TARGET 2023

Abstract Volume

28 July 2023 – Esplanade Hotel, Fremantle, Australia

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Foreword

The **Target 2023** symposium, organised by Geoconferences, was held at the Esplanade Hotel, Fremantle, Perth, Australia on 28 July 2023, and carried on from highly successful precursor Target 2017.

The theme of the symposium, ***Targeting for a New Era of Discovery***, showcased innovations developed to aid the discovery of new tier-one deposits and to broaden the exploration search space under cover.

A curated programme addressed multi-commodity exploration from the whole-lithosphere regional greenfield scale through to camp scale, highlighting:

(i) Key research outcomes that impact our understanding of Mineral Systems and the derived exploration strategies;
(ii) Data capture, integration, interpretation and key exploration targeting inputs across scales;
(iii) Improved targeting strategies and methodologies; and
(iv) the steps that led to a modern giant discovery.

We hope learning from the program will shape and benefit exploration and discoveries in the years to come.

The Target 2023 Organising Committee

Graham Begg (Chair), Helen McFarlane, Nicolas Thebaud, Margaux Le Vaillant, Mark Lindsay, Graeme Broadbent, Rebecca Montsion

In partnership with the 6ias 2023 Perth

Programme

	Presentation Title	Speaker	Type	Description
8.30	**Registration**			
8.50	**Opening address and acknowledgement of country**			
9.00	Putting time and dynamics into improved Mineral Systems prediction	Nicole Januszczak	Keynote 1:	Review of initiatives and developments adding sophistication to Mineral Systems understanding
9.40	Large-scale crustal architecture as a first-order control on mineral systems	David Mole	Talk 1:	Regional isotopic mapping, linking crustal-scale architecture and world-class ore-province formation, offers the potential to reduce search space by 90%.
10.00	Redefining an Archean terrane boundary	Raphael Quentin de-Gromard	Talk 2:	Integrated multi-disciplinary mapping
10.20	Spatial periodicity in self-organized mineral systems	Nick Hayward	Talk 3:	How some of the world richest mineral provinces show surprisingly predictable ore clustering patterns, with emphasis on Au and base-metals.
10.40	**Morning tea**			
11.10	Drilling with a dynamic targeting feedback loop	Michelle Carey	Talk 4:	Currently geoscientists choose between making real time decisions using visual observations or waiting weeks or months for laboratory data to enable more informed choice. How can we use technology to change these workflows?
11.30	A paradigm shift: How continuous, solid-3D digital core is future-proofing the way we explore, mine and process deposits – Critical Mineral and Gold Deposit Case Studies	Heidi Pass	Talk 5:	Examples of how using medical technology to create 250-meter-long thin sections every day is transforming how we discover, model and mine
11.50	Geologically appropriate feature engineering for mineral exploration	Rebecca Montsion	Talk 6:	Identification and validation of mineralization targets using multi disciplinary geoscientific data
12.10	How to use a decision-making process to target geochemical anomalies based on frequency and Bayesian frameworks	Behnam Sadeghi	Talk 7:	Decision-making under uncertainty for geochemical sampling and mineral potential targeting
12.30	**Lunch**			
13.50	Exploration models for lithium pegmatites	Kathryn Goodenough	Keynote 2:	Synthesis plus connections to structure, evolution, key problems for exploration
14.30	Recent advances in the understanding of magmatic nickel sulfide systems and newly developed exploration tools	Margaux Le Vaillant	Talk 8:	Working across the scales relevant to targeting and exploration for nickel sulphides
14.50	Barcoding the geochemistry of Archean basalts	Hugh Smithies	Talk 9:	
15.10	The Julimar Intrusive Complex and Associated Orthomagmatic Ni-Cu-Co-PGE deposits	Kevin Frost, Bruce Kendall	Talk 10:	What worked to discover a giant deposit in the unloved western Yilgarn 70km from Perth!
15.30	**Afternoon tea & mini poster session**			
16.00	Revealing Australia's lithospheric architecture for exploration targeting: Advances from the $225 M Exploring for the Future program (2016-–2024)	Karol Czarnota	Talk 11:	Mineral Systems and lithospheric architecture from surface to mantle. Advances by the Australian Government's $225 M Exploring for the Future program (2016-2024).
16.20	How MT data from multiscale surveys can help to image the footprint of mineral systems in covered terranes	Wenping Jiang	Talk 12:	Multi-scale application of magnetotellurics to minerals targeting
16.40	The use of zircon and apatite as metallogenic fertility indicators in Archean orogenic gold systems	Chris Fisher	Talk 13:	We explore the applicability of accessory minerals as pathfinders in Archean-age gold systems using examples from the Yilgarn Craton
17.00	New horizons in predictive science	Marco Fiorentini	Talk 14:	New scientific knowledge necessary for a step change in the predictive power of exploration already exists, but is simply not implemented
	Close	Graham Begg, Cam McCuaig		
17.30	**Sundowner (sponsored by IMS)**			

