysis. We developed a televiewer image analysis system which uses automated pattern recognition methods for rapid and consistent detection of sinusoidal patterns; and an interactive user interface to support interpreters driving the process and vetting the outcomes of the automated analysis for different objectives. It consists of a new geological zonation algorithm based on image complexity; and a novel sinusoid detection algorithm which can rapidly and consistently detect structures. A suite of tools were developed to detect different types of structures such as fracture, vein, and bedding; to control the sensitivity to the sinusoidal shape variations through confidence analysis; and to facilitate rapid post-processing to classify structure groups and to modify the detected structures. Figure 1 shows an example acoustic televiewer image and automated structure detection outcomes.

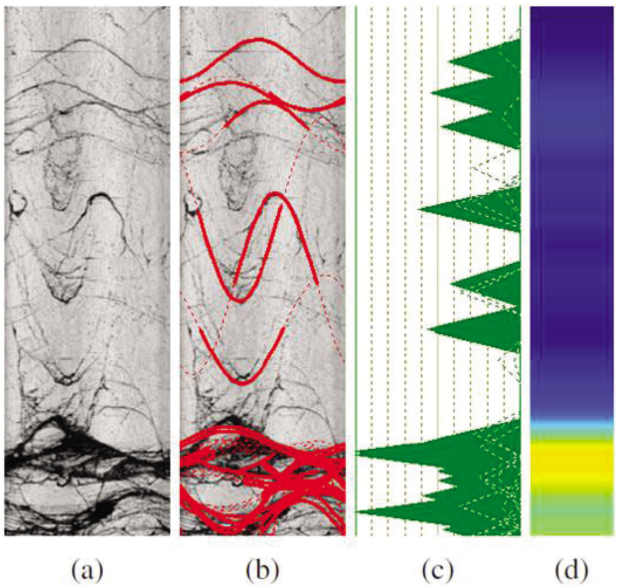

Figure 1. Televiewer Image Analysis System: (a) An example televiewer acoustic image (b) Detected structures (full or partial) in red (c) The structure confidence (d) Image complexity analysis

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Regional scale structure interpretation

Structural and stratigraphic analysis using potential field geophysics data is a routine task in mineral exploration. To support this, various computational algorithms have been developed to automatically detect lineaments/discontinuities within geophysical images. However the lineaments that are detected need to be mapped by an interpreter for the types of structures (e.g. shear zones, faults, dykes etc), and their chronological order. This study explores new data analytics methods that integrate automated lineament detection and interactive visualisation methods into interpreters' workflows to improve the confidence in structural analysis of potential field data (Holden et al., 2016). Automated lineament detection techniques, previously developed for potential field data analysis, are used in two specific ways to assist interpretation. In the first, they are used to generate a quantitative measure of confidence on interpreted lines based on automated data analysis results, which we term feature evidence. Secondly, the confidence of mapped structures is assessed visually using an interactive visualisation interface which displays feature evidence over interpreted structures through highlighting regions with high evidence as shown in Figure 2. This can also provide interpretation guidance as the interpreter traces a structure based on visual ridge/valley/edge characteristics in the geophysical data. Automated analysis highlights the same characteristics in the local neighbourhood to facilitate data-supported interpretation.

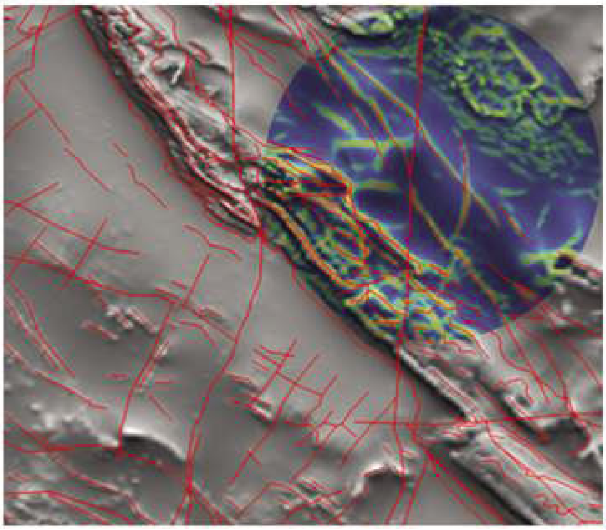

Figure 2. Regional scale structural interpretation support. Interpreted structures (red lines) overlaid on aeromagnetic data (grey) with automatically computed linear feature evidence shown (coloured circle). Note cooler colours denote lesser feature evidence, and hotter (orange-red) denote stronger evidence

Summary

Our geologist-driven and computer-assisted approach for data analytics provides practical benefits for mineral explorers. Harnessing the power of computational algorithms combined with interactive visualisation, geologists are equipped with useful tools for fast and consistent analysis of data while incorporating their geological insights.

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'Future Licence to Prosper' Key to Unlock Mining Sustainability

by

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Sustainable strategy is a crucial, yet ambiguous, aim for mining companies. While sustainable development, both as a policy aim and as its most common definition — development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987) — is widely accepted, neither context specifies exactly what needs to be sustained, or how (Hojem, 2014). Furthermore, the 'bar' of sustainable strategy is continuously rising, reflecting global industry mega-trends and risks (Mudd et al., 2012), diminishing ore quality (McKeith et al., 2010; Schode et al., 2006); increasing ore body complexity (Bryant, 2015); pressured operational and capital development costs (Bryant, 2015); energy, water and carbon constraints (McCuaig et al., 2014); and greater societal expectations (Lacey and Lamont, 2014) that demand reduced physical, energy and environmental footprints (McCuaig et al., 2014) whilst managing heightened volatility in mineral prices and foreign exchange rates (EY Global Mining and Metals Center, 2014; International Monetary Fund, 2015; Mossavar-Rahmani et al., 2015). BHP Billiton Chairman, Jac Nassar presented this view at the 2015 Annual General Meeting: 'As an industry we are dealing with global tensions; the challenges of climate change; steep falls in commodity prices and reshaping our operations and portfolios to deal with a new reality' (BHP Billiton Limited Speeches, 2015). This 'new reality' places demands on companies to clearly define sustainable strategies and to hardwire the many factors that contribute to successful strategy implementation. This paper defines sustainable strategy as one that creates shared value for all stakeholders today and in perpetuity, where shared value simultaneously creates economic and social value (Porter and Kramer, 2011). Building on the well accepted Social Licence to Operate concept (Prno, 2013), we identify three sets of factors, which have evolved as foundations of sustainable strategy in the mining industry: Commercial Licence to Operate, Social Licence to Operate and Future Licence to Prosper.

A **Commercial Licence to Operate** encompasses a set of enduring factors that have been the bedrock of successful mining company strategy since the establishment of the industry with the first opportunistic miners of the Stone Age (Kogel, 2013).

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Securing a fit-for-purpose mineral asset base is a critical factor contributing to sustainable strategy (Sykes et al., 2015). Whilst deposit size and mineral grade are historical antecedents to long-term wealth creation (Schodde et al., 2006), it is increasingly important that mineral deposits are fit-for-purpose (Kanakis, 2014) and selected on the basis of congruity with all aspects of company strategy, whether through acquisition or organic exploration and development. For example, a miner pursuing a technological leader strategy can sustainably select lower grade tenements that capitalise on their technological ability and maintain a sustainable competitive advantage (Porter, 1985).

The operational ability to transform raw minerals into a saleable product is critical to sustainable strategy, particularly with the trend of declining ore grades and increased difficulty of mineral extraction (Bryant, 2015). As mining has evolved, the operational focus has shifted from extracting high-quality minerals using simple processes (Raymond, 1986) to complex processes (e.g. smelting) that enable extraction of harder to access deposits and alternative minerals (Sykes et al., 2015). By developing a specific operational capability focused on technical and humanistic processes (Napier-Munn, 1997), mining companies can maximise the processing recoveries and plant throughput of their fit-for-purpose asset base. This results in a sustainable strategy congruent with operational capabilities and the asset base.

Reliable access to funds — particularly in a cyclical industry like mining (EY et al., 2013) — is an imperative factor contributing to sustainable strategy. Increasingly complex capital markets (KPMG International Cooperative, 2011), larger developments requiring integrated transport and logistics (Deloitte Touche Tohmatsu Ltd, 2013), and intensified competition for investment with the proliferation of mining companies (International Council on Mining and Metals, 2012; Las Vegas Business Press, 1997) have increased its importance. To be profitable, mining companies must appropriately balance various financing mechanisms, ranging from traditional debt and equity funding to contemporary mechanisms such as streaming and royalty financing (Lee, 2013) that can be ably serviced during the inevitable boom and bust periods of the industry (EY et al., 2013).

A S**ocial Licence to Operate** (**SLO**) is an informal, broad and ongoing approval by society for a company to operate (Lacey and Lamont, 2014; Prno, 2013; Owen and Kemp, 2013; Thomson and Boutilier, 2011) that is now accepted by the mining industry as an integral factor contributing to sustainable strategy (Moffat and Zhang, 2014; Prno and

Scott Slocombe, 2012). Societal expectations regarding the industry's performance is increasing (Parsons et al., 2014), extending beyond local impacts to encompass global issues such as climate change, water shortages and poverty (Peterson, 2012), which is shifting the power to approve projects away from miners to the communities in which they operate and the broader society (Parsons et al., 2014; O'Faircheallaigh, 2015).

The hierarchical approach historically taken to sustainable development, where resources are identified and subsequently attempted to be developed sustainably, has evolved in favour of a systemic approach integrating a triple bottom line (society, environment and economy) to all aspects of development (Giurco et al., 2011; Ali, 2010; Marquis et al., 2014;Whittington, 2012). One contemporary approach is the 'justice-based'(Lacey and Lamont, 2014) method to SLO where decision-making is based on the moral values of society.

A Future Licence to Prosper is an emerging set of factors that we believe is critical to achieving sustainable strategy in the 'new reality'. It represents the dynamic capabilities (Teece and Pisano, 1994) required by mining companies to successfully combat future industry challenges and seize opportunities.

Environmental scanning to identify risks and opportunities will be an important factor contributing to sustainable strategy in the 'new reality'. Continuous environmental scanning is required to achieve proactive management and mitigation of risks arising from macro level events including increased market volatility; heightened social and governance risks; increasingly stringent government approvals processes; changes in taxation; and continuous disclosure rules (Featherstone, 2012), and micro (operational) level events such as fatalities and localised environmental and social disasters (Tufano, 1996; Griffin et al., 2016; Hill, 2015). Mining companies are increasingly adopting an organisational resilience approach to risk management, with capital investment decisions and organisational capabilities stress tested against a range of scenarios and shock events (Featherstone, 2012).

In addition, scenario planning can assist in identifying external drivers shaping the environment in which miners operate (World Economic Forum, 2010), allowing them to capitalise upon future opportunities, whether they be alternative mineral markets, focusing on more profitable portions of the value chain (Christensen et al., 2001) or diversification of assets across geography and commodity.

Innovation to drive productivity and flexibility is increasingly important to address the productivity and prosperity challenges of the mining industry (EY Global Mining and Metals Center, 2014). Despite the historical role innovation and technology have played in progress of the mining industry (Sykes et al., 2015), mining has been criticised for under-investing in this area over the past decade (McCuaig et al., 2014; EY Global Mining and Metals Center, 2015). However, there are signs of a 'super-correction' (EY Global Mining and Metals Center, 2015) with innovation hot spots including automation (e.g. autonomous vehicles), knowledge management (Johnson et al., 2008), reduced energy consumption, improved recoveries (Mudd et al., 2012), data analytics and processing (EY Global Mining and Metals Center, 2015), and innovative business models (Owen and Kemp, 2013). Key to innovation bridging the gap in the 'new reality' is advancement of resource science (Batterham and Bearman, 2005) and collaboration and company alliances with world-leading partners such as Rio Tinto's collaboration with Imperial College London on the 'Mine of the Future' (EY Global Mining and Metals Center, 2015; Schweikart, 2009). Business model innovation (Johnson et al., 2008) and the questioning of the ongoing relevance of the traditional functional model of mining companies will also become increasingly prevalent (Owen and Kemp, 2013).

Integrative and informed decision making ensures final decisions are not biased towards one sustainability dimension but are balanced in the best interests of all project stakeholders (Freitas and Magrini, 2013; Lucks, 2010). This involves the inclusion of representatives from each of the key sustainability functions of a mining company in the decision-making process, the effective leveraging of captured organisational learnings and knowledge (Nonaka, 1991), and the allocation of equitable decision-making authority for final investment decisions (Lucks, 2010). Mining companies must also expand upon the project valuation methodology of net present value to factor in incremental, incidental and opportunity costs and benefits relating to the social and environmental dimensions of a project (Fatemi and Fooladi, 2013), which enables more informed prioritisation of projects and capital allocation (West, 2015).

In conclusion, to achieve sustainable strategy it is critical that mining companies continue to protect and nurture their Commercial Licence to Operate whilst recognising the growing importance of a Social Licence to Operate. With the 'new reality' and the continuously rising sustainability 'bar' resulting from global trends and heightened focus on interconnected variables (McCuaig et al., 2014), sustainable companies must again review their definition of success, and embrace the Future Licence to Prosper. We contend this is critical to sustainable mining in the 21st century, creating shared value (Porter and Kramer, 2011) for all stakeholders, and maximising the contribution of the mining industry to future global prosperity.

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Creating a new frontier in detection and data integration for exploration through cover

by

Robert Hough[1]

With the recent declines in greenfields exploration activity and discovery success in Australia, a new wave of technologies and data products are needed. Australia is an old continent with much of its remaining mineral endowment obscured by a thick cover of weathered rock, sediment and soil materials. This presents a critical challenge for mineral exploration now and into the future, as the industry currently lacks the fundamental data, scientific knowledge and technological tools needed to discover new, world-class ore deposits buried beneath this cover. UNCOVER is a national vision in Australia for the future for mineral exploration geoscience research to tackle the geological barriers to more tier 1 discoveries.

UNCOVER as a national initiative, has the potential to position Australian exploration geoscience research for a shift in collaboration for technology development, one that tackles the exploration through deep cover challenge as one of major national importance. As we move into exploring the deeper cover regions of Australia, we need to determine detectable signatures of buried mineral systems and ore systems from a number of varied sample media and with different technologies. Arguably, the challenge posed by the depth of cover to find the mines of the future is going to be in the 100s of metres, given current mining practices from the surface combined with the economic realities. Firstly though, we need to know the extent of that thickness of cover, its stratigraphy, lithogeochemistry and physical properties. Comprehensive data that will in turn aid in more effective processing and interpretation of the regional datasets collected, e.g. magnetics, and increase confidence in our geological models of the sub-surface. While the cover is a barrier it also presents an opportunity and detection through cover may lead to new resource discovery within the cover itself.

When it comes to rapid detection, the DETCRC development of CT drilling plus associated real-time sensing tools provide for an exciting future in new approaches to regional drilling to enable detection of mineral systems at large scales with quick decision-making capability. New research in measuring uncertainty using Bayesian approaches to geophysical interpretations of geological models is improving our knowledge of risk whilst providing us the ability to plan and efficiently reduce that uncertainty as we go. Quantifying the issue of magnetic remanence and its potential effect on our ability to locate and target anomalies is also now possible and a national remanence data-base will also assist us to develop the analytics to data mine regional data for depth to magnetic basement outputs. Finally, our ability to detect an anomaly rests not in the direct detection itself but in being able to place the data point into a regional geological context. For example, research on the geochemistry of the Fortescue Group volcanics assessing burial metasomatism effects has been undertaken in the Capricorn distal footprints project so that we can position the industry to place perceived geochemical anomalism from similar lithologies into a broader geological and, indeed, regional context. Although regional geophysics is commonplace, we still face the challenge of having much less access to geochemistry from buried geology on a regional scale that could support such anomaly identification and reveal the patterns across scales. One vision might be to unlock the vast industry-held dataset of geochemical analyses to provide such data. Targeted collection of new rock property data could then allow this geochemistry to be assessed with the regional geophysical data, providing a path to integration of geochemistry and geophysics with the tools to simulate, image and ultimately detect mineralised mineral systems (and their gradients) through cover.

Australian researchers have long played a globally leading role in developing new approaches and technologies to support the minerals industry in exploration, most often through collaboration involving multiple organisations and with close industry engagement. Cooperative Research Centres and Centres of Excellence are vehicles that have been very important in the focus and drive for innovation to support the industry to tackle technical challenges involved with mineral exploration in Australia. Recently, the Capricorn distal footprints project also reflects a highly collaborative approach to the challenge in a highly multi-disciplinary manner. Finally, the Deep Earth Imaging future science platform in CSIRO is building a new research hub in exploration geophysics capability. It presents an important opportunity for a research focus in areas of modelling, integration and uncertainty to help tackle the UNCOVER challenge!

Acknowledgements

The presentation will include much content from my CSIRO colleagues and I thank each for their important contributions.

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Getting more from your maps: the topology of geology

by

Mark Jessell[1,2*], Vitaliy Ogarko[1] and Sam Thiele[1,3]

Introduction

Geological maps are the primary form of transfer of information from the field geologist to the end user. They provide information on the distribution of rock types and structures, and with the advent of GIS technologies, maps can store both the primary observations, intermediate interprtative layers and the final geological model (the map). Even though maps are now available in digital (vectorial form), their analysis has not evolved much, and geologists still rely primarily on direct observation of the finished map product. Prospectivity mapping aims to go beyond the geologist's interpretation of the map by combining different types of spatially located information (such as distance to fault, fault density, rock type…) to infer likelihood of finding mineral concentrations.

We present a new topological approach to analysing geological maps that parses the map to look for hidden spatial and temporal relationships, which in turn can lead to exploration insights.

The topology of geology

Topology, the relationships between discrete elements of a model, is an important constraint for many geological processes, including deformation and the flow of fluid, heat and electricity. It is commonly considered, though often not explicitly, when evaluating the economic value of a region (e.g., Allan, 1989; Knipe, 1997; Pouliot et al., 2008), planning development projects (e.g., Jing and Stephansson, 1994; Yu et al., 2009) and assessing geohazard risk (e.g. Okubo, 2004).

Spatial topology refers to the properties of space that are maintained under continuous deformation, such as adjacency, overlap or separation (Crossley, 2006). Topology can be analysed in 1D (e.g. well logs); 2D (maps and sections) and 3D (3D geological models) and higher dimensions if time is considered. In geological maps displaying lithology (as distinct from alteration maps or metamorphic maps), there are no overlaps, only neighbour relationships. Burns (1988) describes an extensive framework for representing the topology of geological models, using network diagrams (graphs) in which nodes represent lithology polygons and arcs represent adjacency relationships, and different geological structures display distinct topologies. These relationships can infer stratigraphic associations (Fig. 1) or can be interpreted in terms of mineral systems. To date, little specific work has been developed for the first-order topological manifestation of common geological structures and geological models, even though many types of ore deposits are controlled by topological relationships such as stratigraphic and intrusive contacts, unconformities and fault intersections.

In this paper, we present examples of the topological analysis of different regions in Western Australia and discuss their possible meaning.

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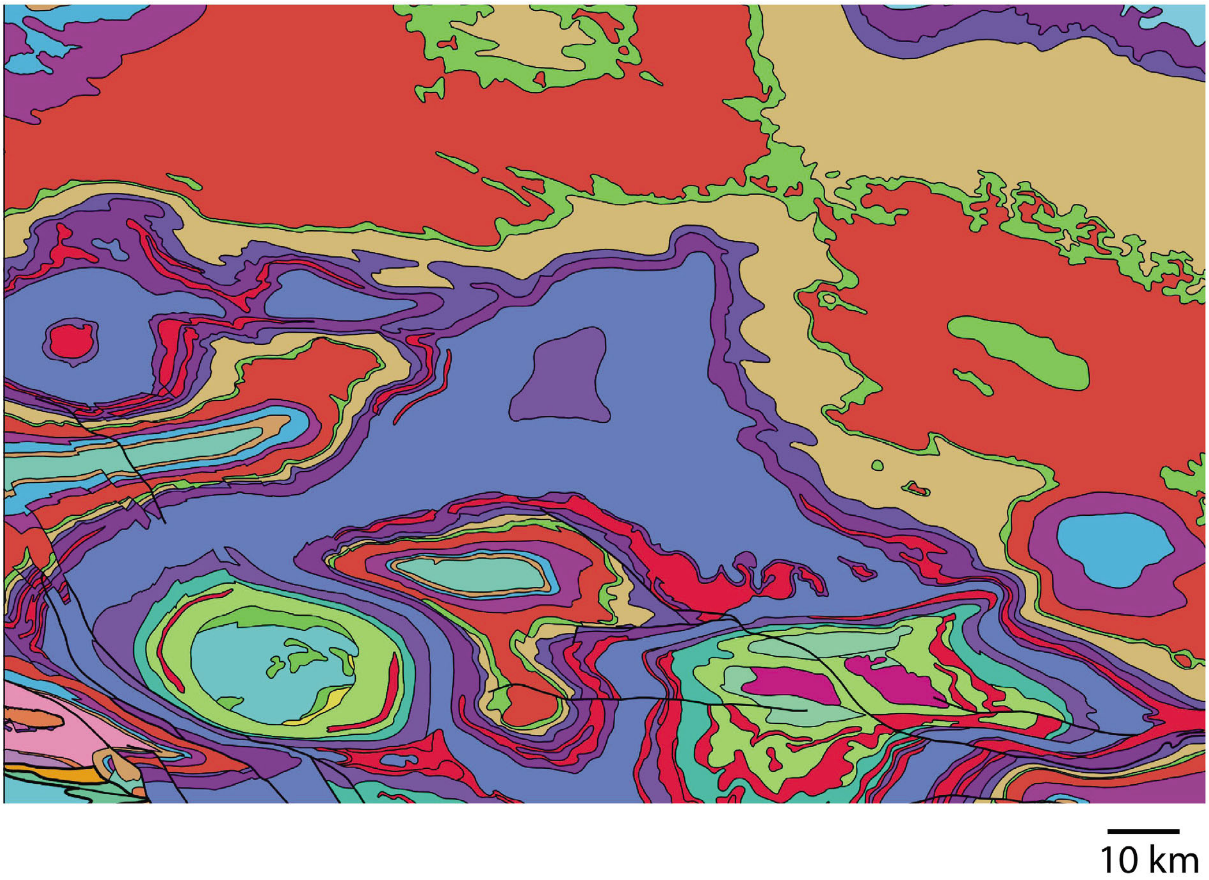
a)



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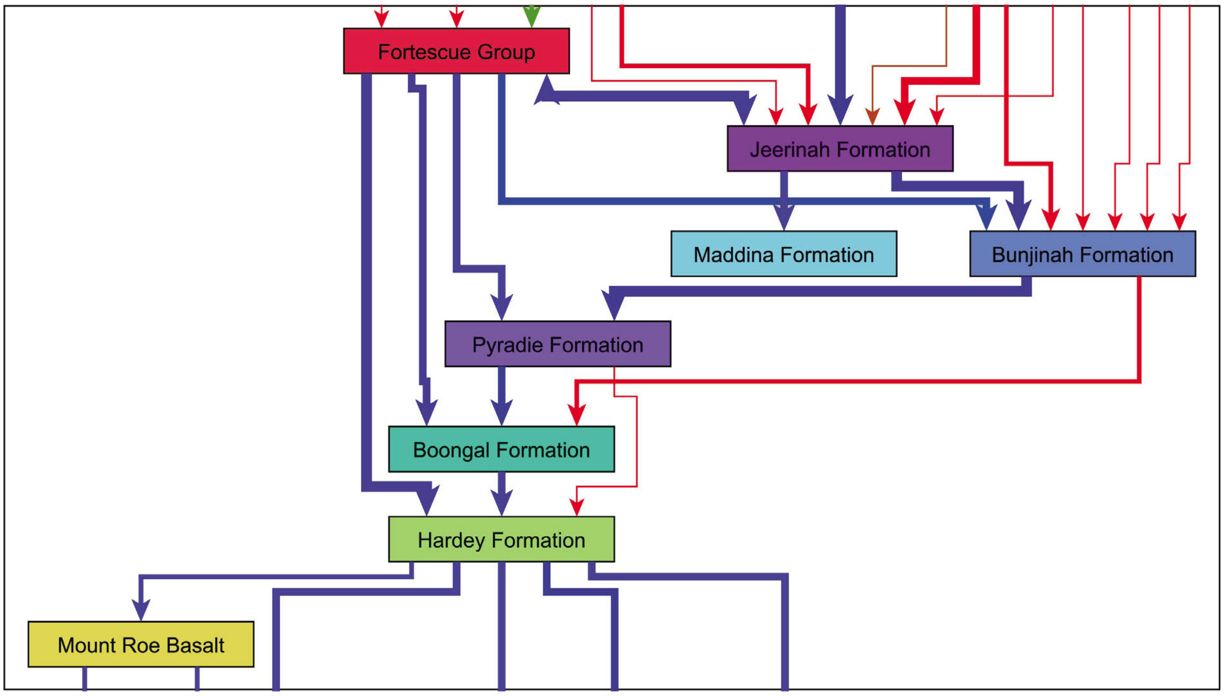

Figure 1. **Topological analysis of the Mount Bruce map sheet. (a) Extract of the 1:500 000 digital map of Western Australia showing the area equivalent to the 1:250 000 Mt Bruce map sheet. (b) Automatically generated formation-level topology visualised as a network diagram for the Fortescue Group. Red lines represent faulted contacts, blue lines represent stratigraphic contacts, and green lines represent relationships which are in part faulted and in part stratigraphic. Line width is a function of total contact length. Arrows point to the unit with the older minimum age, and where the two units have the same minimum age they are drawn with an arrow on both ends.**

Structural controls on the localization of Au and Ni deposits in the Halls Creek Orogen, insight from geodynamic numerical modeling and geophysical interpretation

by

Fariba Kohanpour[1*], Mark Lindsay[1], Weronika Gorczyk[1] and Sandra Occhipinti[1]

Introduction

It is widely accepted that structure is one of the dominant controls on the localization of mineralisation. Deep-crustal or lithospheric-scale structures are understood to influence the development of a wide range of mineral deposits (McCuaig and Hronsky, 2014), thus their identification is critical to the success of mineral system analysis. In addition, damage zones and geological complexities that act as physical throttles for fluid movement are important for prospectivity analysis at camp and deposit scales. In this study geodynamic numerical modeling is used to understand how deep-crustal and lithospheric structures observed in the Hall Creek Orogen may have developed. These structures have been observed in the field through geological offsets and additionally in geophysical datasets. Structures mapped from geophysical datasets have been used in identifying possible fluid and magma conduits associated with Au and Ni mineralisation.

Geological background

The Halls Creek Orogen (HCO) forms part of the 1910–1805 Ma Lamboo Province and developed between the Kimberley and North Australian cratons in northern Australia. The Halls Creek Orogen consists of three parallel, north-northeasterly trending zones (western, central and eastern) that are each interpreted as distinct tectono-stratigraphic terranes. These zones contain geological units formed during the early Paleoproterozoic that may have originated in different settings and times and then juxtaposed during the 1870–1850 Ma Hooper and 1835–1805 Ma Halls Creek orogenies. These zones are separated by major faults (Tyler et al., 1995).

There is some controversy as to how the Halls Creek Orogen developed. The formation of the protolith sedimentary and igneous rocks of Tickalara Metamorphic have been described as either forming in (1) an oceanic island arc setting above an easterly-dipping subduction zone outboard of Kimberley Craton, or in (2) an ensialic marginal basin located closer to the margin of the Kimberley Craton (Sheppard et al., 1999).

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Methods and Results

Geodynamic numerical modeling

The two plausible tectonic scenarios of the Halls Creek Orogen are examined through 2D thermo-mechanical-petrological numerical experiments based on I2VIS code (Gerya and Yuen, 2003). The initial constraints for model setup are appropriate to the inferred tectonic environment for the protoliths to the Tickalara Metamorphics in an intra-ocean subduction or ocean–continent subduction/collision. These numerical models allowed us to examine the conceptual models of geodynamic setting scenarios of the Halls Creek Orogen through time. With this approach, we were able to determine experiments with specific physical parameters that are compatible with the geology observed in the Halls Creek Orogen. Finding the model most compatible with the geology can reveal geological processes which are not observable without the aid of geodynamic simulation. The results indicate that the geology of the Halls Creek Orogen is best represented by the ensialic marginal basin scenario. The geodynamic numerical model also reveals processes which lead in the generation of key lithological units and major structures during the tectonic evolution of the Halls Creek Orogen.

In numerical geodynamic modelling, strain rate is used to characterize the dynamics of change in internal deformation (Gerya, 2010). In this study the second invariant of strain rate ($\dot{\varepsilon}II$) is used to visualize the major shear zones during the evolution of the models (Fig. 1). The models showed that the onset of lithospheric-scale deformation occurs in a region of high strain in response to fluid-induced weakening of the upper lithosphere during ocean subduction, which can be considered as conduits for magma and fluid. After collision, the extent of the high-strain zone increases, leading to lithospheric-scale shearing and faulting. Major shear zones represented by the second strain invariant are deep-seated and consistent with the Angelo – Halls Creek and Ramsay Range – Springvale fault systems which are mapped at the surface (Fig.1). These fault systems are considered to represent boundaries to the zones of the Halls Creek Orogen. These numerical models envisage how the major fault systems of the Halls Creek Orogen are developed during the extensional and collisional regimes. These first-order faults or shear zones may act as lithospheric-scale conduits and pathways for magmatic and hydrothermal fluids to be driven to the upper crust and surface, and appear to control

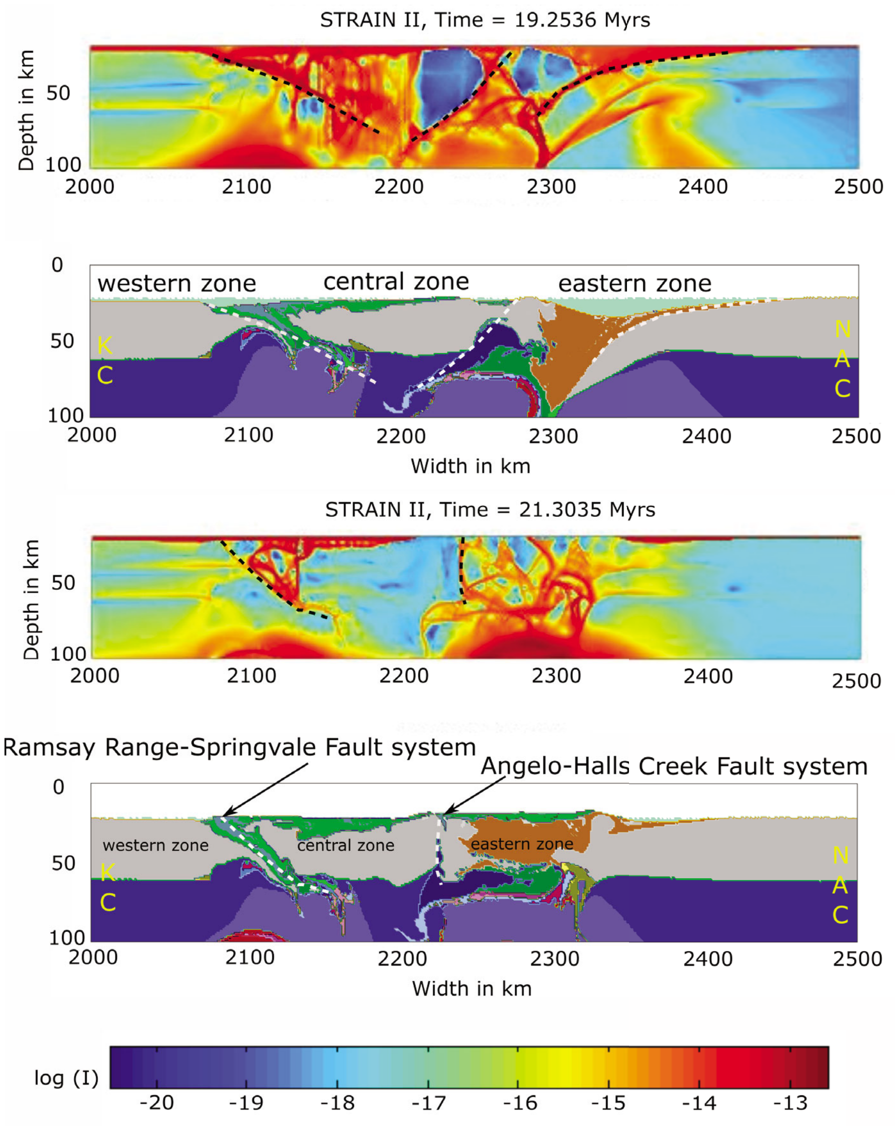

Figure 1. Second invariant of strain rate (ε˙II) illustrated in the development of major structures by numerical modeling

the emplacement of intrusive rocks, and therefore may have directed regional-scale fluid flow.

Geological–geophysical interpretation

The regional aeromagnetic, gravity and Landsat datasets were used as a basis for understanding the structural architecture associated with gold and nickel mineralization. To assist interpretation from the TMI grid, several filtered grids were created by Lindsay et al. (2015), including tilt derivative, vertical derivative and dynamic range compression. The first-order (lithospheric-scale) structures are identified from truncations and discontinuity in the geophysical data, and changes in the strike of linear features in aeromagnetic data. In addition, the location and geometry of shear zones, second- and third-order faults, and fold axes appear coincident with a number of known gold deposits. These geological features are mapped as their formation are considered to have acted as a physical throttle during mineralization (Fig. 2a).

The structural interpretation confirms that predictable and repetitive factors controlling the location of gold deposits in the eastern zone are proximity to first-order (lithospheric scale) faults. The regional distribution of gold mineralisation is controlled by first-order structures but are sited in second- and third-order faults, the high spatial density of faults and folds, proximity to anticlinal structures, fold hinges and overturned limbs in turbidites (e.g. the Olympio Formation). The presence of reactive host rocks (e.g. the Woodward dolerite), proximity to dilational sites such as fault jogs, proximity to cross faults between first-order strike-slip faults are also factors related to gold mineralization distribution (Fig. 2b-e).

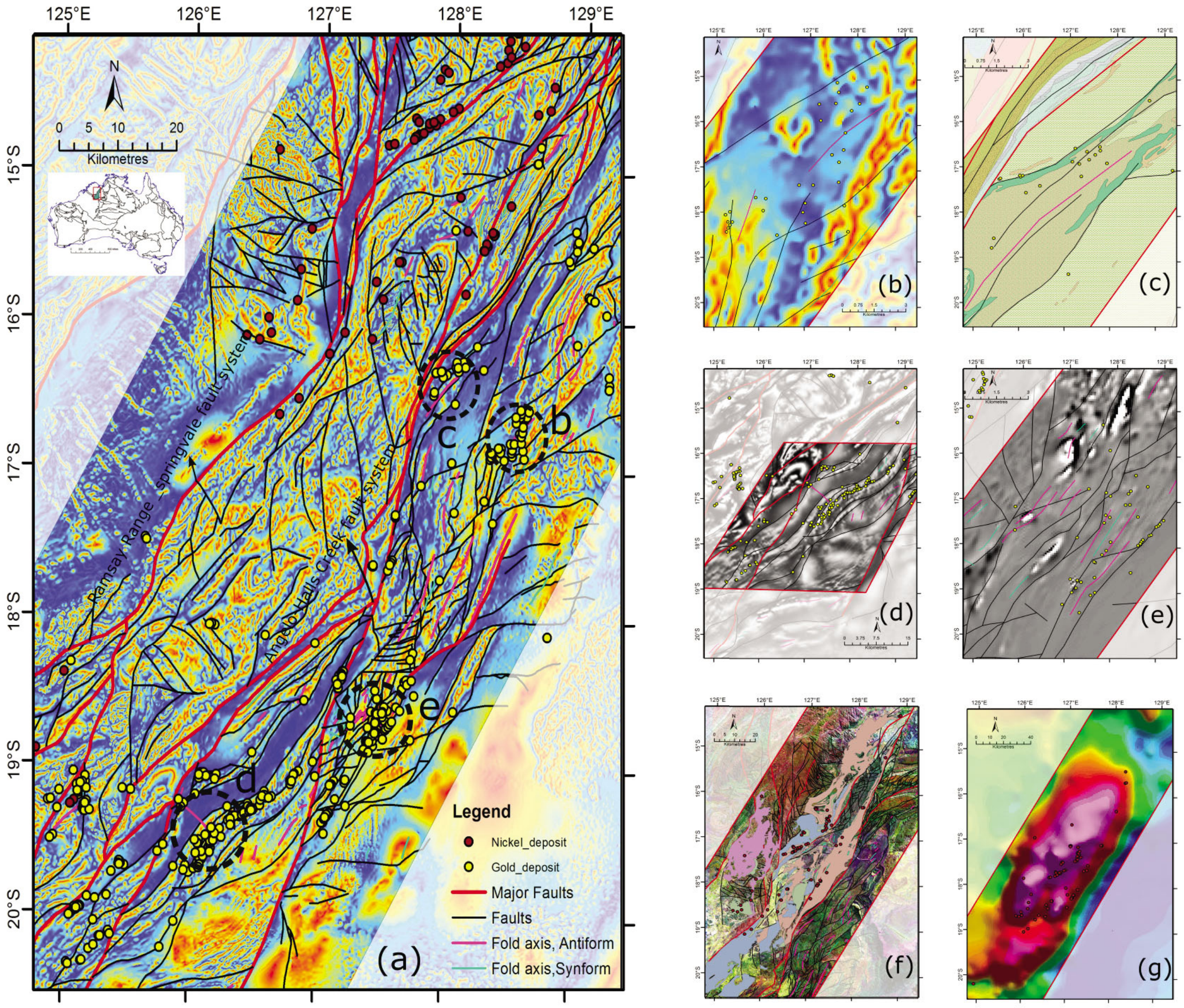

Figure 2. (a) Structures and mineralisation on tilt derivative image of the Halls Creek Orogen; (b-g) controlling structures on mineralisation

The structural features for some known Ni–PGE deposits in the Halls Creek Orogen are recognised by aeromagnetic data, gravity gradiometry, bouguer gravity, and geological data. The key features that control the localization of Ni–PGE at the regional scale are proximity to ancient cratonic boundaries, and long-lived, lithospheric-scale faults; relationship to voluminous mafic–ultramafic intrusions; proximity to margins of mafic and ultramafic intrusions; association of mineralised mafic-ultramafic intrusions with regional positive gravity anomalies, which may be indicative of probable large fluxes of magma into deep crust (Fig. 2a and f–g).

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Fingerprinting ore forming processes with sulfur isotopes: craton to camp scale

by

Crystal LaFlamme[1*], Marco Fiorentini[1], Vikraman Selvaraja[1] and Stefano Caruso[1]

Cratonic margins are structurally and magmatically complex areas of the Earth's crust, having undergone one or more orogenic cycles. A number of studies have recently advocated that in the Archean the geometry of lithospheric block margins played a first-order control on the ascent and focusing of mantle plumes that generated large amounts of partial melting leading to the emplacement of hot magmas, host to orthomagmatic Ni–Cu–PGE deposits, and associated Au and base metal hydrothermal systems (e.g., Foley, 2008; Begg et al., 2010; Mole et al., 2014). The presence of trans-lithospheric faults along craton margins is thought to have facilitated the transfer and focussing of fluids and associated metals broadly synchronous to the aforementioned large-scale emplacement of mantle plumes, which provided a suitable source of energy to drive ore formation processes (e.g. Mole et al., 2014).

It remains largely unclear, however, why much younger margins, formed during the Proterozoic or even Phanerozoic times surrounding Archean lithospheric blocks, should also be prospective for the presence of metal deposits (e.g. iron oxide Cu–Au, orogenic Au, porphyry Cu–Ag: Groves and Bierlein, 2007). Therefore, elucidating the processes that drive volatiles and their associated metal cargoes into orogenic belts that comprise newly formed crust at the margins of reworked Archean Cratons is of importance.

The sulfur cycle and isotopic record

Sulfur is an essential volatile for all life and, as such, its cycle through the Earth's terrestrial spheres has long been studied. Sulfur may form in its elemental state (S_8), in oxidized states (e.g., SO_2, SO_4^{2-}), reduced states (e.g., FeS_2, H_2S and many metal sulfides), and in proteins. Because of its wide range of molecular forms and occurrence in many environments, the sulfur cycle is highly complex. Sulfur occurs naturally as four stable isotopes ^{32}S, ^{33}S, ^{34}S, and ^{36}S with fixed abundances in our Solar System of 94.93%, 0.76%, 4.29%, and 0.02%, respectively. Isotopic fractionation between isotopes is sensitive to valence state, and thus the environment in which the sulfur formed. As molecules bearing sulfur form, the isotopes of sulfur undergo mass-dependent fractionation (MDF-S) with respect to physical conditions (temperature, pressure, oxygen fugacity) associated with the specific sulfur-bearing geochemical reservoir from which the molecule was formed (monitored by $\delta^{34}S$). Therefore, the physical processes that fuel the sulfur cycle may be traced in the isotopic record and are denoted as $\delta^{34}S$.

Complementary to MDF-S, the phenomenon of mass-independent fractionation of sulfur (MIF-S) allows for the identification of sulfur which has been exposed to the Archean atmosphere (Farquhar et al., 2000). In fact, MIF-S is observed in the Archean supracrustal rock record, which results in fractionation of ^{33}S and ^{36}S away from the mass-dependent fractionation relationship with ^{34}S (quantified as positive and negative $\Delta^{33}S$ and $\Delta^{36}S$: Farquhar et al., 2000). Until recently, it was believed that all sulfur isotopes underwent mass dependent fractionation, scaling in proportion to the mass of the isotopes. This anomalous signature was generated by the bombardment of S-bearing gases by short wavelength UV rays in the Archean oxygen-poor atmosphere prior to the Great Oxygenation Event (GOE) at 2.45–2.33 Ga (Farquhar et al., 2000; Farquhar and Wing, 2003; Johnston, 2011; Luo et al., 2016). Positive values of $\Delta^{33}S$ formed in the Archean when atmospherically-derived S_8 colloids crystallised in sedimentary pyrite at the bottom of the water column, most commonly in iron- and/or carbon-rich sediments in marginal basins that were proximal to sources of atmospheric gases (Ono et al., 2003; Farquhar et al., 2013). Conversely, negative values of $\Delta^{33}S$ reflect sulfate sinks that may have been associated with hydrothermal activity (i.e. oceanic sulfate incorporated in volcanogenic massive sulfides and komatiite-hosted ores: Bekker et al., 2009; Farquhar et al., 2013).

Sulfur and ore deposits

Sulfur resides in the Earth's mantle, crust and hydrosphere but is locally concentrated in mineralised systems typically associated with ore deposits, where it acts as the primary complexing ligand in the formation of sulfide minerals. Mantle- and crustally-derived magmas have brought large quantities of economic metals from the Earth's interior to the near surface, and hydrothermal fluids have remobilised and re-precipitated these metals within the crust as different sulfides. The sulfur itself may be sourced from a variety of compositional reservoirs, each with distinct isotopic compositions. Mixing and interactions with the mantle, crustal magmas, hydrothermal fluids, country rocks, or meteoric waters imparts specific isotopic signatures, resulting in minerals with a range of isotopic compositions. As such, intra-grain and inter-grain chemical and isotopic variations in sulfur-rich mineralised

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systems record the interaction of these different reservoirs and offer unique insights into the complex fluid-rock interactions within mineral systems (McCuaig et al., 2010).

For example, in magmatic ore deposits, sulfur isotope data have fingerprinted the source of the sulfur linked to ore genesis (Bekker et al., 2009; Chang et al., 2008; Fiorentini et al., 2012; Hiebert et al., 2013; Penniston-Dorland et al., 2008) and constrained the geodynamic framework where these deposits formed (e.g. LaFlamme et al., 2016; Chen et al., 2015). In addition, such data provides a better understanding of the geodynamic environment in which the mineralising process occurs which impacts on the targeting rationale applied during exploration (e.g. Fiorentini et al., 2012). Consequently, ore deposits are a perfect laboratory for understanding the source and mobility of sulfur in a wide variety of settings.

Tectonic processes driving metal-rich fluids into cratonic margins

The Capricorn orogenic belt of Western Australia formed during the Paleoproterozoic collision of the nickel- and gold-rich Yilgarn and iron- and base metal-rich Pilbara Archean cratons. The belt is flat, altered and poorly exposed, owing to a relatively inactive tectonic history since its formation. However, for this same reason, it is one of few preserved Paleoprotereozoic orogenic belts worldwide. This belt requires advanced geochemical techniques to see through overburden and altered outcrop to unravel is tectonic history and mineral wealth. To better assess the mineral potential of the poorly exposed Capricorn orogen, and to better understand tectonic processes linked with ore deposits at cratonic margins in general, we utilise these sophisticated isotopic tracers paired with detailed mapping and geophysical interpretations.

Figure 1. Dye in a watershed to follow the course of water. We can picture sulfur isotopic tracers ($\delta^{34}S$ and $\Delta^{33}/\Delta^{36}S$) behaving in a similar manner to trace sources of sulfur and hence tectonic processes at craton margins

The Capricorn Orogen is an orogenic belt that is a natural laboratory to understand fluid, volatile and metal transfer to the margins of metal-endowed Archean cratons. The rocks making up cratonic margins have long histories of deformation and hydrothermal fluid alteration — the perfect conditions for focusing of base and precious metals as ore deposits. Understanding the cycling of sulfur and metals from Archean cratons into their margins can be explored using $\delta^{34}S$ – the isotopic tracer sensitive to physical processes of formation — and $\Delta^{33}S$ and $\Delta^{36}S$ — the temporal tracers sensitive to the Archean–Proterozoic transition. These tracers act in a similar way to placing dye in watersheds to see how water travels (Fig. 1).

Results and Summary

Results at the orogen-scale, combined with detailed studies of ore deposits, lend insight into the mixing of geochemical reservoirs and processes controlling sulfide precipitation and ore formation. The Proterozoic Capricorn Orogen records $\Delta^{33}S$ values that range from −0.07‰ to +0.80‰. Spatially, data from this study show that MIF-S anomalies in the Capricorn Orogen occur in localised areas, preferentially located near to the margins with Archean cratons (Fig. 2). Rather than a primary MIF-S signature, it is interpreted that the spatially localized anomalous $\Delta^{33}S$ values in Proterozoic samples reflect a recycled MIF-S component. We use this evidence to put forward the hypothesis that MIF-S can be imparted to the Paleoproterozoic granitoid and hydrothermal record through tectonically-driven crustal formation processes.

The units hosting Archean-sourced MIF-S are dominantly magmatic (granitoids associated with collision and intraplate reworking) and hydrothermal (mineralized samples associated with faulting and veining) in nature. Mineral occurrences that also preserve MIF-S anomalies associated with these environments occur in collisional (2.0 Ga Glenburgh deposit: Selvaraja et al., in review) and intracontinental reworking (1.8 Ga Prairie Downs deposit: this study) settings. Therefore, we propose that magmatic and hydrothermal events associated with collision and intracontinental reworking processes are large-scale mechanisms responsible not only for recycling sulfur across terrain boundaries, but also for potentially transferring metals from endowed Archean reservoirs into their younger orogenic margins.