Target 2023 Abstracts

Putting time and dynamics into improved mineral systems prediction

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The majority of ore deposits have been found where mineralization outcrops at or near surface. In this exploration environment, deposit models are very effective in helping explorers vector to ore deposits. It is recognized that most remaining world-class systems are likely concealed under cover or in environments where direct detection is either extremely challenging or impossible using our current exploration toolkit. In addition, the bulk of research has focused on geochemical processes in the upper crust where ore accumulates and concentrates. Future discoveries under cover will require an improved understanding of the controls on the evolution of mineral systems. Individual ore deposits are part of much larger mineral systems and this is useful because we can predict and image systems at larger scales where we cannot possibly hope to detect individual ore deposits. Predictive modelling is currently being tempered by our ability to image critical processes and the four-dimensional evolution of world-class mineral systems. This has highlighted critical gaps and driven an accelerated research program that recognizes the importance of geodynamics, the deep origins of mineral systems, our incomplete understanding of mineral systems and our current biases and assumptions. New concepts are being explored, new datasets acquired, existing datasets improved or used in new ways, and new technology is being developed to enable reliable prediction of mineral systems and the detection of ore deposits. Systems thinking is the foundation of the exploration process, and not simply a framework used for prospectivity maps. Conceptual predictive models are tested by exploration work programs and a learning loop is established to ensure our understanding of the system, what we are looking for (proxies), and our exploration toolkits are all optimized. The opportunity in this space is truly extraordinary and requires a capacity uplift in exploration teams and their understanding of mineral systems and how they form so that they are empowered to plan and execute effective work programs, make decisions, and progress projects efficiently through the exploration pipeline.

Large-scale crustal architecture as a first-order control on mineral systems

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Lithospheric and crustal architecture — the framework of major tectonic blocks, terranes and their boundaries — represents a fundamental first-order control on major geological systems, including the location of world-class mineral camps. Traditionally, lithospheric and crustal architecture are constrained using predominantly geophysical methods. However, Champion and Cassidy (2007) pioneered the use of regional Sm–Nd isotopic data from felsic igneous rocks to produce isotopic contour maps of the Yilgarn Craton, demonstrating the effectiveness of 'isotopic mapping', and the potential to map 'time-constrained' crustal architecture. Mole et al. (2013) demonstrated the association between lithospheric architecture and mineral systems, highlighting the potential of isotopic mapping as a greenfield area selection tool. Additional work, using Lu-Hf isotopes (Mole et al., 2014), demonstrated that the technique could constrain a range of temporal events via 'time-slice mapping', explaining how Ni-Cu-PGE mineralized komatiite systems migrated with the evolving lithospheric boundary of the Yilgarn Craton from 2.9 to 2.7 Ga. Similar studies have since been conducted in West Africa (Parra-Avila et al., 2018), Tibet (Hou et al., 2015), and Canada (Bjorkman, 2017; Mole et al., 2021; 2022). This work continues in Geoscience Australia's $225 million Exploring for the Future program (2016-present). Isotopic mapping, which forms an integral part of a combined geology-geophysics-geochemistry approach, is currently being applied across southeast Australia, covering the eastern Gawler Craton, Delamerian Orogen, and western Lachlan Orogen, encompassing more than 3 Gyrs of Earth history with demonstrable potential for large mineral systems.

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Redefining an Archean terrane boundary

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Archean terrane boundaries play a first-order control on the migration of mantle-derived melts, a key component of metallogenic mineral systems. As a result of large-scale, data-driven integration of new and existing geophysical, geochemical, geochronological, and metamorphic data with field observations, we have recently redefined and relocated the boundary between the 2705–2600 Ma South West Terrane and the 3010–2610 Ma Youanmi Terrane ~200 km southwestward (Fig. 1; Quentin de Gromard et al., 2021).The crust exposed between the new and the old terrane boundary, including the high-strain Corrigin Tectonic Zone, is a granulite-facies equivalent to the otherwise dominantly greenschist-facies Youanmi Terrane exposed further to the north, that was exhumed during a regional 2665–2635 Ma granulite-facies event. Major gold deposits in this region include Calingiri, Tampia, Griffins Find and Katanning. In contrast, the South West Terrane is generally a lower metamorphic-grade terrane, except along the Darling Fault and the Albany–Fraser Orogen where Proterozoic deformation and metamorphism overprinted Archean fabrics. The South West Terrane contains world-class deposits, including the Boddington gold mine, lithium pegmatites at Greenbushes and the recent major nickel discovery of Julimar. The identification of mantle-tapping structures, including the redefined terrane boundary, based on the close spatial relationship between major shear zones, sanukitoid and sanukitoid-like rocks, high-isotopic gradients and the occurrences of gold and nickel anomalies offer new exploration spaces for mineralized environments in the underexplored — yet highly prospective — portion of the Yilgarn Craton.