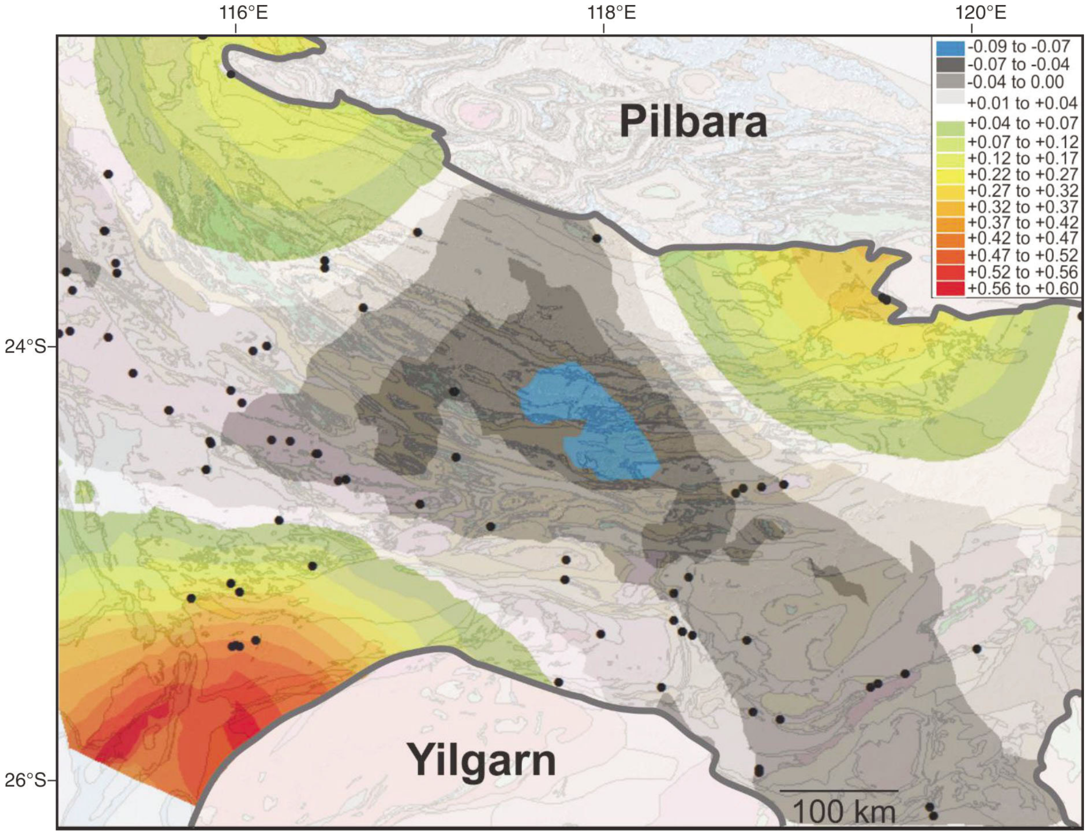

Figure 2. Interpolated model of Δ^{33}S for bulk rock samples of the Capricorn Orogen by ordinary kriging to demonstrate that at craton margins anomalous Δ^{33}S (MIF-S) is being transferred to the Proterozoic rocks of the Capricorn Orogen. Black circles are sample locations

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Ground truthing remote sensing maps — mineralogical composition of regolith and its implications to hydrothermal alteration

by

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Chemical weathering of outcrop and transported regolith landforms (e.g. colluvial, alluvial, sheetwash) present a great challenge for mineral explorers as they obscure signs of hydrothermal alteration footprints potentially associated with ore deposits. Without visual clues, conventional methods of determining the chemical and mineralogical compositions of rocks through whole-rock, X-ray diffractometry (XRD), optical spectroscopy and/or electron microprobe analysis can be time-consuming and costly. Interpretation of remote sensing Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and gamma ray spectroscopy i.e. radiometrics data maps complemented by on-site hyperspectral data acquisition can offer an inexpensive, non-destructive and fast alternative for identifying distal footprints leading to new exploration targets on a regional scale. Our study looks into short wave infrared (SWIR) active mineral relative abundances in the regolith, and compositional variations related to the underlying lithology, with particular interest in white micas and chlorites that are common hydrothermal alteration products and readily identifiable from the SWIR data.

Geological background

The study area, 110 × 60 km in size, is located in the Mesoproterozoic Edmund Basin of the Capricorn Orogen of Western Australia (Fig. 1). Sedimentary rocks of the Edmund Basin — the Irregully and Gooragoora Formations — the latter formerly considered as part of the Kiangi Creek Formation (Cutten et al., 2016; Johnson et al., 2015), host a well-studied but still relatively poorly understood, stratiform and strata-bound Fe–Pb–Cu–Au–Zn–Ba deposit called Abra, and other base-metal occurrences along the same stratigraphic horizon, and the E–W-striking crustal-scale Quartzite Well Fault. The Kiangi Creek, Gooragoora and Irregully Formations contain fine-grained siliciclastic rocks with modal abundances up to 40% of white mica. Coarse-grained rocks are poor in detrital, diagenetic and metamorphic chlorite and white mica (Martin et al., 2005). Lithologies within the Jillawarra Sub-basin of the Edmund Basin (Fig. 1), however, have all undergone widespread silicification, albitization and more localised chloritization that is associated with sericitisation (Vogt, 1995). The Abra deposit is described to include an alteration halo of an unknown extent that consists of siderite, chlorite (Collins and McDonald, 1994) and/or white micas (Pirajno et al., 2016; Rasmussen et al., 2010; Weber, 1994; Zi et al., 2015).

Method

Prior to fieldwork, regolith reflectance spectra were collected using FieldSpec3TM in a laboratory from total 544 un-sieved geochemistry samples collected by Geological Survey of Western Australia (GSWA) in a 4 × 4 km regional grid (GSWA, 2017), and samples collected across the Abra deposit in a 100 × 400 m grid (Spinks et al., 2017) by Commonwealth Scientific Industrial Research Organisation (CSIRO) to establish mineralogical variations in regolith and subcrop within the study area. We used publicly available ASTER Geoscience Product data maps of the Australian continent (AuScope, 2017) together with the potassium radiometric map of Western Australia (Brett, 2016) to identify areas of interest for field sampling. The emphasis was to target localities with high radiometric potassium content and long wavelength AlOH group composition, which could indicate hydrothermal white mica coexisting with the mineral occurrences along the Quartzite Well Fault structural corridor (Fig. 1) but also localities outside. Altogether 1313 measurements were taken in the field along 21 profiles using a TerraSpec 4 Hi-ResTM field spectrometer.

Summary of results

Dominant mineral assemblages were identified from the SWIR reflectance spectra for each sample point and verified through XRD and geochemical analysis. Samples that consisted of poorly crystalline kaolinite (Kln-px) or white mica + poorly crystalline kaolinite (Wm+Kln-px) were commonly from areas mapped as transported regolith materials, such as sheetwash. In remote sensing maps, these areas had low potassium content and short wavelength AlOH group composition (dark blue areas in Fig. 1). Sampling carried out in an area mapped as a lithology in the 1:100 000 scale surface geology maps (Blay et al., 2012a, 2012b; Cutten et al., 2011; Cutten

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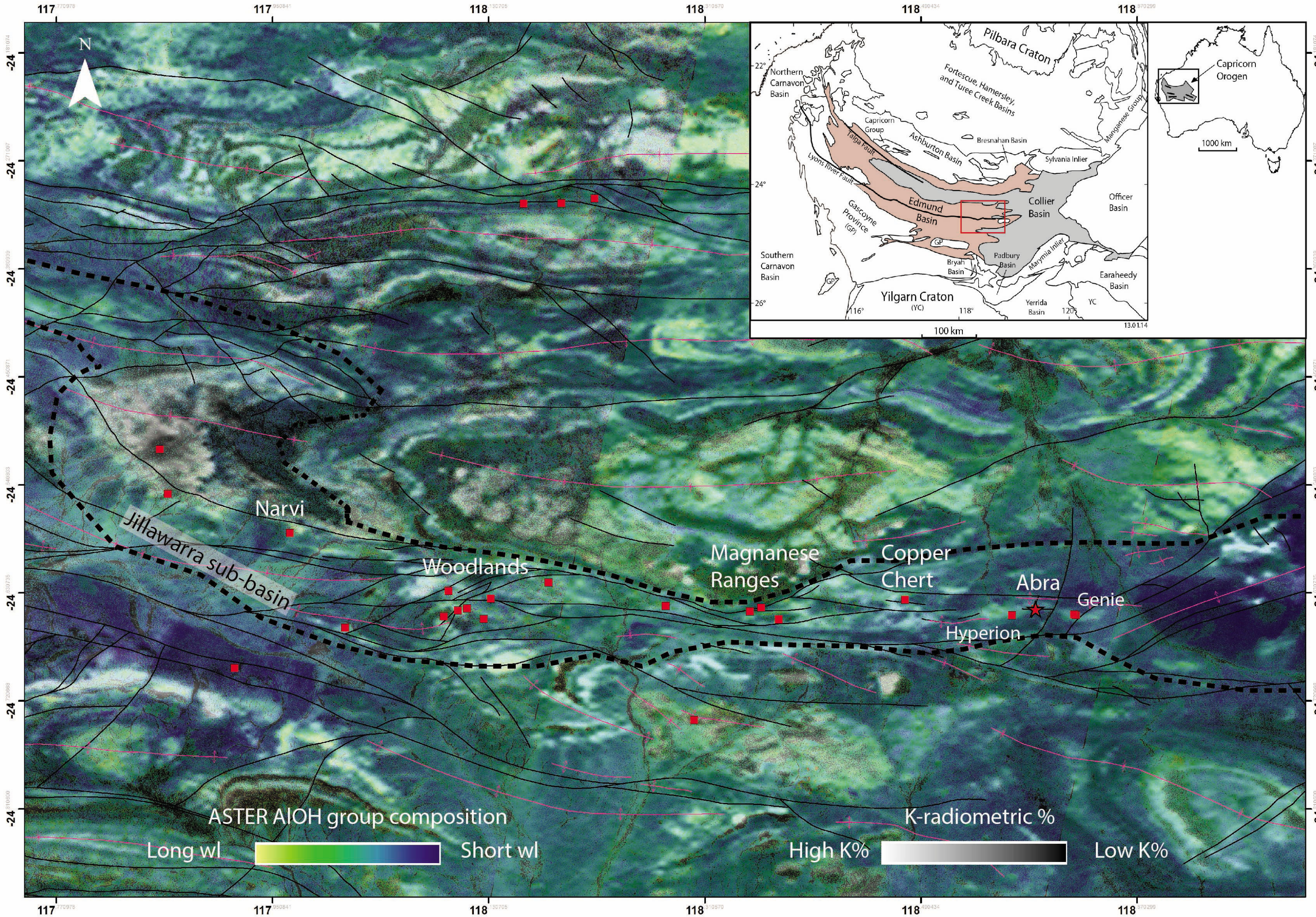

Figure 1. Combined ASTER AlOH group composition (AuScope, 2017) and K-radiometric (Brett, 2016) map with the mineral occurrences in the study area in the Edmund Basin of the Capricorn Orogen, Western Australia. Jillawarra sub-basin of the Edmund Basin is outlined after Vogt (1995). The regional geological setting of the Mesoproterozoic Edmund and Collier basins (top right) within the Capricorn Orogen of Western Australia modified after Cutten et al. (2016). The study area in the Edmund Basin is outlined in red

et al., 2010; Thorne and Cutten, 2010, 2011), were considered to be in situ regolith, and these expressed a variety of SWIR mineral assemblages from well crystalline kaolinite (Kln-wx) to a chlorite + phengitic white mica assemblage, the latter sampled from areas having high radiometric potassium content and long wavelength ASTER AlOH group composition. Figure 2a shows the lithologies hosting the Abra deposit, and prospects Hyperion and Copper Chert, together with the mineral assemblages identified from regolith reflectance spectra. The regolith samples over Gooragoora Formation sandstone in Figure 2a, have relatively high white mica abundances, inconsistent with Martin et al. (2005). Also, the regolith samples having chlorite + phengitic white mica assemblage are located atop both Kiangi Creek Formation sandy siltstone and Gooragoora Formation sandstone that have different mineral composition and modal abundances. These samples are, however, within an E–W-striking area of high potassium content and long wavelength AlOH group composition (Fig. 2b) that crosses over all formations (Fig. 2a), which suggests that the regolith mineral composition is reflecting something other than the primary composition of underlying lithologies, and could be related to hydrothermal alteration described by Vogt (1995).

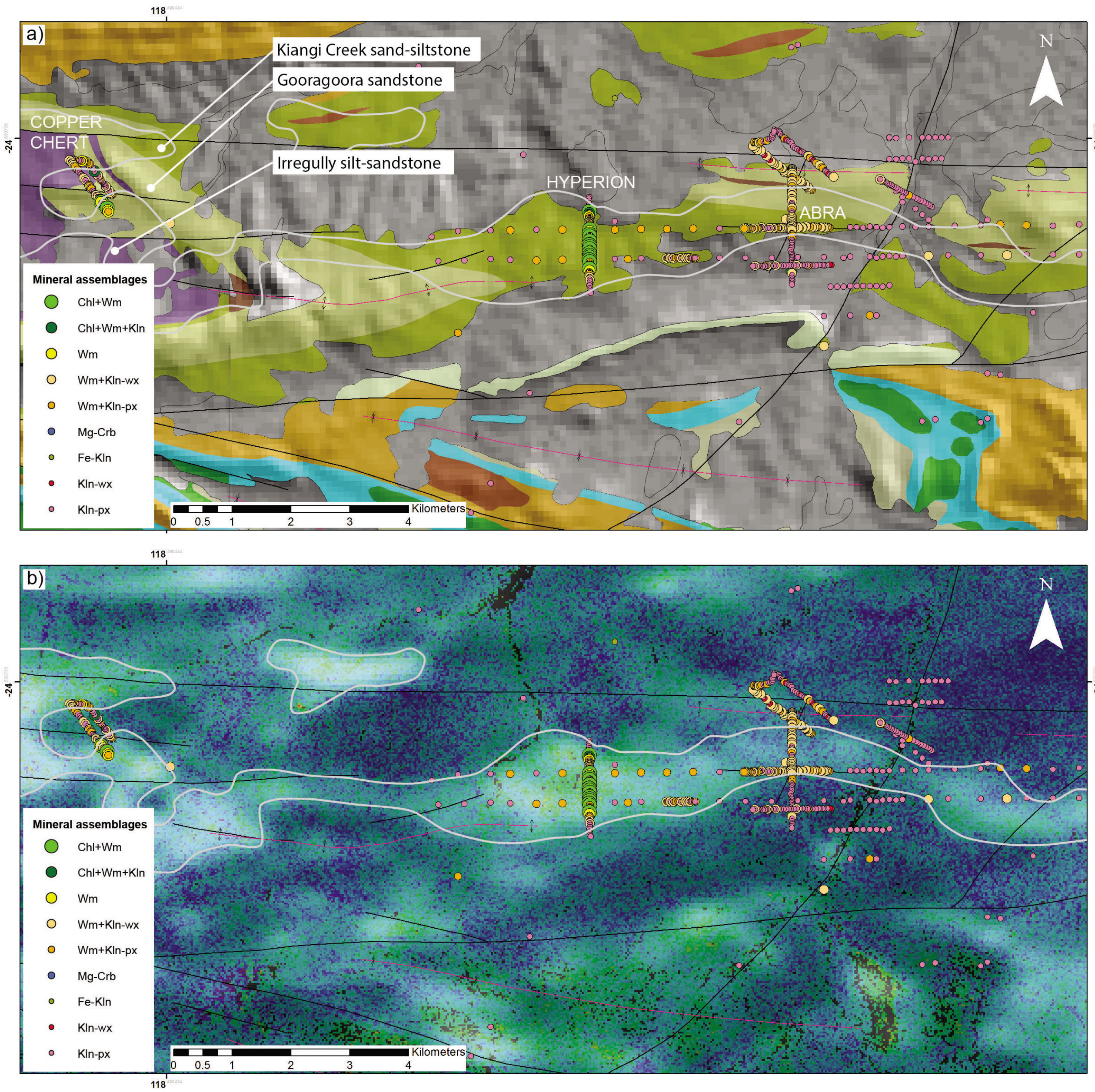

Figure 2. Regolith mineral assemblages identified from the SWIR reflectance spectra a) against 1:100 000 surface geology and b) combined K-radiometric and ASTER AlOH group composition. Mineral assemblage abbreviations: Chl=chlorite, Wm=white mica, Kln=kaolinite, Fe-Kln=Fe-rich kaolinite, Mg-Crb=dolomite, wx=well crystalline, px=poorly crystalline

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Investigating mineral systems across the Australian continent — the NVCL makes it possible!

by

Carsten Laukamp[1]

Mineral systems analysis has gone beyond just pigeon-holing mineral deposits into different categories and endeavours to understand the complexity of, and overlaps between, real world mineral systems for improved exploration and resource characterisation. The first fundamental step for describing mineral systems is the characterisation of the mineral assemblages that define the lithologies and alteration footprints. Usually, this begins with time-consuming core logging next to drill rigs or in drillcore sheds across Australia. Notwithstanding the effort that is put into the visual core logging by the resource companies and their employees, the results can be very subjective and are difficult to use for decision making, let alone in a quantitative way for resource characterisation further down the track. Detailed thin-section analyses of selected samples are the usual way for understanding the mineralogy. However, in many cases, mineral assemblages are calculated from quick and easy geochemical technologies, often accepting disturbing errors, especially when considering areas prospective for hydrothermal ore deposits that were overprinted numerous times. Mineralogy is key and there's now a substantial mineralogical database that covers many of the mineral systems present in Australia: The National Virtual Core Library!

The National Virtual Core Library (NVCL), part of AuScope's national earth science infrastructure program, now comprises over 700 km of hyperspectral drillcore data, sourced from various geological environments and mineral deposit types across the Australian continent (Fig. 1). The 800 spectral channel, line-profiling data were collected at ca. 1 cm resolution using HyLoggerTM systems located at six NVCL nodes operated by State and Territory Geological Surveys, creating arguably one of the world's largest collections of publicly available mineralogical data. The prime objective of the NVCL has been to create a research network utilising the vast resource of geological information from the upper 1–2 km of our Earth's crust that is stored in drillcore libraries and core sheds across Australia.

The 700 km of already collected hyperspectral drillcore data are available to the research community and resources sector via AuScope's Discovery Portal (http://auscope.org.au/site/nvcl.php) and are just the beginning. The HyLoggers now form an integral part of the earth science infrastructure at most Australian State and Territory Geological Surveys, a concept that is increasingly being adopted by Geological Surveys and research institutions around the world.

The uptake of this valuable database by national and international researchers is now going full-steam ahead. In collaboration with the State and Territory Geological Surveys, researchers from companies, universities and the CSIRO are using HyLogger data to characterise, for example, regolith overlying potentially prospective areas and to identify mineralogical footprints related to hydrothermal deposits (e.g. Albany–Fraser Orogen, Capricorn Orogen, Broken Hill, Mt Isa Inlier Eastern Successions, Tasmania's Mt Read Volcanics and Victoria's Stavely province). Other case studies are using HyLogger data for sequence stratigraphic analyses across sedimentary basins (e.g. Centralian Superbasin) or to compare BIF-hosted high-grade iron-ore deposits (e.g. Yilgarn Craton). Finally, the hyperspectral drill core data are being integrated with remote sensing data to create 3D mineral maps at a regional scale (e.g. Queensland 3D Mineral Mapping Project).

This paper showcases the multiple applications of hyperspectral drillcore data contained within the NVCL database and highlights why this Australian made earth science infrastructure should be in every Geo's toolbox.

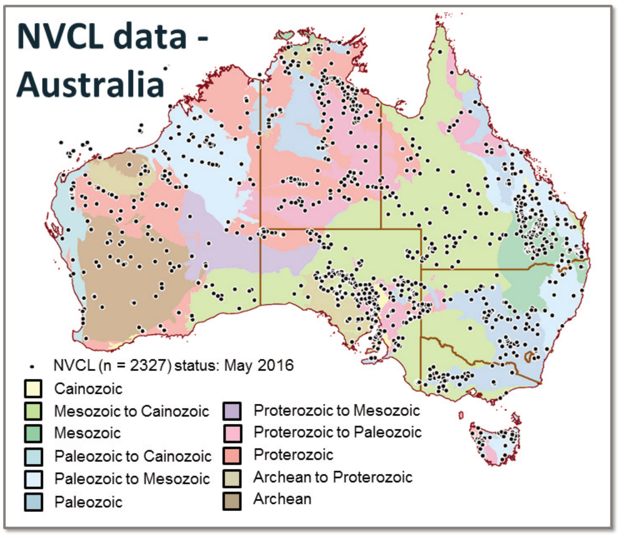

Figure 1. Locations of NVCL drillholes in Australia

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Recent advances and potential leads in lithogeochemical exploration for magmatic nickel sulfide deposits

by

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Magmatic nickel sulfide deposits represent challenging exploration targets and many of the current exploration techniques (Le Vaillant et al., 2016) have now been used for decades with little improvement. More importantly, many of these geochemical tools rely on the geometry of the mineralised system being similar to when the deposit formed, and their size is constrained by the size of the parental magmatic system. Instead of focusing on primary magmatic footprints, a recent study focused on the nature and size of secondary hydrothermal haloes surrounding massive nickel sulfides (Le Vaillant, 2014). These haloes would be consistent with the contemporary geometry of the system and their extent would not be restricted by the size of the hosting magmatic conduit or intrusion.

Hydrothermal Ni–As–PGE haloes

Within this study on secondary hydrothermal haloes, four komatiite-hosted deposits, in Western Australia, were investigated: the Miitel deposit (Widgiemooltha Dome), the Otter Juan and the Durkin deposits (Kambalda Dome), the Perseverance deposit (Agnew–Wiluna greenstone belt) and the Sarah's Find prospect (next to the Mount Keith deposit in the Agnew–Wiluna greenstone belt). Combined results show that arsenic-rich fluids have the potential to remobilise and redeposit metals and precious metals such as platinum group elements (PGE). Indeed, a Ni–As–PGE enriched halo was observed and characterised surrounding two of the studied deposits, Miitel and Sarah's Find (Le Vaillant et al., 2015 a,b). Here we present a short summary of results from both case studies (Figs 1 and 2), where Ni and Pd were remobilised from the massive sulfides into the surrounding lithologies, thus creating a detectable halo extending up to 1.5 km away from the mineralisation. This Ni–As–PGE halo could potentially be used as and exploration vector for magmatic nickel sulfide deposits.

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Nickel-arsenides as indicator minerals?

The hydrothermal haloes observed surrounding the Miitel and the Sarah's Find deposits are due to the presence of nickel-arsenide grains concentrated within small veins or within the foliation of the studied lithologies. We studied the composition of these grains, along with nickel arsenides from other localities used as comparison. Concentrations in trace elements such as PGEs and Au were obtained by laser ablation inductively coupled plasma mass spectroscopy (LA ICP-MS) analyses collected at UQAC (Quebec). Results show that variations in PGEs and Au compositions can be linked back to both the origin of the grains; magmatic vs hydrothermal, and their provenance; Ni-endowed vs Au or Ni and Au endowed areas. These preliminary results suggest that nickel arsenides could potentially be used as indicator minerals for nickel and gold exploration.

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Figure 2. **(opposite, bottom) Summary of results from the study of the Sarah's Find deposit. a) 3D visualisation of concentrations in Pd of all analysed samples, combined with a colour representation of the arsenic concentrations along the footwall contact between the Mount Keith komatiites and the Mount Keith dacite. b) micro-XRF map of one of the sample containing nickel arsenides within the foliation in the dacite footwall. c) Interpretative block model of the geochemical halo observed around the Sarah's Find ore body. Modified from Le Vaillant et al. (2015b)**

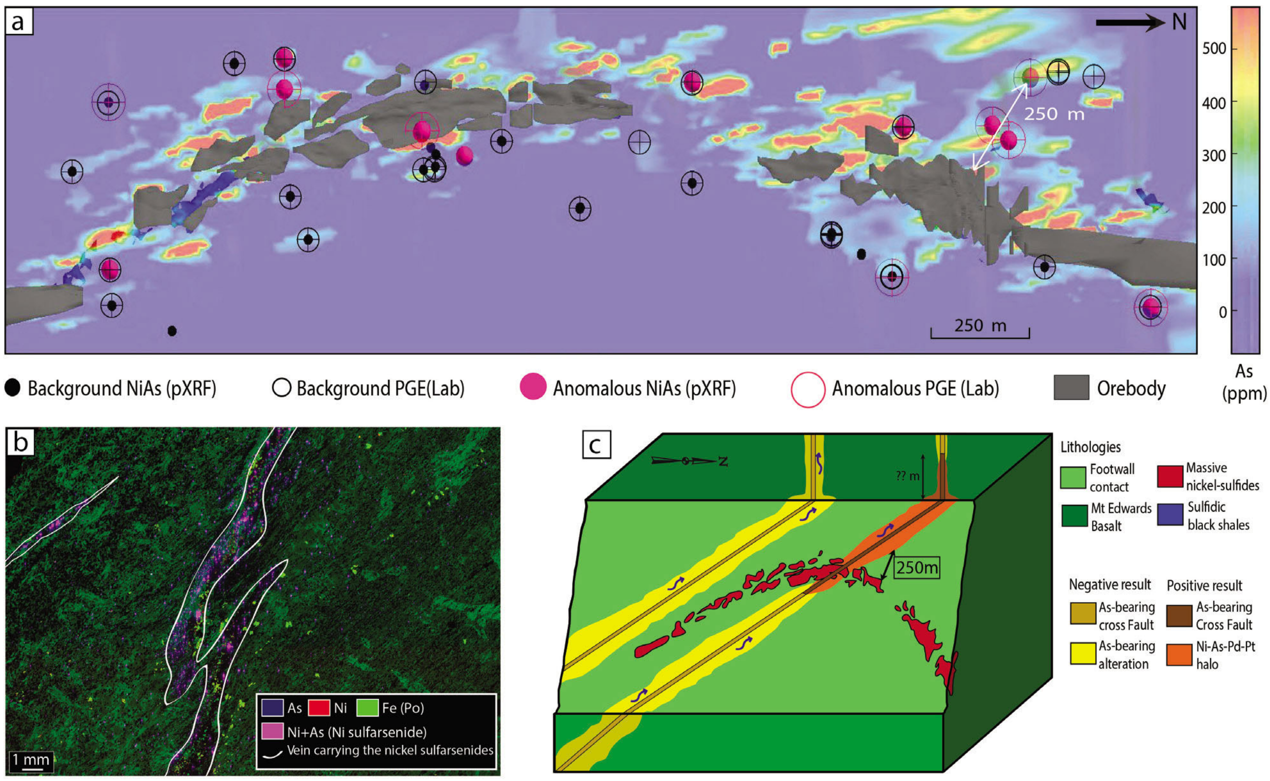
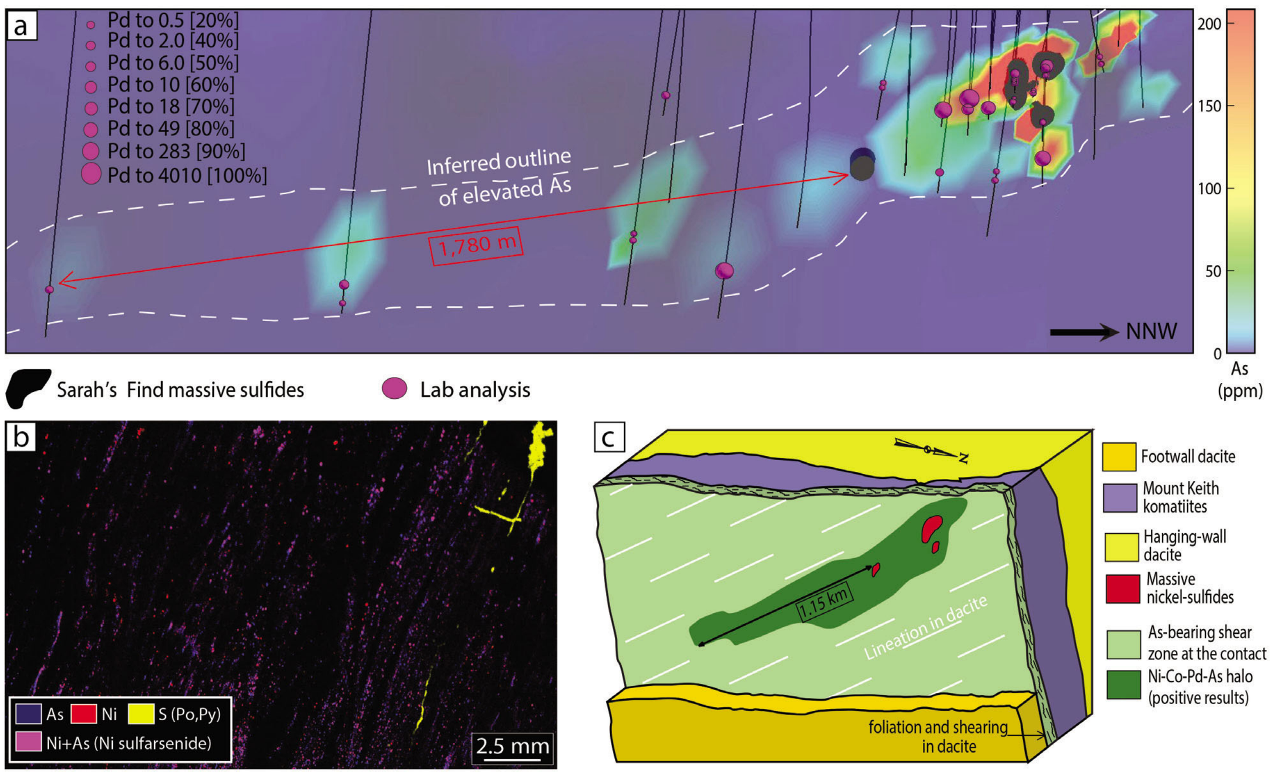


Figure 1. **Summary of results from the study of the Miitel deposit. a) Perspective view from gOcad® of a long section through the 3D model of the Miitel deposit. This image combines: 1) distribution of the arsenic in ppm at the contact between the basalt and the komatiites (model derived using Leapfrog®), 2) location of pXRF analyses showing anomalously high Ni and As concentrations, and 3) location of laboratory PGE analyses highlighting samples enriched in PGE. b) False colour element concentration map (As blue, Ni red, Fe green), of samples DRD918-358.6 which contains nickel arsenides within small hydrothermal quartz and/or carbonate veins cross cutting the Mount Edwards footwall basalt. This map was produced using the data collected with the Maia detector array on the X-ray fluorescence microscopy beamline, at the Australian Synchrotron in Melbourne. c) 3D block model of the Miitel system showing the possible application of the Ni-As-Pd geochemical halo to exploration targeting for nickel sulphides. Modified from Le Vaillant et al. (2015a)**



Interpretation of 3D magnetotelluric with potential field data: identifying mineralisation in the northeast Kimberley region

by

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An integrated interpretation of potential field and magnetotelluric (MT) data was performed in the east Kimberley, northern Western Australia. Structural interpretation of potential field data was constrained by geological field observations, petrophysics, remote sensing and an understanding of the tectonic history of the region. Forward modelling of the potential-field data located along the same survey traverse as the magnetotelluric data allowed comparison between the two datasets to assess complementarity of images and assist interpretation. Interpreted features include the presence of large-scale structures and associated electrical anomalies that indicate the presence of mineralisation deep in the crust, and guide prediction of mineralisation at or near the surface. The King River Fault is revealed to be a crustal-scale, west-dipping structure, the footwall of which bounds the western side of a large resistive body. A conductive anomaly is also located on the hanging wall of the King River Fault. A number of scenarios for the source of conductivity, including the presence of sulphides, saline water and graphite, are discussed. Our assessment suggests that graphitic rocks, most likely with some sulphide content, contribute to the strength of this anomaly, and highlights the known potential of the east Kimberley to host graphite deposits. The conductive anomaly has a spatial and geometric correlation with the Speewah Dome, a known prospective region. The depth of the conductor (about 5 km) precludes mining, but does indicate that the King River Fault is likely to form a mineralising conduit, and may contribute to possible Pb–Zn mineralisation where the fault reaches the surface.

Introduction

We use a variety of geophysical datasets to image the lithosphere of the northern Halls Creek Orogen, Western Australia (Figs 1a, b). Each of these data sets resolves a range of overlapping depth slices, with magnetic data best imaging the near-surface to middle and deep crust, gravity data imaging the middle–upper crust to the lithospheric mantle, and the MT imaging the middle crust to close to the base of the lithosphere. Surface observations are supported by geological field observations and remotely-sensed datasets. Together, the potential field and MT data have been simultaneously employed to produce an integrated structural interpretation that reveals a map of major and minor structures that were subsequently investigated to assess their contribution to mineral prospectivity. In particular, the MT data in combination with potential field forward modelling was effective in developing a understanding of crustal architecture.

Geological background

The two billion year geological evolution of the Kimberley region comprises four major tectonic events: the 1865–1850 Ma Hooper and 1835–1810 Ma Halls Creek Orogenies; the early Neoproterozoic Yampi Orogeny and late Neoproterozoic King Leopold Orogeny (Griffin et al., 2000; Hollis et al., 2014; Sheppard et al., 1999; Tyler and Griffin, 1990). From west to east, the east Kimberley region includes the Kimberley and Speewah Basins, the 1910–1805 Ma Lamboo Province (largely the Halls Creek Orogen), and the Southern Bonaparte and Ord Basins (Fig. 1a). The eastern part of the Lamboo Province, known as the Halls Creek Orogen, is inferred to be a series of northeasterly-trending Archean and Paleoproterozoic terranes (Gunn and Meixner, 1998; Hollis et al., 2014) (Fig. 1c).

The Lamboo Province zones comprise rocks that characterise their tectonic history. The felsic to intermediate rocks of 1865–1850 Ma Paperbark Supersuite and c. 1855 Ma Whitewater Volcanics characterise the western zone are linked to the Hooper Orogeny. Within the western zone, the turbiditic protoliths to the c. 1872 Marboo Formation have been metamorphosed to amphibolite facies (Tyler and Griffin, 1993). The Tickalara Metamorphics characterise the central zone with a metamorphosed group of lithologies attributed to either an ocean arc or ensialic basin formed during the Hooper Orogeny. The central zone is also host to the felsic to mafic intrusive rocks of the 1832–1808 Ma Sally Downs Supersuite, which were emplaced during the Halls Creek Orogeny (Sheppard et al., 2001). The 1880–1847 Ma sedimentary and volcanic rocks of the Halls Creek Group characterise the eastern zone (Tyler et al., 1998). During and following the Halls Creek Orogeny, the Speewah and Kimberley Group rocks were deposited over the Kimberley Craton and areas of the

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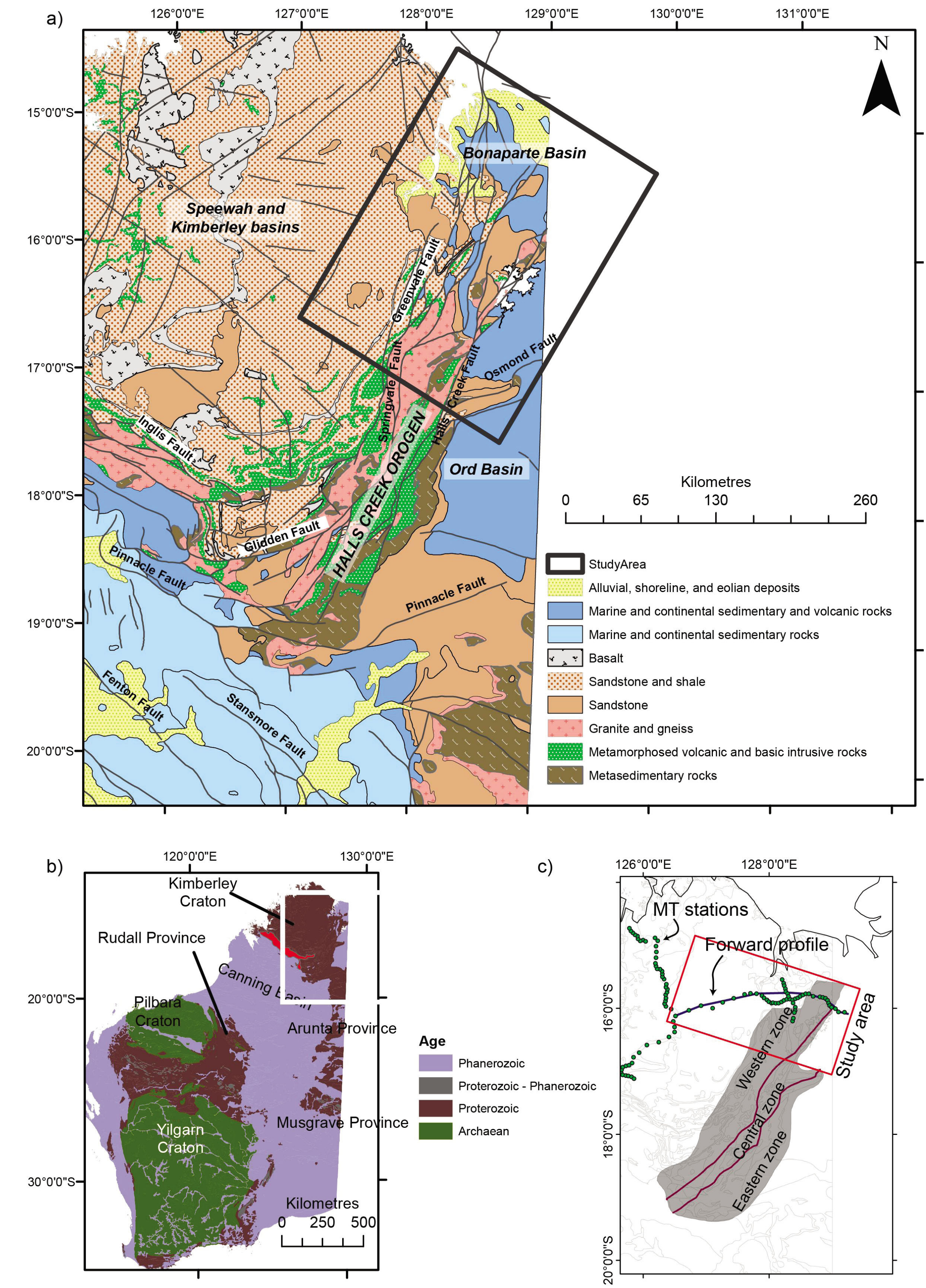

Figure 1. a) Map of the east Kimberley region showing major tectonostratigraphic units of the Lamboo Province. b) Main tectonic units in Western Australia and location of study area. c) Shaded areas indicating the location of the western, central and eastern zones defined by Tyler et al. (1995) within the study area

western and central zone to the north and south of the east Kimberley. Mafic magmatism is represented by the Hart Dolerite and Carson Volcanics rocks, which were intruded into and extruded onto the Speewah and Kimberley Group rocks at c. 1797 Ma. (Griffin et al., 1994). The <1797 Ma Bastion Group, the c. 1200 Ma Carr Boyd Group and the flood basalts of the c. 510 Ma Antrim Plateau Volcanics overlie the Speewah and Kimberley Groups. The Frasnian Cockatoo Group rocks outcrop to the north and east of the study area.

Method and results

Magnetic susceptibility and density measurements were collected from the region and used to constrain the structural interpretation and joint forward modelling of magnetic and gravity data. A regional understanding of geological architecture was developed from structural interpretation of precompetitive magnetic (400 m line spacing) and gravity data (2 to 10 km station spacing) supplied by Geoscience Australia. Appropriate use of different filters and transforms (such as reduction-to-pole, first vertical derivative, automatic-gain control and upward continuation) were applied to each of the datasets to enhance resolution of the geological signal from the geophysical data and support interpretations between these and remotely-sensed datasets. Geological data (such as lithological and structural observations) collected by the authors and obtained from Geological Survey of Western Australia databases were used to constrain the structural interpretation and forward model. Aitken et al. (2013) provided Moho depth estimates used in the forward model. The petrophysical model was forward modelled using Oasis Montaj GM-SYS, from which a geological interpretation was performed using geological field constraints.

Broadband and long-period MT were acquired from 155 sites covering the entire Kimberley region, including the King Leopold Orogen to the south and southwest and the Halls Creek Orogen to the east (Fig. 1c). Station spacings were from five to 20 km, where predicted larger structures were covered with the smaller spacing. Each site was measured for about 40 hours. 2D inversion was performed and imaged the Earth to an estimated depth of 140 km. 3D MT conductivity models were produced using the ModEM 3D inversion code (Egbert and Kelbert, 2012). Additional details for the 2D inversion are provided in Spratt et al. (2014).

Structural interpretation

Crustal-scale structures (heavy black lines), identified through interpretation and supported through previous studies (e.g. Tyler et al. 1995; Gunn and Meixner, 1998), are shown in Figure 2. The intersection of these features coincides with complex structures, such as an elliptical, high frequency magnetic anomaly, interpreted to be Hart Dolerite intruded into Speewah Group sedimentary rocks at Speewah Dome (Fig. 2a). Speewah Dome is prospective for Cu–Au, fluorite, V–Ti and Ni–PGE. Figure 2a shows another location (A) with structural complexity at the intersection of crustal-scale structures, the now-closed Pb–Ag–Au–Cu Shangri-La mine.

Forward modelling potential field geophysics and geology

Figure 3 shows the 310 km forward model. Large-scale differences between the Speewah/Kimberley Basin and the Lamboo Province can be seen. Magnetic data over the Speewah and Kimberley Basins shows a high-frequency character, which has been attributed to the basaltic Carson Volcanics and Hart Dolerite intrusions. A one kilometre layer of magnetic and dense material is modelled at 400 m to two kilometre depths, from the start of the profile in the west to x = 230 km, and is interpreted to be Hart Dolerite sills and intrusions. Several faults have been modelled in this portion of the profile (between x = 170 km and x = 215 km). These faults are considered to be blind as they do not appear on the geological maps. From x = 230 km, modelling suggests that the western and central zones are under cover if they extend this far north. Several major faults known at the surface have been modelled (Fig. 3c, e.g. the Ivanhoe, Cockatoo, and Halls Creek Faults) as well as minor ones (Dillon Springs Fault).

Comparison of MT and potential field modelling

An overlay of the potential field model with the MT data is shown in Figure 4. Structures interpreted from the potential field data and forward modelling are shown with grey lines, and the interpretation of Spratt et al. (2014) from the MT data are shown with white dashed lines. Resistivity is shown in colours. There is some agreement in the position and geometry of the structures interpreted from each data set. Differences between the data sets can be seen in penetration depth of structures. The Halls Creek Fault, near station 155, only penetrates the upper crust, but no deeper, whereas the MT suggests a middle to lower crustal extent. Other interpreted structures are obvious in one model, but subtle (or absent) in the other, highlighting the usefulness of jointly interpreting datasets that respond independently to three different physical fields (resistivity, density and magnetism).

A noteworthy example of integrated interpretation of MT and potential field data is the King River Fault (Fig. 4, station 125). This structure is interpreted to be minor and relatively surficial from the forward model, however the MT reveals a much deeper and extensive west-dipping structure. If this structure does represent a fault, it shows a voluminous resistive anomaly in what would be the footwall, and a strong conductive anomaly in the hanging wall. The conductive anomaly has been examined with 3D MT inversion by Spratt et al. (2014) to find that it has a northeast strike, sub-parallel with interpreted orientation of the King River Fault (Fig. 2a, b). The association of this conductive anomaly with the deeper extent of the King River Fault and possible structural control bears closer scrutiny for implications to mineral prospectivity.

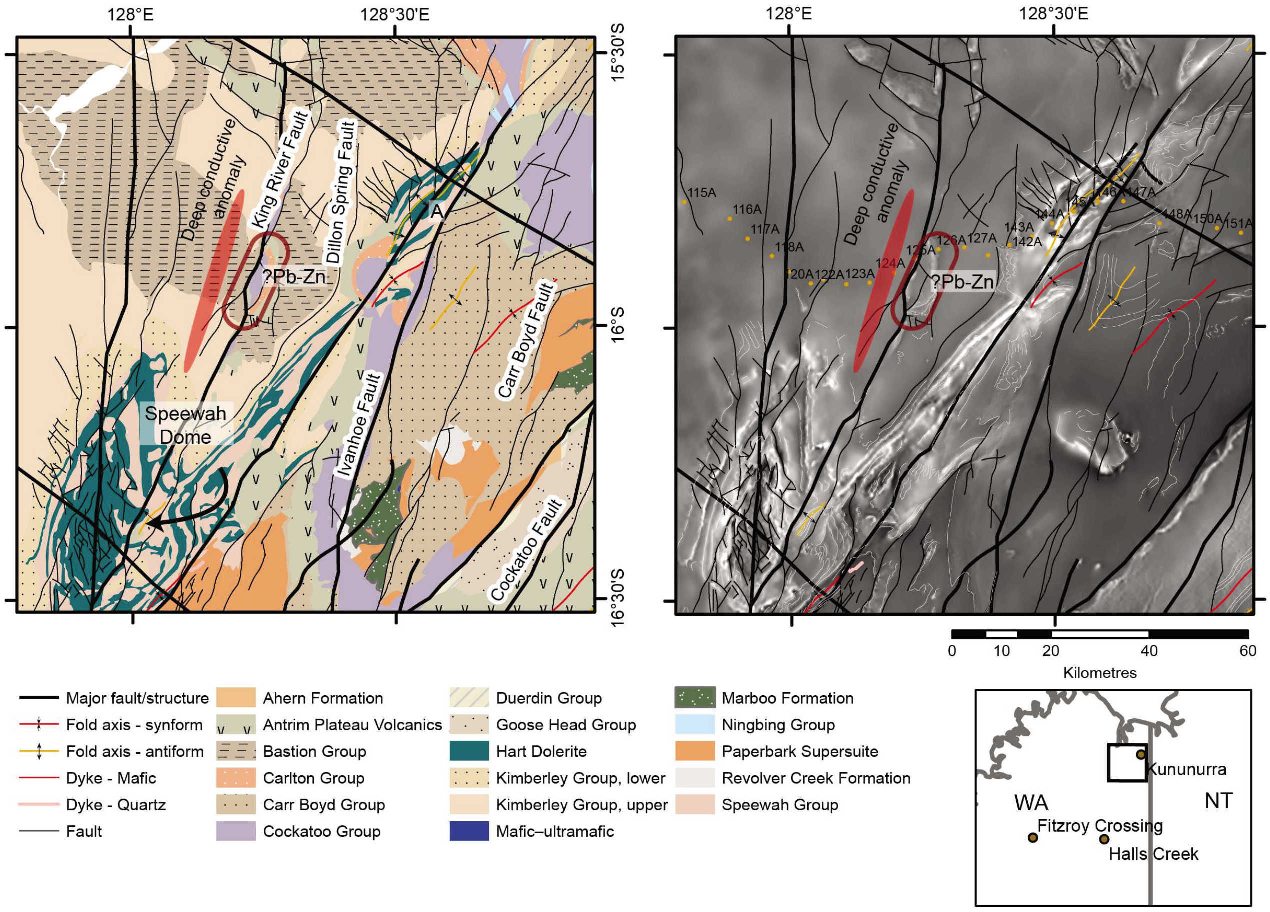

Figure 2. **Detailed geophysical structural interpretation of the study area. a) Interpreted structure overlying geology. b) Interpreted structure overlying TMI magnetic data. Location of MT stations indicated with green points. The position and orientation of a deep conductive anomaly is shown with a filled red ellipse. The location of potential Pb-Zn mineralisation is shown with a hollow red ellipse**

A feasible source of conductivity linked to the anomaly needs to be considered. Three options are: (1) saline water; (2) interconnect sulphides; and (3) graphite. The presence of water is not considered likely by Spratt et al. (2014) due to long residence times, a lack of fluid regeneration mechanisms and high temperatures (125°C to 250°C) at this depth. The presence of sulphides can provide the conductivity to produce such an anomaly, though the values obtained through inversion (4 to 10 Ω·m) may be too low (Keller, 1971). We believe that the presence of graphite, likely with some sulphides, is the most feasible source of conductivity in this location.

Figure 5 shows an isometric view of the 3D MT data shown as 'slices', or multiple sections taken from the 3D resistivity volume, onto which resistivity values have been mapped. Also shown with heavy black lines are structures interpreted and modelled from the potential field data. These are extended downwards to aid visualization of where the structure intersect the MT slices; however, dip angle or direction is not shown (though this could be interpreted from the MT data). This visualization serves to examine our assertion that anomalies and discontinuities observed in the potential field data are also in the MT. Therefore, the location of these structures has not been modified to 'fit' the MT data.

Mineral potential

A history of hydrothermal activity and fault reactivation may be indicated by the presence of graphite on the King River Fault (Nieuwenhuis et al., 2014; Wannamaker and Doerner, 2002). Reactivation and hydrothermal activity then suggests this fault may have acted as a conduit to mineralising fluids (McCuaig et al., 2010), but requires rocks permissive to host mineralisation near the surface. The surface trace of the King River Fault is juxtaposed with the Frasnian Cockatoo Group rocks, which contain a unit of dolomitised carbonaceous rocks (Occhipinti et al., 2015), and thus present a strong possibility for Pb–Zn type mineralisation (Fig. 2a,b). A similar geological scenario is seen at Shangri-La, a location known for hosting Pb–Zn mineralisation. The 3D MT data shows the Shangri-La location has high conductivity (Fig. 5, SL), suggesting that mineralisation may be represented by high conductivity in this part of the east Kimberley.

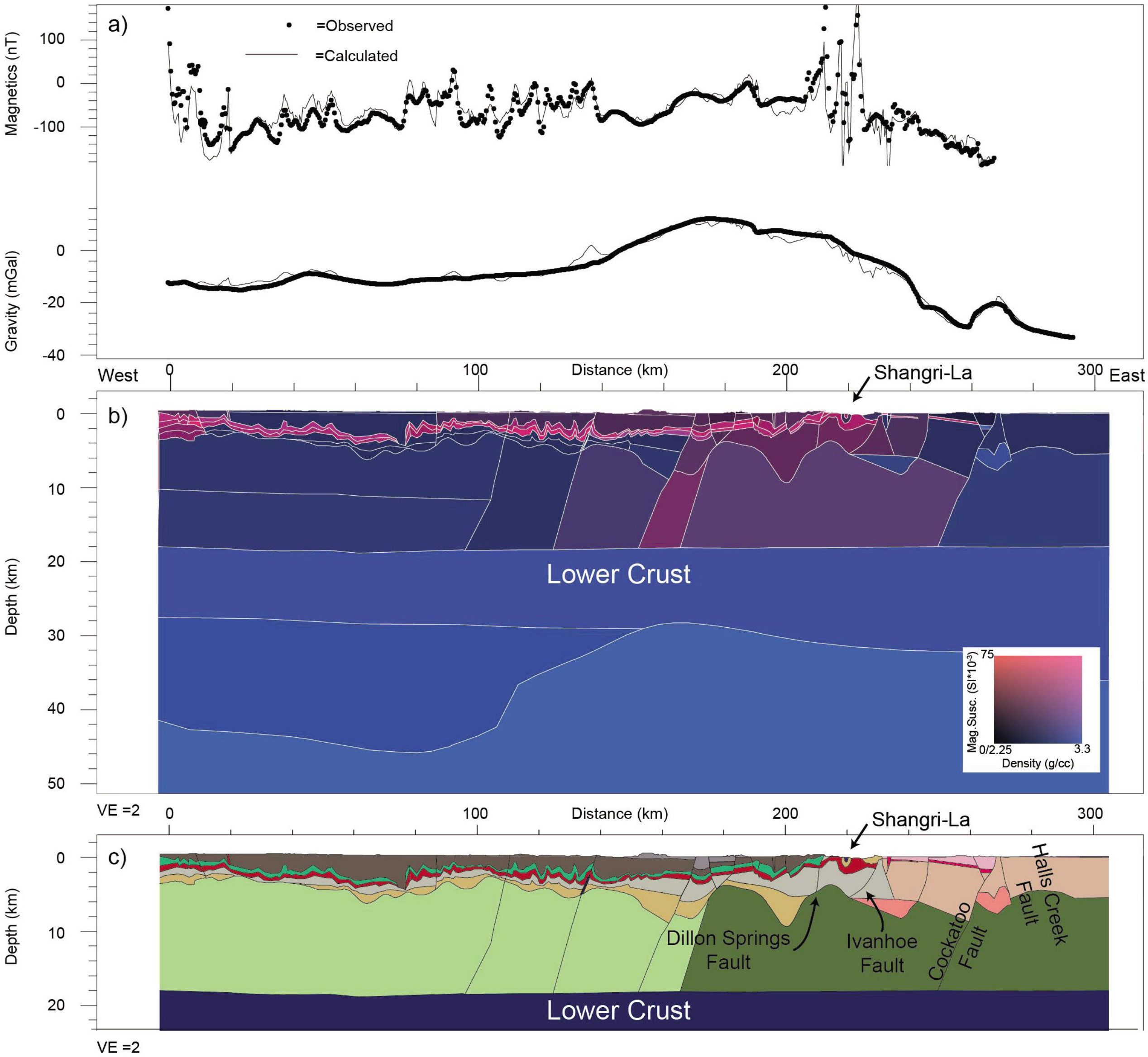

Figure 3. **Combined gravity and magnetic model along the profile shown in Figure 1c. The profile is viewed from the south, with the section starting at the left-hand side in the west, and finishing to the east. VE = x2. a) Observed geophysical signal from magnetics and gravity compared with the calculated response. b) Petrophysical model used to forward model the calculated response. c) Geological section interpreted from the petrophysical model. Note section in part c) is cut off at about 18km**

Conclusions

The results show that jointly interpreted geophysical data can reveal a robust model for mineralisation with judicious use of geological constraints. The MT and potential field data reveal several large-scale structures and describe crustal architecture permissive to mineralisation. We suggest further investigation of a location worthy of further examination for base metals.

Acknowledgements

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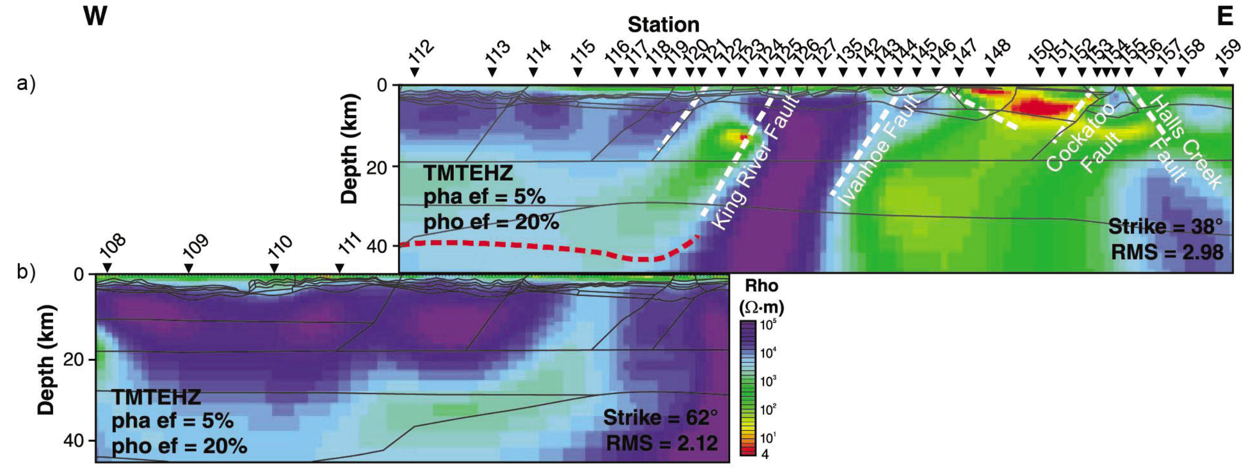

Figure 4. Comparison of the potential field and MT modelling. Two sections are shown as each have been modelled assuming different a different strike resulting in lower RMS error: a) strike = 38°; b) strike = 62° — see Spratt et al. (2014) for details on modelling. The blue colours represent resistive areas and the warm conductive areas. The dashed white lines mark steeply dipping features observed in the upper crust; the red dashed line marks the approximate crust–mantle boundary (Spratt et al., 2014). The thin grey lines overlying the MT sections for comparison are the boundaries modelled from the forward model shown in Figure 3. Modified from Spratt et al. (2014)

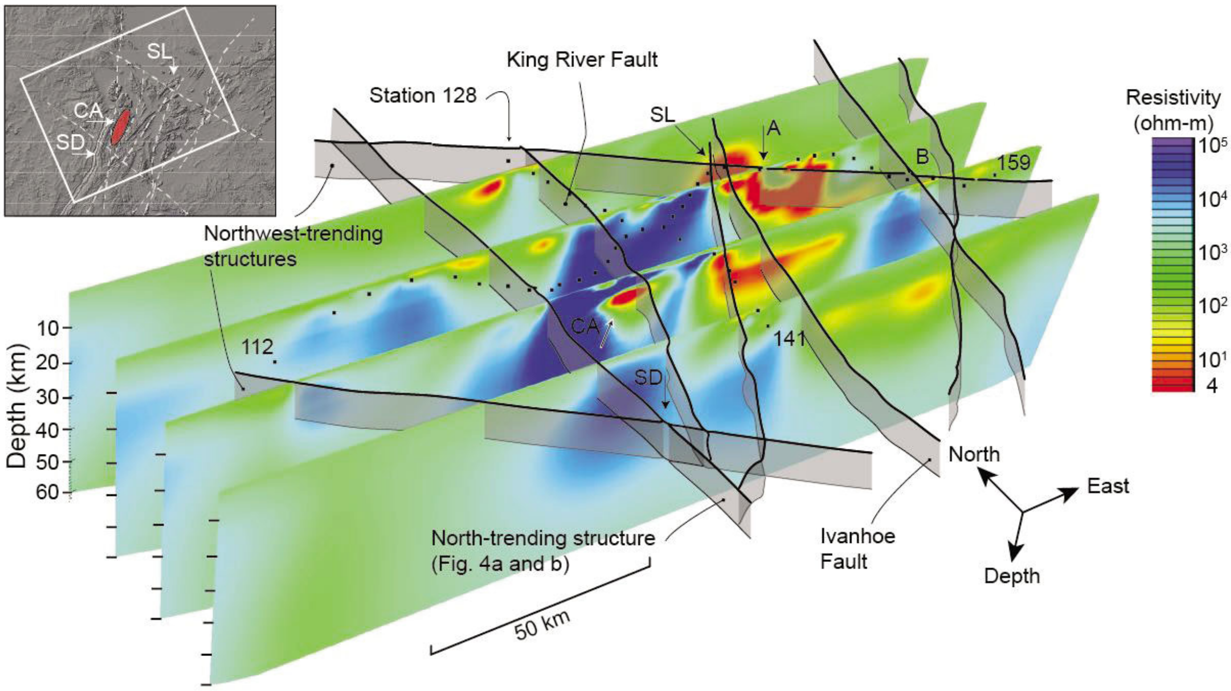

Figure 5. Isometric view from the south of inverted 3D MT data with structures interpreted and modelling using potential field data. ‘Cool’ colours represent high resistivity, ‘hot’ colours low resistivity (scale shown at right). The heavy black lines indicate the position and geometry of structures at the surface interpreted and modelled from potential field data without the aid of the MT. These structures have been extended down vertically to help visualise where each structure may intersect the resistivity structure of the region, though do not indicate dip or dip-direction. The position of the conductive anomaly near the King River Fault (Fig. 4) is indicated as ‘CA’. Black dots indicate the position of MT stations with stations at the extremities of the study area labelled for reference. The inset map shows the approximate extents of the view in the main part of the figure and the digital elevation model. Dashed grey lines indicate the position of the large-scale structures (heavy black lines in the main figure). SD: Speewah Dome; SL: Shangri-La

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Terrane-scale porphyry Cu fertility in the Lhasa terrane, southern Tibet

by

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Porphyry Cu (±Mo±Au) deposits provide around 75%, 50%, and 20% of the world's copper, molybdenum and gold, respectively, and predominantly occur in the circum-Pacific and Tethyan mountain belts (Sillitoe, 2010). Discovery of new deposits is costly and challenging. Scale reduction tools, chemical fingerprinting and/or fertility assessment of potential exploration targets from terrane to deposit scale are urgently needed by industry (e.g. Ballard et al., 2002; Loucks, 2014; McCuaig and Hronsky, 2014; Agnew, 2015; Dilles et al., 2015; Lu et al., 2016).

In porphyry Cu systems, the ore-forming magmas have distinctive whole-rock chemical compositions, such as high Sr/Y, V/Sc, and Eu/Eu* ratios, relative to ordinary nonmineralized arc magmas (e.g. Rohrlach and Loucks, 2005; Chiaradia et al., 2012; Richards et al., 2012; Loucks, 2014). Zircons that crystallized from Cu-ore-forming magmas also have distinctive compositions such as higher Eu/Eu* (>0.3), and 10,000*(Eu/Eu*)/Y (>1) ratios than infertile A-, S-, and I-type granitoids (Lu et al., 2016). These distinctive whole-rock geochemical and zircon trace elemental signatures can be used as ore fertility indicators, and are attributed to high magmatic water and sulfur contents and high oxidation states of the melts. In addition, zircon Lu–Hf isotopic mapping has illustrated that porphyry Cu deposits are clustered within isotopically juvenile crust rather than ancient crust, indicating that such isotopic mapping may be used as a scale reduction tool (Hou et al., 2015a; Wang et al., 2016).

In this study, we report whole-rock geochemical and zircon Lu–Hf isotopic mapping results from approximately 1200 whole-rock samples and approximately 400 zircon samples, respectively, in the Lhasa Terrane in southern Tibet. The aim is to test whether these datasets could be used as terrane-scale fertility indicators and thus help focus exploration on prospective areas. Our results show that the best Cu fertility indicator is whole-rock 10,000*(Eu/Eu*)/Y ratio (Loucks, 2013). The majority of, but not all, porphyry Cu deposits are associated with isotopically juvenile crust, suggesting that isotopic maps should be used together with whole-rock geochemical maps for targeting porphyry Cu systems.

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Regional geology of the Lhasa terrane

The Tibetan plateau consists primarily of three terranes: from south to north, the (1) Lhasa, (2) Qiangtang, and (3) Songpan–Ganze terranes (Fig. 1). These terranes are separated from each other by the Bangong–Nujiang and Jinsha sutures, which represent closure of Meso- and Paleo-Tethyan ocean basins, respectively (Fig. 1; Chung et al., 2005; Zhu et al., 2011). The Lhasa terrane is bounded to the south by the Indus–Yarlung Zangbo suture (IYS), which represents closure of the Neo-Tethyan Ocean. The Neo-Tethyan oceanic lithosphere subducted northwards beneath the Lhasa terrane along the Indus-Yarlung Zangbo suture from the Late Triassic through to the Late Cretaceous, and produced voluminous Late Triassic through Paleocene Gangdese batholiths, Jurassic–Cretaceous arc volcanic rocks and the 69–43 Ma Linzizong volcanic rocks (Fig. 1; Chung et al., 2005; Zhu et al., 2011).

The closure of the Neo-Tethyan ocean and the collision of India with Asia are generally believed to have occurred at 55–50 Ma (e.g. Replumaz et al., 2010). The Neo-Tethyan oceanic lithosphere broke off at 50–45 Ma from the leading edge of the subducting Indian continental lithosphere (Lee et al., 2009; Replumaz et al., 2010). After detachment of the Neo-Tethyan oceanic lithosphere, the leading edge of Indian continental lithosphere and some of its sedimentary cover underthrusted Tibet in the 40–30 Ma time frame (Chemenda et al., 2000; Replumaz et al., 2010). The deeply subducted Indian continental lithosphere, after the buoyant upper crust was scraped off at the Himalayan front (Capitanio et al., 2010), then detached from the shallower, thicker subducting Indian plate along a tear propagating from 25 ± 5 Ma in the west to 10 ± 5 Ma in the east (Replumaz et al., 2010). After the deeply subducted part of the Indian slab detached, flat subduction of the Indian continental lithosphere under the Himalayas and southern Tibet continued. However, since the upper Miocene only the relatively dry mafic lower crust and cool, rigid lithospheric mantle of the Indian plate survived transport as far north as the Gangdese belt (Nábělek et al., 2009).

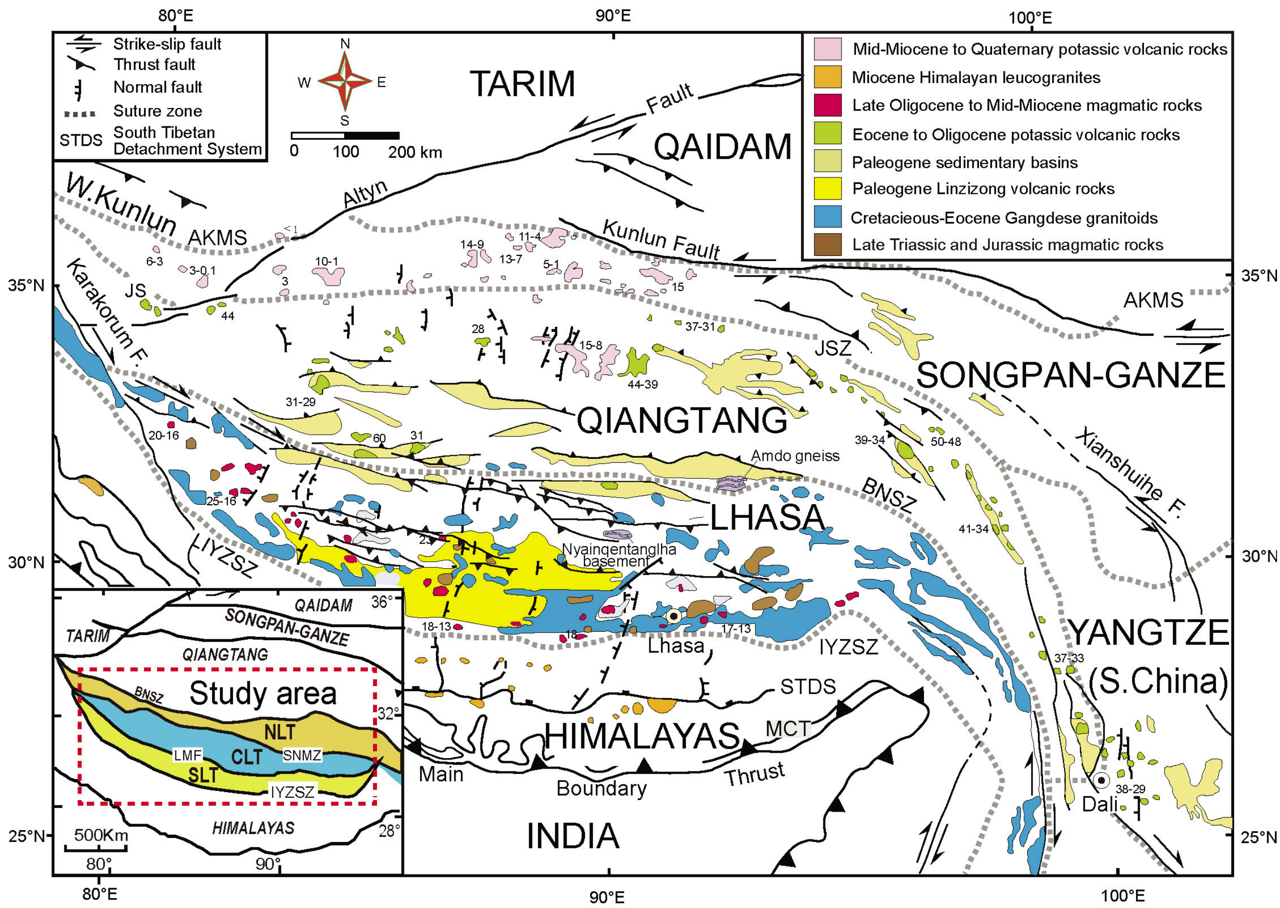

Figure 1. **Tectonic framework of the Tibetan Plateau (after Hou et al., 2015a). Inset shows the subdivision of the Lhasa terrane (after Zhu et al., 2011). The numbers in the figure are ages of magmatic rocks (Ma). Abbreviations: AKMS = Ayimaqin–Kunlun–Muztagh suture zone, BNSZ = Bangong-Nujiang suture zone, CLS = Central Lhasa Subterrane, IYZSZ = Indus–Yarlung–Tsangpo suture zone, JS = Jinsha suture, JSZ = Jinsha suture zone, LMF = Luobadui–Milashan fault, MCT = Main Central thrust, NLS = Northern Lhasa subterrane, RRF = Red River fault, SLS = Southern Lhasa subterrane, STDS = South Tibet detachment system**

Magmatic-hydrothermal deposits in the Lhasa terrane

Three main types of ore deposits are recognized in the Lhasa terrane: porphyry Cu deposits (including porphyry Cu–Au, porphyry±skarn Cu-Mo, porphyry±skarn Cu–W–Mo, and porphyry±skarn Mo±Cu±Pb±Zn deposits), skarn Fe and Fe–Cu deposits, and granite-related Pb-Zn deposits (Fig. 2; Hou et al., 2015a; Yang et al., 2016). Porphyry Cu deposits are the most important deposit types in the Lhasa Terrane and formed from Jurassic to Miocene. Brief descriptions of the major porphyry deposits are given below whereas other deposit types refer to Hou et al. (2015a).

The Jurassic Xiongcun porphyry Cu–Au deposit (874 Mt ore with average of 0.34% Cu and 0.25 g/t Au; Tafti et al., 2014) is located in the Jurassic arc within the southern Lhasa subterrane (Fig. 2). It is genetically associated with quartz dioritic stocks with U–Pb ages of 173 to 171 Ma and the molybdenite Re–Os ages of 173 ± 2 Ma.

The Cretaceous porphyry Cu–Au deposits are developed in a magmatic arc within the northern Lhasa subterrane and the southern Qiangtang terrane (Fig. 2). The large deposits are the Duolong porphyry Cu–Au deposit (690 Mt ore with 0.72% Cu and 0.21 g/t Au; Li et al., 2011a) in the southern Qiangtang terrane and the Gaerqiong porphyry Cu–Au deposit (307 Mt ore with 0.54% Cu and 0.4 g/t Au; Li et al., 2011b) in the northern Lhasa subterrane. The Duolong deposit is associated with multiple granodiorite stocks ranging in zircon U–Pb ages from 121 to 116 Ma and molybdenite Re–Os ages of 118 Ma (Li et al., 2011a).

The Cenozoic porphyry±skarn Cu–Mo, porphyry±skarn Cu–W–Mo, and porphyry±skarn Mo±Cu±Pb±Zn deposits are widely developed in the eastern Gangdese belt in southern Lhasa Terrane (Fig. 2). Representative deposits include two giant (≥2.5 million metric tons (Mt) Cu) deposits of Qulong (1420 Mt ore with 0.5% Cu and 0.03% Mo; Yang et al., 2009) and Jiama (1055 Mt ore with 0.44% Cu and 0.036% Mo; Ying et al., 2014), five large deposits (Zhunuo of 400 Mt ore with 0.57% Cu, Gangjiang of 370 Mt ore with 0.35% Cu, Tinggong of

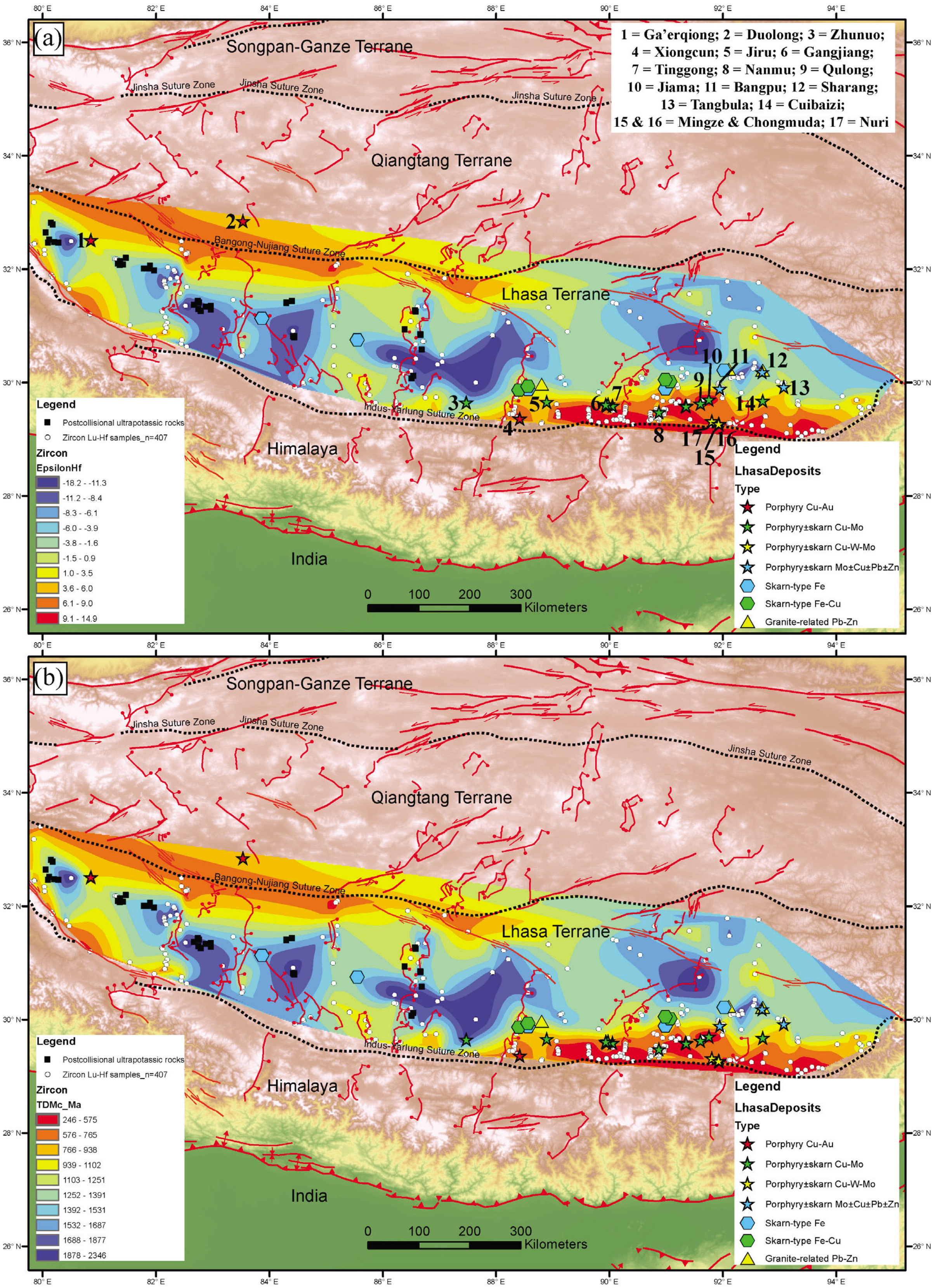

Figure 2. Contour map of the zircon Epsilon Hf (a) and TDMc values (b) for the granitoid rocks and felsic volcanic rocks in the Lhasa terrane, southern Tibet. Also shown are major mineral deposits in the Lhasa terrane (Hou et al., 2015a; Yang et al., 2016). The names of the main porphyry Cu deposits are listed on (a). The Miocene postcollisonal ultrapotassic rocks (barren alkaline melts) are highlighted as black squares. Note the Zhunuo porphyry±skarn Cu–Mo deposit is located in a cold-colour domain whereas all other porphyry±skarn Cu–Mo deposits are in warm-colour domain

200 Mt ore with 0.5% Cu, Nanmu of 100 Mt ore with 0.45% Cu and Bangpu of 80 Mt ore with 0.28% Cu; ≥0.5 Mt Cu), and several smaller Cu deposits (Fig. 2a), with average grades of 0.3 to 0.5% Cu and total resources of >20 Mt Cu (Yang et al., 2016). There is a spatial zonation of economic metals of the Cenozoic porphyry deposits in the Gangdese belt, ranging from Cu–W–Mo-rich deposits in the south (e.g., Mingze, Chongmuda, Nuri), northward to Cu–Mo-rich deposits (e.g., Qulong, Tinggong), and then to northernmost Mo±Cu±P ±Zn-rich deposits in the central Lhasa terrane (Bangpu, and Tangbula; Fig. 2a; Yang et al., 2016). Mineralization ages of the Cenozoic porphyry deposits in the belt also show a decreasing trend from south to north, being ~30 Ma for the deposits in the south and 21 to 13 Ma for the deposits in the north (Yang et al., 2016).

Data compilation and visualisation approach

Whole-rock geochemistry of igneous rocks in the Lhasa Terrane, southern Tibet were compiled from Hou et al. (2015a), Yang et al. (2016) and Lu et al. (unpublished). The selection criteria for acceptable analyses are loss on ignition (LOI) <3.5 wt%, and europium anomalies Eu/Eu* <1.3 to exclude crystal cumulates (Loucks, 2014), which leaves approximately 1200 acceptable analyses. Zircon Lu–Hf isotopic data were from Hou et al. (2015a) and Hou et al. (unpublished), which include data from approximately 400 granitoid rocks and felsic volcanic rocks.

The data visualisation approach used here follows that of Champion (2013) and Champion and Huston (2016), who found that natural neighbour classification using natural breaks in data values (as against equal intervals or equal counts) worked well. Contour maps were produced using the Spatial Analyst Tools in ArcMap using Natural Neighbour Interpolation with intervals based on Natural Breaks (Jenks), that is, intervals were determined by the software (the reason for the non-linear intervals in the resultant images). The zircon Lu–Hf isotopic map and whole-rock geochemical maps (V/Sc, Eu/Eu*, Sr/Y, 10000*Eu/Eu*/Y ratios) are presented in Figures 2 and 3, respectively.

Discussion

The zircon Lu–Hf isotopic maps identified three main crustal blocks within the Lhasa Terrane (Fig. 2). They include a central ancient Precambrian microcontinent with low Epsilon Hf values (down to –18) and old crustal Hf model ages (TDMc as old as c. 2400 Ma), and two juvenile Phanerozoic crustal blocks in the southeastern and northwestern margins with high Epsilon Hf values (up to 15) and young TDMc (as young as 250 Ma). This is consistent with the findings of Hou et al. (2015a), who used a different interpolation method of geometric interval in the Geostatistical Analyst Tools of ArcMap. It is noteworthy that the postcollisional ultrapotassic rocks (barren alkaline magmas) are all located within the ancient central Lhasa terrane with low Epsilon Hf values.

All porphyry deposits, except the Zhunuo porphyry±skarn Cu–Mo deposit, are located within the two juvenile crustal blocks with Epsilon Hf values >1 (Fig. 2a). This is consistent with the Cu-ore-forming magmas in Tibet mainly sourced from the Tibetan mantle (Lu et al., 2015) or juvenile lower crust (Hou et al., 2015b; Yang et al., 2015). The link of many but not all porphyry Cu deposits with isotopically juvenile magmas is also demonstrated in the Eocene porphyry Cu deposits in eastern Tibet and western Yunnan (Lu et al., 2013; Wang et al., 2016) and El Teniente porphyry Cu–Mo deposit in Chile (Munoz et al., 2012). However, the ore-forming porphyries at Zhunuo have crust-like isotopic compositions ($[^{87}Sr/^{86}Sr]_i = 0.7072–0.7079$; εNd(t) = –5.5 to –8.0; $[^{206}Pb/^{204}Pb]_i$ = 18.56–18.81; and zircon Epsilon Hf(t) = –4.2 to –0.7), that are similar to the coeval high-Mg dioritic rocks derived from Tibetan mantle highly metasomatized by subducted Indian continental material (Sun et al., 2017a). This crust-like isotopic composition of Zhunuo deposit is similar to that of the OK Tedi porphyry Cu–Au deposit in Papua New Guinea, the latter with zircon Epsilon Hf values of –8, indicating recycling of Proterozoic crust in Pleistocene asthenospheric mantle-derived juvenile magma (Van Dongen et al., 2010). It is noted that Zhunuo is located in the western Gangdese belt (west of E88º), which has distinct geodynamic process from the eastern Gangdese belt and the differing magmatic history resulted in the different isotopic compositions of the porphyry magmas (Sun et al., 2017b). Nevertheless, the majority of porphyry Cu deposits in the Lhasa Terrane, particularly the giant deposits such as Qulong and Jiama, cluster within juvenile crust strongly suggest the important role of juvenile magmas in the deposit formation (Fig. 2).

The whole-rock geochemical maps show somewhat different patterns from the zircon Lu–Hf isotopic maps (Fig. 3). On the V/Sc ratio contour map (Fig. 3a), both the porphyry deposits and barren postcollisional ultrapotasic rocks are within high V/Sc (>5) domains. On the Eu/Eu* map (Fig. 3b), all porphyry deposits including Zhunuo are within high Eu/Eu* (>0.7 and up to 1.2) domains and barren postcollisional ultrapotassic rocks are within both high and low Eu/Eu* domains (Eu/Eu* = 0.4–0.9 with median = 0.6). On the Sr/Y ratio map (Fig. 3c), all porphyry deposits including Zhunuo are located in the high Sr/Y (>35) domains and barren postcollisional ultrapotassic rocks are within both high and low Sr/Y domains (Sr/Y= 12–108 with median = 37). On the 10000*(Eu/Eu*)/Y map (Fig. 3d), all porphyry deposits are within high 10000*(Eu/Eu*)/Y domain (>500). By contrast, the barren postcollisional ultrapotassic rocks have distinctly low 10 000*(Eu/Eu*)/Y ratios (114–490 with median of 250; Fig. 3d). This suggests that 10 000*(Eu/Eu*)/Y ratio, proposed as the best zircon fertility indicator by Lu et al. (2016), is also the best whole-rock fertility indicator (following Loucks, 2013). It is interpreted to indicate extremely high magmatic water content which induces early and prolific hornblende fractionation and suppresses early plagioclase crystallization (Loucks, 2014; Lu et al., 2016).

Finally, despite the crust-like isotopic compositions for Zhunuo deposit, the high V/Sc, Sr/Y, Eu/Eu* and 10 000*(Eu/Eu*)/Y ratios from magmas in the Zhunuo

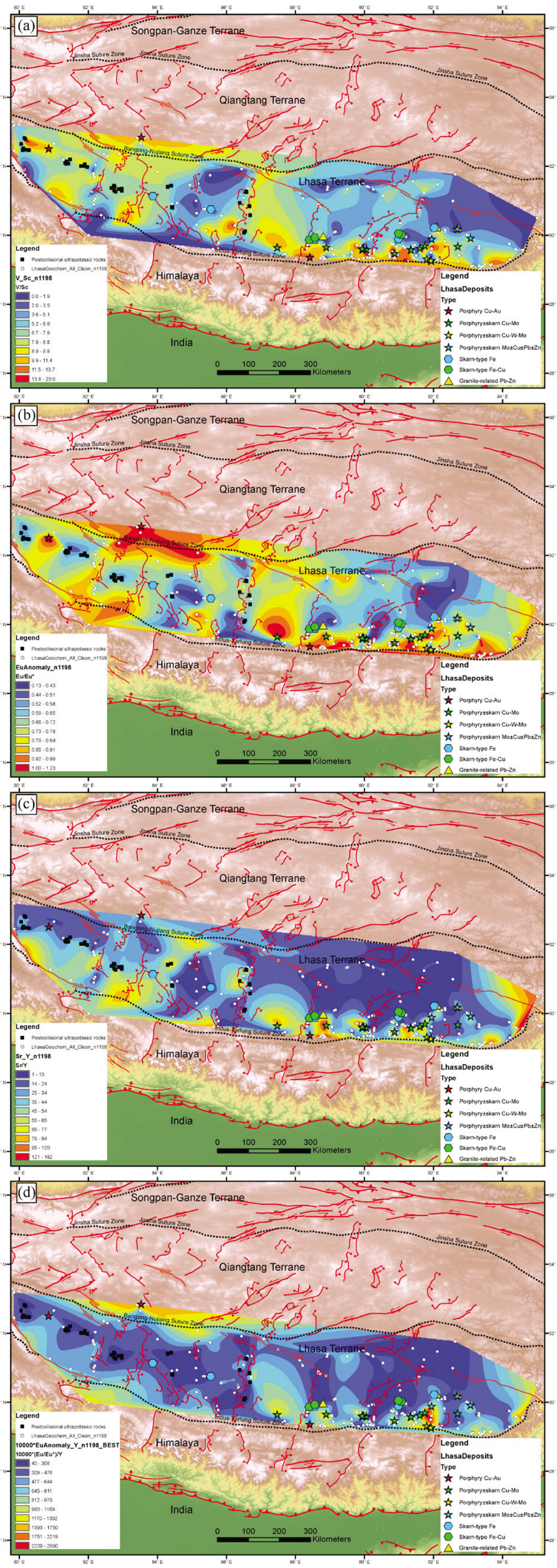

Figure 3. **Contour map of whole-rock geochemical ratios of V/Sc (a), Eu/Eu* (b), Sr/Y (c), and 10000*(Eu/Eu*)/Y (d) for mafic to felsic intrusive and volcanic rocks in the Lhasa Terrane, southern Tibet. Also shown are major mineral deposits in the Lhasa Terrane (Hou et al., 2015a; Yang et al., 2016). Refer to Figure 2(a) for the names of the main porphyry Cu deposits. The Miocene postcollisonal ultrapotassic rocks (barren alkaline melts) are highlighted as black squares. Note the Zhunuo porphyry±skarn Cu–Mo deposit is located in warm-color domain, same as all other porphyry±skarn Cu–Mo deposits**

deposit are similar to those from all other porphyry Cu deposits in the Lhasa Terrane (Fig. 3), suggesting that the ore-forming magmas at Zhunuo are also very hydrous.

Conclusion

Exploration is a scale reduction process. Zircon Lu–Hf isotopic mapping is powerful in identifying juvenile crust domains which are preferable for porphyry Cu formation. However, there are exceptions such as the Zhunuo porphyry Cu deposit, which shows crust-like isotopic compositions. Despite this, all porphyry Cu deposits in the Lhasa Terrane including Zhunuo are characterized by distinctly high whole-rock 10000*(Eu/Eu*)/Y ratios (>500), which is the best fertility indicator. The combined isotopic mapping and whole-rock 10 000*(Eu/Eu*)/Y ratio mapping has the great potential to help focus exploration on prospective areas.

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The tectono-magmatic framework to world-class gold mineralisation in the Kédougou-Kénieba inlier, West Africa: new insights from the Sadiola-Yatela gold camp.

by

Quentin Masurel[1*], Nicolas Thébaud[1], John Miller[2] and Stanislav Ulrich[3]

The Kédougou-Kénieba inlier is the westernmost exposure of Birimian (2200–2000 Ma) crust in the West African Craton and a world-class gold province (>30 Moz gold endowment). Unravelling the tectono-magmatic evolution of that region hence appears critical in terms of mineral system, whereby gold deposits are viewed as local expressions of orogen- to lithospheric-scale processes (e.g. Bierlein et al., 2006; McCuaig et al., 2010; McCuaig and Hronsky, 2014). This multiscale and multidisciplinary study integrated new field data, new whole rock geochemistry data, new U–Pb geochronology and Lu–Hf data, and a recent interpretation of aeromagnetic data with published data in journal articles in order to provide the tectono-magmatic framework to mineralisation in the Kédougou-Kénieba inlier.

The key results of this study are: (i) the stratigraphic succession in the inlier consists of 2200–2150 Ma bimodal volcanic rocks overlain by 2125–2090 Ma sequences of volcaniclastic rocks and detrital epiclastic rocks with minor intercalations of bimodal volcanic and pyroclastic rocks; (ii) the granitoids in the inlier display a temporal evolution from 2150–2080 Ma calc-alkaline metaluminous plutons (e.g. diorite, biotite–hornblende-bearing granodiorite) to 2080–2060 Ma peraluminous high-K granites (e.g. biotite-monzogranite, biotite-muscovite-bearing granite); (iii) the REE patterns associated with Eburnean (2115–2060 Ma) volcanic and plutonic rocks in the inlier suggest derivation from either a metasomatised mantle source with crustal contamination or melting of an enriched lower-crustal garnet-amphibolite source; (iv) the Lu–Hf signature associated with these magmas indicate a juvenile character; (v) the polycyclic deformation recorded in country rocks and magmatic rocks in the region includes a period of early convergence (D_{1s}), followed by a period of fold-and-thrust tectonics (D_{2s}), and later transcurrent tectonics (D_{3s}–D_{4s}); and (vi) the bulk of the gold mineralisation in the region occurred during D_{3s}, with sinistral displacement and hydrothermal fluid circulation along regional-scale shear zones and higher-order, NNE-trending brittle–ductile shear zones connected to structural traps in adjacent volcanic belts and sedimentary basins.

The results of this study suggest that the late Eburnean tectono-thermal event between c. 2080 and 2060 Ma represented the geodynamic engine that empowered world-class gold mineralisation in the Kédougou-Kénieba inlier (Fig. 1). Such an event likely reflected the conjunction in time and space of a fertile upper-mantle source region, a favourable transient remobilisation event, and favourable lithospheric-scale plumbing structure (Hronsky et al., 2012).

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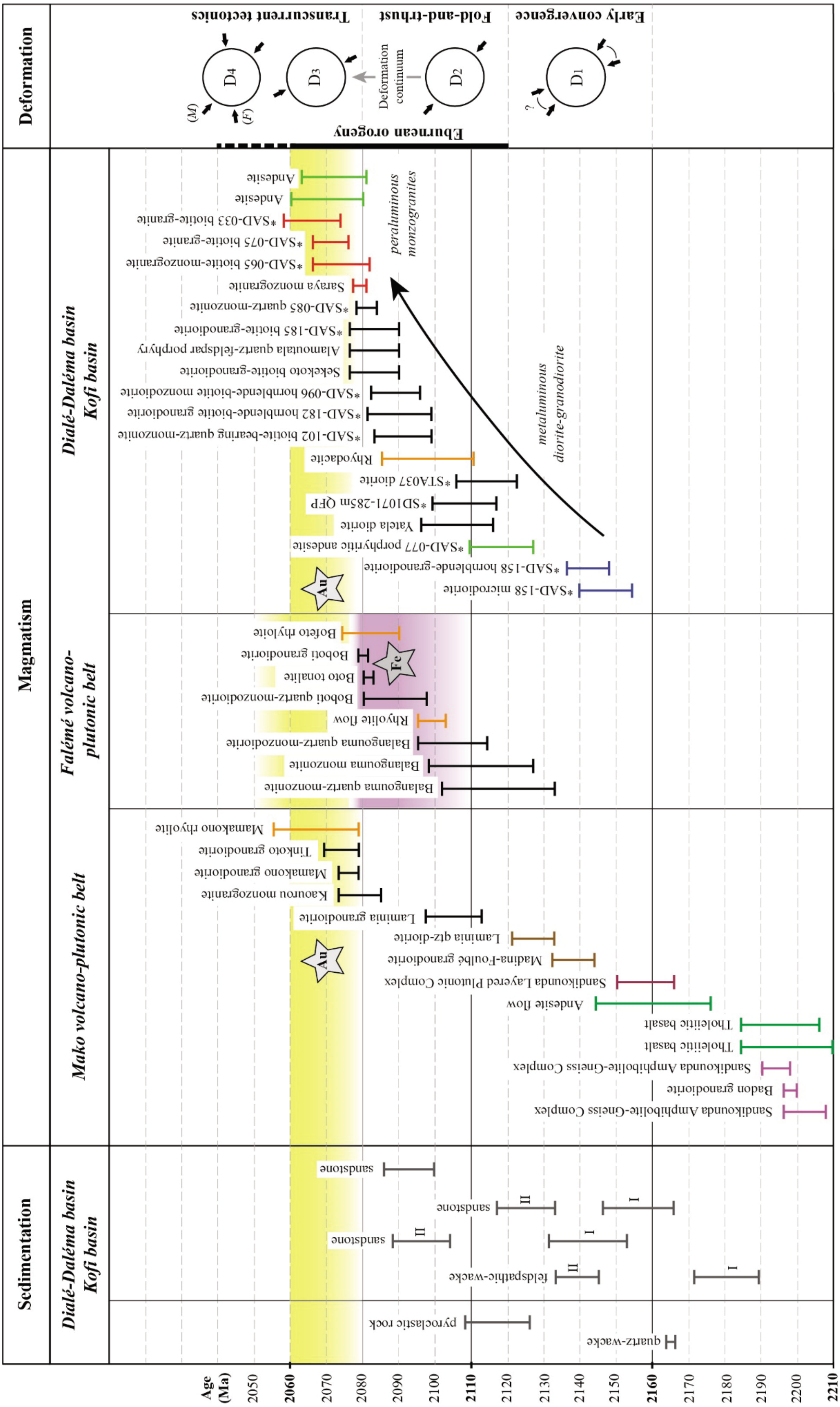

Figure 1. Summary space–time chart for the Kédougou-Kénieba inlier

Exploration targeting across scales – where to from here?

by

T. Campbell McCuaig[1]

Targeting is an exercise, undertaken across a range of scales, that seeks to focus our finite people, time and money to increase the probability of success in discovering new resources of sufficient quality for our business. 'Quality' of resources is not just tonnes and grade. It is a multiparameter space (McCuaig et al., 2014), including 'above ground' factors such as social license and geopolitical trends affecting resource access, corporate needs, financial and physical infrastructure and engineering considerations as well as the traditional 'below ground' factors we generally consider as geologists. This contribution is focussed only on the 'below ground' geoscientific aspects of targeting.

Approaches to targeting

Approaches to exploration targeting generally fall somewhere on a spectrum between empirical and conceptual targeting (Fig. 1; Woodall, 1994; Lewis, 2001). Empirical targeting focusses on recognising emergent patterns in spatial datasets and using these correlations as guides to ground selection. Conceptual targeting focusses on understanding the processes controlling the behaviour of the commodity of interest in Earth systems and predicting how and where these processes would combine to create an economic deposit.

Empirical targeting approaches have several strengths: they are data-driven and therefore less prone to the systemic bias introduced by humans; they also allow recognition of the unforeseen pattern or correlation, which in turn can identify the high-value research questions to ask regarding the underlying fundamental processes that control the pattern.

Weaknesses of empirical approaches are that they are biased to data-rich areas with a high number of known deposits or occurrences. These approaches struggle with non-uniform data coverage and, therefore, are much less effective in covered terranes. Empirical approaches to targeting are only likely to find analogues of the deposit styles already known and will not find the previously unknown expression of ore (Woodall, 1994). Empirical correlations often exhibit provinciality on the cluster or terrane scale, and correlations in one region often do not hold in other clusters or terranes. Moreover, empirical correlations with mineralisation are plagued by false positives — correlation is not necessarily causation.