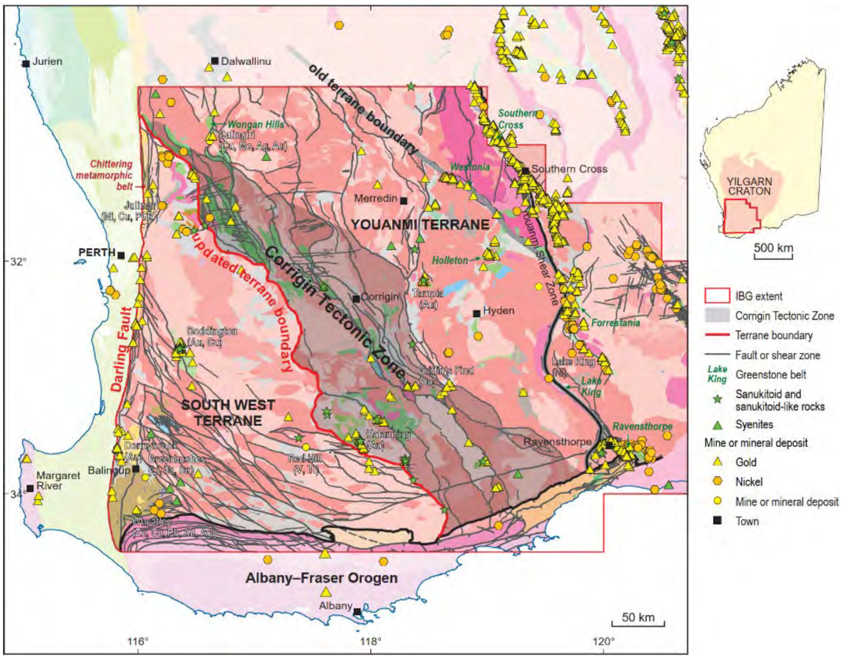

Figure. Simplified interpreted bedrock geology of the southwest Yilgarn Craton showing the updated location of the terrane boundary between the South West and Youanmi Terranes.

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Spatial periodicity in self-organized mineral systems

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Mineral systems exhibit complex and nonlinear behaviours as result of competitive feedback process between system constituents. This complexity presents enormous challenges for forward modelling and invokes a sense of unpredictability. Yet predictable patterns, such as spatial periodicity and power-law size-frequency distributions among multiple geological elements, can spontaneously emerge in certain mineral systems from self-organization, which occurs in order to dissipate large energy gradients in the most efficient manner and maximize entropy production. Early identification or prediction of spatial recurrence patterns in mineral systems can help guide area selection and targeting for new discoveries. Importantly, it leads to new insights into the scale and efficiency of processes that underpin exploration models. Most published mineral system models have yet to embrace the feedback loop concept, or to address self-organizing patterns that emerge from interactions across the whole system.

Recent studies demonstrated that a semi-regular to regular spacing exists for large mineral deposits along some exceptionally well-endowed structural corridors for diverse deposit types (e.g. orogenic gold, sediment-hosted Cu and Zn, porphyry Cu deposits and kimberlite pipes; Hayward et al., 2018), but there are many more less well-endowed structural corridors that lack evidence for spatial periodicity. For orogenic gold, the most common median spacing is ~30-40 km, or at half spacings (median ~15-20 km) for smaller deposits along some corridors. This pattern was determined from 22 structural corridors across 6 provinces, ranging from Neoarchean greenstone belts to Palaeozoic flysch belts. These common spacings arise regardless of age and setting and appear to be a fundamental yet poorly understood property of some large orogenic Au systems. As the best examples of spatial periodicity of ore deposits identified to date are associated with some of the world's best endowed mineral provinces, it is possible that province endowment is linked to both the degree of self-organization and the magnitude of regional energy gradients.

Two speculative new models are considered to explain how spatial periodicity can emerge among orogenic Au (and other deposit type) systems. The first model invokes localisation of steeply plunging conduits at the intersection of transverse translithospheric fault intersections, which were inherited from older self-organized fault networks. Such translithospheric conduits localised ascent of Au-rich mantle-derived alkaline melts. The second model invokes natural periodic segmentation of regional scale transpressional fault zones at spacing proportional to the average thickness of the seismogenic zone (x = 15-20 km). Convective circulation of meteoric fluids through open fracture networks (Zhao et al., 2008) formed upwelling zones at 2x spacing. In turn, shallow upwelling zones localised transient discharge of over-pressured deep crustal fluid reservoirs during the Au mineralization episode, thereby stabilizing mass and energy flow from source to trap through competitive feedback process. These models are not mutually exclusive and either model could lead to new target prediction paradigms for large new Au discoveries.

Reference(s)

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Drilling with a dynamic targeting feedback loop

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Currently geoscientists choose between making real time decisions using visual observations or waiting weeks or months for laboratory data to enable more informed choice. How can we use technology to change these workflows?

Technology to support data based real time logging and decision making has progressed a long way in the last ten years. IoT or as we like to call them IoG (Internet of Geosensing) systems that transfer data from the field to the office are nearly standard industry process, there are an absolute plethora of downhole and core scanning technologies on the market and similarly data science approaches – both commercially available, and developed in house within mining companies, proliferate.

So what's stopping us? I think there are two key factors, one human based and one technology based. Starting with the technology challenge. With so many solutions available how do you choose which one? Does it really make sense to only pick one? None of them are a silver bullet, it is highly likely that the best results are going to come from integrating data from more than one source. Impeding us from doing that are two things; systems which aggregate the data together to allow its combined use in data science applications and limited collaboration between technology providers.

Next we turn to the human factors. Introducing these new approaches is disruptive to existing workflows. I want to use an example based on core photography to explain this. To use computer vision approaches to map structures for Geotech processes as well as log lithologies, there is "boring" pre work required to ensure the core depths are all correct and take into account core loss. This process is 80% automated but takes some input from the core logging geologists. The time taken to do this is far less than actually logging the core, but the problem is that whilst introducing the process you need to complete both in parallel adding more time and work to a resource pool that is already massively stretched. How do we plan and resource ourselves to enable change? The second factor is that automated approaches to lithology definition won't be like for like with what a geologist will do – how do we make these outputs consumable and thus facilitate change.

The urgent need for us to discover more critical metals occurring against a back drop of less and less geoscientists means we need to resolve these issues and find a way to use these technologies to our advantage.

A paradigm shift: How continuous, solid-3D digital core is future-proofing the way we explore, mine and process deposits – Critical Mineral and Gold Deposit Case Studies

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With the ever-present thirst for reduced risk, speed and orebody knowledge, the past two decades have seen the use of hyperspectral, pXRF and other mineral and elemental drill-core sensors gain industry acceptance. However, these tools are often limited to 2D surface scans or require destruction of part or all of the core, thereby severely limiting analysis and reducing archive to photographs, subjective logs and possibly sample pulps. Additionally, multiple instruments are needed to provide both mineral and elemental information.

Drill-core logging and analysis remain essential tools in any exploration and mining project. Many logging and sample selection output variables are limited to database codes and subject to the discretion of the human eye and (in)expertise, with samples recording discrete point data or bulk averages in heterogeneous systems. Inconsistencies are common, compound over time and lead to uncertainty and even additional drilling to satisfy the specific needs of different workflows. Blind, continuous and destructive sampling is a partial solution, but removes the possibility for additional investigations and concept testing now and in the future. Core archiving is reduced to static 2D photos, subjective logs and possibly sample pulps. Regardless, the result is added cost, time and risk to critical decisions across the value chain.

The novel Orexplore Technology Platform is an industry-first, non-destructive, drill core sensing and analysis system. High-resolution X-ray tomography (as used in hospital CT scanners) capture the complete surface and internal core volume to 200 micrometers. Powerful X-ray fluorescence scanners sense the entire 360° core surface. These data streams are integrated using advanced physics and mathematical modelling to produce a detailed digital twin of the core in 15min/meter on-site or in a warehouse (Fig. 1).