Conceptual targeting has the advantage of being applicable without the requirement of known mineralisation 'training' data and can deal with incomplete or partial datasets. It involves breaking down the understanding of the mineral systems to targeting elements that can be mapped directly or by proxy in available or obtainable geoscience datasets (McCuaig et al., 2010). Being based on fundamental processes controlling element mobility in earth systems, it also has the potential to find the hitherto unknown expression of ore. Applied correctly, it highlights the gaps in understanding the mineral systems and identifies the highest-value research questions to pursue that will increase the understanding of the systems and, therefore, the efficiency of exploration targeting.

The challenge with conceptual targeting is that it is rife with systemic bias, due to our imperfect understanding of the mineralising systems as well as our imperfect ability to interpret geoscience datasets.

Targeting across scales

Exploration is an exercise in scale reduction, and has a number of natural decision points that map to scale (Figs 2, 3):

- Regional-scale targeting — what basin/belt/arc has the probability of hosting a substantial mineral system?
- Camp/cluster-scale targeting — where within the region of interest could a number of deposits be clustered? It is here that the company starts to deploy expensive detection technology in anger.
- Prospect/deposit — where is there an orebody of sufficient quality within the camp or cluster of deposits?

Also shown at the top of Figures 2 and 3 is the tradeoff between the relative inputs of prediction technology and detection technology, and the concomitant escalation of expenditure with decreasing scale in the exploration process (McCuaig and Hronsky, 2000; Hronsky and Groves, 2008; McCuaig et al., 2010). These figures also highlight that, although the direct costs of targeting at broad regional scales are relatively low, the opportunity cost of making suboptimal decisions at this scale is extremely high, and can doom a company to failure from the outset.

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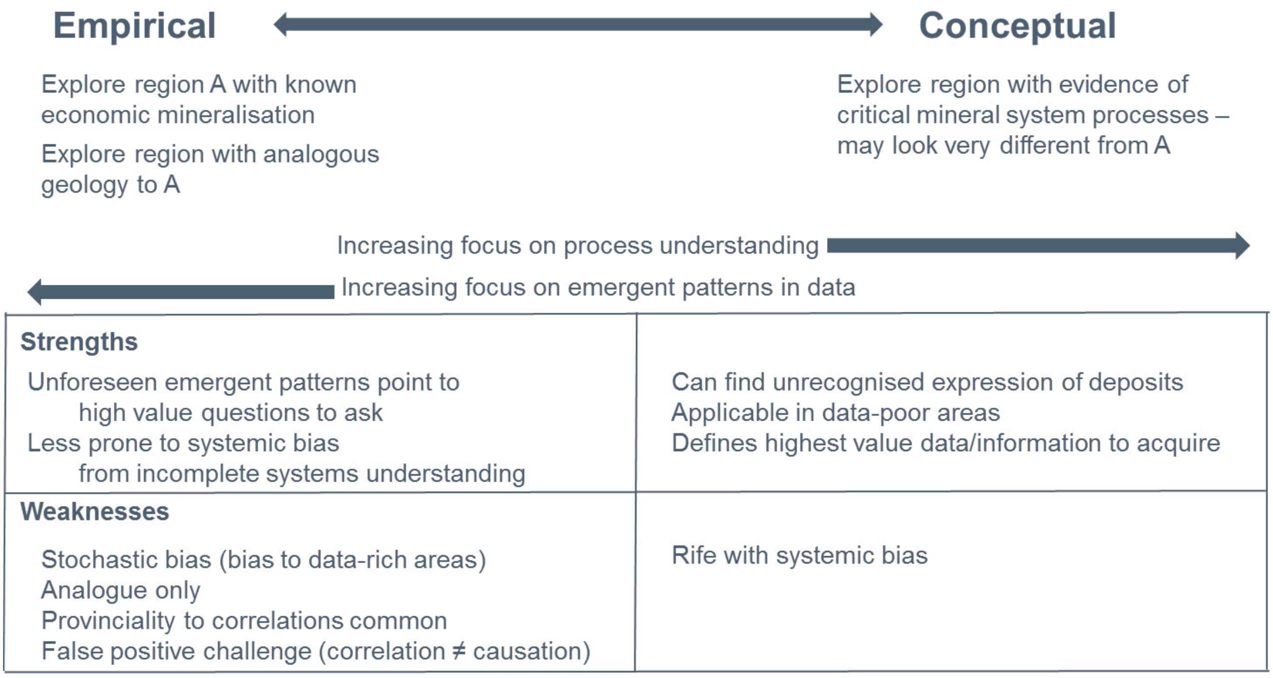

Figure 1. **Diagram summarising the spectrum between empirical and conceptual targeting approaches.**

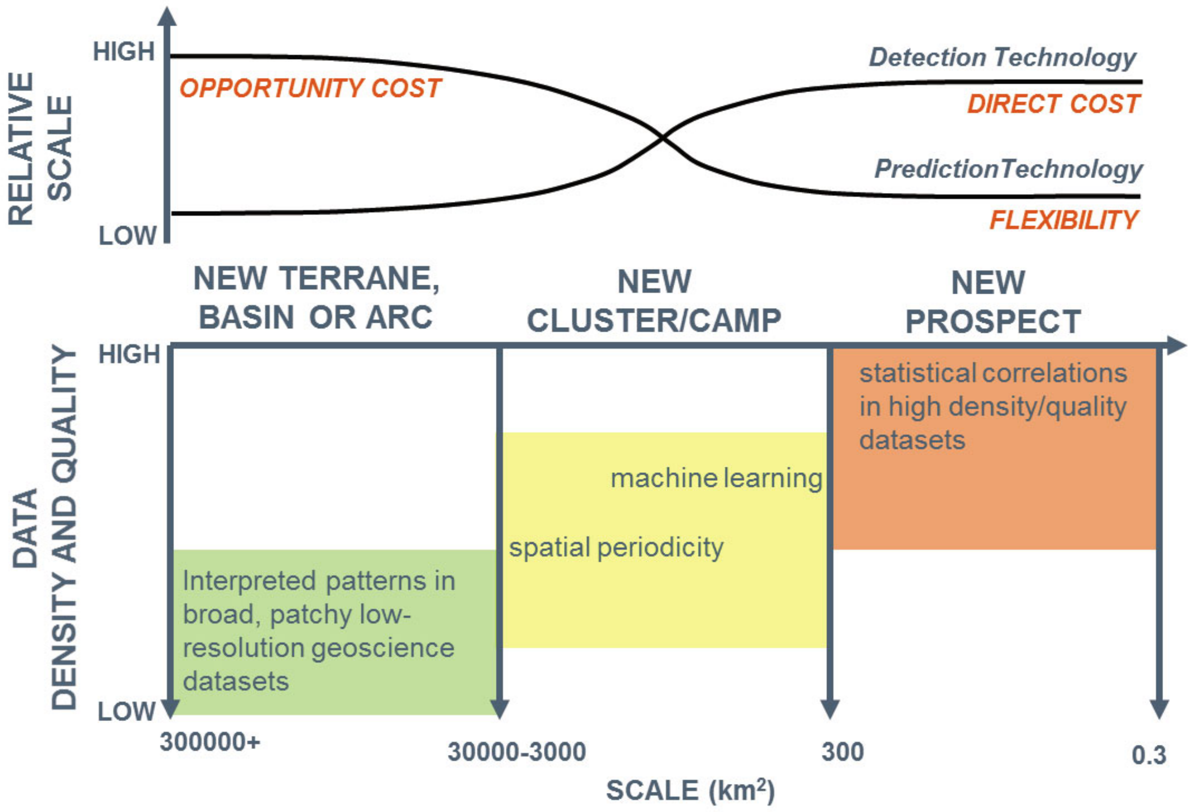

Figure 2. **Diagram summarising use of empirical targeting approaches across scale. Top of diagram illustrates tradeoff between availability and effectiveness of detection technology versus prediction technology (after McCuaig et al., 2010). Also shown is relative trends in flexibility of exploration program, and direct costs versus opportunity costs. Bottom diagram shows potential use of empirical targeting across scales. The effectiveness of empirical targeting increases with reducing scale, due to the concomitant increase of internally consistent, high density and high quality geoscience datasets, and the tendency for empirical correlations to be more consistent within than between terranes.**

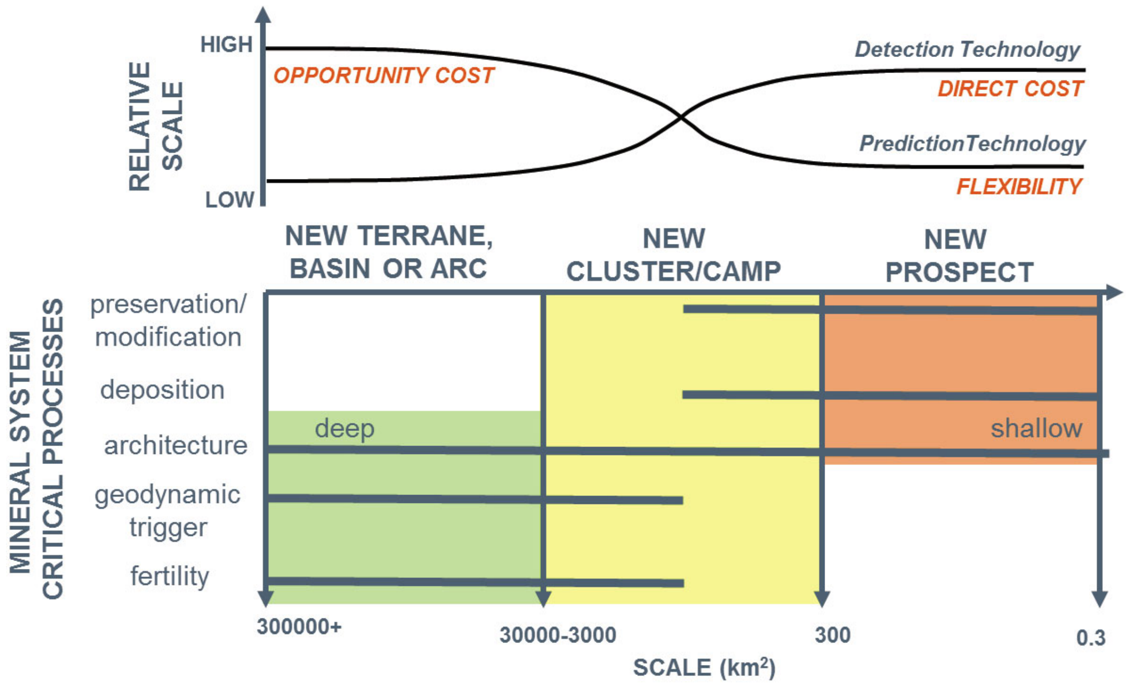

Figure 3. Diagram summarising the application of conceptual targeting across scales with respect to the critical processes of mineral systems. Key point is that at different scales, different processes are more or less relevant, such that separate targeting exercises must be done across this scale hierarchy, each giving different weights to the respective critical processes.

Conceptual targeting across scale

The approach of mineral systems has been increasingly adopted in the resources industry over the past 40+ years, starting with the Petroleum industry (Magoon and Beaumont, 1991), and followed much more slowly by the minerals industry (Wyborn et al., 1994; McCuaig and Hronsky, 2014). The uptake in the minerals industry has been accelerated over the past decade. However, the term 'mineral systems' has been bandied about in academia and industry and means very different things to different people. To some, a mineral system encapsulates all of the processes leading to the formation of a single deposit. To others, it is the processes leading to a cluster of deposits. In reality, the mineral system is linked to the entire Earth system — the secular evolution of the Earth (the linked evolution of the Earth's hydrosphere–biosphere–atmosphere–lithosphere–mantle–core) — however, practical subdivisions of this system need to be made. Consideration of core–mantle evolution has little value to add when making decisions to target prospects within a camp. Yet, by the same token, the processes of metal deposition have little to do with the decision of where on a continental scale on Earth to explore, for example, for the next giant copper system. The boundaries put on the mineral system need to map to natural scales of exploration decision as noted above. A proposed subdivision of the mineral system tied to natural business decision points is given in Figures 2 and 3.

These 'decision point' boundaries of the mineral system must be incorporated into prospectivity analyses exercises and the prioritising of regions across scales to which companies commit their limited people, time and money.

Definition of critical components of the mineral system across scale

Figure 3 also shows all of the critical processes that must coincide to create a high-quality mineral system, and the practical subdivision of these processes into the natural exploration decision points of regional terrane, cluster and prospect scales. These processes are (after McCuaig and Hronsky, 2014): fertility (source of commodity of interest; source of ligands and transporting agent — fluid or magma — to transport the commodity); transient geodynamic triggers (major tectonic changes that provide a combination of heat and stress field changes that trigger the moment of mineralisation — similar to critical moments in oil systems); whole-lithosphere architecture that provides pathways for mass and energy transfer across a range of scales to transport and focus the movement of the commodity in the transporting agent; depositional mechanisms to concentrate the commodity into a small volume of rock and form a deposit; and preservation/modification of the deposit such that it is at a depth amenable to economic extraction and potentially has had appropriate interaction with surficial weathering environments so that is it either upgraded or not destroyed.

Search space and residual endowment

No matter the approach to targeting taken, an assessment of the residual endowment of the area of interest for the size of deposit targeted must be undertaken — does it remain to be found? Approaches such as the percentage of metal discovered with proportion of drilling (e.g. petroleum 'creaming curves'; Meisner and Demirmen, 1981) or size-rank distributions (e.g. Guj et al., 2011) have commonly been employed in petroleum to estimate the residual endowment and therefore the maturity of basins, but has had only sporadic uptake in minerals. Such methods are very useful tools, with the caveat that they need to be geologically interpreted in terms of the search space being explored (Hronsky, 2009) – could I conceal the footprint of a mineralising system of the size I seek throughout the exploration history of the search space?

Where to from here?

Considering the preceding discussion, a systematic marriage between empirical and conceptual targeting clearly has highest merit. In terms of empirical targeting, our ability to collect large, high quality datasets faster and cheaper, in concert with the ever increasing computational power and evolving artificial intelligence (AI) algorithms (supervised and unsupervised), will provide opportunity to improve our ability to target across a range of scales. Emergent patterns in these large datasets will point us not only to possible targets directly, but to fundamental science questions to ask about the system itself to improve our conceptual targeting.

In conceptual targeting, the biggest barrier at present is our narrow-focussed commitment to different system models, or styles of mineralisation. The next big breakthrough is to understand element systems within the Earth system (e.g. the full Cu system through time, rather than Porphyry, sediment hosted Cu, IOCG, etc). A key difference between petroleum and minerals exploration is the relative confidence in understanding the respective systems and their translation to proxies in geoscience datasets to map elements of the systems. The petroleum system is well understood across a range of spatial and temporal scales, such that the industry is willing to risk much capital based on conceptual targets. In the minerals industry, the mineralising systems are often more complex than petroleum, have had not nearly the level of systems thinking applied to them, and lag far behind in terms of a comprehensive understanding of the processes that source, transport and deposit large accumulations of metal. As a result, conceptual targeting in the minerals industry is much less effective, and most of the minerals industry is much less confident in applying it.

There is hope in this space however. The understanding of self-organised critical systems (SOCS) has changed our way of looking at the earth and mineral systems (Bak, 1996; Hronsky, 2011; McCuaig and Hronsky, 2014), and puts science behind some of the patterns we see that are fractal in nature (Bak, 1996), have power law size distributions (Robert et al., 2005; Guj et al., 2011), and exhibit spatial periodicity (Doutre et al., 2015). The earth itself is a SOCS — so what are the agents that operate across a range of scales that change a geological system to a mineralising system and ore system? This is where fundamental geoscience research efforts need to be focused.

Acknowledgements

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From intrusion-related to orogenic gold mineralization: The example of the Wasamac deposit, Abitibi Greenstone Belt, Canada

by

Nicolas Mériaud[1*] and Michel Jébrak[2]

The Wasamac deposit (83.46 t Au; Figs 1–3) is an example of an Archean greenstone-hosted gold deposit located in the Abitibi Greenstone Belt, 15 km southwest of Rouyn-Noranda, Quebec, Canada. The deposit sits along a second-order ductile shear zone, two kilometres north of the crustal-scale Cadillac – Larder Lake Fault Zone (CLLFZ). Within the Wasamac deposit, gold distribution is constrained to the altered mylonitized portion of the fault; lode systems are absent. Gold mineralization occurs as pervasive replacement of the metavolcanic units of the Blake River Group. The hydrothermal signature displays two distinct alkaline alteration assemblages: potassic and albitic: both are pyrite rich. Potassic alteration is characterized by the crystallization of microcline and carbonates, along with porous pyrite enriched in Te–Ag–Au–Mo–Pb–Bi–W, deposited under oxidizing conditions. Such characteristics are widely described in the neighboring Kirkland Lake area, and are found in prominent examples of syenite-related gold mineralization within Archean greenstone belts. The albitic alteration assemblage, composed of albite, sericite and carbonates, reflects more reduced hydrothermal conditions, and mineralization is characterized by free native gold. The brecciation of gold-rich pyrite coeval with this hydrothermal event reflects a structural overprint that controlled late-stage gold characteristics. These alteration and structural features are common in orogenic gold deposits both worldwide and regionally, particularly at the bordering Kerr-Addison and Francoeur deposits, and in lode-gold systems such as in the Sigma-Lamaque deposit in the Abitibi Greenstone Belt.

Hydrothermal and structural crosscutting relationships at Wasamac indicate a structurally controlled orogenic hydrothermal signature overprinting an earlier potassic magmatic-hydrothermal alteration. This observation supports a multistage process of gold concentration during which new gold characteristics, metal anomalies, fluid conditions and alteration assemblages replaced earlier stages of gold enrichment, in places completely obliterating previous signatures. The intriguing continuity between the orogenic gold district of Noranda and the district of Kirkland Lake dominated by intrusion-related style of gold deposits led Robert (2001) to suggest a re-examination of the classification of some gold deposits along the CLLFZ. The specific location of the Wasamac

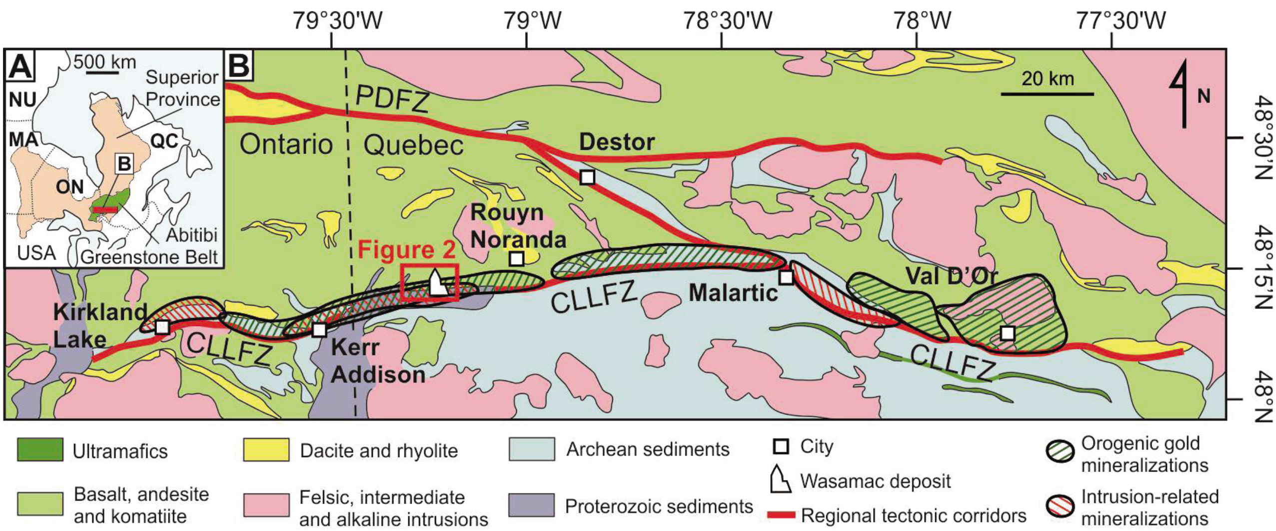

Figure 1. The main structural corridors of southern Abitibi: the Cadillac-Larder Lake Fault Zone (CLLFZ) and the Porcupine Destor Fault Zone (PDFZ). Disposition of orogenic and intrusion-related styles of mineralization with respect to hydrothermal fields proposed by Rafini (2014). Modified from Robert (2001), Rabeau et al. (2013) and Rafini (2014)

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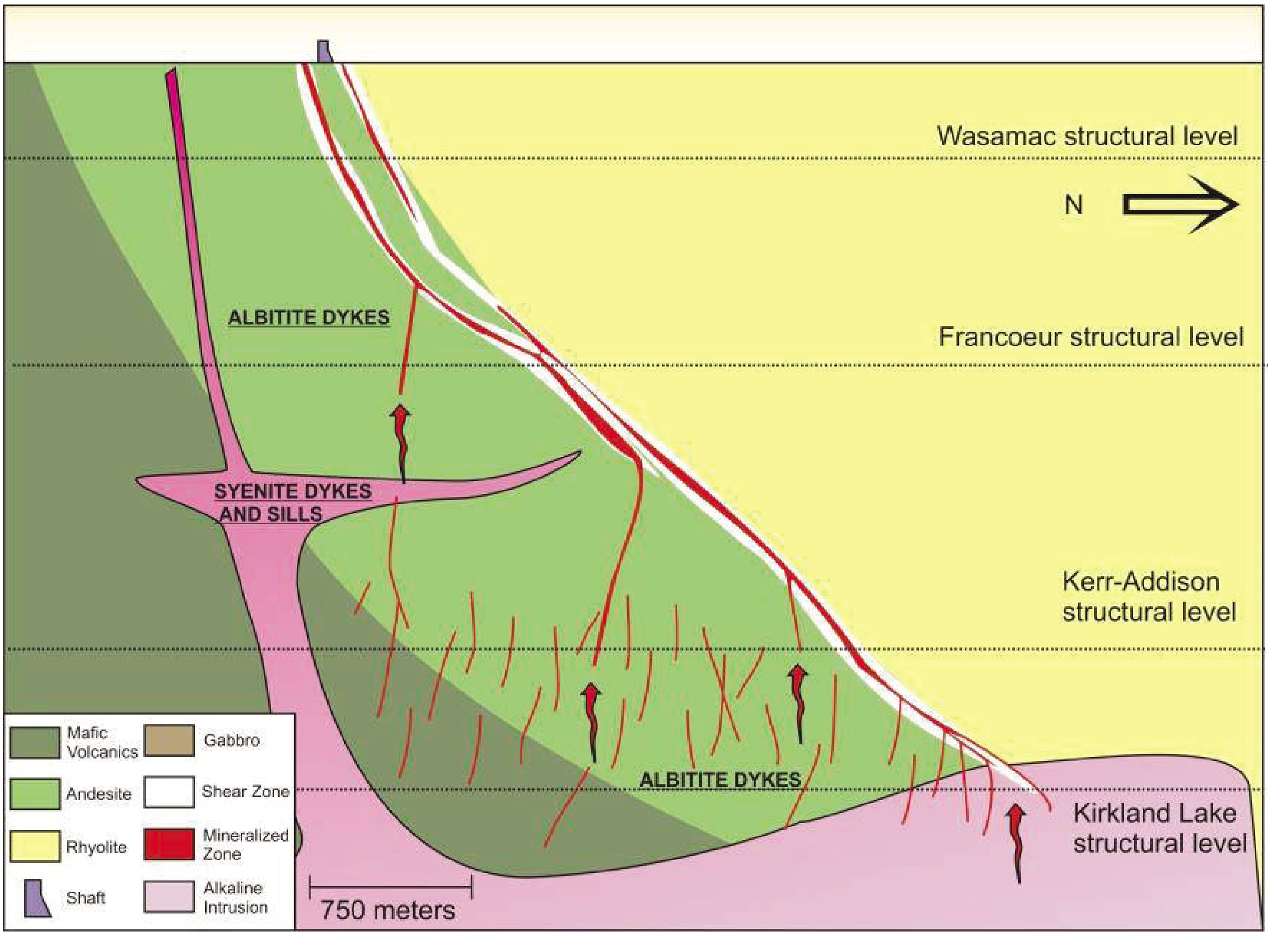

Figure 2. Schematic interpretation of Wasamac deposits hydrothermal and tectonic processes associated with gold mineralization. Gold-rich porous pyrite (stage 2) is associated with the early potassic hydrothermal event. A second hydrothermal phase follows crystallizing pyrite stage 3 during albitic alteration. Thirdly, the maintenance of tectonic activity fractured previous pyrite overgrowths. This late tectonic activity is proposed to be associated with gold remobilization and concentration

deposit sets it apart as a prime candidate for investigating hydrothermal processes along the CLLFZ, as it shares similarities with both intrusion-related and orogenic gold deposits. We propose that the Wasamac deposit was originally related to an alkaline intrusion buried at depth beneath the Francoeur–Wasa Shear Zone.

This work, bringing to light new data on this transitional metallogenic region, also records the relationship between two gold mineralization styles commonly observed amongst Archean and Palaeo-Proterozoic gold belts. The geochemical characteristics of each hydrothermal assemblage detailed in this study and the proposed genetic model provide valuable insights for exploration targeting in these environments.

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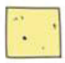
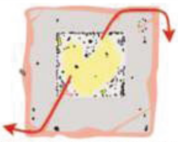
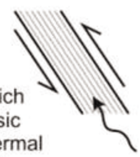
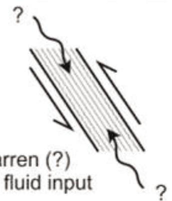
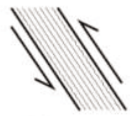
Structural features	- S1 main foliation and local S2 ductile deformation creation and maintenance		- Brecciation of K-feldspar altered units - Structural partitioning	- Brecciation of K-feldspar altered units - Pyrite fracturation
Alteration chemistry	- Regional metamorphic signature - Carbonate veinlets towards the strain zone	- Red potassic pervasive alteration - K_2O, K, Mo, W, Pb, Bi strong values - Strong red-ox variations	- Greyish-beige albitic pervasive alteration overprinting K-altered units and fresh metavolcanic rocks - Na_2O, Na, Cu, W, Pb, and Bi strong values	- Greyish-beige albitic pervasive alteration - Na_2O, Na, Cu, W, Pb, and Bi strong values
Gold characteristics	None	- Invisible gold telluride minerals trapped in spongy pyrite structure - Few visible gold telluride inclusions in pyrite	- Recycling gold material from gold-rich pyrite - Possible new gold input	- Abundant gold tellurides and native gold filling pyrite fractures, ultimately released in the alteration assemblage - Gold tellurides <5µm free native gold >5µm
Pyrite chemical enrichments	- Fluctuating Ni and Co enrichment - Few inclusions and porosities	- Cu, Zn, Pb, Bi, Co, Ag, Te, Au - Prevalent anatase, hematite and chalcopyrite inclusions	- Fluctuating Ni and Co enrichment - Few inclusions and porosities - Local gold-tellurides inclusions	- Pb, Bi, Ti, Zn, Cu, Au +/- Te, Ag - Late metal enrichments remobilizations along fractures and around pyrite
Pyrite textural characteristics	 Crystallisation of barren pyrite stage 1	 - Dissolution-recrystallization process - Gold-rich spongy pyrite stage 2	 Pyrite stage 3 crystallisation Local gold recycling	 Brittle pyrite deformation Native gold release (stage 4)
Proposed model of tectonic and hydrothermal activity	 Initiation of reverse ductile faulting	 Gold-rich potassic hydrothermal input	 Barren (?) sodic fluid input	 Gold evolution and remobilization

Figure 3. **Proposed geological setting in cross section of Wasamac, Francouer, Kerr-Adison and Kirkland Lake deposits. The structural level of gold deposits seems to deepen going west. This might be linked with variably rising heights of intrusive stocks as the metamorphic grade does not increase towards the west**

Geodynamics and Au–U metallogeny: insights from the Mayo Kebbi Massif in southwestern Chad (Central Africa)

by

Isseini Moussa[1*], Diondoh Mbaguedje[1], Olivier Vanderhaeghe[2] and Anne-Sylvie Andre-Mayer[3]

The Mayo Kebbi Massif, in southwestern Chad, is poorly investigated despite its key location between the Congo Craton to the south and the West African Craton to the west (Fig. 1). It has previously been defined as part of the Saharan Metacraton (Abdelsalam et al., 2002; Liégeois et al., 2013) despite the lack of isotopic data attesting to the presence of a pre-Neoproterozoic crust remobilized during the Pan-African orogeny. In fact, the term Metacraton defined by Abdelsalam et al. (2002) refers to 'a craton that has been remobilized during an orogenic event but that is still recognizable dominantly through its rheological, geochronological and isotopic characteristics.' However, these authors proposed this model for a broad region extending between the Raghan and Keraf–Kabus–Sekerr Shear Zones, while most of the central part of the region, including the Mayo Kebbi Massif, is poorly investigated. Accordingly, most of the Precambrian rocks outcropping in this area need to be investigated in terms of juvenile accretion vs remobilization during the Pan-African orogeny. Here, we address these key issues at the scale of the Mayo Kebbi Massif with emphasis on the links between geodynamics and metallogeny, especially for gold and uranium. For this purpose, we present and discuss new petrologic, geochemical, zircon U–Pb and Nd isotopic data for different samples collected from various rock types, highlighting the role of deformation during metallogenesis. Analyses have been carried out on the main rock groups outcropping in the Mayo Kebbi Massif, consisting of (i) Mafic Intermediate Plutonic Complex ; (ii) Volcanic Sedimentary Series (VSS) ; and (iii) Granitic Plutonic Complex (tonalites and granites). The first two groups, characterized by the presence of a pervasive foliation underlined by greenschist facies minerals, are pre-tectonic with respect to the main deformation phase ; the tonalites, with evidences for high-temperature intracrystalline plastic deformation of quartz and feldspar crystals, are syntectonic, while the granites, where deformation is lacking or localized within narrow shear zones, are described as post-tectonic.

Combining zircon U–Pb geochronology and whole-rock Nd isotopic systematics allowed a clear distinction between the pre-tectonic rocks on the one hand, and the syn-to post-tectonic rocks on the other. Actually, pre-tectonic rocks are characterized by similar zircon U–Pb crystallization and Nd model ages (800–700 Ma), while syn-tectonic and post-tectonic rocks display younger crystallization U–Pb ages (670–570 Ma) in comparison to Nd model ages (1350–800 Ma). Both rock groups exhibit Nb–Ta negative anomalies and LILE enrichment relative to HFSE, suggesting their crystallization in a subduction-related tectonic setting.

Gold occurs as (i) small Au–Ag grains associated with pyrite and disseminated within schists from the VSS ; (ii) native gold and electrum grains (Au–Ag solid solution) disseminated within transposed quartz veins along NNE–SSW-trending shear zones ; (iii) or native gold and electrum grains (Au–Ag solid solution) within late microscopic fractures affecting quartz veins.

Uranium is described within the Zabili A-type granite in the western part of the Mayo Kebbi Massif (Isseini et al., 2012). This granite lacks pervasive deformation, except within localized E–W-trending shear zones. The undeformed granite exhibits U and Th concentrations in the magmatic levels with Th/U ≈ 4. In contrast, higher U concentrations are reached within albitized shear zones (up to 10000 ppm) while Th remains at granitic concentration levels (8–12 ppm), indicating a hydrothermal trend. Microscopic observations revealed that U is associated with relict uraninite and uranothorite within the fresh, undeformed granite, while secondary uranophane filling microscopic veins is identified within the shear zones.

According to the previous descriptions, the following interpretation is proposed :

- The Mayo Kebbi Massif is a juvenile Neoproterozoic oceanic crust tectonically accreted onto an older Precambrian basement during the Pan-African orogeny. This is attested by the chemical and isotopic affinities of its earliest magmatic rocks, which are similar to those produced in modern island-arc tectonic settings. The younger magmatic bodies, displaying older Nd model ages (up to 1350 Ma), suggest a shift towards an active continental margin at the onset of collision. Accordingly, the Mayo Kebbi Massif could not be described as part of the Saharan Metacraton.
- Gold was extracted from the depleted mantle during the Neoproterozoic while the source of primary U concentration could be the mantle (re-enriched by subduction related processes?) or contamination from ancient sediments derived from the erosion of a pre-Neoproterozoic craton that collided with the Massif.

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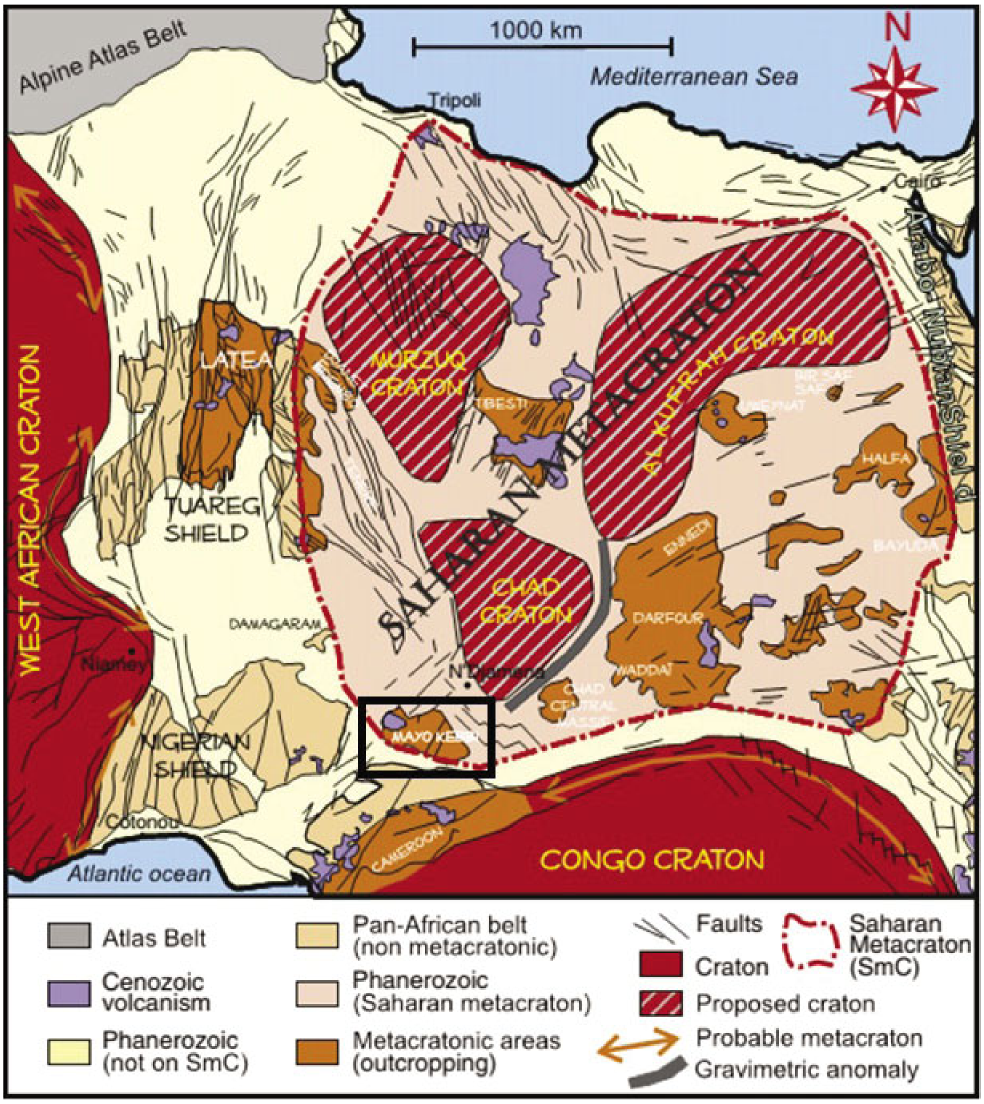

Figure 1. Location of the Mayo Kebbi Massif (MKM) between the Congo Craton (CC), The West African Craton (WAC) and the Saharan Metacraton (SM). Liegeois et al. (2013) defined the MKM as part of the SM. Modified after Liégeois et al., 2013

The nature of such a craton remains to be identified by further investigations, and new data are required in order to choose between the two models.

- Tectonic processes and associated hydrothermal activity played a major role in this orogenic setting in terms of leaching, and transport and deposition of secondary gold and uranium bearing minerals.
- More specifically, the Zabili granite displays, in its unaltered parts, U concentrations typical for common, although extremely differentiated, granitic rocks ($Eu/Eu^* = 0.04–0.4$). However, due to its specific chemical composition of mantle-derived A-type granite (Eby, 1992: high Ga, Nb, REE, Zr,Y ; low Ba and Sr ; rich in F, etc.) U has been trapped within zircon as well as magmatic uraninite and uranothorite. The latter two minerals being more sensitive to hydrothermalism than zircon, their destabilization accounts for U enrichment in albitized shear zones.

These results show the need to re-evaluate the metacraton model and its implications for the links between geodynamics and metallogeny during the Pan-African orogeny.

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Subtle near surface geochemical signatures – frontiers in partial extraction and passive soil gas analyses

by

Ryan RP Noble[1*] and Ravi R Anand[1]

Traditional, near surface (soil, lag, stream sediment) geochemical sampling techniques have been effective in mineral discovery in areas of residual and shallow transported regolith, but as mineral exploration transitions from exploring in residual outcropping terrains into deeper covered terrains, new and improved exploration methods are required. Geochemical signatures are diluted and the ability to successfully discern subtle geochemical signatures becomes essential. Two potential improvements for near surface exploration that have not been well studied are to use very weak, partial extraction by deionized water or employ passive soil-gas collectors, both of which aim to identify subtle geochemical signatures from weathering ore deposits.

Water partial extractions of soil samples and passive soil gas were tested at a number of sites for the ability to recognise mineralisation through cover. The sites included the Jaguar and Bentley base metal VMS deposits, in WA; Inca de Oro Cu deposit in Chile and the major study site of the North Miitel Ni deposit in Western Australia. In addition, a series of laboratory experiments (ore weathering cells) and field tests (pits and orientation traverses) were conducted with varying analytical methods to confirm the field observations with respect to soil hydrocarbon and gaseous element migration through overburden.

The North Miitel deposit is 'geochemically-blind' at surface and is covered by 10–15 m of transported overburden above weakly enriched saprolite. However, passive soil gas hydrocarbon collection and weak water extractions from soil (10–20 cm depth) both proved successful using minimum hypergeometric probability (MHP) statistics to evaluate the targeting of mineralisation (Figs 1 and 2). Approximately 100 soil samples (10–20 cm depth) from three traverses were analysed over the mineralisation. Soil samples were subjected to distilled water, 0.1M hydroxylamine hydrochloride and aqua regia extractions. The water-extractable concentrations of Ni, Co, Mo, Sb and Sn delineated the mineralisation.

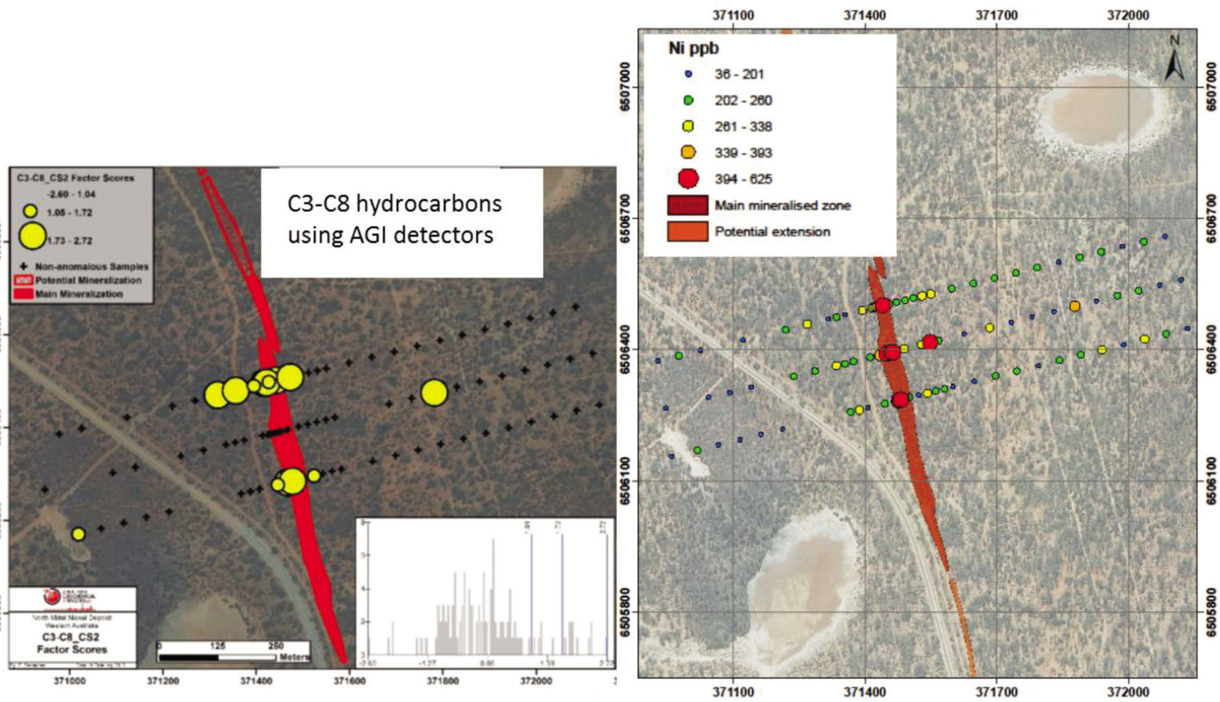

Figure 1. **Plot of passive soil gas summed C3–C8 hydrocarbons (left) and Ni extracted from soil (right) at North Miitel. The vertical projection of the mineralisation is depicted in red**

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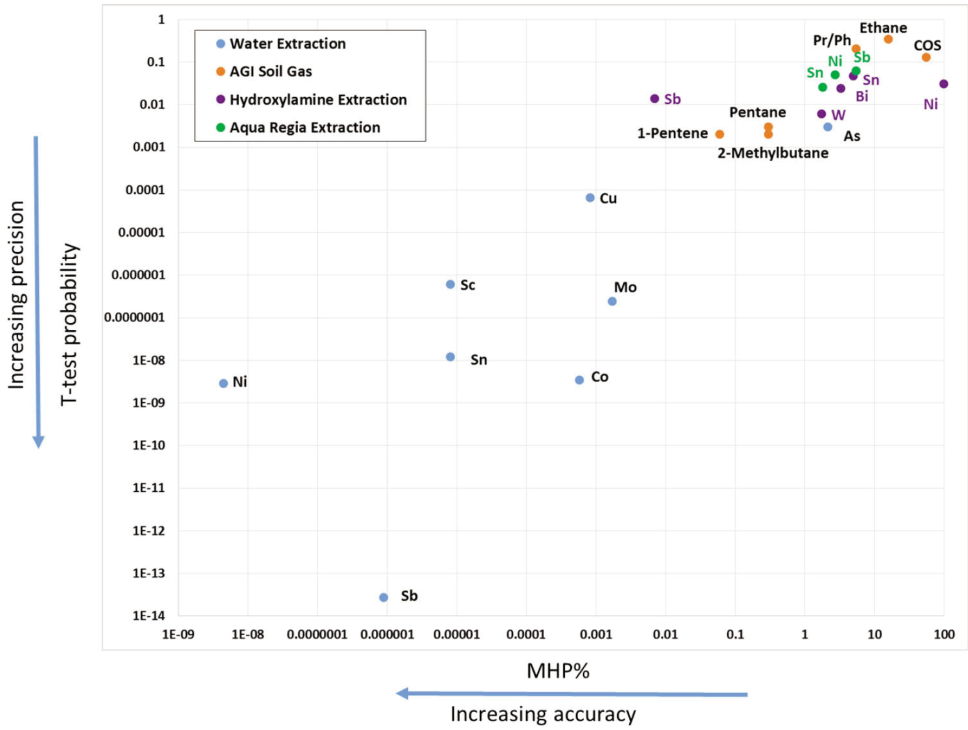

Figure 2. **Logarithmic scatterplot of MHP (accuracy) and t-test probability statistic (contrast) for selected water, hydroxylamine hydrochloride and aqua regia extracted elements and selected organic compounds. Exploration accuracy and geochemical contrast improve towards zero**

The hydrocarbons, 2-methylbutane, pentane and 1-pentene were also successful at identifying the zone of mineralisation. Of the detection techniques used, the water extraction performed the best using MHP-classified accuracy to identify mineralisation. The passive soil gas data were the second most effective, and superior to the stronger partial extractions (hydroxylamine and aqua regia), which failed to identify the mineralised zone. However, both water extraction and passive soil gas showed a greater degree of variability than the stronger extractions in duplicate sampling tests.

Site studies indicated that subtle geochemical signatures exist in the surface and that soil gaseous compounds may also be effective pathfinders (Fig. 1). However, initial weathering experiments indicate that many of these metal and metalloid particles were not liberated as a true gaseous phase. Only sulphur (as an unknown S-bearing compound) was detected as a true gas phase from weathering S-rich ore — the actual S-bearing compound is not known. In these experiments, weathering of different ore types produced similar longer-chain hydrocarbons (C6–C12) and some larger alkanes but do not provide reliable exploration pathfinder compounds. Pit experiments have demonstrated that geochemical anomalies (Au, Cu) can form quickly through two metres of transported overburden. Similar Au–Cu mobility is confirmed by laboratory experimental work with the same ore types. These signatures are highly labile (and mobile) and potentially better detected by water extraction than passive soil gas collection in thinner <15 m cover based on results from these study sites.

Weak partial extractions should be considered in areas with cover <15 m and anticipated transient metal signatures, but passive soil gas geochemistry probably has greater potential as a deep-penetrating geochemical technique. A gaseous migration mechanism is possible for metals, although contradictions between the field and laboratory make it impossible to clearly reject or accept this hypothesis and its relationship to ore weathering. Significant multidisciplinary research is required to realise the potential of passive gas sampling as a near-surface exploration method.

Application of recurrence plots to orebody exploration data

by

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Introduction

A recurring question in mineral exploration is to predict the spatial distribution of ore-bearing minerals, to determine both (i) the economic value of a prospective deposit, and (ii) the optimal locations for mineral discovery (Jébrak M, 1997). In hydrothermal gold deposits such as the Imperial deposit, in the Yilgarn of Western Australia, the gold exhibits a highly variable spatial distribution, causing great difficulties for ore recovery and mine planning; the hypothesis is that such variability results from orebody formation by a non-equilibrium open chemical reactor process with complex chemical-flow-heat-mechanical couplings (Ord et al., 2012, 2016; Lester et al., 2012). With this insight, an important goal is to develop new computational methods to analyse drill-core data to extract key features of the underlying dynamical system, so as to shed light on the orebody formation mechanism(s). In order to discover whether prediction is possible in such systems we need to establish whether the patterns of alteration and mineralisation are intrinsically random or have an underlying deterministic origin.

We here report such an analysis of drill-core data from the Imperial deposit, consisting of a 100 m core string, explored through infrared reflectance spectra/hyperspectral image analyses for alteration mineral products such as sericite and chlorite at millimetre scales, and also data for elemental gold at one metre intervals. By considering the spatial data as a series of events of a dynamical system, we test whether a deterministic model can explain the patterns of mineral and gold abundance. By the use of scatter plots and cross-recurrence plots (as a generalisation of the cross-correlation function: Marwan et al., 2007), we find that sericite and chlorite are linearly correlated and that gold is nonlinearly and deterministically interrelated to sericite and chlorite rather than the result of a random process. These findings offer the hope that the orebody formation system for this deposit, and for others, can be partially explained by simple, although possibly chaotic, deterministic models.