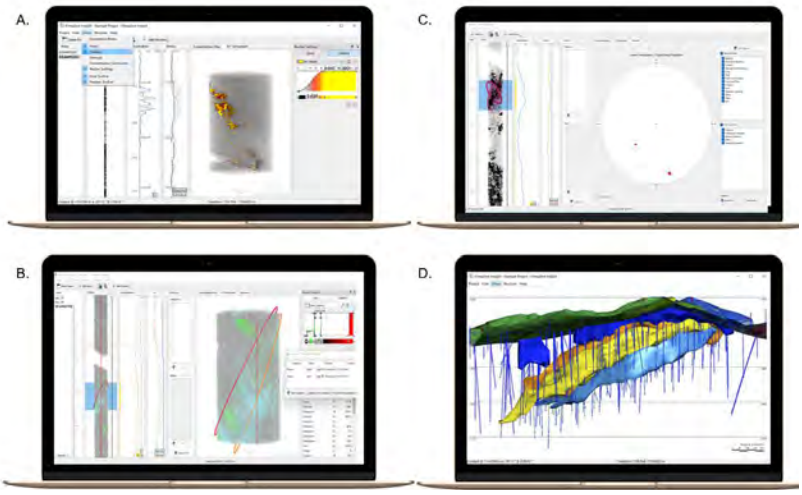

Figure. Interrograting solid-3D digital core twin reveals insitu high density sulfide particles (A), alteration mineralogy and struture (B), strutural characteristics (C), and orebody knowledge (D).

Presented here are three new case studies, highlighting the significance of continuous, objective downhole identification and preservation in solid-3D of co-located minerals, textures, elements, structures, density, and rock breaks from one instrument. These case studies illustrate how the combination of these foundational data sets (as well as their derived products) reveal and bring forward key net-present-value decision-making information into the exploration stage, enabling pro-active decisions on large capital investment plus repeated interrogation and testing of new concepts of operation and practical scenarios at any scale required, now and into the future.

Geologically-appropriate feature engineering for mineral exploration

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Methodological advances in machine learning frequently focus on improved model prediction with limited consideration for the representativeness of geological features / processes in layers defining target characteristics. Commonly applied inputs for machine learning are sometimes oversimplifications derived from variably subjective constraints or are purely empirical data containing convoluted signals. To build on existing techniques, hybridized approaches that integrate expert knowledge with multi-disciplinary data using a variety of statistical methods are used to develop enhanced feature engineering techniques. This integrated approach has been applied to the Timmins and Dryden regions of the southern Abitibi and western Wabigoon subprovinces of the Superior Craton, respectively (Ontario, Canada) and has produced feature maps representing pre- to syn- deformation non-Euclidean distances for fluid transport, semi-discrete interpolation of geochemistry, discrete gridding of rock properties, as well as rheological and chemical contrast/gradients maps. Additionally, assemblage, mobile element gain / loss, structural complexity, and airborne magnetic intensity maps are used to comprehensively capture components controlling fertility in magmatic, volcanogenic, and orogenic mineral systems. Comparisons between conceptual mineral system models to ranked feature importance from random forests confirm that the combination of enhanced feature maps are generally representative of naturally complex local geology and may provide new geological insight about mineral systems.