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Materials and Methods

Geological exploration data are rarely considered as a result of dynamical non-equilibrium processes. However recently, Ord et al. (2016) studied the multifractality of hydrothermal systems by establishing singularity spectra with the hypothesis that such systems operate as open-flow, hydrothermal chemical reactors. A dynamical system has a phase space, continuous or discrete time, and a time evolution law represented by a time-discretisable physical flow (Marwan et al., 2007). This time series is represented by a measured observation function (Oberst and Lai, 2011). By employing embedding theorems, a reconstructed copy of the original attractor is generated in phase space. Using space instead of time provides an analogue time series, which requires analogue continuous space and a space evolution law (Marwan et al., 2016; Krantz and Schreiber, 2004).

Using the mutual information and Kennel's false nearest neighbour algorithm, a delay τ and a maximum embedding dimension m of the two phase spaces which were to be correlated, were determined (Marwan et al., 2007). With these parameters, vectors $\mathbf{s_n}$ were formed, which span the embedding space.

Then, the dynamical system can be represented using a binary recurrence matrix (Marwan et al., 2007; Oberst and Lai, 2011, 2015; Krantz and Schreiber, 2004):

$$\mathbf{R}_{i,j}(\epsilon) = \Theta(\epsilon - ||\mathbf{s}(i) - \mathbf{s}(j)||, \; i,j = 1,...,N \text{ with } \mathbf{s}(i) \approx \mathbf{s}(j) \Leftrightarrow \mathbf{R}_{i,j} = 1 \quad (1)$$

Here, Θ is the Heavyside function, with an ε - environment and || . || describes an arbitrary norm. A recurrence plot shows recurrent states as diagonal lines. In a cross-recurrence plot $\mathbf{s}(i)$ and $\mathbf{s}(j)$ come from two different dynamical systems (such as those that produce sericite and gold) and the diagonal lines indicate a correlation, that is, similar evolution of the trajectories. Based on the recurrence plots, quantification measures can be calculated which are based on either the histograms of the diagonal or the vertical line segments. Here we calculated the recurrence rate (*RR*), the determinism (*DET*), laminarity (*LAM*), average diagonal line length (*LL*) and the maximum diagonal line length (L_{MAX}) (Marwan et al., 2007). *RR* is defined as

$$RR(\epsilon) = \frac{1}{N^2}\sum_{i,j=1}^{N}\mathbf{R}_{i,j}(\epsilon) \quad (2)$$

with N being the total number of points and $\mathbf{R}i,j$ being the recurrence as a function of ε. The ratio of the number of recurrence points that form diagonal structures to the overall number of recurrences delivers *DET*, a measure of predictability (and correlation) (Marwan et al., 2007; Oberst and Lai, 2015)

$$DET = \frac{\sum_{l=lmin}^{N} lP(l)}{N^2 RR(\epsilon)} \quad (3)$$

with lmin being the minimum line length and P(l) being the histogram of diagonal lines (Ord et al., 2016). The ratio of vertical lines to the overall recurrences is the *LAM* and higher for stationary states (distances without much change); *LL* relates to the predictability depth (the larger the longer the distance to predict a state) (Lester et al., 2012; Ord et al., 2016). Thirdly, we calculated the divergence of the trajectory *DIV* as the inverse of the maximum line length L_{max},

$$L\text{max} = \max(\{l_i\})_{i=1}^{N_d} = DIV^{-1} \quad (4)$$

which is related to the Renyi entropy and the Lyapunov spectrum (Marwan et al., 2007; Oberst and Lai, 2011; Krantz and Schreiber, 2004), with li being diagonal lines and *Nd* the total number of diagonal lines.

Results

Figure 1a–c depicts the measured abundance of sericite, chlorite and gold over drill depth. We determine whether these data are linearly or nonlinearly correlated as well as whether the data is deterministic and hence predictable in principle. Figure 1d–f shows the scatter plots of Chl-Au, Ser–Au and Ser–Chl. Au vs Ser or Chl indicates that no linear correlation exists while Ser–Chl seems to be moderately linearly correlated (ρ = 0.27, $CI_{95\%}$ = [0.079, 0.445], ρ <0.01).

Figure 2 provides the cross recurrence plots using embedded data, employing a constant delay of d = 1, embedding dimensions of $m_{\text{Ser,Au}}$ = 10, $m_{\text{Chl,Au}}$ = 10 and $m_{\text{Ser,Chl}}$ = 5 and a fixed amount of neighbours (2% of maximum phase space dimension) (Marwan et al., 2007). The delay was chosen as unity owing to the spatial character of the data, which is similar to that of a discrete map (Marwan et al., 2007; Oberst and Lai, 2011). All cross-recurrence plots show disrupted diagonals, which indicates that deterministic, aperiodic processes are present and that the data is nonlinearly correlated. Calculating the cross-recurrence quantification measures (Figure 2 d–f) further shows that that Au vs Ser and Chl behave similarly: the underlying diagonal line features provide relatively high value in *DET* and a near to zero value of *LAM*. The values of *LL* as well as those of DIV are similar or nonzero. The small value in LL indicates sudden changes with depth and the nonzero DIV is a further indication of predictability (Marwan et al., 2007). For Ser vs Chl however, some laminarity is visible which is indicative for linear correlations (Marwan et al., 2007) and indicates that the two systems remain unchanged and similar in structure at some depth. The value of *DET* is slightly lower and the divergence is here the highest, which is due to the overall shorter line lengths presumably also due to the stationary states.

Conclusions

We present preliminary findings of the application of nonlinear time series analysis in particular the use of cross-recurrence plots and associated quantification measures. The results provide insights into the correlation between mineral and element data. Sericite and chlorite were linearly correlated to each other; the structure of the drill core data belonging to gold with respect to the mineral abundance is predictable (hence deterministic) but requires the consideration of nonlinear correlations. Whether the spatial data can be used to identify attractors or whether invariant measures can be calculated needs to be further explored. In this abstract a relatively small data set is explored. Work involving substantially larger data of mineral assemblages is underway.

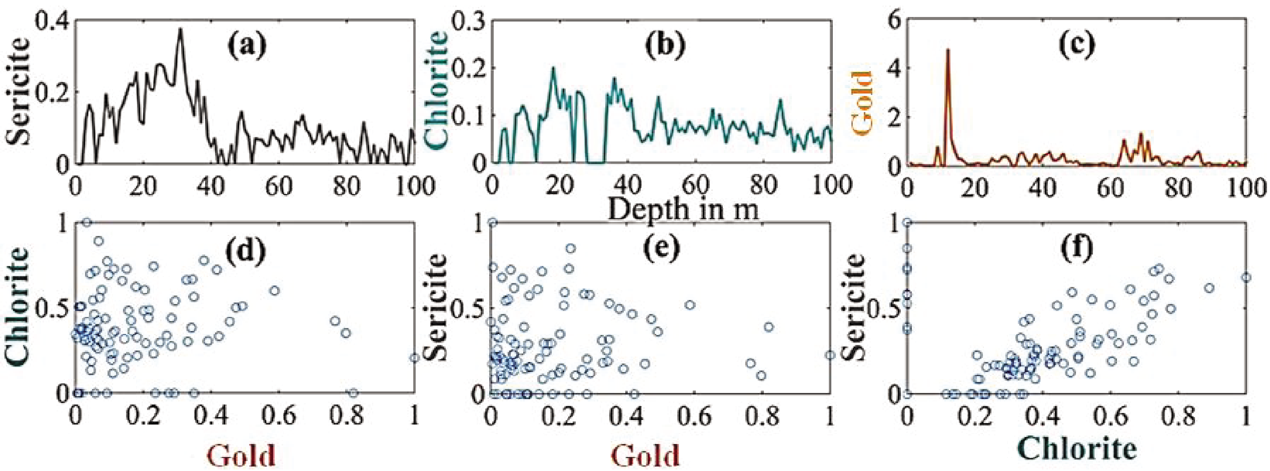

Figure 1. Abundance over depth of (a) sericite (Ser), (b) chlorite (Chl), and (c) gold (Au). and scatter plots of (d) chlorite vs gold (ρ = 0.02, $CI_{95\%}$= [-0.17,0.22], ρ = 0.81), (e) sericite vs gold (ρ = 0.0362, $CI_{95\%}$= [-0.1614, 0.2310], ρ = 0.7207) and (f) sericite vs chlorite (ρ = 0.27, CI95%= [0.079, 0.445], ρ <0.01); only sericite vs chlorite seem to be linearly correlated

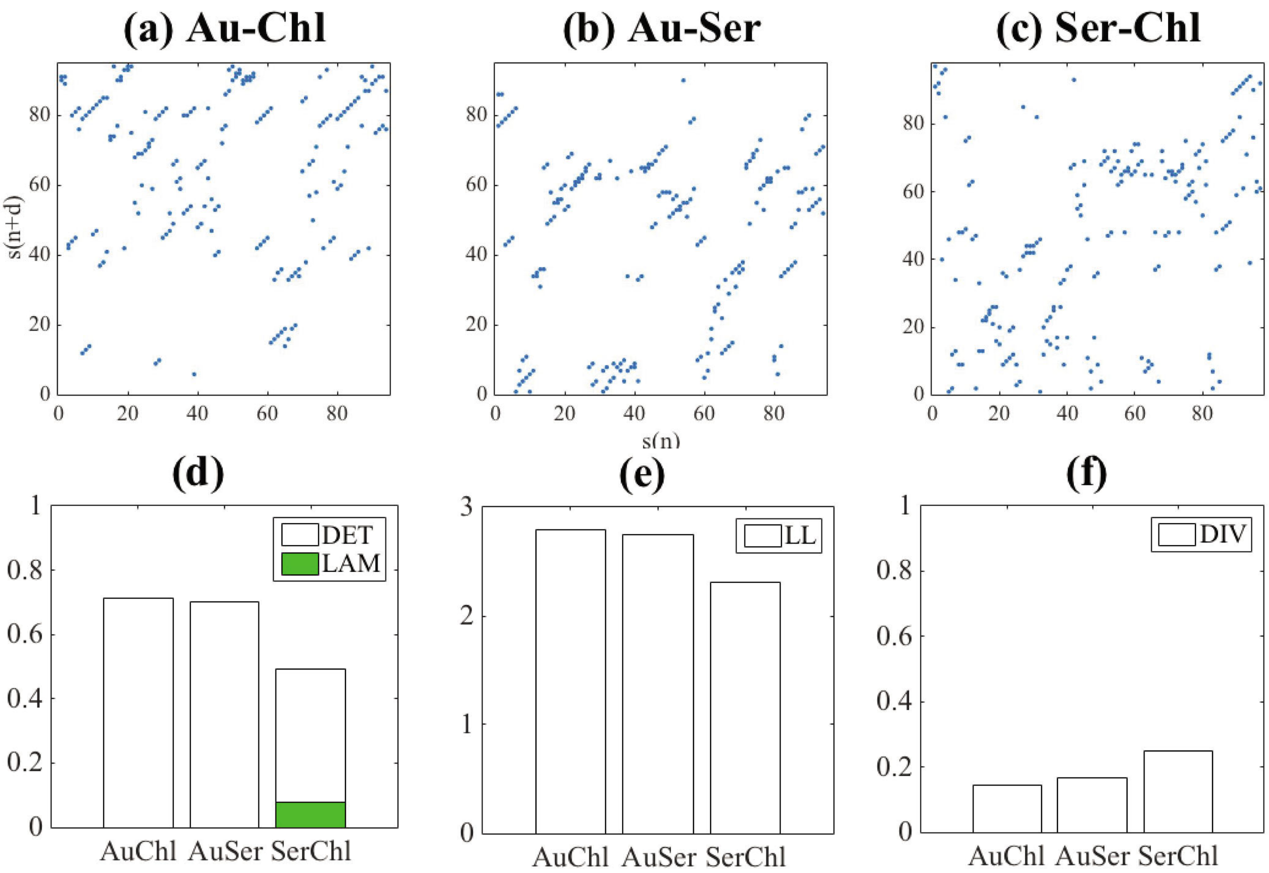

Figure 2. **All cross-recurrence plots for (a) gold-chlorite; (b) gold-sericite; and (c) sericite-chlorite show disruptive diagonal lines; the recurrence plot quantification measures (d) – (f) however, indicate slight differences with respect to determinism (DET), laminarity (LAM), avg. line length (LL), divergence (DIV) and clustering coefficient (CC)**

Acknowledgements

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Methods of targeting across all scales — toolbox from the Capricorn Distal Footprints study

by

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Introduction

Most mineral systems analyses use publicly available government datasets, and sometimes company prospect or camp scale datasets collected for various purposes during an exploration cycle in a data integration exercise. These data integration exercises can range from simply overlaying different data sets and completing empirical analyses or deriving particular evidence layers from the data to input into a prospectivity modelling and mapping program. Both methods of analyses are equally valid and have their pros and cons. Mineral systems analyses are often completed with the focus on single commodities, or individual ore deposit styles, and rarely take into account a broader-scale view that predicts the development of particular styles of ore deposits through space and time in any given region.

Very few mineral systems analyses are completed with data collected solely for the purpose of completing the analyses. The Capricorn Distal Footprints study has been designed to collect data for the purpose of completing mineral systems analysis. It is a multidisciplinary, multi-institutional collaboration between the Commonwealth Scientific and Industrial Research Organisation (CSIRO), University of Western Australia (UWA), Curtin University, Geological Survey of Western Australia (GSWA) and large to small mineral exploration companies. The study is supported through these institutions and companies with significant funding from the Science and Industry Endowment Fund (SIEF) and Minerals Research Institute of Western Australia (MRIWA). The project partners recognise that adding value to pre-competitive government datasets, whilst assessing their efficacy and collecting additional data at a range of scales, should decrease the risk in mineral exploration, thus increasing relative exploration success rates.

The program works on the premise of completing multi-commodity mineral systems analyses with input data that includes the most up-to-date structural and fertility mapping techniques.

Mappable criteria in Mineral Systems Analysis

We recognise that, in order for an ore deposit to form and be deposited, a number of critical factors must coalesce. These might include the development or reactivation of deep, crustal-scale structures in a variety of tectonic settings, a geodynamic throttle that drives diverse processes such as magmatism or changes in plate motion, periods of secular atmospheric change, connectivity of the crust to the mantle, presence or absence of evaporitic carbonates in the upper crust and many other factors. These can be summarized as critical elements pertaining to lithospheric architecture, tectonic triggers, fertility, and depositional sites (Fig. 1; Occhipinti et al., 2016).

Deep Crustal Scale Structures in the Capricorn region have been, and are being, mapped through the integration of 3D passive seismic, regional reflection seismic line interpretation, regional broadband receiver function seismic, 3D magnetotelluric inversions, gravity-tomographic inversion models, gravity, magnetic data. Of these data, passive seismic, broadband/receiver function seismic and magnetotelluric data acquisition programs have been designed around the project area to produce an integrated 3D architecture of the region.

New findings include that the Glenburgh Terrane extends to the north and east, beneath Mesoproterozoic basins, and mapping of individual Archean greenstone belts or crustal-scale elements under basins cover. The coincidence of a high-density unit in the Bryah Basin (north of the Yilgarn Craton) with a highly conductive unit may have implications for VMS mineralisation models. In addition, the depth and breadth of Proterozoic sedimentary basin development over their Archean basement is being mapped in 3D, rather than along single seismic lines as was previously done.

Tectonic framework/triggers are being assessed through a re-interpretation of basin development and orogeny in the Capricorn Orogen. Traditionally, individual basins have been studied in isolation. For this project, basin development through time is being studied, with a focus on recognising possible facies changes and variation in depositional environments through time. In addition, the project attempts to map timescales of basin development through detailed sampling and geochronological and isotopic analyses (Lu–Hf/Sm–Nd) in key areas, across key stratigraphic sections.

Possible depositional sites can be mapped if our understanding of ore deposit models is applied to district- and regional-scale datasets. This is being completed through focussed, integrated interpretation of geological, potential fields and remote sensing data, and application of ore-deposit model ideas to individual units mapped in a GIS framework.

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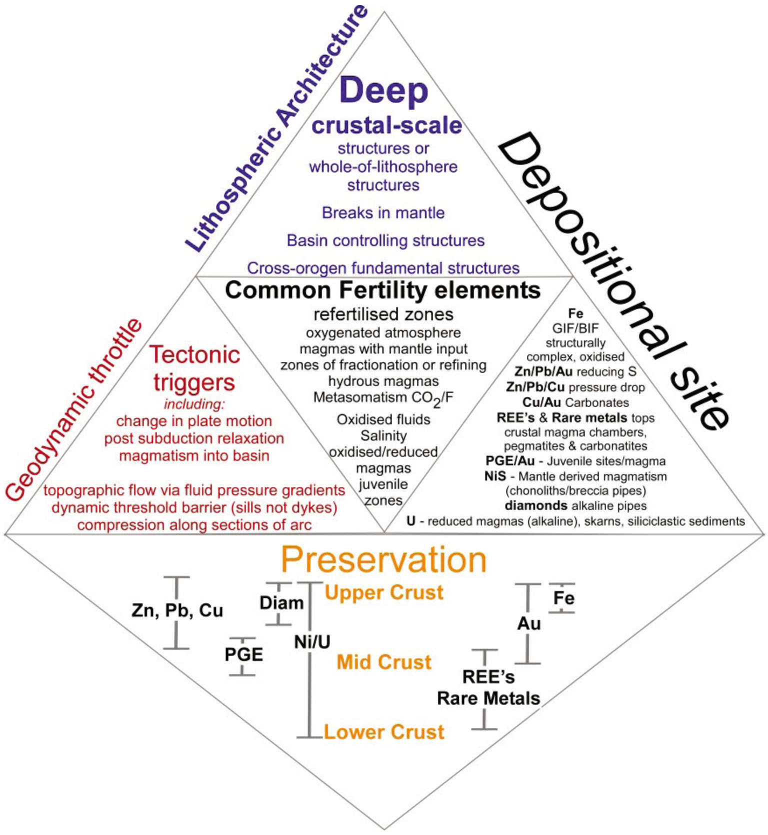

Figure 1. **Mineral Systems diamond summarizing some of the critical elements required to form and preserve a mineral deposit**

Fertility related to the development of mineral deposits can be mapped at a range of scales. For example, if interested in NiS, then a critical fertility element might be the presence of mafic–ultramafic intrusive rocks that form part of a large igneous province. Many critical fertility elements overlap between deposit styles but, within a mineral systems framework, we can use our understanding of commonalities between different mineralisation styles to vector to a range of ore deposit types. In the Capricorn Orogen, apart from mapping these types of critical elements using the new geological–geophysical interpretations, the application of vectoring to mineralisation by mapping trace elements in titanite in rutile is being tested at a regional to camp scale, or vectoring to gold or base metal mineralisation through regolith geochemistry and hydrogeochemical analyses at a camp scale.

Of these techniques, the ability to collect multi-element geochemical data (accessory phases) on individual grains through laser split-stream analyses has proved a major step change in mapping crustal residence ages, mineral fertility and changing geochemistry through time, for example, in rutile and titanite, which are common minerals found in a range of rock types and stable at a range of metamorphic grades. The concentrations of elements such as W, Sn, V and Sb have been shown to be higher when rutile is associated with various types of mineral deposits, including gold deposits (Clark and Williams, 2004), suggesting that it can be used to vector towards mineralised zones.

Mineral deposits are known to form and be deposited in at specific depths in the Earth. In this project, a generalised metamorphic map of the Capricorn region is being developed as a proxy to the exposure of different crustal levels in the region. This will be used to inform the preservation component of the mineral systems analysis.

Toolbox

During the project, new ways of integrating geophysical datasets that image the upper crust to within the mantle have been used in order to map the 3D crustal architecture of the Capricorn Orogen (Fig. 2). These, when used in conjunction with geochronological data and isotopic maps of Lu–Hf and Sm–Nd across the region, serve as powerful tools that may help with understanding the tectonic evolution of the region through time. Geological mapping and geophysical–geological interpretations have led to an improved synthesis of the tectonic development of the region. From these data and interpretations, a first-pass mineral systems analysis has been made along with construction of prospectivity models and resulting maps, which can be used in area selection for exploration

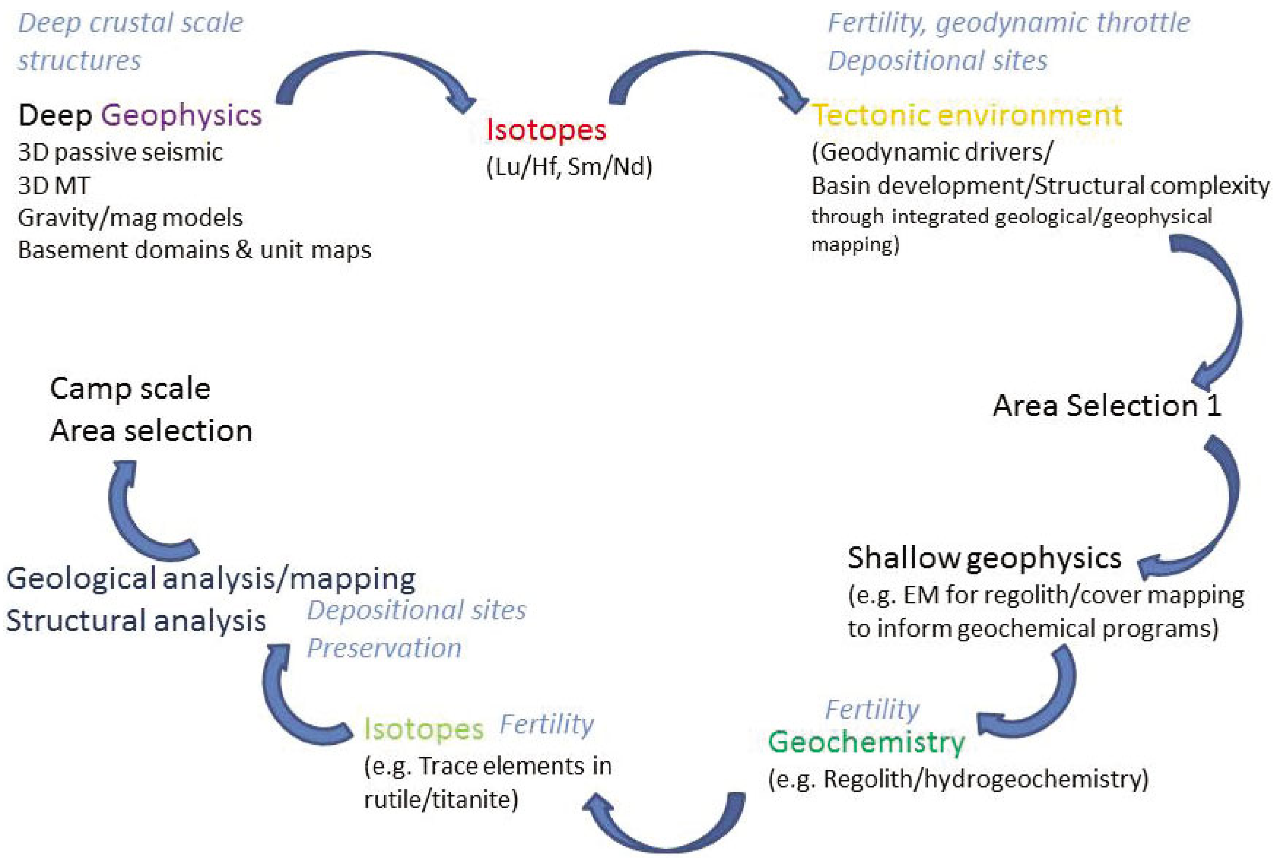

Figure 2. **Knowledge-based workflow for mapping footprints of ore bodies from very large scale to prospect scale (within a camp)**

programs. This automated analysis can be re-run, using slightly different input parameters so that a range of solutions are attained.

Further work, within tenement blocks involving regolith landform mapping that has benefited from analysis of regional scale electromagnetic (EM) data, has been useful in a bid to target and understand results from regolith and hydrogeochemical sampling programs. Trace-element geochemistry in rutile and titanite from a range of rock types across the area appears to highlight regions of relatively higher Au prospectivity. Further structural analysis and geological mapping using all of the aforementioned interpretations and data will be used as an input into a second stage of mineral systems analysis, prospectivity modelling and mapping to further refine exploration targeting areas.

Conclusion

A knowledge-based toolbox has been developed that aims to reduce exploration risk in greenfields and brownfields programs (Fig. 2). Learnings from the project include which parts of the workflow can be achieved by individual companies, which parts require input from universities, and which parts require the government to be involved in data acquisition and data archiving. For the most part, the first part of the workflow, involving the acquisition of deep geophysics, crustal-scale isotopic mapping and regional scale tectonic interpretations and mapping are in the realms of government agencies. However, once the first round of area selection has been completed a second phase of work that informs a mineral systems and prospectivity analysis can be completed. This automated analysis can be re-run by the end-user, with different input parameters assigned to explore the range of possibilities.

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Fusing geochemistry and structure for near-mine exploration

by

Nicholas H.S. Oliver[1*], Timothy J. Coughlin[1], Richard K. Valenta[1], Rodney J. Holcombe[1], Michael J. Nugus[2], Dave Lawie[3], Michelle Carey[3] and James Cleverley[3]

Introduction

Too often the analysis of geochemical, structural and geophysical data is pigeonholed according to specialisation within companies and research groups, particularly in the area of fusing geochemistry and structural geology. This contribution presents workflows and case histories from gold projects that exemplify the use of geochemistry and structural geology together, to specifically assist near-mine target generation directly, or indirectly through greatly improved conceptual models. The overall procedure includes: a) extracting lithogeochemical data to validate or replace logged lithology, b) combining structural boundaries from mapping, geophysics and lithogeochemistry, c) identification of vein-related dilation from the geochemical dataset by using immobile elements normalised against lithogeochemical units, d) in 3D, structural fusion of geochemical data via a new stereographic projection function in ioGAS.

Lithogeochemistry, alteration and veining

The generation of lithogeochemical 'bins' to describe rock types via geochemical data is well developed for orthomagmatic deposits where such information is perceived as directly applicable in the search for Cr and Ni. More poorly understood in gold and base metal exploration is the need to use the same principles as a lynch-pin on which to hang more specifically relevant appraisal of alteration and mineralization — for example using lithogeochemistry to recognise sharp, discordant boundaries which may represent potentially mineralised or post-mineralisation faults. Although high quality data is desirable (e.g. 4-acid digest ICPMS), new and/or stored materials (soils, drillcore pulps) can also now be re-analysed quickly with a remedial portable XRF — one of the better ways to quickly and cheaply get an old program moving forward again. The Al and Ti contents of most sequences of siliciclastic and igneous rock packages will reveal a wealth of information on alteration and veining — because these elements classically behave in an immobile fashion for the majority of hydrothermal systems. Lithogeochemistry is particularly crucial when the sampled materials are not pristine core — e.g. soils, RC chips, pulps — or when the logging has been unreliable, or the alteration and/or weathering make the task very difficult.

The influx of large volumes of silica, carbonates or iron oxides as vein or breccia infill during mineralization is one of the hallmarks of structurally-controlled hydrothermal mineral deposits. However, because silica is rarely analysed, the concept of 'silica flooding' is often relegated to logging data. After all, how difficult is it to recognise vein quartz? It is certainly not easy to accurately quantify '% vein quartz' from soils, RC chips and even from drill core with poor recovery due to high clay, gouge or alteration contents. In the examples below, quartz vein % was logged poorly (broken core with clay gouge) or not at all due to the materials being sampled (soil). An understanding that rock-hosted Ti and Al were diluted in inverse proportions relative to the influx of hydrothermal silica was used to extract a '% quartz' proxy from the geochemical data.

These data, when mapped onto gold assay data and structural maps, show a clear relationship to mineralisation, allowed recognition of the structural control on dilatancy, and provided a specific tool to expand the exploration targets (Fig. 1).

Domaining structures, gold grades and geochemistry in 3D

A very rapid method has been developed in ioGAS that allows the cross-fusion of structural spatial domains, orientational domains (as per stereographic projection), and geochemical data, and provides a new opportunity for recognition of key patterns withing mining data that will assist development and near-mine exploration. Figure 2 shows a benchmark example used as the development data for the ioGAS function, from which the true, folded stockwork behaviour of this part of the Sunrise Dam Gold Deposit (Eastern Goldfields) could be determined. Although Leapfrog can display structures by oriented disks, the additional power that the full geochemical tools of ioGAS bring will allow many more attributes to be visualised, such as the relationhip between structure, assays, and alteration types.

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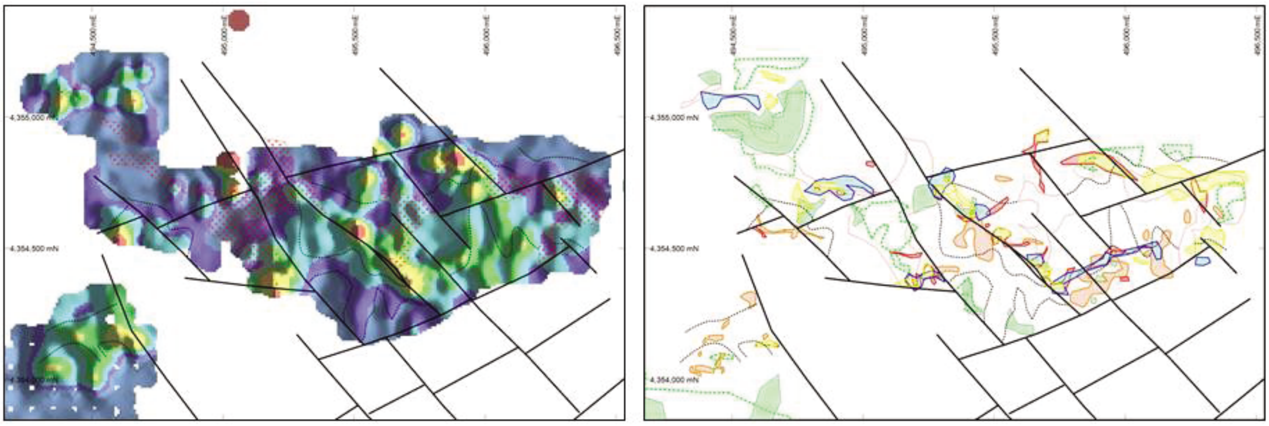

Figure 1. **Gomec epithermal Au-Ag prospect, Western Turkey (Tigris Resources/HCOVGlobal). Fault array (heavier lines) inferred by combining geophysics, mapping, and lithogeochemistry (thinner curved lines are lithogeochemical boundaries). Left – contoured 1/Al% content from soils data as a proxy for dilational flooding by silica, warm colours are highest % calculated quartz; Right – Au-As anomalism (yellow, blue), potassic alteration (pink, red), and a base metal – carbonate alteration association (greens), all extracted from the soils data and overlain on lithogeochemical units, show a clear relationship to the faults, some lithogeochemical units, and the calculated % quartz**

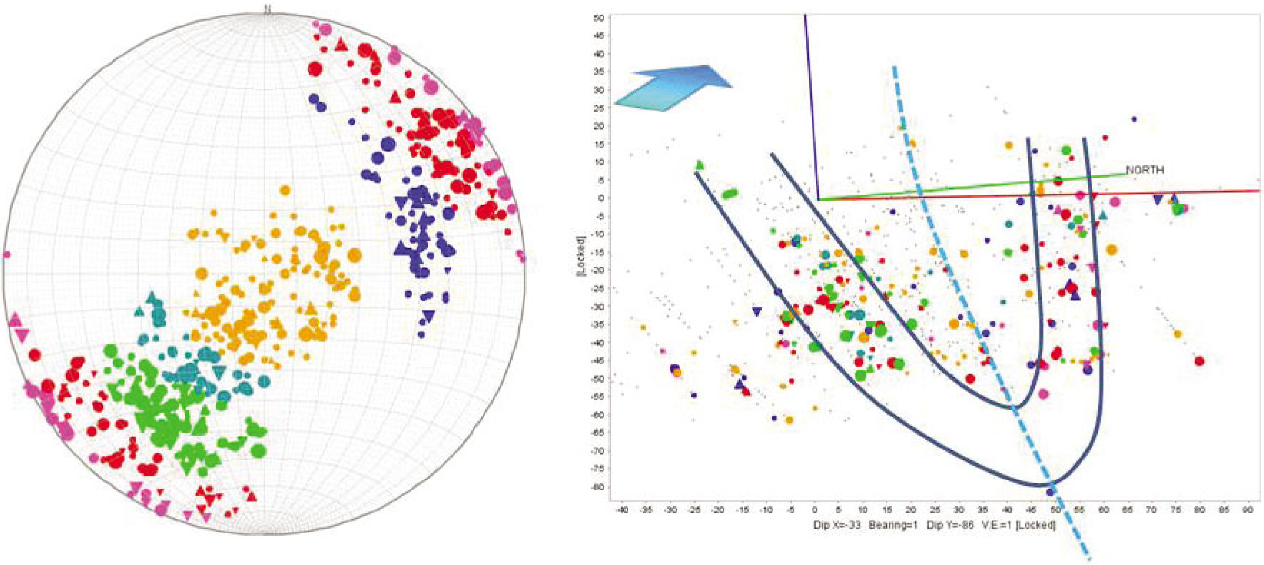

Figure 2. **Assay and orientation data (in ioGAS) for veined intervals at Puma/Western Shear at Sunrise Dam. Left: vein orientation and Au data are plotted here as poles with dot size equivalent to Au grade and colour representing orientational domains; Right, same data projected into 3D looking in section view towards grid NW, showing that vein orientation is best described by a fold as shown, and that the hinge zone may have had some Au removal during deformation**

Summary

Strategic advantage can be gained by comprehensive fusion of geochemistry and structural data, domains that are normally separated by default (sorry, bad pun). The very best datasets are potentially amenable to fully coupled modelling (e.g. computational process modelling or neural-network-level prospectivity analaysis). However, there is a much broader potential for improved practical application of fused structure and geochemistry within 'average' datasets.

Raman spectroscopy in mineral exploration for albitite hosted uranium deposits — Michelin, Labrador

by

Alexander Otto[1*] and Michael Kelly[2]

Introduction

Albitite-hosted uranium deposits (also known as Na-metasomatite-type) are recognised worldwide and predominantly occur in Paleoproterozoic terrains (Wilde, 2013). Many deposits share similar hydrothermal alteration mineralogy that include albite, sodic amphiboles and pyroxenes, titanate, magnetite, hematite, and zircon. At Michelin, the uranium mineralization along with its alteration halo is hosted in deformed and metamorphosed rhyolites. Hydrothermal alteration led to the replacement of quartz and potassic minerals (microcline, biotite) by sodic minerals (albite, sodic amphibole, aegerine). While intensively altered samples are characterized by pale red coloration due to hematite dusting, weakly albitized samples are more ambiguous to identify. The change from potassic to sodic assemblages is key to identify alteration zones of albitite hosted uranium mineralization. Methods such as polarizing microscopy or x-ray diffraction analysis are costly and have long turnaround times. Chemical methods are cheaper but also incur lengthy turnaround. Many of the alteration minerals are also inactive in the short to medium wavelength of infrared spectrometer. The overall goal of this study is to demonstrate the application of a small affordable Raman system that aids exploration efforts in remote areas with fast turnaround times.

Raman spectroscopy and method

Raman spectroscopy utilizes the inelastic scattering of monochromatic light when interacting with matter. The scattered light is shifted in its frequency and contains information about vibrational and rotational properties of molecules (Raman and Krishnan, 1928). The main advantage of Raman spectroscopy is that it is non-destructive and hydrous solutions can be analysed. In geoscience the two main applications are fluid inclusion analysis (Frezzotti et al., 2012), and planetary robot missions such as the Mars 2020 Rover mission (nasa.org; Freeman et al., 2008).

In this study, we used the portable i-RAMAN® Plus spectrometer from BWtek. The spectrometer is equipped with a 785nm Laser excitation and a CCD detector with a range between 65 cm^{-1} and 2800 cm^{-1} at a resolution of 3.5 cm^{-1}. The system is equipped with a fibre optic probe and a video microscope stage. Measurement time was generally 30 seconds at full power (320 mW). The laser spot size is ~40 µm and ~200 µm for the microscope and fibre-optic probe, respectively. The samples were cut off blocks from thin sections. Verification of the detected minerals was done with a petrographic microscope.

An additional goal in this study was the analysis for carbonate content in samples to estimate potential acid consumption. To demonstrate the suitability of quantitative analysis, artificial mixtures of quartz and calcite, and albite and calcite, were analysed to generate calibration models.

Results

The samples included unaltered metarhyolites and strongly altered and mineralized rhyolites. The Raman spectrometer was able to distinguish between microcline in the unaltered samples and the albite in the altered sample. Both minerals have their main peak in the 500 cm^{-1} to 550 cm^{-1} range. The main albite peak is at 505 cm^{-1} whereas the microcline peak shifted to 512 cm^{-1}. Other minerals that were identified include quartz, pyroxene, amphibole, calcite, titanate, epidote and apatite (Fig. 1). One sample was presumed to be a moderately sodic altered rhyolites. However the results indicate that the visual and microscopic description were inaccurate and that it contained mostly microcline and quartz. In another sample we successfully identified pyrite with its main peaks at 342 cm^{-1} and 785 cm^{-1}.

The measurement of calcite in binary mixtures with albite and quartz, respectively showed promising results with errors below 15% and the ability to detect calcite in the mixture down to 1–2%. Calcite has a prominent peak at 1084 cm^{-1} that was utilized to calculate a calibration for the estimation of calcite in albite mixtures (Fig. 2).

Conclusions

This study demonstrates that small, robust Raman spectrometer can be successfully applied in exploration camps to aid mineral identification. Analysis with the Raman spectrometer is low cost, fast and flexible. Comparable methods such as light microscopy or X-ray diffraction analysis have long turnaround times and higher cost per analysis.

Acknowledgements

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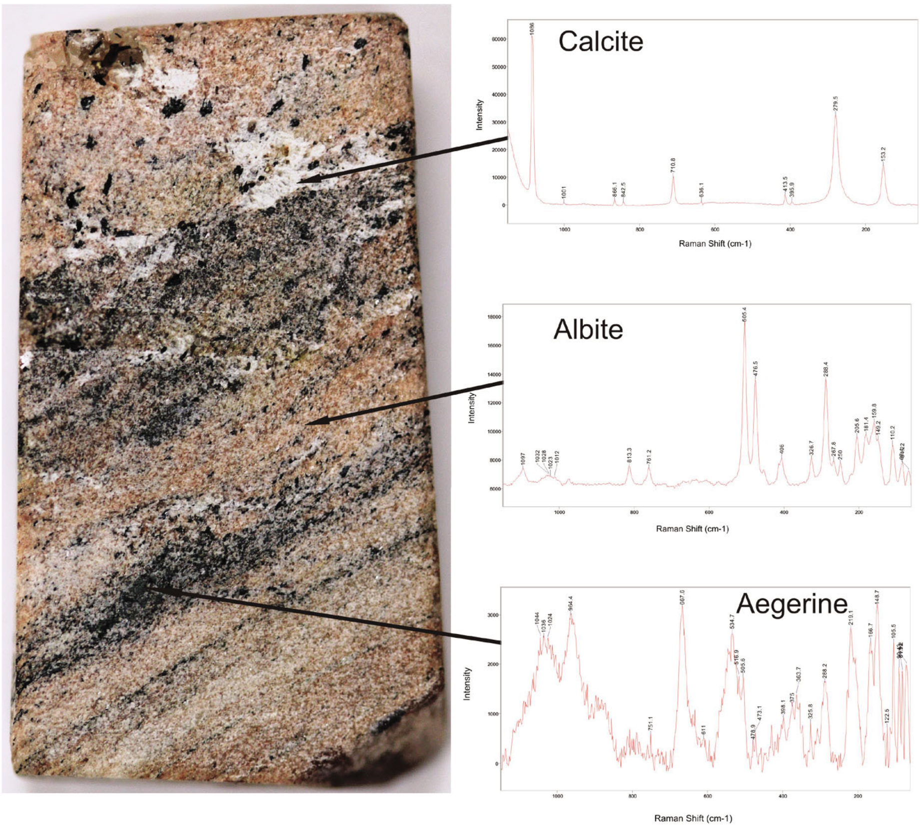

Figure 1. Cut-off block from thin section (2.5x1.5 cm) with measured Raman spectra

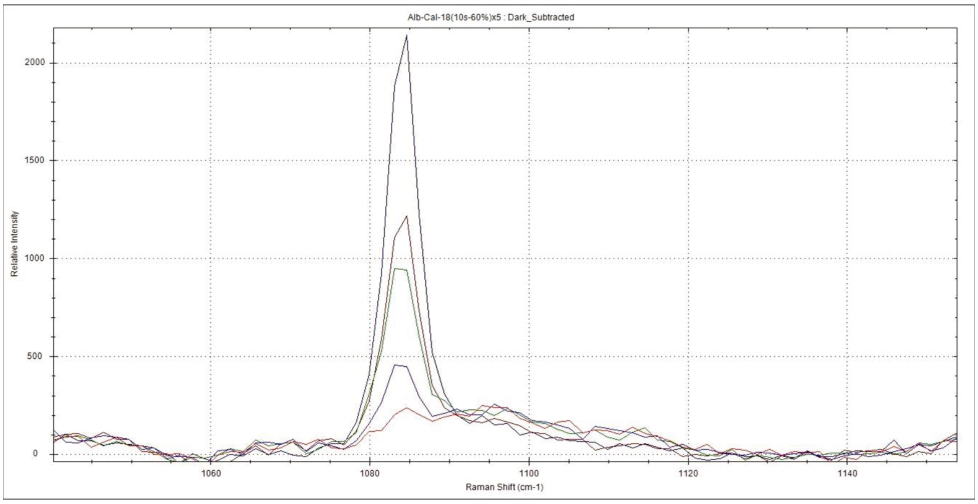

Figure 2. Calcite peak in albite matrix of mixtures containing 1%, 2.5%, 8%, 10%, and 18% calcite

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Role of geometallurgy in developing albitite-type uranium deposits

by

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Introduction

Albitite-type uranium deposits collectively contain as much uranium as the better known unconformity-type deposits, although at grades which are typically an order of magnitude or more lower. Given the low grades, a good understanding of deposit geometallurgy is even more crucial to informed decisions on investment. In this paper we present studies on the deposits of Valhalla (Queensland, Australia) and Michelin (Labrador, Canada).

Geological setting

The Mount Isa North district hosts 16 albitite-type resources, including Valhalla, all hosted by the Orosirian Eastern Creek Volcanics, a sequence of metabasalt and interbedded metamorphosed siltstones. Valhalla occurs within a near-vertical albitized mylonite discordant to primary bedding (Wilde et al., 2013). Albitized mylonite and breccia types each account for 40% and massive albitite the remaining 20% of ore.

The Central Mineral Belt of Labrador is a Proterozoic thrust belt containing nine substantial deposits, including the Michelin deposit, which is hosted by the Orosirian Aillik Group. Uranium occurs within a slightly discordant body of albitized mylonite developed in alternating equigranular and porphyritic metarhyolites intruded by composite intermediate dykes.

Uranium mineralogy

Two of the most important ore characteristics from the point of view of processing are projected acid consumption and the leachability of uranium phases. Neither can be estimated by visual logging of drill core or percussion chip samples. Recent mineralogical investigations have used scanning electron microscopy (SEM) and quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN; Polito et al., 2007; Wilde et al., 2013). A significant portion of uranium phases at both deposits are finer than three microns, i.e. at the resolution limit of conventional SEM, thus requiring use of higher spatial resolution tools such as hyperprobe or field emission gun (FEG) scanning electron microscope (Wilde et al., 2013).

Four principal uranium minerals were found in Valhalla samples using CSIRO's hyperprobe: an unnamed U-Ti phase, a solid solution between hydrated $USiO_4$ and $ZrSiO_4$ and an oxide, probably uraninite (Wilde et al., 2013). QEMSCAN showed that the main gangue phases are albite and amphibole (riebeckite) plus carbonate minerals, hydrothermal apatite and (uranium-poor) hydrothermal zircon and iron oxides.

The main uranium mineral at Michelin was originally identified as wolsendorffite ((Pb,Ca,Ba) U_2O_7 $2H_2O$) but is now known to be lead-rich (up to 20%) uraninite (Fig. 1). Other phases identified using QEMSCAN and field emission gun (FEG) SEM are U-rich ilmenite, uranophane, coffinite, and an unidentified uraniferous titanium mineral. The main gangue phases are albite, aegerine, amphibole, titanite and magnetite/hematite. Only traces of hydrothermal apatite and zircon were identified.

The variability of uranium mineral assemblages at the hand specimen scale in both deposits is substantial. This is an important observation and requires that samples for metallurgical testwork represent the observed variation in uranium mineralogy, particularly in respect to potentially variation in solubility of the various uranium phases.

Ore characterisation at the orebody scale

Valhalla ore is visually inhomogeneous, particularly with respect to the abundance of post-uranium carbonate-filled veins and patches. Bulk chemical data were used to estimate acid consumption and to derive an empirical factor that could be applied to a block model. Michelin ore appears visually homogeneous, nevertheless bulk chemical data were used to establish whether there were chemically distinct ore types and to obtain insight into the mineralising processes. Immobile element plots confirm the mobility of elements such as Nb, Zr, Y and Nd in the deposit. This restricts the use of preserved element ratio plots to quantify alteration processes in the mineralized system. The bulk chemical data were unable to define discrete ore types but highlighted considerable variability in major element composition, which may have implications for reagent consumption and comminution characteristics.

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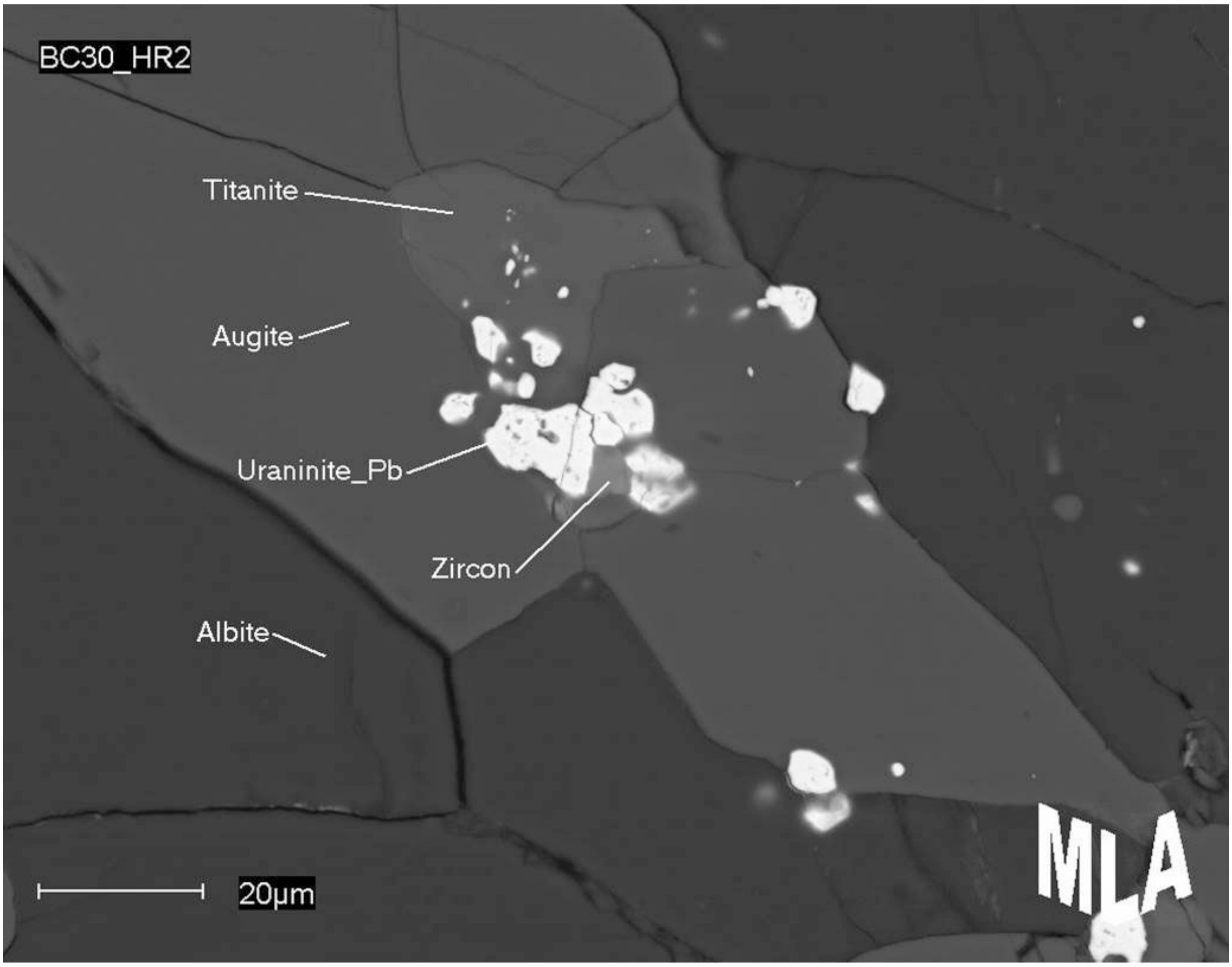

BC30_HR2_1-2-3_Uraninite_in_zircon_titanite_Augite_Albite_2000X_001_Annot

Figure 1. Fine-grained uraninite intergrown with zircon, titanate in pyroxene (augite) and albite matrix, Michelin deposit

Near infra-red (NIR) spectroscopy holds promise for quantifying uranium minerals in core and percussion chip samples (Andrews et al., 2015). W Andrews is undertaking a study at RMIT using samples from Valhalla and synthetic standards to determine the viability of quantification of uranium phases in drill core data. The results to date have been encouraging. This is the first time U minerals have been identified by NIR throughout a uranium deposit. Coffinite and (uraniferous) zircon ($ZrSiO_4$) both have a 1500 nm absorption feature, while coffinite also has a distinctive 1550 nm absorption feature (Baron et al. 2014). These spectral features are strongly correlated to U and Zr abundance in assay data (W Andrews, unpublished data).

A study undertaken at Michelin showed promise for the use of Raman spectroscopy in identifying uranium and gangue minerals in core samples (Ramanaidou, pers. comm., 2013). A portable spectrometer was purchased to investigate mineralogy of the Michelin deposit. The study showed that it can easily distinguish between albite and K-feldspar, which is often not possible in hand sample. Other characteristic minerals of albitite-type deposits have been identified such as aegerine, various amphiboles, carbonates, iron oxides, and titanate. Early-stage successful investigation in quantifying minerals in powders has been attained by estimating calcite content in artificial mixtures with quartz and albite.

Conclusions

As lower grade orebodies are being exploited, the importance of understanding the variability and processing characteristics of ores becomes even more important. Bulk chemical analysis has proved useful in establishing ore variability at the deposit scale, particularly at Valhalla. Predicting uranium recoveries, however, requires some knowledge of uranium mineralogy. A significant problem is the extremely fine grain size of a substantial portion of the uranium minerals at Valhalla and Michelin. High spatial resolution electron microprobe and scanning electron microscopy has allowed the identification of a suite of minerals, many of which do not conform to the stoichiometry of known uranium minerals. For example, a solid solution between coffinite and a Zr-rich endmember. Further work is required to better characterize such unnamed phases and establish their solubility under various conditions.

Ideally, we should be able define the variability in uranium phases at the deposit scale. Infra-red spectroscopy at Valhalla has provided some encouragement that this goal might be attainable in the short term and research into the use of Raman spectroscopy is ongoing.

Acknowledgements

We thank Paladin Energy Ltd for the access to the data presented in this paper.

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Controls and genesis of high-grade ore-shoots at Callie world-class gold deposit, Northern Territory, Australia

by

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In a context of growing mining operations cost and commodity prices declining, understanding factors controlling high-grade mineralisation is becoming critical to the mineral industry. Factors controlling high-grade Au mineralisation remain poorly understood. Unlike magmatic-hydrothermal systems, which can carry important quantities of gold (~0.015 ppm) as shown by on Simmons and Brown (2006) on an active geothermal system, metamorphic fluids commonly proposed as responsible for orogenic gold mineralisation are considered to have low gold concentrations (0.003 to 0.03 ppm; Rauchenstein-Martinek et al., 2014). Such low metal concentration poses the question as to the process required to form an economic ore body (enrichment between 3 and 4 orders of magnitude when compared to background Au abundance in crustal material). A high-grade ore-shoot has been interpreted to result from gold remobilisation as demonstrated by investigation in both the Obuasi ultra high-grade gold deposit in Ghana (Fougerouse et al., 2016) or the Red Lake deposit in Canada (Dubé et al., 2004). In order to further the understanding of the formation of a high-grade ore-shoot, this paper present the preliminary results on the formation of high-grade mineralisation in the various gold deposits within the Dead Bullock Soak Mining Lease, including the Callie world-class deposit held by Newmont in Northern Territory.

The Callie gold mine presents significant high-grade mineralisation (intersects up to 10 000 ppm) and offers an excellent opportunity to conduct such project. The Dead Bullock Soak Mining Lease is located 650 km northwest of Alice Springs within the Granites–Tanami Orogen (Northern Territory, Australia). The Granites–Tanami Orogen consists of folded Paleoproterozoic sediments of the Tanami Group and volcanic units, metamorphosed at greenshist and amphibolite facies, that are intruded by granitic rocks and doleritic dykes. It is known for hosting important occurrences of gold, with the Callie deposit being the largest producer.

At Callie, the host units consist of planar-laminated Paleoproterozoic siltstones referred to as the Callie Laminated Beds, the Magpie Schist, the Lower Auron Beds and, to a lesser extent, the Lower Blake Laminations (Fig. 1). These units are well bedded, often laminated, and consist mainly of feldspars, quartz, chlorite, biotite and sericite, and graphite within the Magpie Schist and Callie Laminated Beds. The Callie Laminated Beds are also characterised by the presence of ilmenite in coarser-grained laminations.

The metasediments of the Dead Bullock Formation are affected by tight folds that plunge about 40º to the east-southeast, which is the first deformation event preserved. Callie gold mineralisation occurs during a post-folding deformational event with visible gold hosted within centimetre-scale quartz, carbonate, chlorite and epidote vein sets. These veins trend from 030º to 070º and dip steeply towards the southeast, they crosscut the main east-plunging folds and are interpreted to be associated with similarly trending high-strain zones with a reverse movement (Miller, 2010). The deposit is also affected by a later deformational event that locally offsets the mineralisation zone. While the vein system is continuous, the gold distribution is restricted to specific finely laminated stratigraphic horizons (Fig. 2).

Combining field-based structural investigation and petrographic analysis together with cutting-edge X-ray element mapping using energy dispersive spectrometer and micro-XRF techniques, we present the key paragenetic sequences associated with high-grade ore-shoot formation. In combining these various techniques, we show that mapping the mineralogical and geochemical footprint onto the 3D deposit architecture is key to furthering the geochemical proxies that may be used to map out the fluid pathways and therefore fingerprint spatially such high-grade deposits.

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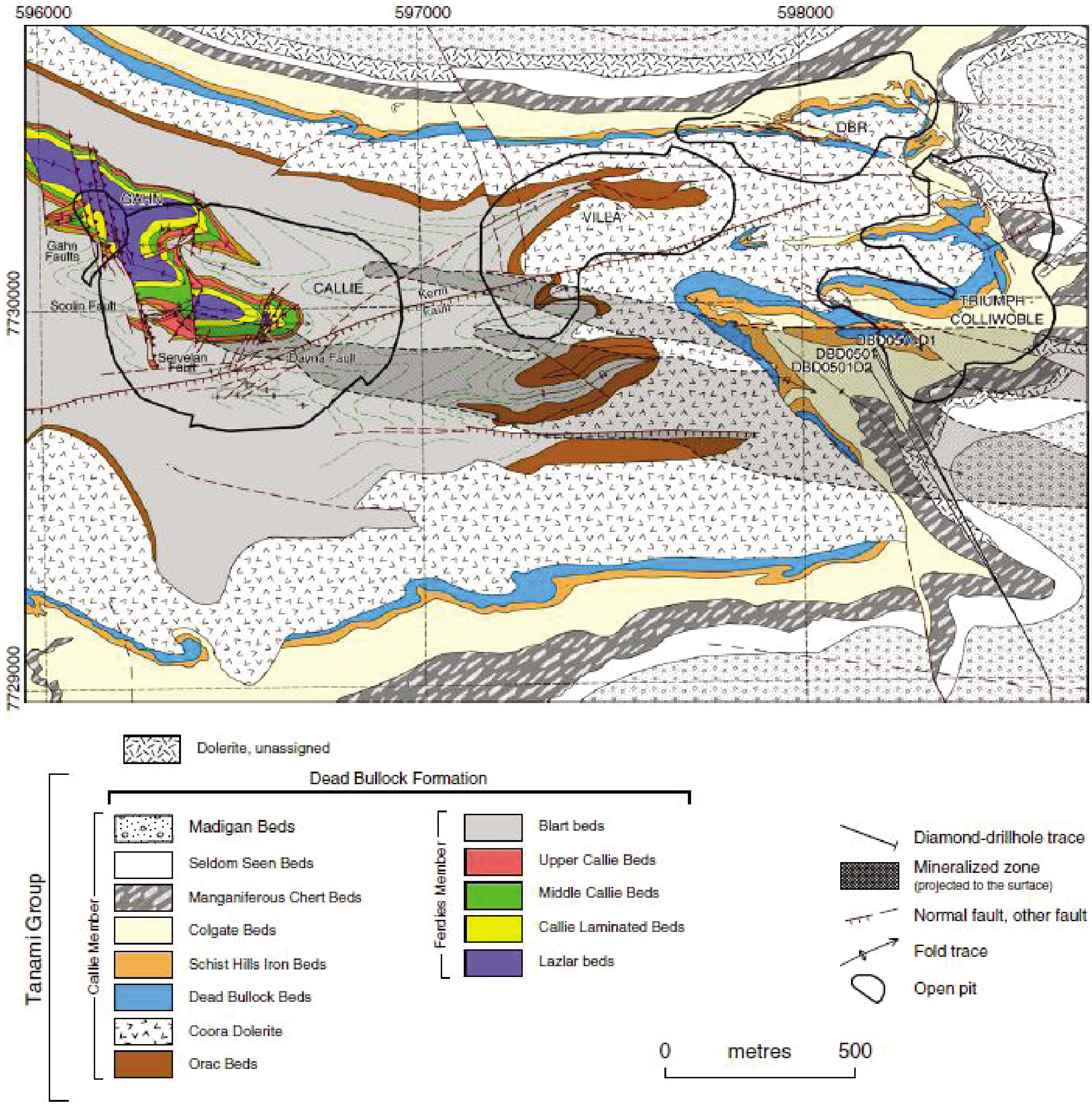

Figure 1. **Geological map of the Dead Bullock Soak gold deposits from Li et al. (2014)**

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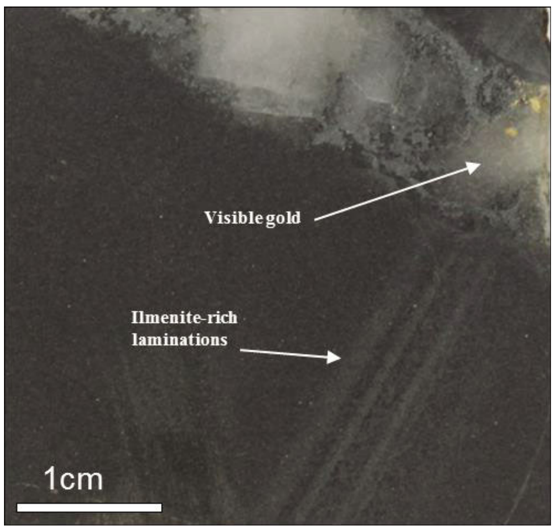

Figure 2. **Example of visible gold within a quartz vein intersecting ilmenite-rich laminations in the Lower Auron Bed (L275-7748 @ 42 m)**

Uncertainty mapping in GIS-based prospectivity modelling

by

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GIS-based mineral prospectivity models are beset by three types of uncertainties, namely, stochastic, systemic and model uncertainties. Stochastic uncertainties have their origin in the input data and are results of incomplete and/or inconsistent data coverage, interpolations of under-sampled or censored data, inaccurate georeferencing, problems in ontology alignment of geological data from different sources, etc. Systemic uncertainties have their origin in human cognition and arise from incomplete understanding of mineral systems and their manifestations in geospatial data. Model uncertainties have their origin in mathematical theories and mainly arise from invalid model assumptions such as complete spatial randomness of mineral deposits that ignore spatial adjacency and neighbourhood effects. Most GIS-based prospectivity models quantify prospectivity of a given unit area in terms of various favourability indices; however, it is equally critical to assign a confidence level to the favourability value in order to make an informed exploration decision. In this presentation, I will discuss the sources of uncertainty in prospectivity modelling and also outline some innovative techniques for qualification of uncertainty.

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Stratigraphy and structural architecture of the Bryah and Padbury Basins from integrated geophysical and geological data: understanding controls on mineralization

by

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Introduction

The Paleoproterozoic Bryah and Padbury Basins are situated along the north margin of the Yilgarn Craton, in the southeastern part of the Capricorn Orogen (Fig. 1a). These basins have developed due to extension and tectonic processes resulting from the Glenburgh Orogeny (2005–1960 Ma; Occhipinti et al., 2004). The Bryah Basin was formed in a rift setting along the Yilgarn margin and contains volcano-sedimentary rocks of the Bryah Group (c. 2018 Ma). The Padbury Basin comprises carbonate, siliciclastic and banded iron-formation rocks of the Padbury Group (2000–1800 Ma), deposited over the Bryah Group, in a pro-foreland basin.

Mineralization in the Bryah and Padbury Basins include volcanogenic massive sulphides (VMS) and orogenic lode-gold deposits (Pirajno, 2004). The orogenic gold mineralization is associated with hydrothermal fluid transport through shear zones, during the last stages of deformation and metamorphism during the Capricorn Orogen (1830–1780 Ma; Occhipinti et al., 1998). The VMS deposits are hosted by felsic volcanic rocks or related to an interfingering sequence of sedimentary and mafic volcanic rocks within the two lowest units of the Bryah Group: the Karalundi and Narracoota Formations (Hawke et al., 2015).

Although the resources potential in the Bryah and Padbury groups are considerable (Pirajno et al., 2004; Johnson, 2013), the thickness of the regolith and the lack of outcrop makes mineral exploration difficult. Thus, interpretation of magnetic and gravity data, integrated with field work and drill core analysis, is necessary to understand the structural architecture and stratigraphy in the Bryah and Padbury Basins, leading to a better understanding of mineralization controls in the region.

Basin architecture investigation through geophysical datasets

Geophysical datasets have been interpreted with the view to characterizing basin structures and architecture in Paleoproterozoic terrains. The mapping of large-scale structures in the Bryah and Padbury Basins through magnetic and gravity images allows the recognition of major discontinuities, such as faults, folds, and shear zones, as well as lithological contacts and major unconformities. The interpretation of magnetic data has helped to delineate the basin structural pattern by revealing information of the basement surface, morphology, and faults. Gravity data has been useful in the identification of basin thickness, and in the delimitation and estimation of the mafic magmatism, which present a density contrast in relation with sedimentary basin infill (Fig. 1b).

Geophysical datasets have also been used in an attempt to establish a spatial association between basin stratigraphy/structures and mineralization. The identification of structures at different scales is an important step in orogenic gold exploration, since gold deposits are often located in structures adjacent to major crustal-scale shear zones. This analysis is also important to VMS exploration if the structures related to the active rifting stage are identified. Additionally, the differentiation of the volcanic and/or sedimentary piles in volcano-sedimentary basins provides information to help with VMS exploration models as it may indicate favourable sites for VMS mineralization.

Summary

The integrated analysis of geophysical and geological data reveals new elements of the Bryah and Padbury Basins that can identify mineralization controls in the region. The use of gravity data to identify the extent of a mafic magmatic domain, which is coincident with a positive gravity anomaly (Fig. 1b), and to delineate contacts between the magmatic rocks and the sedimentary infill, can assist the VMS exploration models. Similarly, the structural framework interpreted through magnetic data is important to understand the control of the orogenic gold mineralization, as well as the structures related to the active rift stage. Additionally, mapping of discontinuities in the crust and mantle lithosphere through interpretation of geophysical datasets will be used to determine the lithospheric architecture of the Bryah Basin, which is crucial for the mineralization systems understanding in the region.

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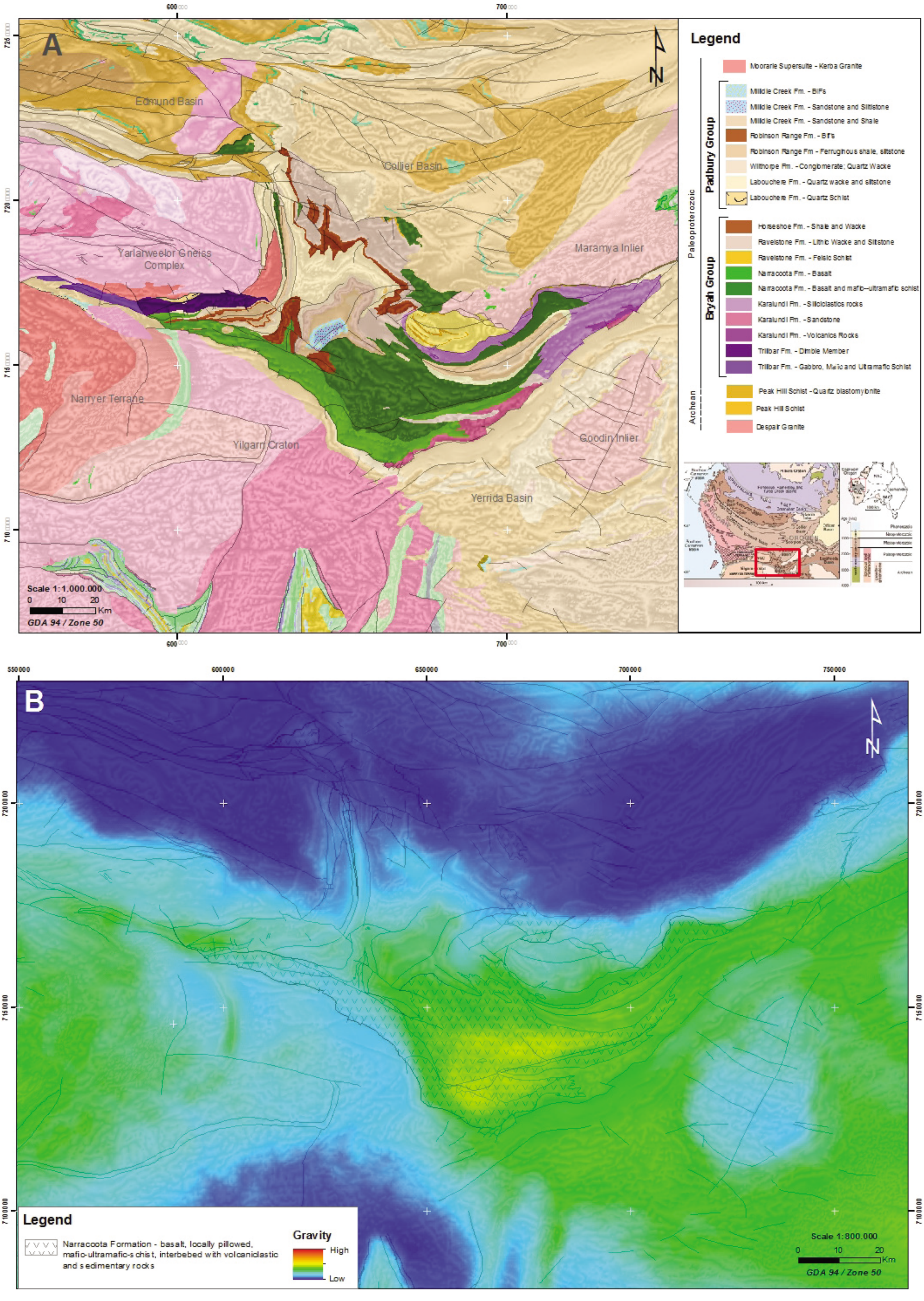

Figure 1. **a) Geological map of the Bryah and Padbury Basins and surrounding terrains over the tilt derivative image (TDR); b) mafic rocks of the Narracoota Formation over Bouguer anomaly image**

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Realising a decade of Australian Government investments in eResearch infrastructure to fuel the next generation of data intensive minerals exploration undercover

by

Tim Rawling[1,2*], Ben Evans[3] and Lesley Wyborn[3]

Introduction

The Australian Minerals Industry has access to vast data assets that have the capacity to make exploration more cost effective, reduce exploration risk and ultimately find new deposits under increasing thicknesses of cover. Industry, the State, Territory and National Geological Surveys and, more recently, the research community have collected substantial volumes of geophysical, geological, geochemical and Earth observation data, much of which is accessible free of charge via the internet or at the cost of transfer. Data volumes accessible to the minerals industry continue to grow exponentially as improvements in the capacity and capability of instruments mean that new data is collected at far higher resolutions that was previously possible. Theoretically, this should have contributed to an increased rate of discovery and made Australia an attractive place for exploration, yet discovery rates are not improving.

The reality is that the distribution of geoscience data is highly variable, being extremely dense around mines or prospects but becoming sparse away from brownfields areas. With surface or near-surface resources progressively becoming exhausted, there is an increasing emphasis on exploration deeper undercover. This means that the predictions of the composition and structure of the subsurface need to be inferred from geophysical and other remote sensing techniques, and these can only be calibrated using direct observations and measurements from boreholes, which, in greenfields areas, are scarce to nonexistent.

Industry has been collaborating with the research community for many years through partnerships with AMIRA and initiatives such as the Predictive Mineral Discovery Cooperative Research Centre (CRC), Deep Exploration Technologies CRC, Australia Research Council (ARC) Linkage Grants and, more recently, the Uncover initiative. All have made/are making valuable contributions to improving exploration techniques and developing new technologies. However, whilst many of these programs have involved simulation and modelling components they have typically been based on the development of desktop-based codes and workflows.

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The national collaborative research infrastructure strategy

In 2004, the Australian Government developed the National Collaborative Research Infrastructure Strategy (NCRIS) to drive research excellence and collaboration between researchers, government and industry. Specific to the Geosciences, AuScope, formed in 2006, aimed to build a world-class infrastructure to assist Australian researchers in monitoring and understanding the structure and evolution of the Australian Continent. In 2009, this initial tranche of funding was followed by the Super Science budget which invested over $350 million in eResearch infrastructures (petascale computers and data repositories, cloud infrastructures, high-speed networks, data registries and data services). A total of over $2.8 billion has been invested to deliver world-class research infrastructure, with more than $1 billion in co-investment from State and Territory governments, universities, research facilities and industry. The NCRIS infrastructures offered new opportunities for the minerals industry to trial data intensive techniques (e.g. dynamic 3D modelling, machine learning, uncertainty quantification) at scales and resolutions never before possible.

Leveraging NCRIS infrastructures for mineral exploration

In the last decade, the global oil industry has progressively moved onto equivalent supercomputing infrastructures and there are at least five supercomputers dedicated to oil exploration in the latest Top 100 Supercomputer list released in November 2016 (Strohmeier et al., 2016). In contrast, the minerals industry has been slower to move onto equivalent infrastructures, in part because of start-up costs but mainly because the application of High Performance Computing (HPC) to mineral-system analysis and predictive exploration is not nearly as straightforward as it is for oil and gas exploration. Much of the application of HPC capacity in oil and gas exploration is to build 3D geological models from very rich geophysical datasets and then to model the buoyancy-driven migration of fluids through those geometrically constrained systems.

In comparison, mineral deposits commonly form in structurally complex regions during periods of significant deformation and perturbation of pressure and thermal systems. In addition, the data constraining the geometry of the systems tends to be sparse and the current geometry may bear little relation to the geometry that existed at the time of mineralisation. As a result, the application of simulation and modelling of mineral deposit formation provides less opportunity for application of generalised simulation workflows.

Since 2006, AuScope, in collaboration with the government agencies, has done a considerable amount of pioneering work in developing geoscience data infrastructures that harmonised geological observational and mineral resource data from the individual agencies, enabled interoperability of data between individual agencies, and enhanced programmatic access through internationally agreed standard interfaces and vocabularies.

Initially, very little geoscience software could take full advantage of cloud and HPC infrastructures: rewriting to use HPC systems is non-trivial and requires both scientific and computational science skills to understand the existing algorithms and then rewrite to use scalable parallel algorithms. AuScope researchers from several universities have been developing open source codes (eScript, GPLATES, Underworld, iEarth) that are shareable and can take advantage of the some of these new infrastructures.

But changing to HPC systems alone was not enough. As data volumes continued to grow and there was a need to engage in real-world scenarios, it was clear that there was a requirement for HPC systems to also be able to readily access sufficient volumes of reference data. New partnerships emerged as the government agencies were data rich, whilst the research groups with skills in developing the algorithms and next generation processing software did not have access to the data.

This need to co-locate HPC and High Performance Data (HPD) infrastructures with collaborative approaches to expertise in computational and data analysis techniques has been experienced in many other areas of the Earth sciences. In Australia, the scaling-up of the infrastructures has been most prominent at the National Computational Infrastructure (NCI), Canberra. Over 10 Petabytes of HPD collections spanning the geosciences, geophysics, environment, climate and elevation have been co-located with a 1.2 Petaflop supercomputer and a HPC class 3000-core OpenStack cloud system.

With the core computational infrastructure in place, the issue then became how to better organise the data for the potential capability. Geoscience data is notoriously complex and, for utilisation in HPC environments, 'Big Data' earth science collections needed to be created from a plethora of heterogeneous files that were often fragmented and non-standardised, and transformed into well-managed reference datasets. That is, they needed to be reorganised into self-describing 'High Performance Data' (HPD) collections (Evans et al., 2015; Wyborn and Evans, 2015) that are enabled for programmatic access that allow the computational techniques to be easily applied. As most of these large data sets are remote proxies of real world observations, there was an increased requirement to use observational datasets from different domains of the Earth systems (e.g., rock properties, geochronology) to either train or provide ground truth.

As a result of the increased use of shared computational infrastructure, a better partnership has now formed between the government and research sectors. For example, since 2011, through the approach to shared data, software, expertise and infrastructure at NCI, Geoscience Australia, in partnership with the research sector, has now been able to explore these HPC/HPD techniques and has proven that much larger datasets are able to be analysed at higher resolution and vastly improved timeframes (e.g. it now takes less than 10 hours to conduct a variable reduction to the pole over the whole of the magnetic map of Australia (Wyborn et al., 2016)).

Conclusion

To fully utilise the last decade of developments, and ensure that they are used to gain as much as possible from Australia's vast data assets, the partnership needs to expand to be a three-way collaboration between the minerals industry, the government and the research sectors. These groups working in concert will more effectively leverage the investments by the Australian government in data and computational infrastructures and lead to the development of HPD techniques and HPC tools that genuinely impact future exploration success.

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Evaluation of mineral exploration projects; working towards a better model

by

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The mining industry utilises financial valuations as routine practice for understanding the projected returns related to investment decisions involving: (1) financing (e.g. asset evaluations, revenue maximisation); (2) investments (e.g. capital allocation and developments); or to a lesser degree (3) portfolio management (e.g. acquisition, organic growth, etc.) (Copeland et al., 2000; Koller et al., 2005; Guj, 2011).

The terms 'evaluation' and 'valuation' are often used interchangeably in the context of reviewing projects or assets in the mining industry. For the purposes of clarity, valuation represents a financial estimation of the value of a project or the projected returns from a project or decision. Evaluations encompass a more holistic process combining, amongst other things, financial valuations, technical and non-technical assessments. In the mining industry, evaluations are more appropriate for early-stage exploration projects, projects with a reported mineral resource (often called resource evaluations) and/or feasibility studies. Valuations are more appropriate for decisions related to operating assets or acquisition transactions (Bartrop and White, 1995).

Project evaluations in the mining industry

As defined by Lawrence (2001), financial valuations in the mining industry can be divided into three broad categories: cost-based, market-based and income-based. A conventional approach used by the mining industry is based on income-based financial valuations — modelled using cash flow and revenue — with the most widely used technique being discounted cash flow modelling (DCF) (Bartrop and White, 1995; Guj, 2013). Income-based techniques provide a deterministic and objective modelling of cash flows for the life of a project using a specific static time- and risk-adjusted discount rate. These techniques work best for projects where the costs related to mining the resource or developing the project are reliably understood (Lawrence, 2001; Guj, 2013). Thus, income-based models are suitable for exploration or mining projects at advanced stages (i.e. with a defined economic resource) and established mining assets (either under development or producing). The downside is that income-based techniques frequently struggle to evaluate projects with high degrees of uncertainty and risk (Guj, 2013). Exploration projects normally have significantly varied risk profiles along with highly uncertain technical inputs and low probabilities of success (Bartrop and Guj, 2009; Schodde, 2010). Without adequate risk analysis, income-based evaluations (particularly DCF) are not well suited to handling the ubiquitous uncertainty in exploration projects (Guj, 2013). DCF modelling also struggles to adequately capture the long-term embedded option value associated with successful discovery of mineral resources for two reasons (Goodyear, 2006). First, the time taken to discover and develop mineral resources is often longer than the time horizon utilised in conventional DCF so little value can be assigned to mineral exploration success. Second, the evaluation of an exploration project at the time of a mineral discovery fails to assign any value to additional resources that may be discovered over time.

Cost- and market-based valuations are considered more appropriate for exploration projects. Lawrence (2001) discusses the benefits and drawbacks of using various market-based approaches, including benchmark/comparable sales, joint venture (JV) terms, yardsticks and transactional rules-of-thumb. The major drawback of market-based methods is that comparable transactions are rare, often biased by market sentiment at the time of the transaction, and generally it is hard for the evaluator to know the exact terms of the deal due to confidentiality (Lawrence, 2001; Guj, 2013). Roscoe (2001) discusses cost-based methods (such as appraisal value, multiples of exploration expenditure, etc.), which are ideally suited for prospective exploration projects with no reported mineral resources. These methods focus on using exploration expenditure already committed to the project as a base to determine what expenditure is required to test/validate the remaining potential of the project (i.e. its residual prospectivity). The final project value is the remaining expenditure required multiplied by a variable representing the residual prospectivity. The downside of cost-based techniques (and similarly for market-based techniques) is their reliance on past events and information, which may or may not be representative of the future value of the project (Guj, 2013).

Others (e.g. Lord et al., 2001; Lonergan, 2002; Kreuzer et al., 2008) have proposed a probabilistic approach as a means of handling the risk and uncertainty associated with exploration projects. The approach by Kreuzer et al. (2008) combines geological understanding of the project based on the mineral system approach which focuses on understanding geological processes responsible

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for mineralisation (Hronsky, 2004) and aspects of probabilistic theory such as assigning probabilities to key management decisions and outcomes (Lord et al., 2001) to generate a value proposition associated with each outcome. This methodology is likely the most effective at handling the uncertainties associated with mineral exploration projects and has been utilised in the oil and gas industry for several decades with relative success (Rose, 1999, 2007). However, the major impediment with the probabilistic approach in mineral exploration is the lack of genuine understanding of the actual probabilities of success associated with exploration projects (Kreuzer and Etheridge, 2010). Despite several attempts (Ball and Brown, 1979; Eggert, 1993; Ord, 1998; Lord et al., 2001; Schodde, 2004; Leveille and Doggett, 2006; Bartrop and Guj, 2009), actual success rates of mineral exploration projects have been hard to quantitatively determine, particularly with respect to expenditure committed. To overcome this, estimates of discovery success rates are often used, which may lead to biased results. Building on the basic probabilistic approach are far more sophisticated methods of handling the associated risk and uncertainty. These can be either through a Bayesian/Decision Tree approach, a Monte Carlo stochastic simulation, or Real Option Value (ROV) modelling (Guj, 2016). All of the aforementioned methods are covered in more detail by (Guj, 2013).

Missing the value of upside potential in exploration projects

As mentioned by Goodyear (2006), an oversight in the valuation of exploration projects is the lack of value attributed to the likely growth of the mineral resource. Most mineral resources grow over time, particularly in world class examples as shown by Goodyear (2006). In financial valuations, an 'upside' business case is often modelled, effectively representing a potential for future gain or an arbitrage that can be exploited at some point. Mining projects can have several sources of associated upside. The most obvious is resource growth through exploration — colloquially termed 'exploration upside'. Another could be changes in ore body characteristics (e.g. geometry, thickness, continuity, etc.) during mining operations resulting in reduction of mining costs and increased profitability. External to the mineral resource or asset itself, changes in foreign exchange rates or commodity supply/demand can result in increased revenue from mining the resource. Perhaps a more appropriate term for external factors not directly related to the mineral resource/asset would be arbitrage, in its standard business definition of an advantage gained through changing prices of an entity. In most mining projects, the greatest arbitrage or upside potential most likely resides in potential growth of the resource, as that offers transformational or exponential growth that could positively impact the economics of the project.

Although it may be generally understood that resources can grow over time (e.g. Goodyear, 2006), this is rarely translated into a tangible value incorporated into mining project evaluations. One reason for this is the relatively poor discovery success rate (i.e. the discovery 'base-rate') in the mineral exploration industry (Schodde, 2010). Another reason is the current lack of adequate metrics for identifying industry-wide success and, subsequently, the value generated by exploration. Combined, these factors make it difficult to tangibly identify value generated by exploring for the upside potential in a project. Most published studies looking at mineral discovery success rates focus on the global exploration industry and suggest that investment returns through exploration on an industry-averaged basis are low (below the level of return targeted given the high risk of failure) (Ball and Brown, 1979; Eggert, 1993; Ord, 1998; Schodde and C, 2004; Leveille and Doggett, 2006). This may be artificially enhanced by treating all exploration projects as equal. Clearly, there are winners and losers across the industry, such that the 'average' return may not of itself provide full insight for decision-making purposes. Perhaps by adopting a different approach to evaluating mining projects, particularly exploration projects, the actual returns on investment can be better expressed (e.g. Doggett and Leveille, 2010). The learnings can subsequently be utilised to more effectively model upside potential in exploration projects and acquisition targets.

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3D geological simulations of ore-forming processes: improving the workflow heading

by

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Numerical simulation of hydrothermal ore deposits is an increasingly important tool for improving our understanding of the key processes that are active in mineral systems and for predicting the signatures of these deposits. The formation of these deposits involves the complex interaction between deformation, fluid flow, heat transport and chemical reactions (and associated physical processes). In order for geologists to test the importance of these interactions and the influence of individual processes (and parameters), they must have a suite of computational simulation tools to carry out numerical experiments and to test 'what if' scenarios.

A current impediment to testing more than one geometrically complex and geologically realistic numerical simulation is the time that it takes to construct the numerical mesh for the model. At present, the construction of numerical models with complex geometry that accurately represent the data and the geologist's interpretation is a time-consuming task. We are able to utilise triangulated surfaces to build numerical meshes but, if there are many geologic units of irregular shape, many intersecting faults, or thin tapering units, then the process is very labour intensive. Once the mesh is constructed, modifying the orientation of an existing geologic contact or adding a new one often requires as much time and effort as that for creating the original model.

We present a workflow for creating and simulating multiple deformation – fluid-flow simulations using a combination of commercial, free and open-source software on desktop and parallel computing facilities. The workflow allows the user to create multiple geometrically complex geologic scenarios in a reasonably short time as well as the ability to quickly modify existing models. This dramatically improves our ability to efficiently test a wide range of geological models where geometry, rock properties and boundary conditions can all be quickly modified. It also allows for better sensitivity analysis and the potential for calculating uncertainty.

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Mineral potential mapping of lithospheric-scale mineral systems: intrusion-hosted Ni–Cu–PGE and iron oxide Cu–Au prospectivity of Australia

by

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The mineral systems concept, formulated originally for Proterozoic hydrothermal ore-forming systems (Wyborn et al., 1994), has been increasingly applied in mineral exploration and in studies of mineral potential. A modified version of the framework is currently used in mineral potential assessments by Geoscience Australia. For the practical purpose of mapping prospectivity at regional and continental scales, a four-component mineral system scheme has been developed that focuses on the critical 'ingredients' of ore-forming mineral systems, and considers these at lithospheric- to district- and deposit-scales. The four components are: (i) sources of energy, (ii) architecture of fluid or magma pathways, (iii) sources of ore metals, and (iv) gradients in ore depositional physico-chemical parameters. The modified mineral systems scheme also incorporates the concept of an ore-forming time window, which is based on the assumption that all of the essential ore-forming processes must have been active or present simultaneously at the sites of ore formation (Skirrow, 2009).

Most previous knowledge-driven and data-driven GIS-based assessments of mineral potential have been undertaken at regional scales and applied to hydrothermal systems, including previous Geoscience Australia studies of uranium and iron oxide copper–gold (IOCG) mineral potential. Here we report a recent study in which the mineral systems concept has been applied in continental-scale mapping of the potential for a magmatic ore deposit type, tholeiitic intrusion-hosted nickel–copper–platinum-group element (Ni–Cu–PGE) deposits (Dulfer et al., 2016). To our knowledge, this represents the first knowledge-driven assessment of mineral potential at continental scale using a GIS-based overlay approach.

Conceptual and mappable criteria representing each of the four mineral system components were developed, based on a conceptual mineral system model. The GIS-based modelling involved 13 principal geological, geophysical and geochemical datasets and derivatives for a total of 17 input datasets that are proxies for the conceptual and mappable criteria. Uncertainties in the applicability and spatial resolution of data were incorporated in the modelling using subjectively-assigned, fuzzy-logic-based weightings of input datasets. Rasters based on input data for each of the four mineral system components were combined in the GIS by simple overlay methods to yield a set of four intermediate maps. The final map of prospectivity (Fig. 1) combines all four mineral system components, each of which was allowed to contribute up to 25% of the final result so as to honour the principle that all mineral system components are necessary for ore formation. To prevent bias, the locations of known deposits of the type sought were explicitly not included as input data in the modelling. The successful prediction of the regions within which these few known intrusion-hosted Ni–Cu–PGE deposits are located (Fig. 1) is taken as validation of the approach, and provides a basis for confidence in predictions of high potential in other areas of Australia.

Known limitations of the modelling include: the uneven distribution of some input datasets, particularly point data such as whole-rock geochemistry; subjectivity in assignment of weightings to input datasets; incomplete coverages of the distributions of large igneous provinces (Proterozoic only); and use of surface geology for mafic–ultramafic rock units of Phanerozoic age rather than interpreted 'solid geology' that was available for Precambrian mafic and ultramafic rocks (Thorne et al., 2014). Limitations in the use of unevenly distributed point data were mitigated to some extent by assigning properties derived from point data to polygons (e.g. whole-rock geochemical sample points located within polygons of map units). The issue of subjective assignment of weightings, and the sensitivity of the final results to individual input datasets, have been addressed by conducting Monte Carlo-type simulations in which multiple values of weightings have been tested. Further improvements to the mineral potential modelling method along with increased data coverage will undoubtedly yield improved results. Nevertheless, the results of this initial study represent a 'minimum' view of prospectivity in so far as new areas of high potential are expected to emerge as more data (e.g. geochemistry, drill hole intersections of mafic and ultramafic rocks) with higher spatial resolution become available.

A key aim of the study is to highlight areas of the Australian continent where follow-up data acquisition is required to more fully determine the presence or otherwise of once-active ore-forming systems. Importantly, the results show possible extensions of several known magmatic Ni–Cu–PGE provinces under cover as well as a number of greenfields target areas where there are currently no known intrusion-hosted Ni–Cu–PGE deposits.

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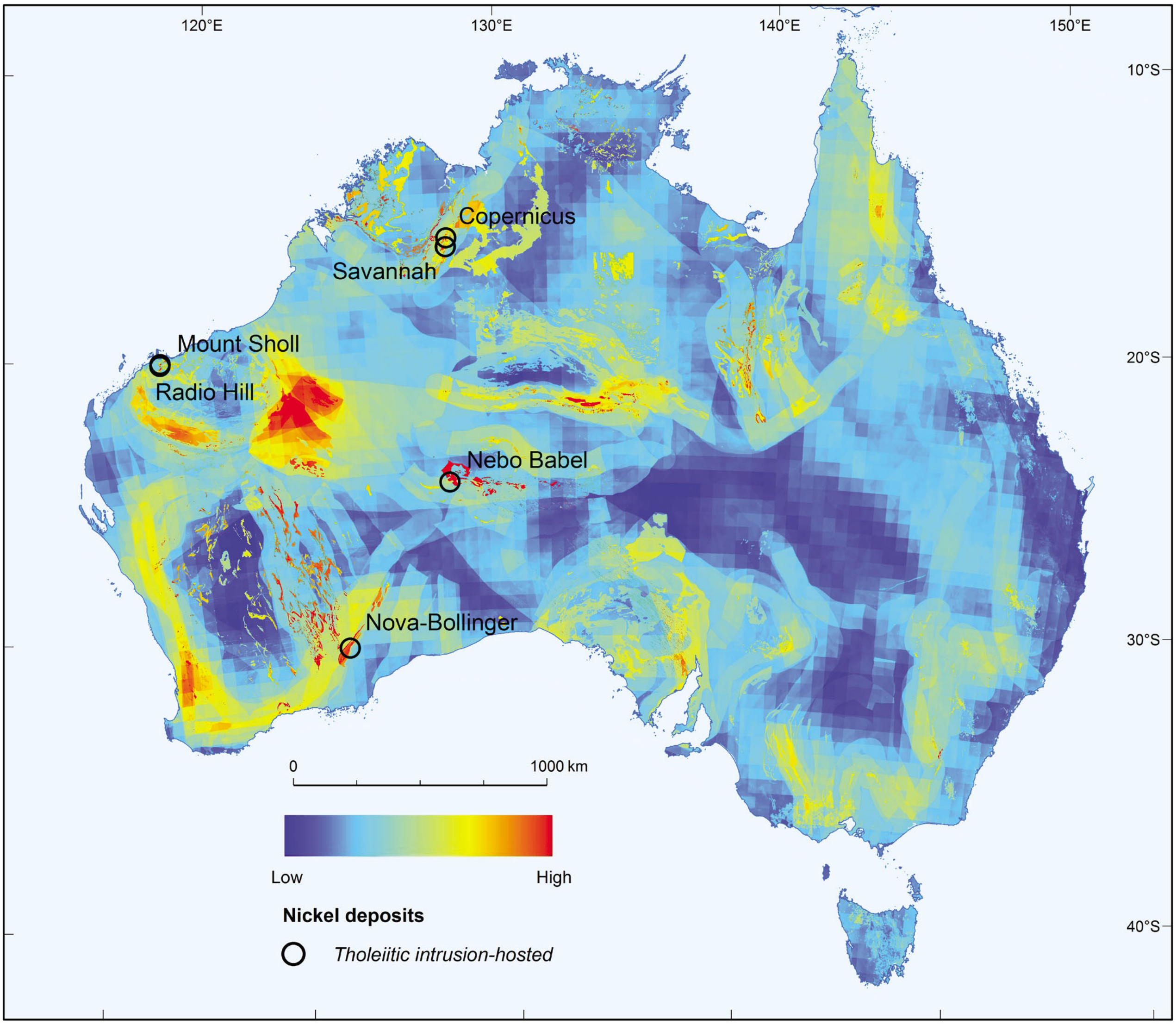

Figure 1. Map of potential for intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia (Dulfer et al., 2016)

The methodology applied in this continental-scale study of mineral potential is transferable to other mineral system types, and indeed several of the input datasets (e.g. crustal and lithospheric mantle architecture) will be of direct use in such modelling of other systems.

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The business of greenfields minerals exploration

by

John P. Sykes[1,2] and Allan Trench[1,3,4]

The minerals exploration sector is under strain. Junior explorers have struggled to raise funds, whilst explorers within larger companies have found budgets cut, or their roles eliminated entirely (Groves and Trench, 2014). Greenfields exploration, which is perceived to be higher risk, has been particularly badly affected.

In part, this is a response to negative external market factors (Groves and Trench, 2014). However, the exploration sector has also often provided unattractive returns (Wood, 2016), struggling with falling discovery rates, falling discovery quality and increased discovery costs (Bartrop, 2010; Groves and Trench, 2014; Wood, 2016). In addition, the exploration sector has faced newer challenges relating to environmentalism, native title, sustainable development and 'social licence to operate'. As such, explorers have found that the opportunities of globalisation have been more limited than expected (Franks et al., 2014; Sykes and Trench, 2016c).

It is, therefore, worth outlining the traditional business case for exploration, in particular, greenfields exploration, before considering a renewed business case for exploration that is better able to take on the challenges of the 'social licence to operate'. The aim of this review is to help the exploration sector outline to investors and corporate parents why they should fund greenfields minerals exploration and related research activities.

Better discoveries, not more resources

The traditional business case for greenfields exploration is the search for 'better' mineral deposits, not just 'more' resources (Schodde and Hronsky, 2006). Better mineral deposits replace existing poorer quality mines and projects, providing owners with a lasting competitive advantage (Sykes and Trench, 2015; Trench and Sykes, 2016). Greenfields exploration is, therefore, akin to 'disruptive innovation' (Christensen, 1997).

Whilst explorers are more likely to make a discovery in a brownfield environment; it is less likely to be a world-class discovery. Conversely whilst explorers are less likely to make a discovery in a greenfields environment, they are more likely to make a discovery of significance (Bartrop and Guj, 2009, Bartrop, 2010). The key value driver of greenfields exploration, therefore, is the discovery of better quality deposits. The value-generating role of greenfields discoveries has repeatedly been demonstrated in Australia over the last decade at DeGrussa, Nova-Bollinger and Gruyere, to name a few.

Prediction, not detection

To maintain its 'commercial licence to operate' (Andrews et al., 2016) the exploration sector must conduct exploration in an efficient manner, finding deposits more frequently and for lower cost. In this area, economic thinking, especially about decision-making theory (Eggert, 1993; Kreuzer, 2007; Guj, 2008; Kreuzer et al., 2008; Guj, 2013; Bynevelt, 2016) and improvements in detection technologies have been successful (Hronsky and Groves, 2008).

However, the focus on efficiency must not come at the expense of finding 'better' deposits. The key here is opening up new search space (Hronsky, 2009; Hronsky and Groves, 2008; Sykes and Trench, 2014a, Sykes et al., 2016b; Trench and Sykes, 2016). In a brownfields environment, the search space is mature so explorers can rely on direct detection technologies; however, in a new search space, there are no existing deposits to use as targeting proxies, so explorers, instead, have to predict where deposits should be. Such predictive exploration has both conceptual and technological components.