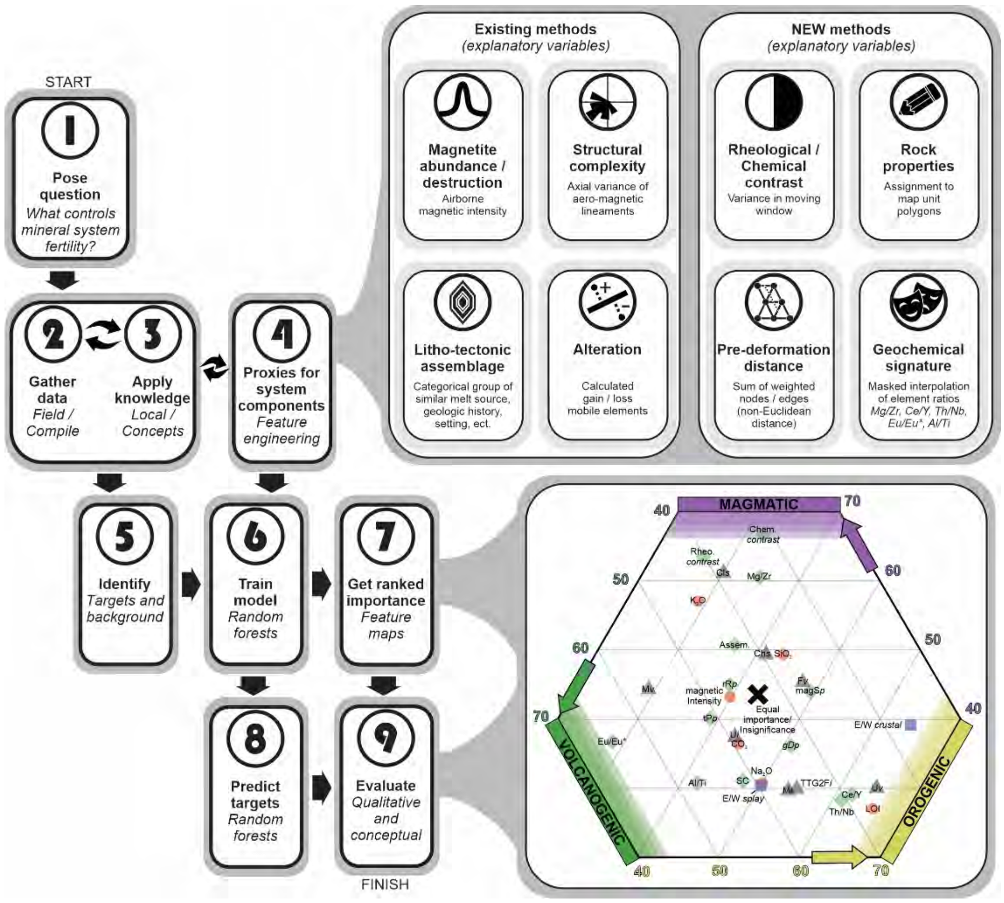

Figure. Workflow diagram of broad methodological phases typical of for prospectivity analysis. Initial phases involve assessing the geological problem, gathering data, and using geological knowledge to attribute value to each dataset. This information is used to design relevant feature engineering techniques that isolate signals/generate representations of mineral system components. New and existing feature engineering methods used herein are indicated as an inset to the diagram. Target and background locations are synchronously identified and used to constrain training random forests classification and generate a ranked list of feature importance.

How to use a decision-making process to target geochemical anomalies based on frequency and Bayesian frameworks

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In mineral exploration, it is often necessary to generate interpolated maps based on geochemical data due to some reasons such as lack of budget, limitations in number of the samples or access to certain areas. However, this process can result in errors and uncertainties due to differences between real and estimated values in unsampled areas. To address this issue, this research aims to quantify and model the spatial uncertainty of geochemical data in a multi-variate manner. This was done by applying a centered log-ratio (clr) transformation to the concentrations of Cu VMS-related elements in soil samples from Cyprus, as a case-study. The spatial uncertainty was quantified through the use of sequential Gaussian simulation (SGSIM), which generated 1000 geological simulated scenarios (called 'realisations') of the datasets. The dissimilarity of these realisations was then calculated using a Euclidean distance-based model. This allowed for the quantification of the spatial uncertainty of the tF1 scores, representing the clr-transformed geochemical data. In other words, the quantile P50 represents the required 'return', and 1/P90-P10 represents the 'spatial uncertainty' or 'risk'. Then the efficient frontier (EF) plot, based on the 'return' vs. 'risk', was generated to identify the classes with the highest return, i.e., target element's concentration/frequency and lowest spatial uncertainty (i.e., highest probability of the occurrence), which were then characterised and mapped as the best target areas for follow-up exploration.

Exploration models for lithium pegmatites

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The global shift towards electric vehicles is driving rising demand for battery raw materials, particularly lithium. In recent years, lithium production has been split roughly equally between extraction from brines in the Lithium Triangle of South America, and extraction from pegmatites, dominantly in Australia. However, increasing demand for lithium is driving exploration for pegmatites across the world. There is a need for greatly improved exploration models to guide more efficient and effective exploration.

The most widely accepted exploration model is based on the classic concept that lithium pegmatites represent the most evolved magmas derived from a parental granite, and thus that they should be expected to occur in a concentric zone around the margins of a granite pluton (Bradley et al., 2017). However recent research has highlighted an alternative model, in which the parental magmas for lithium pegmatites may be produced by low-degree partial melting of metamorphic host rocks (e.g. Shaw et al., 2016; Simmons et al., 2016). In the real world, it is very likely that these two models represent end-members, and many pegmatites are formed by a combination of processes. Granitic intrusions may contribute fluids and heat that promote melting of fertile country rocks; the resulting melts may migrate and undergo a certain amount of fractional crystallisation to form true lithium pegmatites. As part of a UKRI-funded research project, LiFT (Lithium for Future Technology) we are working to develop exploration models and propose targeting criteria for lithium pegmatites.