Mineral systems theory (McCuaig and Hronsky, 2014) has already helped explorers predict where undiscovered major deposits may lay in new search spaces. The focus has now moved to targeting 'ore quality' so that explorers can predict where the 'best' deposits are likely to be unveiled (McCuaig and Hronsky, 2014; McCuaig et al., 2014; Wood, 2016). Economic quality, however, does not simply mean focusing on ore grade; it is likely other geological factors, such as deposit geometry and homogeneity, will need incorporating into exploration targeting theory (Kanakis, 2014; Ulrich et al., 2016). Another area where economic thinking may be helpful is in the practical implementation of mineral systems theory within the industry (Davies, 2016). Technological advances are also required to identify mineral systems components in unexplored areas. Technology also has a role in opening up previously unreachable search space, such as deep under cover (Rowe and Seymon, 2015; DET CRC, 2016; Wood, 2016). Finally, as environmental and socio-political factors widen the definition of 'deposit quality' explorers will also have to better predict the presence of favourable environmental and socio-political

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conditions for exploration and mining (Sykes et al., 2016c).

Creativity, not analysis

The division of exploration into 'greenfields' and 'brownfields' is, however, unhelpful: instead, in line with sector economics, it can be divided into exploring for 'better' deposits and exploring for 'more' resource.

Initially, it seems that greenfields exploration is about finding 'better' deposits and brownfields exploration is about finding 'more' resource; however, only 'first-mover' greenfields exploration provides the consistent chance of finding better deposits by opening up new search space (Hronsky and Groves, 2008). The follow-up 'elephant country' (Hronsky and Groves, 2008) and re-evaluation (Bartrop and Guj, 2009, Bartrop, 2010; Wood, 2016) types of greenfields exploration can be successful over the shorter-term but are focused on filling in search spaces and thus conceptually similar to traditional brownfields exploration. Conversely, the creative re-invention of brownfields search spaces is an important way of re-generating search spaces. Conceptually this type of brownfields exploration is similar to 'first-mover' greenfields exploration, focused on seeing what others have not yet seen and thus being the first into a 'renewed' search space (Sykes et al., 2016a).

New environments which often lack good data for analytical thinking are more reliant on creative scientific thinking (Foster and Beaumont, 1992; Eggert, 1993) – 'hypothesis generation' takes primacy over 'hypothesis testing' in this situation (Sykes and Trench, 2014a; Sykes et al., 2016a). There needs to be a greater focus on developing creative scientific thinkers, and collaborating with truly 'big' and creative thinkers by the exploration community (Foster and Beaumont, 1992; Eggert, 1993; Sykes and Trench, 2014a; McCuaig et al., 2014; Sykes and Trench, 2014b; Craske, 2016).

Shared value, not just economic value

Irreversible technological and societal shifts over the last few decades mean that the traditional 'small' exploration model (Sykes et al., 2016c; Trench, 2016), based on maintaining its 'commercial licence to operate' by exploring for better deposits in a more cost effective and timely manner, is now out-dated. The exploration sector must maintain both its 'commercial licence to operate' and its 'social licence to operate' (Andrews et al., 2016). It must justify its commercial importance to corporate parents and investors, and its societal utility via the generation of shared value (Porter and Kramer, 2011) – the concept of 'big exploration' (Sykes et al., 2016c; Trench, 2016). Both a focus on technological innovation and societal contact can help explorers gain a 'social licence to operate'.

Explorers, as archetypal entrepreneurial teams have the opportunity to become technological first-movers (Trench, 2016). Technological entrepreneurialism should help improve exploration efficiency and find 'better' mineral deposits – the key to 'small' exploration. However, it also allows exploration teams to trial innovations before wider adoption by both their corporate parents, further securing the 'commercial licence to operate' and amongst wider society as a whole, helping secure the 'social licence to operate'. To become technological first-movers explorers will need an international focus, being abreast of global research trends. However, they will also need to be local innovators able to adapt new technologies to each local environment in which they operate, and where possible source local innovations and bring them to the world stage (Sykes and Trench, 2016a,b; Sykes et al., 2016c, 2017).

'Creative' exploration already has a key role in society, as the most likely source of the world-class discoveries that generate most of the mining industry's contribution to economic development (Schodde and Hronsky, 2006). Similarly, world-class discoveries are also likely to have a smaller unit footprint, helping minimise societal impact (Schodde and Hronsky, 2006). However, explorers themselves also have a critical role in securing the 'social licence to operate'. As the first point of contact in many areas, explorers are key to developing local relationships (Trench, 2016), where they must, at least, prevent the premature closure of search spaces due to societal conflict (Franks et al., 2014). However, local contact can also be a source of opportunity with the most adept explorers potentially able to open up search spaces unavailable to competitors (Sykes et al., 2016c).

Finally, in a globalised world, local problems quickly become international problems, and vice-versa. Thus explorers must be abreast of global environmental and socio-political trends (Sykes and Trench, 2016a,b; Sykes et al., 2016c, 2017). Again, this is partly to prevent the premature closure of search space due to conflict with governments and NGOs, but, again, it can also present an opportunity (Sykes and Trench, 2016a; Sykes et al., 2016b,c; Trench, 2016). Exploration is a key part of development aid (Collier, 2010), whilst mining is one of the few opportunities available for undeveloped economies and stagnated parts of developed economies to generate long-term economic growth (Collier, 2010). Thus there is the opportunity not only to source funds directly from development organisations but also to benefit from pre-competitive exploration research efforts (Sykes, 2015).

Co-opetition, not competition

Even if more explorers were to adopt the 'big' exploration approach, there remains a problem in its implementation. The negative activities of one company, team or even individual in a globalised world damages the reputation of all apparently 'similar' entities, whether this is justified or not (Sykes et al., 2016c). In such a situation, it is important to avoid a race to the bottom, with explorers focusing ever more on 'small exploration'. If explorers ignore shared value and just focus on short-term, narrow economic value, they will be limited to a shrinking range of prospects and beholden to a shrinking number of short-termist investors (Sykes et al., 2016c).

Explorers must, therefore, encourage collective 'big' exploration, by establishing partnerships with technologists, economists, environmentalists and social scientists; setting best standards for 'big' exploration; and training and rewarding explorers in an appropriately broad-minded manner — co-opetition (Brandenburger and Nalebuff, 1997), rather than strict competition.

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The future(s) of minerals exploration

by

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For a mineral resource to become a mine, not only must a geological discovery be made, the deposit must also prove economically viable, and environmentally and socio-politically accessible (Sykes and Trench, 2014a,b; Sykes, 2015a), as represented in Figure 1. Explorers should therefore aim to find ‘undiscovered accessible reserves’. The inherent complexity and uncertainty surrounding the future means it is not possible to predict exactly what the nature of ‘undiscovered accessible reserves’ will be several decades into the future. One suggestion is that explorers should therefore aim to develop ‘multiple working hypotheses’ (Chamberlin, 1890) about the future of mining to appropriately process this complexity and uncertainty. More specifically, it is suggested that they should develop ‘multiple hypothetical reserves’, as represented in Figure 2 — different ideas about currently undiscovered mineral accumulations that could extractable in the future (Sykes and Trench, 2014a; Sykes, 2015a). The Centre for Exploration Targeting ‘Future of Minerals Exploration’ scenarios program was launched with the aim of developing the idea of ‘multiple hypothetical reserves’ using the Oxford Scenario Planning Approach (Ramirez and Wilkinson, 2016). The initial results of the program are summarised below.

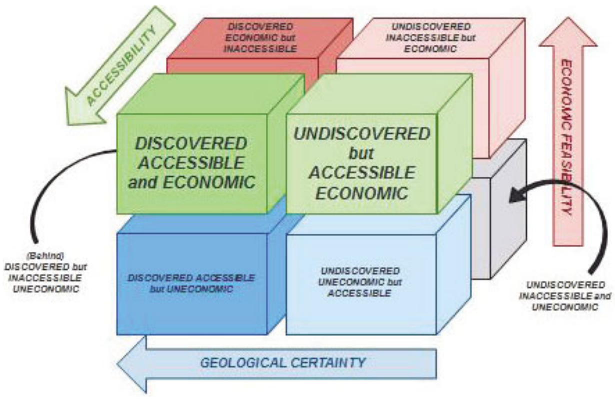

Figure 1. A categorisation of discovered and undiscovered mineral resources modified from Sykes and Trench (2014a)

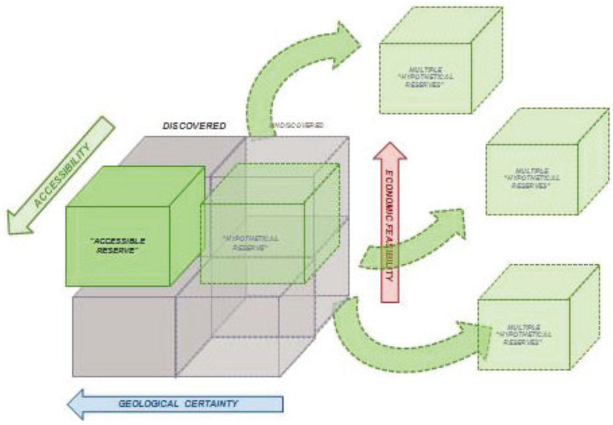

Figure 2. The concept of ‘multiple hypothetical reserves’ based on Chamberlin’s (1890) ‘multiple working hypotheses’ (Chamberlin, 1890) modified from Sykes and Trench (2014a)

Stage 1: testing industry adaptivity

The first stage aimed to develop a range of scenarios about the future of copper mining and then compare them to the leading copper mines and projects and their owners to determine how well the industry could adapt to multiple plausible, yet very different, futures (Sykes, 2015b; Sykes and Trench, 2015a,b,c,d; Sykes and Trench, 2016e; Trench and Sykes, 2016).

Two axes representing two key strategic levers for industry framed the scenarios:

1. **Short-term margin optimisation**: representing the battle between the industry’s technical capabilities and asset decline. Margins are either increasing or decreasing. Margin optimisation represents the short-run future of the industry (Maxwell, 2013).

2. **Long-term idea space generation**: this represents all that is unknown and yet to be discovered about the industry but will nonetheless have a major impact in the very long-run future (Maxwell, 2013). The idea space is either expanding or contracting.

Four scenarios represented the end members of these axes, summarised in Figure 3 and below:

- **Under Siege**: poor short-term performance leads to a lack of investment in the long-term, with few new ideas generated. The industry goes into decline (Sykes and Trench, 2015a; Trench and Sykes, 2016).

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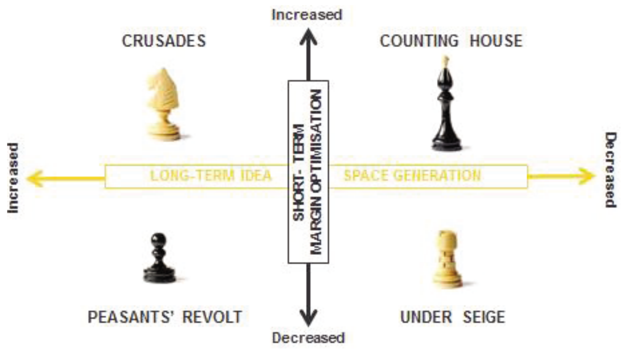

Figure 3. The four scenarios developed in Stage 1 of the CET 'Future of Minerals Exploration' scenarios program modified from Sykes and Trench (2016e)

- **Crusades**: substantial short-term profits allow for successful investment in a range of new ideas, strengthening the industry over the long run (Sykes and Trench, 2015d; Trench and Sykes, 2016).
- **Counting House**: a profitable industry focuses solely on more short-term profits and thus goes into a gradual, albeit initially profitable, decline (Sykes and Trench, 2015b; Trench and Sykes, 2016).
- **Peasants' Revolt**: a struggling industry nonetheless manages to re-invent itself with thrifty, yet bold, innovation, passing into a successful but very different, long-term future (Sykes and Trench, 2015c; Trench and Sykes, 2016).

When 'wind-tunnelled' against each of these scenarios (Erdmann et al., 2015; Ramirez and Wilkinson, 2016), no copper mine, project or company was robust against multiple futures. The industry is, thus, strategically brittle. This leaves the industry with two options:

1. Create portfolios from the numerous brittle assets to make an overall robust portfolio in line with modern portfolio theory (Markowitz, 1952) and generally focusing on the 'margin optimisation' asset lever;
2. Generate new ideas as to what a robust mine may look like focusing on the 'idea space' strategic lever and thus the core competencies of the industry (Prahalad and Hamel, 1990).

Stage 2: generating a path to the future

Mining industry strategic thinking is generally asset and portfolio orientated (Sykes and Trench, 2016a,d) so a focus on industry capabilities seemed more likely to be fruitful in developing new ideas. The next scenarios therefore looked at the whole mining industry and its professional capabilities (Sykes and Trench, 2016b; Wright et al., 2016; Sykes et al., in press).

Old World is the scenario in which we live currently. This world is unsustainable, but it is not clear how long it will last: years, decades, longer? Three scenarios were developed along a pathway to the future, as pictured in Figure 4:

- **The Transition**: eventually the new world arrives. However, it is neither fully predictable when it will arrive nor possible to see clearly what world lies beyond the transition.
- **Wonderland**: what can be said about the world beyond is that there are two broad types of transition: voluntary and forced (van der Heijden, 2004). The Wonderland scenario describes a business-driven transition in which only the most aggressive innovators survive.
- **Battlefield**: in the other scenario, the 'Western' world is forced through an energy transition as global turmoil means petroleum supplies are dramatically curtailed. The West eventually responds by developing a state-led self-sufficient green economy.

In order to operate in all three scenarios, two key capability sets were highlighted:

1. Working at a high-level with government;
2. Working on the ground with emerging innovators.

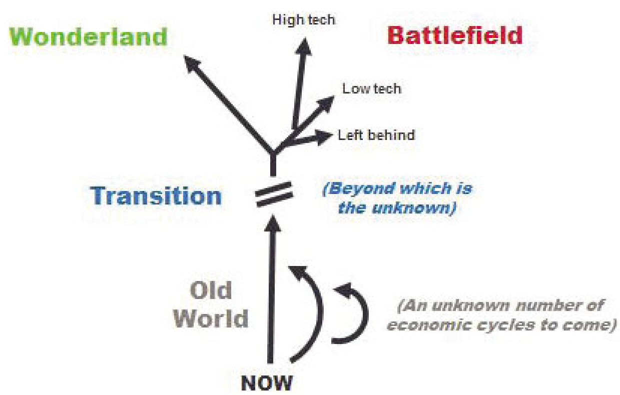

Figure 4. The three scenarios and strategic pathway to the future developed in Stage 2 of the CET 'Future of Minerals Exploration' scenarios program after Wright et al. (2016)

Stage 3: transforming the future

The determination in this workshop (Sykes and Trench, 2016c; Sykes et al., 2016), contrary to previous workshops, was that technology and skills play an important role in building the mining industry's reputation (i.e. social licence to operate). Explorers must not just focus on their 'commercial licence to operate' (Andrews et al., 2016), previously dubbed 'small exploration' (Trench, 2016) by simply finding more mineral deposits, quickly and cheaply: they must also work on securing their 'social licence to operate'.

Two scenarios were developed, shown in Figure 5, that describe the results of focusing only 'commercial licence to operate' and, instead, focusing on both the commercial and 'social licence to operate':

- **Two Peoples**: in this scenario, the mining industry is trapped in a cycle of revolution and counter-revolution between a well-educated, technologically sophisticated elite and the masses.
- **iWorld**: in this scenario, the mining industry is able to help society break the cycle of revolution, with technology and education used to create a sophisticated, well-educated, wealthy, yet relatively egalitarian society.

The ability to use technology and social contact, at both international and local scales, in order to secure the exploration and mining industry's 'social licence to operate' is known as 'big exploration' (Trench, 2016). In this scenario set, 'big exploration' is used to 'break the cycle' and move into the preferred 'iWorld' scenario, whilst 'small exploration' reinforces societal inequity and traps the world in the 'Two Peoples' scenario.

However, an important realisation for explorers wanting to pursue 'big exploration' is that the industry remains vulnerable to collective liability, where the negative actions of one company, team or individual can damage the 'social licence' of everyone in the industry, whether justified as not. 'Big explorers' therefore need to encourage the whole exploration sector to become involved in the movement. At this stage, the workshop had become a 'transformative' scenario planning workshop (Kahane, 2012) and so the effort required was dubbed 'transformative exploration' (Sykes et al., 2016).

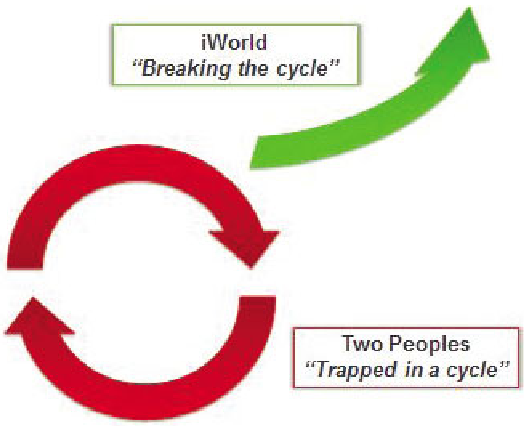

Figure 5. **The two scenarios and systemic interaction developed in Stage 3 of the CET 'Future of Minerals Exploration' scenarios program after Sykes et al. (2016)**

Stage 4: bringing it all together

The final scenarios workshop examined how strategic thinking about the future of exploration had changed since Stage 1 and if there were now any viable robust strategies.

The scenarios were based on two socio-economic axes:

1. **Economic versus shared value**: whether the role of business is to generate profits for shareholders (economic value) or for wider society (shared value: Porter and Kramer, 2011).
2. **Globalisation versus global division**: whether the world is focused on globalisation and free trade, or division and protectionism.

Four scenarios were developed, exploring the extremes of the two axes (also portrayed in Figure 6):

- **(Green) Nirvana**: represents a liberal, globalised world, which has transitioned into a green economy and achieved both wealth creation and re-distribution, with strong international institutions providing a guiding hand.
- **Money, Money, Money**: represents a globalised world, but one in which strict economic value rules. Due to government financial problems, major international corporations have stepped into the governance gap.
- **Culture Club(s)**: sees a divided world, with each faction responding to environmental and social challenges in its own way, triggering a cultural 'Cold War'.
- **Rebel Yell**: again sees a divided world, but this time one in which a 'hot war' between major geopolitical blocks breaks out. The environment and local communities become subservient to national survival.

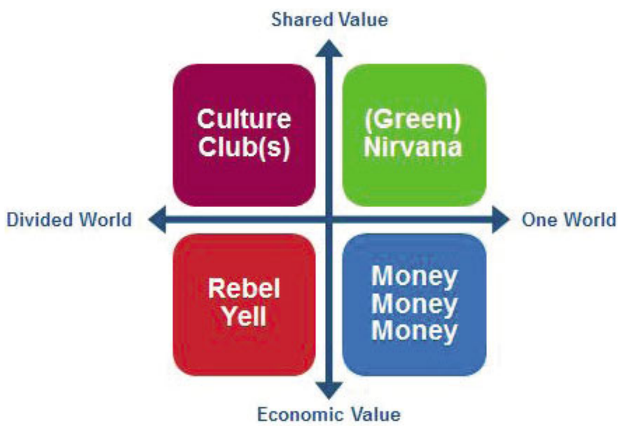

Figure 6. **The four scenarios developed in the final Stage 4 of the CET "Future of Minerals Exploration" scenarios program**

Preliminary conclusion: a sector unable to see what is already here

Although the workshop results are still being processed, what already appears clear is that the 'adaptive' approach focused on identifying 'multiple hypothetical reserves' has proved very challenging. This is likely partly because assets are the most common focus of mining and exploration industry strategy so there is more limited scope for innovation, and partly because some aspects of the future are simply unforeseeable, which creates too much uncertainty to pin hopes on one asset type.

Finally, it is plausible that the industry is currently not capable of seeing the future, even if it is already visible to permissive eyes. It does appear that whilst explorers seem confident in their understanding and control over scientific and technological development, this is not the case with socio-economic change. Much of the workshops were devoted to discussing exploration competencies and socio-economic change. It is perhaps in this area that the future of exploration will be generated.

The exploration sector's current predicament may best be summarised by an anecdote from a workshop participant on the decline of Sydney Ferries Limited: once the world's largest ferry company. The company quite literally failed to see the future being built behind them in the shape of the Sydney Harbour Bridge. After the bridge opened in 1932, ferry use dropped from 30 million passengers to 13 million passengers almost overnight (Wikipedia, 2016).

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Tracing sulfur sources in the Agnew gold camp: an illustration of Archean orogenic gold deposits diversity

by

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Introduction

In the highly metal-endowed Yilgarn Craton of Western Australia, field-based structural reviews and geochronological datasets obtained on Precambrian orogenic gold provinces point toward multiple periods of mineralisation developing continuously during a period ranging from c. 2670 to 2630 Ma (Thebaud and Miller, 2015). The key question remains as to what is the metal and/or fluid source? Proposed fluid sources include proximal source models, in which ore fluids are derived from mid- to upper-crustal granitoids (e.g. Doublier et al., 2014), and distal models, in which gold-bearing fluids were derived from deep metamorphic (e.g. Phillips and Powell, 2010) or, distal magmatic/mantle fluids (Salier et al., 2005). Whereas orogenic lode-gold deposit fluid inclusions studies favour a single ore-fluid source, isotopic and noble-gas data suggest a diversity of potential fluid compositions (Goldfarb and Groves, 2015).

Accordingly, isotopic investigation focused on sulfur, one of the critical elements commonly associated with gold mineralisation, in order to fingerprint its potential source reservoir/s (Alt et al., 1993). However, because $\delta^{34}S$ isotopic variation is sensitive to chemical processes, the measured orogenic ore-fluid compositions may reflect the influence of fluid–rock interactions along fluid pathways and ore-depositional processes at the deposit site rather than being indicative of its source (e.g. Ridley and Diamond, 2000; Hodkiewicz et al., 2009). Recent developments in the acquisition of mass-independent fractionation of sulfur (MIF-S) offer an isotopic signature unique to a single reservoir, the Archean sedimentary record (Farquhar et al., 2000), that is chemically conservative and, importantly, not affected by the dynamic chemical processes. Recently, MIF-S has been identified in Archean orogenic gold deposits (e.g. Agangi et al., 2017), demonstrating that some orogenic gold deposits source a portion of their sulfur from Archean sediments. Here, we further this observation by presenting a camp-scale, multiple sulfur-isotope study from sulfides in equilibrium with gold mineralisation in three distinct deposits in the Agnew Gold Camp: the Waroonga, Turret, and Songvang deposits. We combine deposit-scale structural observations and constraints on mineralisation ages with multiple sulfur-isotope data to lend insight into the diversity of fluid reservoirs at play in the rapid formation of a world-class orogenic gold camp.

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The Agnew Gold Camp

The Agnew Gold Camp sits in the southwest corner of the Agnew–Wiluna belt in the Eastern Goldfields Superterrane (Fig. 1), and consists of a moderately to tightly folded greenstone belt. Supracrustal rocks comprise a basal interlayered greenstone pile that consists of fine-grained tholeiitic basalt, high-Mg basalt, ultramafic rock, and gabbro, gabbro–pyroxenite and peridotite sills, with minor interbedded sedimentary layers, deposited between c. 2720 Ma and 2690 Ma (Sapkota, 2016a). The upper greenstone sequence is the Scotty Creek sequence and comprises polymictic conglomerate and quartzo-feldspathic sandstones (Sapkota, 2016b). Coarse beds from the Scotty Creek sequence near the New Holland – Genesis deposit (Fig. 1) host detrital zircons that provided a maximum depositional age for the sandstone of 2664 ± 5 Ma, with an inherited zircon population ages of 2700–2690 Ma and 2820–2810 Ma (SHRIMP U–Pb on zircon: Dunphy et al., 2003). Granitoids intrude the hinge of the Lawlers antiform through successive pulses dated at 2690 ± 6 Ma, 2665 ± 4 Ma and 2622 ± 6 Ma (SHRIMP U–Pb on zircon: Champion, Geoscience Australia, unpublished, 2003; and Thébaud et al., 2013).

On the western limb of the Lawlers Antiform, the NNE-trending Emu Shear zone hosts or is close to the majority of existing high-grade Au deposits (Aoukar and Whelan, 1990). These include, from north to south, the New Holland – Genesis, the Waroonga, the Turret, the Redeemer, the Crusader, and the Songvang deposits. For each of these deposits, gold mineral assemblage exhibits large variability including magnetite-rich quartz and sulfide-poor Au mineralisation at Crusader, a gold- and silver-rich system with biotite–fluorite–amphibole–chalcopyrite in Songvang, gold- and copper-rich system with carbonate–chalcopyrite breccia in Turret, and quartz–arsenopyrite–pyrite–biotite–amphibole in the New Holland – Genesis, Waroonga, and Redeemer deposits.

Combining structural geology together with targeted geochronology, Thébaud et al. (2013) demonstrated that mineralisation developed over a two-stage process coeval with the formation of the Lawlers Antiform during regional E–W contraction. The initial event was dated at c. 2662 Ma in the Songvang deposit and has affinities with magmatic intrusion-related mineralisation. The second mineralisation

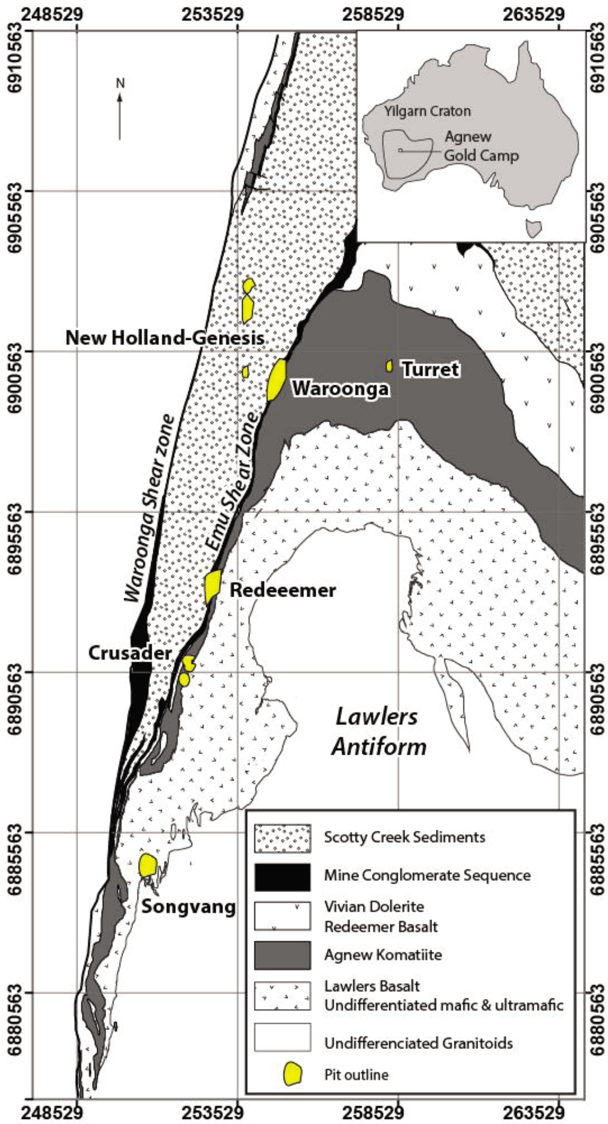

Figure 1. Geological map of the Agnew Gold Camp

event was dated in both Redeemer and Turret to be c. 2625 Ma, which is coeval with typical Archean orogenic-like gold mineralisation, and has developed at a late stage of the Lawlers Antiform formation. Together with the atypical mineral assemblage associated with some of the deposits investigated (Crusader, Songvang, Turret), the coeval emplacement of successive magmatic pulses in the Lawlers antiform were interpreted as key drivers for the ore formation process (Thébaud et al., 2013). The model proposed that mineralisation developed during a polyphased and protracted process involving contrasting fluid sources. In the absence of direct fluid tracers, it remained, however, difficult to ascertain the involvement of a magmatic source.

Methods

In order to further assess the fluid sources at play in the formation of orogenic gold deposit in the Agnew Gold Camp, three deposits were further investigated using in-situ sulfur isotope techniques on the basis of their contrasted style of mineralisation. Characterisation of <50 µm sulfides by Energy-dispersive X-ray spectroscopy, and identification of fractures, inclusions and zoning by backscatter electron (BSE) imaging occurred using a FEI Verios 460 XHR SEM under conditions of 15 kV with a focused 6.0 nA beam at the CMCA, University of Western Australia (UWA). Multiple sulfur isotopic ratios were determined using a CAMECA IMS1280 large-geometry ion microprobe located at CMCA–UWA. Mounts (25 mm diameter) were made by coring pucks (3.2 mm in diameter) of rock and casted in epoxy. After polishing, mounts were coated with 30 nm of Au and loaded with a standard block into the sample chamber. A 3.7–4.6 nA focused Cs+ primary beam interacted with the sample at 20 keV. The beam, in Gaussian mode, bombarded the sample surface to create a 15 µm analytical pit. Isotopes 32S, 33S and 34S were simultaneously detected by three Faraday Cups using amplifiers with 1010 Ω (L'2), 1011 Ω (L1), and 1011 Ω (FC2 or H1) resistors. Data were collected over 123 s of acquisition time in 20 integration cycles. Measurements were interspersed with Sierra pyrite ($\delta^{34}S$ = +2.17‰, $\Delta^{33}S$ = −0.02‰) to correct for drift and monitor internal sample repeatability. As well, analyses of matrix-matched reference material were used to calibrate isotope ratios following procedures in LaFlamme et al. (2016). Measurement error on $\delta^{34}S$ is equal to about ~0.4‰ and on $\Delta^{33}S$ is ~0.25‰.

Results and Conclusions

Sulfur isotope analyses of three of the deposits forming the Agnew Gold Camp yield contrasting $\delta^{34}S$ values. $\delta^{34}S$ variations across the deposits is consistent with that of Archean orogenic gold deposits and may illustrate processes specific to the deposition site and therefore difficult to attribute to a specific source (Palin and Xu, 2000; Hodkiewicz et al., 2008). MIF-S signature, in contrast, exhibits internally consistent MIF-S signatures specific to each of the deposits investigated. Songvang Au mineralisation assemblage dated at 2662 ± 7 Ma exhibits restricted $\Delta^{33}S$ values with a mean value calculated at 0.03 ± 0.12 ‰ (2σ). Together with the atypical metal inventory associated with this deposit, the MIF-S values obtained on Songvang mineral assemblage suggest a sulfur source that has not undergone mass-independent fractionation pointing toward a mantle-derived sulfur source (Farquhar and Wing, 2003).

Samples from the Waroonga deposit, interpreted to have formed at 2636 ± 8 Ma, return consistently positive $\Delta^{33}S$ signature ranging from 0.08 ‰ to 0.55 ‰. Such positive $\Delta^{33}S$ values imply that the sulfur source interacted with

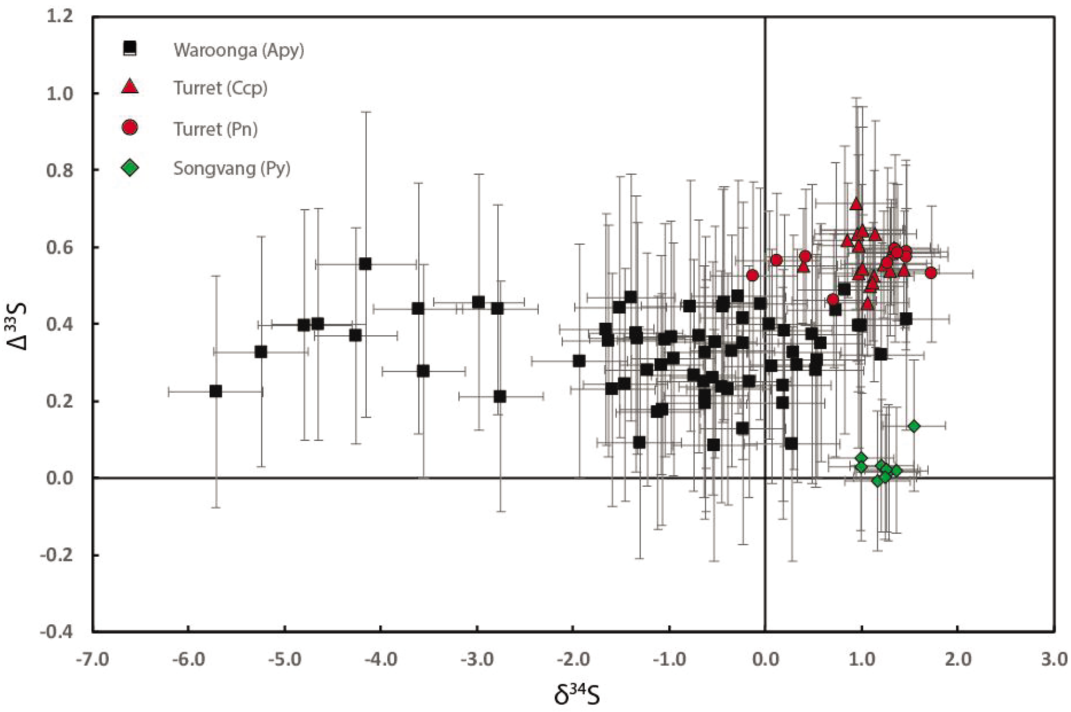

Figure 2. Multiple sulfur isotope results from gold related sulfides from the Waroonga, Turret and Songvang deposits

the Archean atmosphere, causing the mass-independent fractionation processes (e.g. Farquhar et al., 2000) and therefore suggest that sulfur in the Waroonga deposit was at least partially derived from a sedimentary reservoir.

Finally, the Turret deposit, associated with overprinting alteration stages, shows a rather more complex $\Delta^{33}S$ distribution. Ccp and Po associated with the early alteration stage preserving a weighted mean value $\Delta^{33}S = 0.11 \pm 0.2$ ‰ (2σ). With $\Delta^{33}S$ values close to 0 ‰, the early alteration in the Turret deposit associated with Cb, Ccp and Po mineralisation present affinity with a sulfur reservoir that has not undergone mass-independent fractionation and therefore akin to a mantle-derived source rather than solely crustal derived. Stage 2 of Turret alteration record is associated with gold mineralisation dated within error to Redeemer/Waroonga mineralisation at 2622 ± 12 Ma. In situ multiple sulfur isotope analysis returned positive $\Delta^{33}S$ values with a weighted mean at 0.55 ± 0.06 ‰ (2σ), suggesting that sulfur in the Turret deposit was partially derived from a sedimentary reservoir.

Our study confirms that the Agnew Gold Camp resulted from the protracted and polyphased mineralisation process that took place over ~40 m.y. and is associated with contrasted $\Delta^{33}S$ signatures pointing toward contrasted fluid and or metal sources. In the case of the Songvang deposit, MIF-S values are compatible with a magmatic sulfur reservoir whereas deposits such as Waroonga and Turret exhibit positive $\Delta^{33}S$ signature, implying a sedimentary contribution to the sulfur budget. The latter results greatly contrast with the initial interpretation proposed for the Turret deposit and suggest a magmatic affinity. It is, however, notable that although a nil $\Delta^{33}S$ value must highlight a mantle-derived source reservoir, positive $\Delta^{33}S$ values could be acquired through fluid–rock interaction processes as deeply sourced fluids percolate through the crust.

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Linking seismic images to geology in mineralised terrains

by

Turner[1*], G, Hird[1], G, Kinkela[1], J, Neild[1], J and Zulic[1], S

Seismic reflection methods potentially offer a revolutionary view of the subsurface in known areas of mineral endowment (e.g. near-mine exploration). This is due to the high resolution images that can be obtained at depths well in excess of those that can typically be investigated by more conventional geophysical tools applied to mineral exploration.

For all geophysical methods, including seismic, the key to linking images to geology is an understanding of the controls on physical property variations in the subsurface. Until recently, the available data on seismic properties in mineralised terrains have been sparse and typically restricted to a few measurements in significant lithologies.

In recent years, HiSeis has been routinely acquiring detailed seismic rock property data from drill core and downhole measurements in a wide variety of terrains. These data sets commonly show considerable variation in seismic properties within individual lithological units indicating that the technique is sensitive to more than just lithology itself. An understanding of these variations has enabled much richer geological information to be extracted from 2D and 3D seismic reflection data sets.

Some of the variations that have been observed have been correlated with:

- differing types of alteration
- differing intensities of alteration (e.g. see Figure 1)
- changes in mineralogy
- changes in fracture density (e.g. see Fig. 2)
- changes in grain alteration
- changes in porosity
- changes in grain size

In our presentation, we will show examples of measurements that highlight these variations and demonstrate how how these manifest in seismic images. Case histories will be drawn mainly from Australian gold deposits and will illustrate the ability of seismic to map potential fluid sources, conduits, traps and favourable host lithologies. This information provides direct input for exploration targeting and geological modelling as well as valuable geotechnical information for mine planning.

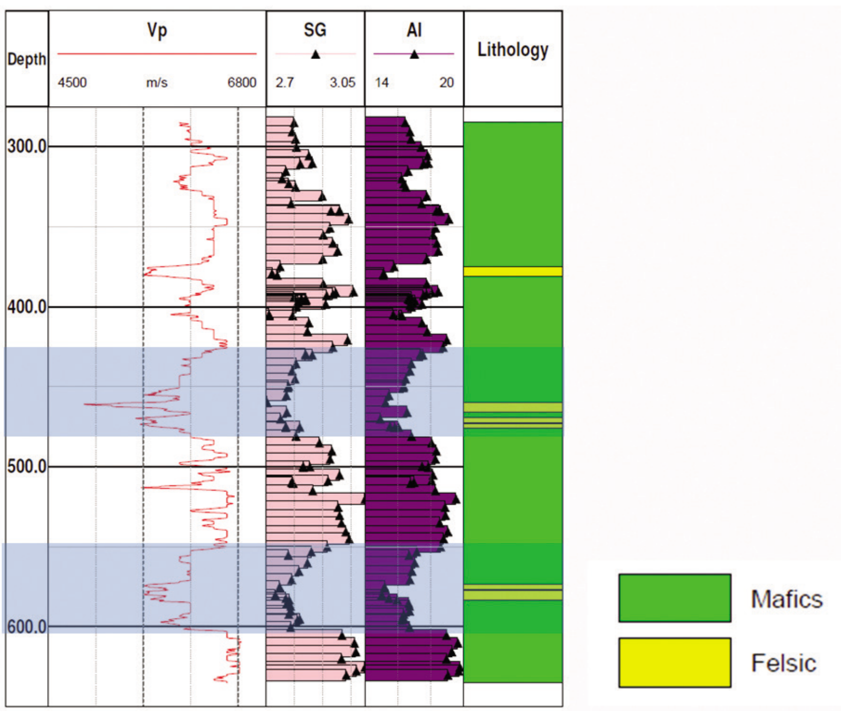

Figure 1. **Example from the Yilgarn in WA of seismic rock property variations within a lithological unit. This example highlights zones of the significant reduction in AI within mafic rocks around some felsic intrusives. We infer the reduction to be due to alteration from fluids associated with the intrusives. The alteration greatly enhances the reflectivity associated with these felsic intrusives. We infer that there is considerably less alteration around the upper felsic intrusive which would therefore have lower reflectivity. The difference in reflectivity may therefore assist in identify changes related to prospectivity. (Vp = seismic P wave velocity, SG = density, AI = acoustic impedance)**

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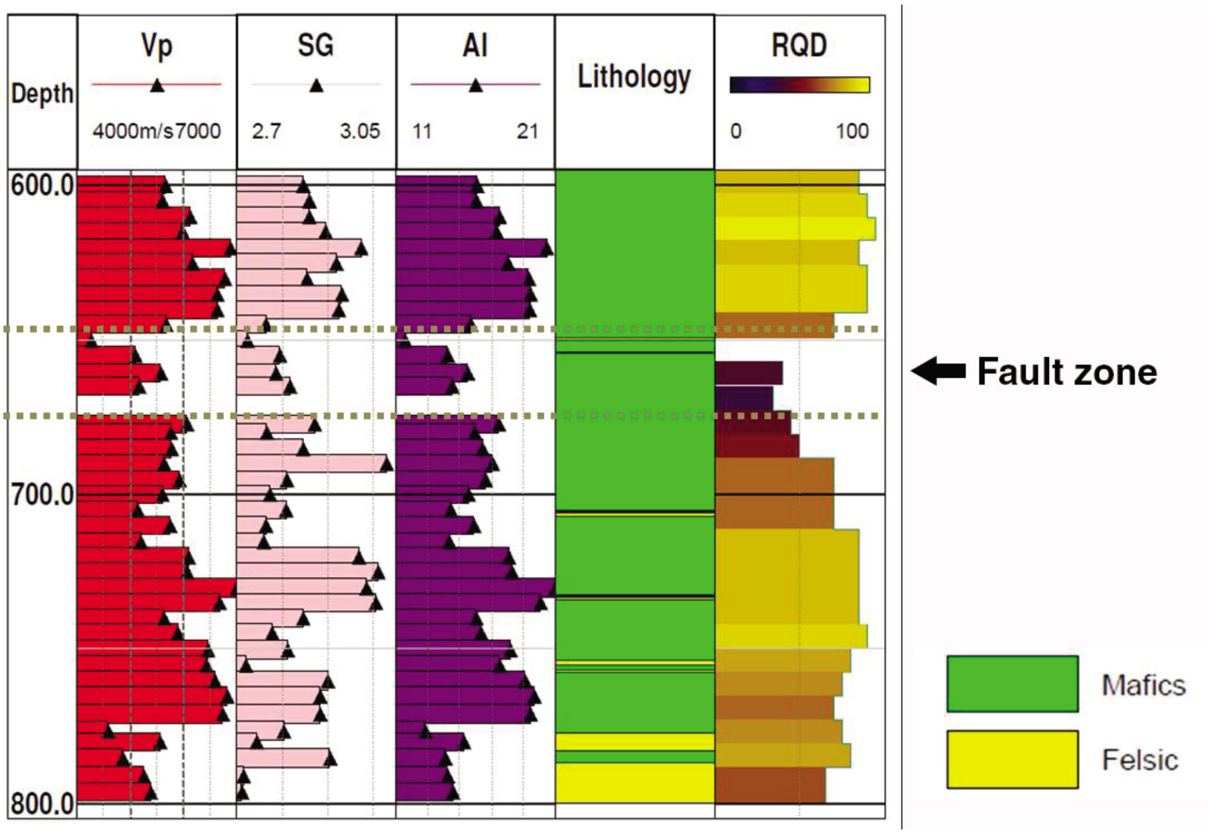

Figure 2. Example from the Yilgarn in WA of seismic rock property variations within a lithological unit. This example highlights a zone of the significant reduction in AI through a zone of increased fracturing associated with a fault zone. The magnitude and thickness of the zone is sufficient to generate a seismic reflection. (Vp = seismic P wave velocity, SG = density, AI = acoustic impedance, RQD = rock quality designation or measure of degree of fracturing)

Refractory Au in arsenian-pyrite and arsenopyrite in the Pataz gold deposit: resource and metallurgical implications

by

Francois Voute[1*], Steffen Hagemann[1], Tony Kemp[1], Nicolas Thébaud[1] and Carlos Villanes[2]

Pyrite is a common and abundant constituent of hydrothermal mineralization in ore systems including epithermal gold, orogenic gold, porphyry copper, iron oxide copper gold (IOCG) deposits and intrusion-related gold systems. Complex textures in pyrites, including oscillatory growth and sector zoning is commonly associated with incorporation of elements both in solid solution and in nanoparticles. Therefore, pyrite not only scavenges metals but also reflects the hydrothermal fluid composition changes through time which can be potentially used as a vectoring tool in mineral exploration. This study emphasizes the importance of quantifying in-situ gold concentration in pyrite and arsenopyrite from the Pataz deposit using new and innovative analytical methods.

The Pataz goldfields are located 470 km north of Lima, on the eastern side of the Marañón Valley, in the Paleozoic Eastern Andean Cordillera of the northern Peruvian Andes. A total of 8 Moz Au has been produced over the past 100 years from more than 20 underground mines. Gold mineralization at Pataz consists of quartz–carbonate–sulfide (pyrite–arsenopyrite–galena–sphalerite–chalcopyrite) veins hosted by the dioritic to monzogranitic Pataz batholith. Significant variations in thickness, texture and sulfide content have been observed along major veins. These include the alternation of: (1) laminated quartz vein with minor pyrite and arsenopyrite content (<5 vol %) returning a grade of less than 5 g/t gold, and (2) massive to brecciated pyrite, arsenopyrite and base metals sulfides representing up to 70 vol.% of the vein returning up to several hundreds of g/t gold. Vein formation began with deposition of pyrite and arsenopyrite. The veins are then fractured and infilled by galena, sphalerite and minor chalcopyrite. Visible gold consists of electrum, mainly hosted in fractured pyrite and arsenopyrite but also more rarely as inclusions in chalcopyrite and sphalerite.

Scanning Electron Microscopy with backscattered electron imaging of pyrite and arsenopyrite shows complex oscillatory zoning (Fig.1a). Based on textural observations, three generations of pyrite and two generations of arsenopyrite have been distinguished. In-situ sulfides analyses have been completed by Electron Probe MicroAnalyser (Fig.1b) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry to quantify gold and other trace elements (Fig.1c). Mineral chemistry results show: (1) As-poor pyrite characterized by relatively high base metal content (e.g. ~4000ppm Zn, ~200ppm Cu, and ~100ppm Pb), low arsenic (~30ppm), and low gold concentration (<0.3ppm Au); (2) As-rich pyrite (1 to 2.5% As) with moderate gold (5 to 30ppm Au) and relatively low base metal (<10ppm Zn, Cu and Pb) concentration; (3) Au-poor arsenopyrite (~1.5ppm Au); and (4) Au-rich arsenopyrite (80 to 150ppm Au).

In the Pataz gold deposit, sulfides can represent up to 70 volume % of the vein; therefore submicroscopic gold contained in the predominantly pyrite and arsenopyrite represent a significant quantity of refractory gold which directly impact on resource estimation. The identification of gold complexing with arsenic-rich sulfides offers a specific pathfinder element in geochemical exploration.

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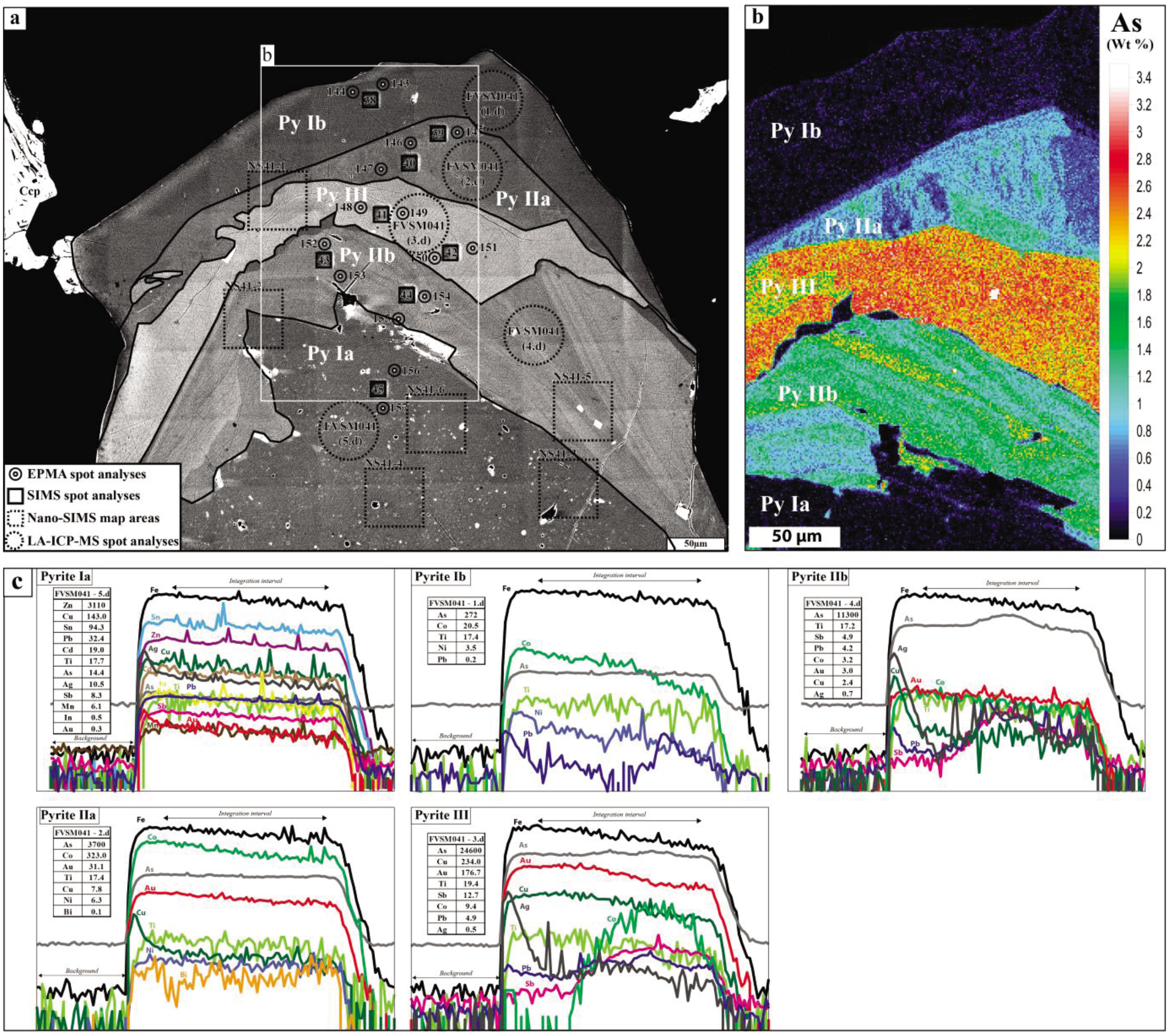

Figure 1. a) Backscattered image of pyrite grain showing complex zoning textures and in situ analyses locations; b) arsenic EPMA distribution map; c) LA-ICPMS spectrum and associated quantification

Mapping basement through deep conductive cover by audio and broadband magnetotellurics

by

Liejun Wang[1*], Jingming Duan[1] and Tristan Kemp[1]

In recent years, Geoscience Australia, in partnership with State and Territory Geological Surveys, has applied the magnetotellurics (MT) method to understand the depth and nature of sedimentary cover and the extent of highly-prospective basement rocks underneath, for the discovery of new resources as part of the UNCOVER initiative.

Methods

The Audio frequency MT (AMT) and Broadband MT (BBMT) methods are passive electromagnetic (EM) techniques that utilise variations of the Earth's natural magnetic and electric (telluric) fields in a frequency range from 10 kHz to 1 Hz (AMT), and 1 kHz to 0.001 Hz (BBMT). AMT and BBMT target accessible depths of the crust where the exploration depth depends upon the frequencies sampled and local resistivity distribution. For example, most of the resistivities in the Australian sedimentary basins fall in a range from 10 Ω·m to 103 Ω·m. Their corresponding electromagnetic skin depths (δ) at 1 Hz are from 1.5 km to 15 km; the exploration depth of the MT is a fraction of a skin depth with a rule of thumb being δ/10. Therefore, AMT can achieve the depths of ~150 m to ~1500 m at 1 Hz. Similarly BBMT can achieve the depths of ~5 km to ~50 km at 0.001 Hz. MT sounding data were collected near existing drillholes throughout different regions of Australia. These data were used to determine the depth to basement (DTB) or cover thickness, as well as imaging the basement architecture. Results of the MT method were then benchmarked against other methods and actual results from drilling.

Example from the Thomson Orogen

The basement rocks of the Thomson Orogen are concealed under thickly stacked Middle Palaeozoic to Mesozoic sedimentary basins, which include, from top to bottom, the Early Jurassic to Late Cretaceous Eromanga Basin, the Permian to Triassic Cooper and Galilee Basins and the Devonian Adavale Basin (Spampinato et al., 2015). A total of 458 stations were acquired, mainly in three BBMT (199 sites) and four (259 sites) AMT 2-D survey lines (Wang et al., 2016). The BBMT model of Line 1, presented in Figure 1, mapped the resistivity structure of the upper and lower crust including the gross architecture of the covering basin. Blue and purple colours in Figure 1 denote highly resistive basement, and orange and red colours indicate the conductive Mesozoic and Cenozoic sedimentary basin cover. The AMT data at the same profile defined the cover sequence in higher spatial resolution and was able to penetrate at least one kilometre beneath the surface of the Earth (Fig. 1). The outcrop of granite between distances of 35 km to 45 km along the profile in Figure 2 is successfully imaged.

Example from the Georgina Basin

AMT data were obtained from several profiles which are orthogonal to the regional south–north geological strike at a site spacing of 500 m over the Georgina Basin (Fig. 2, bottom right). The AMT profile line 1800 is about 30 km to the south of 2006 06GA-M6 seismic line (Fig. 2, bottom left), in parallel with a section from CDP12 000 to 16 500 (Gibson et al., 2015). Interpretation of the section (CDP 12 000 to 16 500) reveals the top Cenozoic and younger succession in the basin thickens towards the east with the strata being relatively flatlying, and the lowermost Cambrian sequence overlies a major angular unconformity above Proterozoic basement. The AMT electrical conductivity model (Fig. 2, top) provides a detailed image of the sedimentary succession: a shallow, highly conductive overburden layer 10 Ω·m overlies relatively resistive layers of a few hundred Ω·m to a depth of 100 m in the middle of the profile. Conductive layers (50 Ω·m) within depths of 100 m to 200 m provide a thin, patchy veneer of higher conductivity in several places. On the eastern margin, the conductivity model shows the eroded section of the conductive layers, which dip to the east at the end of the profile. The underlying elements of basin stratigraphy shows as relatively resistive. The base of the Georgina Basin is interpreted by the change from ~300 Ω·m to ~1000 Ω·m at depths of 600 m to 800 m.

Conclusion

Magnetotellurics is a cost-effective method for exploring to great depths. Geoscience Australia has applied magnetotellurics to determine the nature and thickness of cover and to characterise the basement architecture in regions around Australia. The depth of cover assessments produced by MT surveys agrees with depth of cover assessments made by other geophysical techniques, e.g. Airborne Electromagnetic (AEM) for the top 100 m (Roach, 2015), GABWRA (Ransley and Smerdon, 2012), and is being tested by an ongoing program of stratigraphic drilling.

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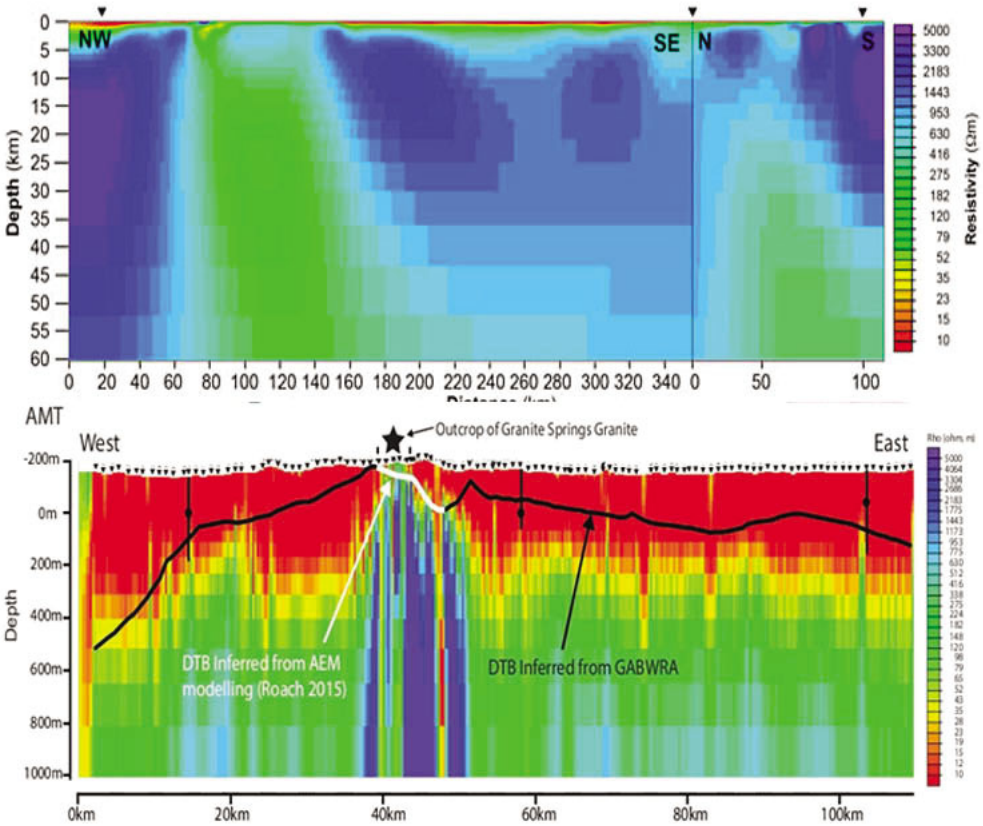

Figure 1. Top panel: Thomson Orogen: A 2D model for BBMT line 1. Blue and purple colours denote highly resistive basement, and orange and red colours indicate the conductive Mesozoic and Cenozoic sedimentary basin cover. Bottom panel : AMT model of Thomson Orogen Zoomed-in area of the BBMT model (top) from NW 60 km to 160km to a depth of one kilometre. Interpreted depth to basement (DTB) was compiled by Folkes (2016) from the GABWRA model (Ransley and Smerdon, 2012) and the AEM interpretation (Roach, 2015)

Acknowledgement

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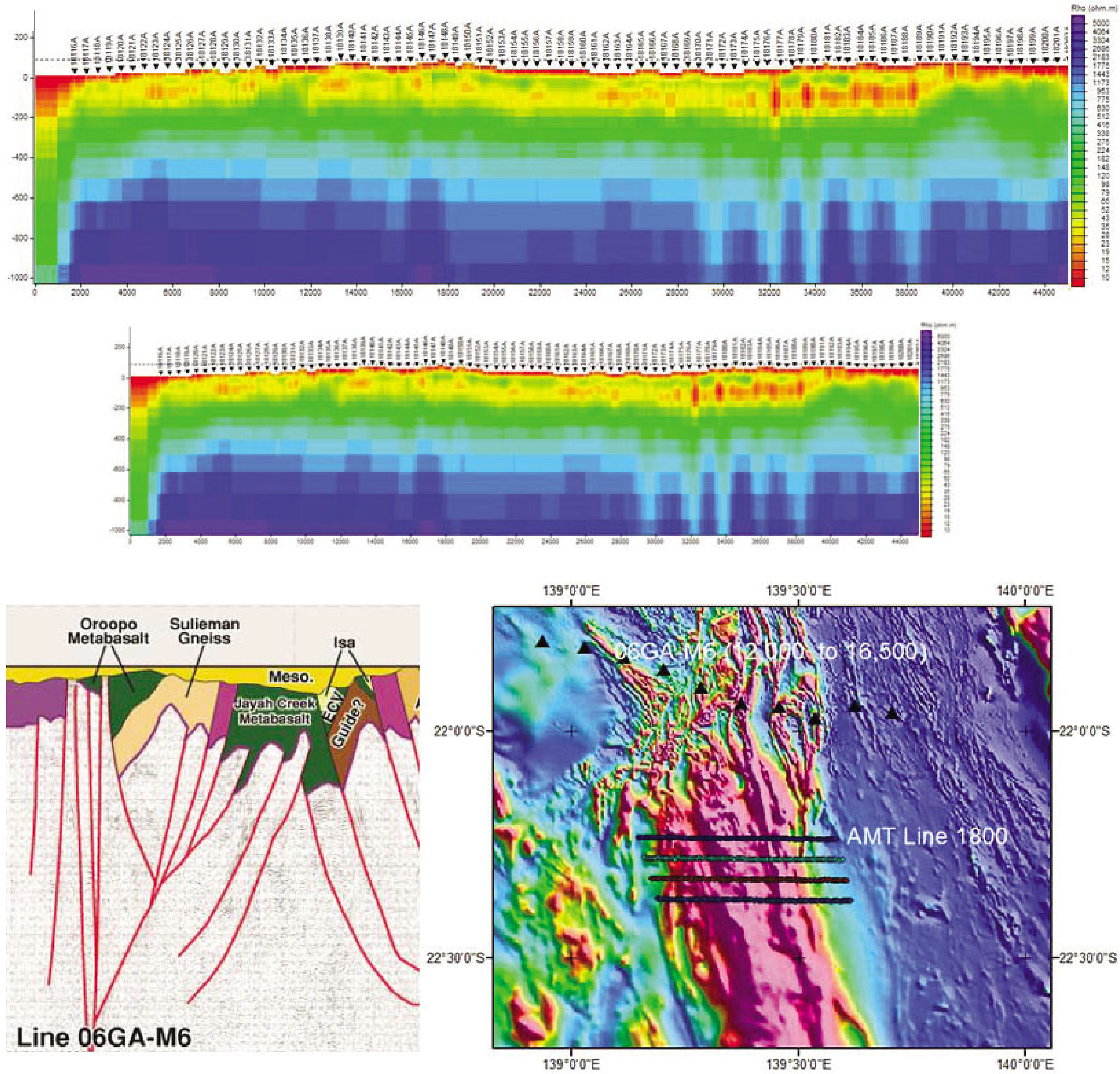

Figure 2. **Data obtained over the Georgina Basin south of Mt Isa highlighted the variable thickness of this basin. The base of the basin is interpreted by the change from green (~300 Ω·m) to blue (~1000 Ω·m). Although the major feature apparent in these data is the base of the Georgina Basin, a conductive overburden layer plus some elements of basin stratigraphy are imaged by the AMT data (top). Interpretation of seismic line 06GA-M6 from CDP 12000 to 16500 marked by the black triangles (Gibson, et al., 2015) (bottom left) and locations of AMT line 1800 and other three AMT lines and seismic line 06GA-M6 on total magnetic intensity image (bottom right)**

Machine-assisted validation of drillhole logging data in iron ore exploration

by

Daniel Wedge[1*], Andrew Lewan[2], Mark Paine[2], Eun-Jung Holden[1] and Thomas Green[2]

Geologists routinely log material from exploration drillholes, from which logging accuracy is crucial for resource evaluation and to ensure the efficiency of mine operation for the minerals industry. A logged composition for a sample records a number of different material types (Box et al., 2002), comprising the percentages of each type, as well as physical charactersistics of an interval including colour and chip shape (Sommerville et al., 2014). There are natural variations in the range of material types logged based on the mineralisation and geology of the exploration area, but manual logging is subjective and can result in highly variable outcomes, leading to significant challenges for the industry. Validation of the logging is performed whereby changes are made to the logged material types and their percentages, in order for a validated composition's theoretical assay values to match laboratory assay values for each two-metre interval. Importantly, the changes in material type must be geologically informed such that the validated composition is geologically sensible, and has similar physical characteristics to the original logging. Validation is subjective, laborious and time consuming, taking approximately two minutes per two-metre interval, and a company may need to validate hundreds of kilometres of drillholes annually (Sommerville et al., 2014).

We report on a new data-mining technique developed to improve the integrity of the drillhole logging data by analysing expert geologists' logging validation patterns. Our algorithm is named the Auto-Validation Assistant (AVA) to emphasise that it assists the user to rapidly find a validated composition while the geologist is still in control of the final result, rather than the process being fully automated. AVA presents the user with validated compositions, each with a confidence value that incorporates assay, and similarities to the logged mineralogical hardness, chip shape and other properties, to rapidly assist geologists in validating a large amount of data.

Learning validation patterns

Training data for AVA was collected by recording expert geologists validating six holes: three holes from one site and three from a second site. Each hole was logged by a different field geologist, thus providing variations in logging biases. A further 20 'standard' intervals were validated, in which theoretical assays were computed from known material type combinations and provided alongside plausible but deliberately incorrect logging for the user to validate. The geologists validated 4520 training intervals in total.

Step-by-step changes from the logged to the validated compositions were recorded. For each step, validators reduced a total assay error by swapping a percentage of one material type directly for another material type with similar physical characteristics. Thus we captured incremental improvements from the logged composition to the validated composition. At each validation step, we recorded a validation rule comprising the difference between the laboratory assay value and the theoretical assay value calculated from the material types and their percentages (i.e. the assay error to be corrected), along with the material types swapped by the validator.

Further data mining from over 60,000 logged and validated compositions was used to determine the association rules (Agrawal and Srikant, 1994) underpinning the sets of material types that were included in logged compositions, to model the geological plausibility of material types being logged together.

Auto-Validation Assistant

AVA uses an iterative method that mimics the human validation process, while exploiting computational power to apply many potential validation rules in parallel within each iteration. AVA selects validation rules from the training data that corrected similar historical assay errors. The set of logged material types are updated (in parallel) according to the swaps applied in the rules. Material type percentages are determined via an optimisation to minimise the assay error and changes in hardness characteristics. Potential compositions are ranked in each iteration according to their conformance to geological rules and logged physical properties. The top-ranked compositions are used as input for the next iteration of the algorithm. This continues for five iterations (based on the number of manual validation steps).

Finally, a set of proposed validated compositions are presented to the user, each with a confidence value based on the association rules, which are used to evaluate the geological plausibility of the sets of material types selected for each potential solution, the material types swapped, the remaining assay error, and consistency with the logged physical properties. The geologist can then

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use their knowledge and experience to select what they judge as the best validated composition. Thus, geologists' knowledge and experience still play a crucial role in validation. The algorithm is auditable and the validation rules learned in the training process can be examined and updated easily.

Results and discussion

In our first experiment, geologists used AVA to validate 1996 intervals from a range of deposits across the Hamersley province, covering variations in geology. Of these intervals, 74.3% had an auto-validated composition selected as the final validated composition without further change, and for a further 9.3% of intervals, only the percentages of the material types (not the material types themselves) were adjusted manually. Therefore AVA selected geologically plausible material types in 83.6% of intervals. As the mean time taken to validate an interval manually is two minutes, presenting an acceptable composition in real time by AVA is a significant time saving. Importantly, of these selected compositions, the composition with the highest confidence value was selected 833 times (56.2% of the intervals) while the mean ranking of the selected composition was 2.1, demonstrating that users do not need to spend time examining a large number of proposed compositions.

Further experiments compared manual and AVA auto-validated compositions for 14,600 intervals from one entire deposit. The collated results in Figure 1 display the ratio of the mean actual error to the maximum allowable error per element (*error tolerance factors*) in the logged, manually validated, and AVA-validated compositions. These results show that in terms of assay error, AVA produced similar, if not more accurate, results than manual validation, but in a faster time.

The Auto-Validation Assistant enables geologists to validate their field logging rapidly and consistently, leading to savings in labour and improved orebody modelling, while the geologist retains control of selecting the final validated composition. The algorithm can be adapted to different material types and training datasets, which can have applications beyond iron ore exploration.

Acknowledgements

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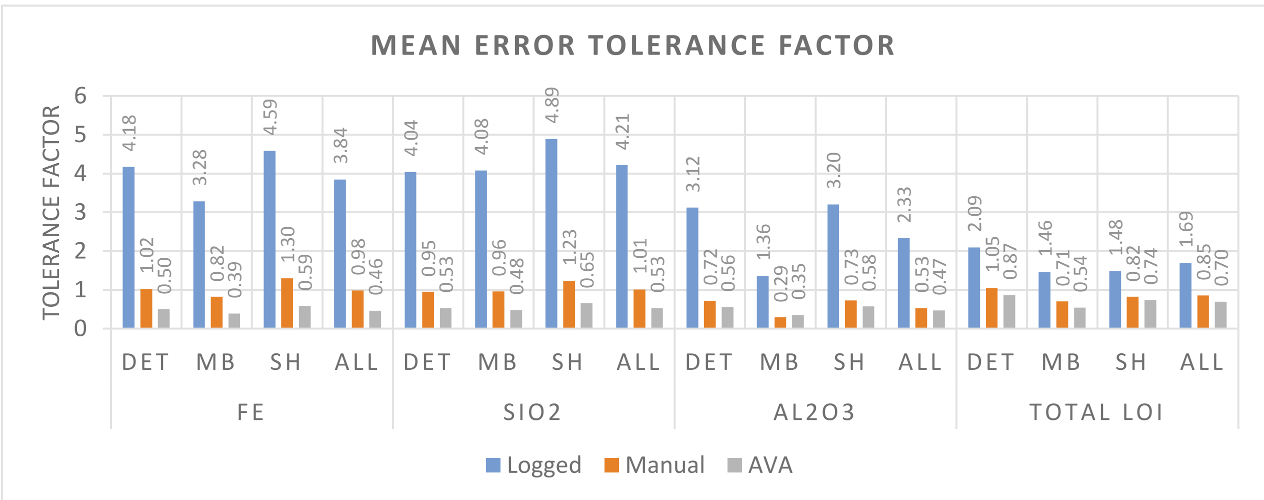

Figure 1. **Mean error tolerance factor over an entire deposit. Intervals are divided by stratigraphy: detritals (DET), mineralised bedded (MB), shales (SH), and all intervals. An error tolerance factor of 1 indicates the maximum permissible assay variation for that element**

Geophysics at the small end of the scale: understanding the resource

by

Chris Wijns[1,2]

The value added by filling in the unsampled space between drillholes does not stop at any scale, and the only techniques for filling in this space with measured data are geophysical. While the need to replenish, if not expand, the world's global mineral resource base drives an urgency to broaden our exploration search spaces, optimising the mining and processing of ore deposits will likewise contribute to feeding a resource-hungry world. For example, given global copper production of 19.1 Mt in 2015 (International Copper Study Group, 2016), a combination of lowering dilution and increasing recovery by 5% as a global average is equivalent to the annual production of La Escondida, the world's largest copper mine. Geophysical techniques are not a ubiquitous solution, but they are inexpensive, relatively rapid, and can often aid in characterising an ore body. Such aid can be, for example, geometrical, mineralogical, or mechanical. Geometrical characterisation stems from mapping interfaces such as ore boundaries or geological faults and contacts that affect the resource geometry. Mineralogical characterisation is possible when minerals of concern have detectable petrophysical responses, such as graphite and pyrrhotite for example, whose relative concentrations (in the absence of magnetite) could be individually mapped using a combination of magnetic and conductivity surveying. Rock mechanical characterisation, for example, hardness, can be achieved in high resolution through seismic surveying. None of these examples have pretensions of cutting edge physics or technology. The straightforward application of tried and tested geophysical techniques will often add incremental to step-change understanding of a deposit in terms of various characterisitics that feed into more efficient mining and processing of the ore.

Resource Density Models

A resource density model is fundamental to a mining operation because it is used to predict ore tonnages milled and, ultimately, metal produced. Uncertainty and error in a resource density model may have as big an impact on reconciliation of predicted versus actual production as uncertainty and error in the corresponding ore grade model. Surface gravity data collected over a mineral resource represent a direct reflection of subsurface density variations and can be used to improve a resource model otherwise based only on borehole or core density readings. A constrained gravity inversion is an intelligent interpolator between borehole density readings. At one of the Ravensthorpe nickel laterite deposits in Western Australia, the measured gravity signal shows significant differences with the theoretical gravity signal of the resource model when the latter is based only on downhole measurements (Fig. 1). This points immediately to areas of problematic reconciliation where more density information is required and a constrained gravity inversion can be used to better join the drillhole information. A constrained inversion at Ravensthorpe honoured all downhole density measurements but turned the resource density model into one that matched real gravity data and therefore real rock properties unsampled by the drilling.

Alteration Mapping

Rock alteration affects material properties in ways that change mineralogy, with implications for mineral processing, and that change rock competence or hardness, which can affect blasting and crushing characteristics. At the Kevitsa Ni-Cu-PGE mine in northern Finland, petrophysical logging demonstrates that talc-altered (serpentinised) mafic host rock is both lower in density and higher in magnetic susceptibility than in its less altered state. Talc alteration is important to map for two reasons: it floats with sulphides during processing and leads to unwanted high levels of magnesium in the concentrate, and it softens the rock such that crushing time is extended compared to less altered and more easily shattered rocks. Very detailed ground magnetic surveys carried out in the pit are able to map magnetic variations that correlate with distance from major structures that are known to be more talc altered. The more magnetic zones also grossly correspond to zones of weaker or softer rock as mapped by seismic velocity variations (Fig. 2). Ground magnetic surveys are extremely cheap and quick and can return detailed mapping of mineralogical and alteration variability that is useful at the scale of mining.

Rock Hardness

Seismic surveys represent the highest resolution geophysical technique currently available for depth penetration of hundreds of metres or more. At the Kevitsa mine, seismic velocity variations discriminate between overburden, fractured and weathered bedrock, and intact bedrock. The very tight correlation with RQD from drill

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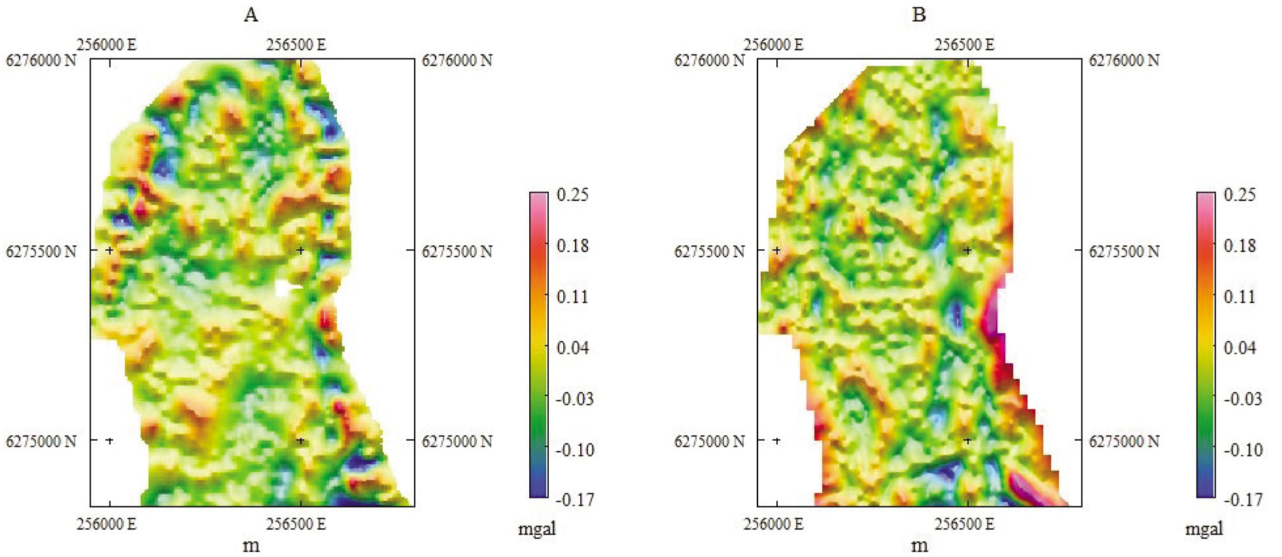

Figure 1. **Comparison between (A) theoretical gravity response of the initial resource density model and (B), measured gravity, both high pass filtered at a 200 m wavelength. Both images share a common colour scale. The areas of deficiency in the resource density model are apparent via the differences in gravity anomalies**

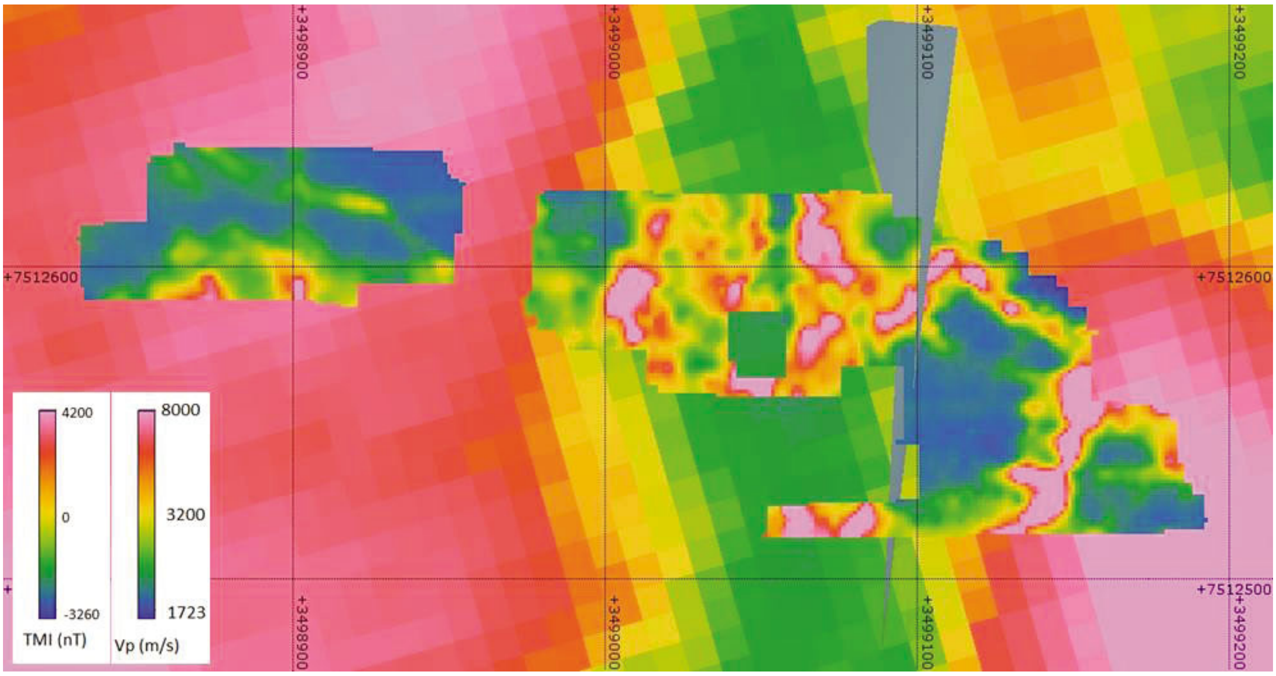

Figure 2. **A detailed ground magnetic survey in a mine pit highlights the variations in magnetite content that reflect degrees of talc alteration (serpentinisation) associated with structures. The area of higher overall alteration in the centre is coincident with lower (green) seismic velocity that equally reflects the softer talc-altered rock. The grey plane shows the footwall (dipping west) of one of the largest structures traversing the resource area, where the hanging wall above it is much more deeply weathered and altered**

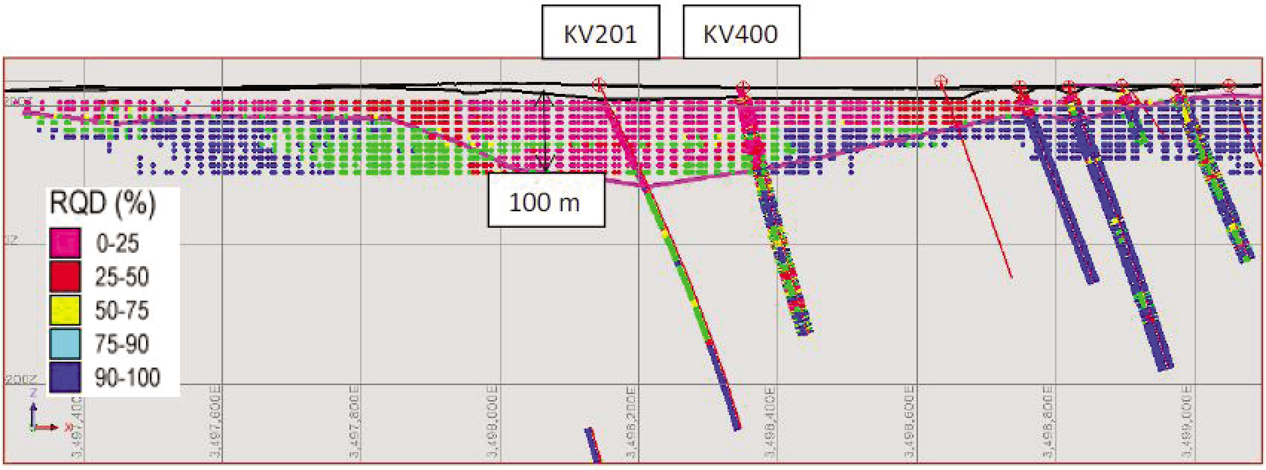

Figure 3. **The correspondence between seismic velocity V_p and RQD is very tight, such that a 3D velocity model can be used for geotechnical purposes. At fresh rock depth, V_p maps rock competence that is directly related to fracturing or alteration intensity**

core (Fig. 3) means that a 3D seismic velocity model can provide a detailed RQD model for geotechnical purposes. Below the overburden and weathered zones and inside the mafic host intrusion, the velocity V_p is largely a reflection of the variation in alteration intensity associated with major structures. The serpentinisation process lowers the density and the seismic velocity, such that low velocity indicates either highly fractured or soft (serpentinised) rock. In both cases, this will affect the response to blasting, and as described above, the softer, more altered rock will consume more energy during comminution due to its longer residence time in the crusher. Being able to map out these variations in advance can lead to better planning of blast patterns or charging, and potential blending of throughput during the comminution process.

Conclusion

In the scheme of innovation for future mining and getting the most out of mineral assets, the value of geophysical surveying at the mine scale lies in increasing the definition, beyond the sparse sampling of drill holes, of orebody characteristics that have an impact on the forward planning and efficiency of mining and processing. Improvements in defining geometry, density, mineralogy, or rock mechanical behaviour can all contribute to increasing metal production. The logistics of carrying out in-pit or pre-mining geophysical surveys is sometimes challenging but hardly ever insurmountable and rarely expensive. The interpretation and translation of geophysical characteristics into information that is useable by the mine is equally not a difficult technical task, but it does demand methods by which to absorb the information into the mine workflow in a timely way, such that it becomes useful and used. This last step is the common stumbling block, and the cases presented above have not been immune to this hurdle.

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Prospectivity mapping and the evaluation of permissive tracts in the search for economic uranium deposits

by

AR Wilde[1*], FP Bierlein[1], MD Bruce[1], OP Kreuzer[1] and C Knox-Robinson[2]

It is likely that most of the planet's outcropping uranium deposits had been discovered by 1980. Oversupply resulted and from 1980 to 2005 there was little global investment in uranium exploration although exploration continued at a reduced level. An increasing uranium price during the early part of the 21st century lead to a transient resurgence of investment and consequently discovery. Fast forward to 2017 and investment in uranium exploration is again almost non-existent. Most credible sources predict that a massive supply/demand imbalance is looming. This imbalance could possibly be exacerbated as most known undeveloped uranium deposits are unlikely to be mined because of their small size and low grade and/or metallurgical, political and environmental issues. Hence, new discoveries will be required to satisfy the predicted supply shortage. In this context we examine how the definition of permissive tracts and mineral prospectivity analysis (MPA) might yield new, potentially economic resources rapidly and at relatively low discovery cost, particularly when these resources are buried by barren cover and thus lack detectable surface response.

Perhaps the most effective way to accelerate greenfields discovery and reduce overall discovery cost will be to systematically evaluate and prioritise numerous permissive tracts and then to carry out efficient target generation and priorisation exercises within these tracts. In this paper, we look at several permissive tracts in Australia and Africa and illustrate the process of target definition. We then look at the definition of the permissive tract boundaries and how MPA has a role to play in this. Such rigorous definition of the tract boundary and quantitative mineral resource assessment (QMRA) could have a significant impact on the assessment of undiscovered endowment and ultimately on the decision to deploy limited shareholder funds to systematically explore a particular tract.

Mineral prospectivity analysis

Definition of specific target areas large enough to use for tenement acquisition or small enough to define individual drill targets is a key outcome of MPA. There is also a basis for prioritisation because targets are attributed with prospectivity values. This is important because limited funds must be channelled preferentially into targets with the maximum probability of becoming economic deposits. MPA encapsulates the author's understanding of ore deposit models and involves translating the model to a set of spatial criteria that can be represented as digital layers or 'predictor' maps. These layers are combined, typically using fuzzy logic, to generate a map in which each pixel is attributed with a prospectivity value. Expert opinion is essential in converting the geoscientific model to the most appropriate set of input layers, in assigning realistic weights to each layer and in assessing spatial relationships within each layer.

We provide four examples of MPA in uranium exploration:

1. Albitite-type, Mount Isa, Queensland (Wilde et al., in press). Potentially economic albitite-type deposits fall within high prospectivity areas whereas sub-economic deposits occur with lower prospectivity areas, suggesting that the method not only identifies prospective areas but allows effective prioritisation of those prospective for larger deposits. A similar MPA formed an integral part of the float of Regalpoint Resources and directly to the discovery of the Skevi deposit (Kreuzer et al., 2009).

2. Surficial (calcrete-hosted), Yeelirrie area, Western Australia (Porwal et al., 2014). Known deposits fall within high prospectivity areas, whereas minor showings and anomalies fall within low prospectivity areas, providing further confidence that the method aids effective prioritisation of targets.

3. Alaskite-hosted, Erongo region, Namibia. This MPA is noteworthy because of the use of remanent magnetisation to map leucogranite intrusions, which are the ultimate source of uranium in these deposits. It formed the basis of Deep Yellow's ongoing grass roots exploration in Namibia.

4. Sandstone-type, Australia. This is perhaps the world's first continental scale MPA (Bierlein and Bruce, in press). Tracts known to host sandstone-hosted deposits were highlighted but, crucially, so were several previously unrecognised tracts.

Quantitative mineral resource assessments

MPA also provides a method of defining the boundaries of permissive tracts by adopting a particular threshold prospectivity value beyond which the probability of discovery is deemed to be negligible. This permits more rigorous quantitative mineral resource assessments

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and prioritisation of individual tracts. We present three examples:

1. Surficial uranium deposits, Yilgarn, Western Australia. This exercise may serve as a best-practice template for identifying undiscovered uranium resources elsewhere. It involved three stages. First was the development of a process-based deposit model. Second, MPA was used to define permissive tracts. Third, several techniques were employed to estimate the number of undiscovered deposits in these tracts and their uranium endowment. These techniques included use of regression models of deposit density and endowment density, the United States Geological Survey three-part assessment approach and Zipf's Law analysis. This resulted in what is the world's first published quantitative mineral resource assessment (QMRA) employing three different methods and builds upon the results of systematic prospectivity analysis (Kreuzer et al., in press).

The assessment indicates that the study area probably contains an undiscovered endowment of over 180 000 t U, contained in as many as 145 deposits. Surficial uranium deposits are most likely to be found within permissive tracts in the remote, commonly sand dune-covered northern and eastern parts of the study area. These areas have had little, if any, uranium exploration.

2. Unconformity-type uranium deposits, Pine Creek region, Northern Territory. This region is host to world-class deposits such as Ranger and Jabiluka. The outline of the permissive tract generated using our new MPA is compared to the arbitrary tract boundaries of Singer and Jaireth (2015). Using the arbitrary tract definition, there is a 90% probability of nine undiscovered deposits and 50% probability of 25 deposits (Singer and Jaireth, 2015). The implications of the revised tract definition for estimated endowment are currently being assessed.

3. Albitite-type deposits, Mount Isa, Queensland. A tract boundary has been defined for the first time using the MPA discussed above. Preliminary QMRA indicates that there should be at least 10 undiscovered deposits within the tract with resources in excess of 1000 t U (V Lisitsin, in preparation).

Such systematic delineation and statistical evaluation of a large number of comparable permissive tracts should provide a far more rigorous basis for investment of exploration dollars than any currently available (and of course this applies to commodities other than uranium as well).

Ground truthing

The success of MPA is ultimately only measureable in new discoveries. While there are many examples of MPA in the literature there are no examples where systematic testing of MPA targets has been documented. An auger drilling program was undertaken at Mount Isa North in order to systematically test the many targets generated by the MPA. Although the program was terminated due to lack of funds the preliminary results suggest that the exercise could yield additional resources. The MPA undertaken for Regalpoint Resources Ltd, however, provides an excellent confirmation that the technique can yield discovery, as the Skevi deposit was unknown prior to Regalpoint's exploration program in 2010 (Kreuzer et al., 2009).

Conclusions

Mineral prospectivity analysis is a proven, yet underutilised exploration tool that is ideally suited to capturing and analysing all available data in the context of a conceptual ore deposit model, and providing the basis for rigorous delineation of permissive tract boundaries. Coupling this with well-established methods of estimating metal endowment permits more effective prioritisation of exploration dollars into the most favourable tracts. MPA also represents possibly the most effective means of identifying conceptual exploration targets within tracts prior to field investigations. However, we note that there are few if any documented examples of exploration programs aimed at systematically testing the best targets generated by MPA within permissive tracts.

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Crowdsourcing: The Future of Targeting?

by

AR Wilde[1,2] and OP Kreuzer[2,3]

Declining Discovery Rates

The discovery rate of new metal deposits has been dropping since the heady days of the 1960s and 70s. Most outcropping deposits, the low-hanging fruit, appear to have been discovered prior to 2000. Vast tracts of land controlled by centrally-planned economies of China and the former USSR have been scoured by quasi mililtary organisations involving (probably) millions of people, while prospectors and state-owned and private companies have been active in the post-colonial world, leaving few areas of the globe without at least some surface mineral exploration. An obvious explanation for the declining discovery rate lies in the fact that exploration targets are now likely to buried beneath cover, which in extreme cases may consist of hundreds of metres if not kilometres of barren rock. Hence, locating metal deposits has become far more intellectually demanding and expensive, and the greater depth component makes them less likely to be economic compared to near-surface deposits.

In this context, we consider whether it may be possible to dramatically improve our ability to target and discover metal deposits at depth through crowdsourcing, employing the intellectual power of hundreds to thousands of people instead of only a few talented mining company employees or external consultants as is today's norm. According to Wikipedia, crowdsourcing is 'the process of obtaining needed services, ideas, or content by soliciting contributions from a large group of people, especially an online community, rather than from employees or suppliers. [The term] was coined in 2005 as a portmanteau of crowd and outsourcing.' Crowdsourcing offers an alternative to the traditional exploration targeting approach because it facilitates harnessing the accumulated wisdom of a much wider and more diverse group of individuals and teams. Participants may not necessarily be trained in geoscience but may possess skills and contribute ideas promoting application of novel technology and disruptive innovation.

In this contribution, we present three examples of crowdsourcing as applied to gold exploration (Wilde and Kreuzer, 2016) and discuss possible implications for the future of metal exploration.

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Goldcorp Challenge 2000

The Goldcorp Challenge was the brainchild of chairman and CEO Rob McEwen. Contestants were given access to 500 Mb of geological data from Goldcorp's high-grade Red Lake gold mine in Ontario, Canada and to state-of-the-art software for 3D visualisation. The objective was to identify exploration targets with the potential for discovery of the next 6 Moz of gold at Red Lake. A total of US$575 000 was offered in prize money, equivalent to US$800 000 in 2016 dollars. More than 1400 people registered for the challenge, including geoscientists, engineers, mathematicians and military officers.

The challenge identified, or helped to confirm, 110 exploration targets. Half of these targets were previously unknown to Goldcorp. In following years the company discovered 8 Moz of gold exceeding US$6 billion in ground value. What proportion of these 8 Moz was found in previously unknown targets has not been documented by Goldcorp, however, there is no doubt that this crowdsourcing initiative was very successful given that more than 80% of the previously unknown targets yielded significant gold reserves. Furthermore, the time otherwise required to generate so many top-tier targets was reduced by an estimated two to three years.

Karelian Gold Rush Challenge 2015

There was a 15 year hiatus before Finnish gold producer Endomines AB announced the next exploration crowdsourcing competition: The Karelian Gold Rush Challenge of 2015. This global competition aimed at targeting a major gold discovery within a 40 km section of the Archean Ilomantsi greenstone belt in eastern Finland. Participants were provided with data from more than 30 years of exploration. Total prize money was US$45 000. The competition attracted 150 contestants and 15 individual exploration proposals at a nominal cost to Endomines of US$3000 per proposal. It would be premature to judge the success of this initiative, but 15 different proposals for a relatively modest outlay would seem to be a worthwhile and cost-effective outcome.

Integra Gold Rush Challenge 2015

Canadian junior gold miner Integra Gold Corp also launched its Gold Rush Challenge in 2015. The objective was to identify exploration targets with potential for a major gold discovery within Integra's Sigma-Lamaque property at Val-d'Or, Quebec. Participants were given access to 6TB of mining and exploration data accumulated over 70 years and state-of-the-art 3D visualisation software. The challenge was advertised and marketed widely, with the CAN$1 million (US$765 000) offered in prize money no doubt having contributed significantly to the popularity of this contest. A total of 1342 participants registered for the competition and over 100 individual submissions were received at a nominal cost of US$7650 per proposal. A panel of five high-profile judges with substantial geoscience and exploration experience assessed the submissions and selected the best five entries. The top five were then invited to attend a charity event attended by over 400 invited guests at the annual PDAC convention in Toronto, Canada, where they competed 'shark tank-style' before five industry 'titans' (including Rob McEwen) to win their share of the prize money.

With Integra just having announced the commencement of a 2500 m drill program on the first Gold Rush Challenge target, it would be premature to speculate on the success of this venture. Undoubtedly, though, the competition has already done its bit to significantly raise Integra's profile in the global investment community, an early result that ultimately could be as beneficial as any new gold discoveries.

Discussion

The widely acknowledged success of the Goldcorp Challenge became known only years after the competition was completed. Nevertheless, the lack of any follow-up events until 2015 is perhaps surprising. Success for Endomines and Integra could provide impetus for crowdsourcing to be more widely adopted in metal exploration in the future. But the timing of such crowdsourcing initiatives appears to be very important. All crowdsourcing challenges described above occurred during major industry downturns, probably because it would be rather difficult to attract and engage a suitable number of high-quality competitors during industry boom periods. A high rate of underemployment among talented geoscience professionals might be what is needed to encourage individuals or groups to spend significant time working on these problems without any guarantee of success and financial reward.

A major impediment to the routine and regular use of crowdsourcing in solving exploration problems is the lack of rigorous proof of the benefits. The notion that someone who is not well versed in exploration geoscience could produce superior targets to a well-trained and experienced geoscientist will be hard for many in the industry to accept. Widespread adoption of crowdsourcing, however, could have major structural implications for the industry. For example, it could lessen companies' need for specialised staff and for consultants. The target generation role within companies could evolve into that of an assimilator of ideas and one who vets and prioritises targets rather than one who creates them. A niche role might emerge for companies or individuals providing crowdfunding platforms specific to the mining industry with the ability to distribute large volumes of data and to provide access to crucial software (similar perhaps to the crowdsourcing graphic design sites designcrowd and 99designs). Such a service might be more desirable for junior companies that cannot afford an effective target generation group. And we could perhaps see state and federal geological surveys running crowdsourcing initiatives in an attempt to make the most out of their pre-competitive data and increase perception of exploration attractiveness and hence investment.

Clearly, the industry should keep a careful eye on the outcomes of the Endomines and Integra crowdsourcing intiatives.

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TARGET 2017, PERTH, AUSTRALIA: ABSTRACTS

Wyche and Witt