We are investigating a case study in Ghana, around Atlantic Lithium's Ewoyaa prospect, where a variety of pegmatites are intruded into Palaeoproterozoic metasedimentary rocks adjacent to Eburnean granitic plutons. The area contains spodumene-bearing lithium pegmatites; pegmatites with lithium-rich micas; pegmatites with columbite group minerals but no lithium minerals; and barren pegmatites. Potential controls on pegmatite type include distance from granitic plutons; composition of source rocks; and major structures as melt and fluid channels. This talk will present our latest available data on this case study, and combine it with information from other pegmatite localities across Africa to propose a set of targeting criteria for lithium pegmatites.

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Recent advances in the understanding of magmatic nickel sulfide systems and newly developed exploration tools

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2. ISTO, UMR 7327, CNRS, Université d'Orléans, BRGM, F-45071 Orléans, France.
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Magmatic nickel sulfide systems are generally well understood compared to many other commodities' mineral systems. The key genetic processes are 1) the source; the metals being sourced from the mafic-ultramafic silicate melt and the S being sourced (in most cases) from the assimilated crustal rocks, 2) the metal enrichment process linked with important interaction between the silicate melt and the sulfide melt, i.e. a dynamic magmatic system, and 3) the trap (Barnes et al. 2016). Traps are the least understood of these processes, mainly because sulfide liquid behaviour is difficult to predict and depends on the geometry of the intrusive system, the dynamics of the melt and the rigidity of the crystal framework. But understanding this is key to help explorers target these ore bodies within magmatic intrusive systems.

This presentation starts by a short overview of the magmatic Ni-Cu-PGE sulfide mineral system as we currently see it, highlighting what genetic process are generally well agreed upon and understood, as well as other processes that might have an important role to play and are currently being investigated. It then gives an overview of existing tools currently available for explorers to map out these genetic processes, especially focusing on lithogeochemistry and mineral chemistry (Le Vaillant et al 2016, Schoneveld et al. 2020, Barnes et al. 2023, Barnes 2023).

Finally, some of the more recent experimental results looking at the physical behaviour of liquid sulfides, and the potential role of volatiles in ore genetic processes will be presented. These include analogue models studying sulfide coalescence and infiltration. Sulfides are the last phases to crystallize in these systems and understanding how they might move around in both non-consolidated, semi-consolidated and even consolidated cumulate rocks in intrusive complexes to understand trapping mechanisms. The second type of experiments are high pressure high temperature experiments recreating the conditions at which these ore deposits form and studying the impact the presence of volatiles has on sulfide transport, sulfide coalescence and metal enrichment processes.

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Barcoding the geochemistry of Archean basalts

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We use an expanding dataset of high quality geochemical data covering at least six adjoining fault-bounded 'domains' in the Ora Banda – Kambalda region of the Eastern Goldfields Superterrane (EGST)(Yilgarn Craton) to construct, from better constrained sequences, chemostratigraphic 'barcodes' that can be extrapolated to stratigraphically assign samples taken from areas of poor geological context. The combined greenstone stratigraphy comprises at least twenty-six distinct mafic compositional units, identified mainly from bivariate plots utilizing strongly incompatible trace elements. Individual established lithostratigraphic units, typically of formation level, comprise at least two distinct geochemical units, most of which also occur at multiple stratigraphic levels in specific and neighbouring domain stratigraphies. Individual stratigraphic formations comprise overlapping flow fields each representing the products of a discrete eruptive event and/or eruptive centres that tapped genetically unrelated magma sources. Instances where a single geochemical analysis uniquely identifies a stratigraphic position are rare. But likewise, instances, in any specific domain, where several samples taken across a short stratigraphic string fail to uniquely identify a stratigraphic position are also rare. These barcodes attach significant stratigraphic predictability to lithogeochemistry collected during mineral exploration. The regional distribution of mafic chemostratigraphic associations is distinctly asymmetric, in many cases, ignoring previously established domain boundaries. A broadly north-trending structure incorporating segments of several mapped shear zones does appear to broadly separate 'western domains' from 'eastern domains'. The distinctive chemostratigraphy of these domain groups probably reflect a fundamental crustal architectural control – some mafic units in the western domains probably reflect melting of a more depleted source in thicker lithospheric mantle – and provides some basis for reassessing present domain boundaries. The chemostratigraphic differences between the western and eastern domains appears to extend to the sanukitoid felsic volcanic rocks of the overlying Black Flag Group.

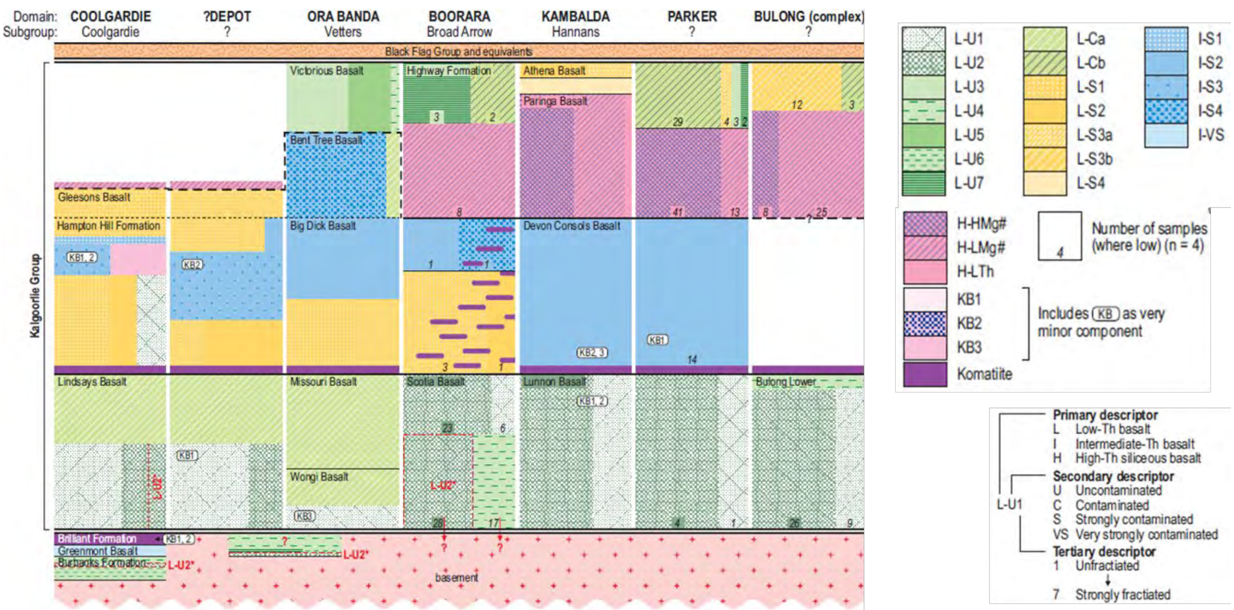

Figure. Chemostratigraphy of various domains within the study area

The Julimar Intrusive Complex and Associated Orthomagmatic Ni-Cu-Co-PGE deposits

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The Julimar Complex is a newly recognised ultramafic to mafic intrusive system located 70km north east of Perth and only 13km east of the Darling Fault which represents the westernmost margin of the Archaean Yilgarn Craton. Chalice Mining conceptualised a ~30km long trend of airborne magnetic anomalies may represent an ultramafic to mafic intrusive complex and the first drill hole test of a combined magnetic/ ground electromagnetic target with anomalous Ni/Cu soil geochemistry resulted in a spectacular maiden drill-hole discovery of near-surface high-grade Ni, Cu, Co and PGE orthomagmatic sulphides subsequently named the Gonneville Ni-Cu-Co-PGE deposit. An extensive resource drill out campaign underway since March 2020 has shown Gonneville to be the largest PGE resource in Australia (~16Moz PGE) and on a Ni equivalent basis (~3.0Mt Nieq) the largest nickel deposit discovered in Australia since 2000.

The Gonneville deposit comprises up to 13 zones (termed G Zones) of principally disseminated orthomagmatic sulphides with localised matrix to massive sulphides hosted in a ~2km long x 650m thick ultramafic to mafic intrusion. Low-grade PGE-dominant mineralisation is extensive throughout the ultramafic and mafic domains and forms a halo to the more sulphide-rich G zones. The igneous phases of the intrusion are almost entirely replaced by hydrous minerals indicative of upper greenschist to lower amphibolite grade metamorphism including serpentine (after olivine), amphibole (low and high Ca; after orthopyroxene), clinozoisite (after plagioclase) and Cr-mt (after chromite) although igneous textures are evident including relict olivine cumulates (meso to orthocumulate), coarse-grained poikilitic opx and relict chromite cores attesting to intrusive parentage of the host geology.

The Gonneville intrusion is subdivided into a series of ultramafic to mafic subunits using major and minor element lithogeochemistry which defines a well-defined macro-layering of harzburgite, pyroxenite and leucogabbro(norite) with most sulphide mineralisation restricted to the ultramafic domains (harzburgite, pyroxenite). The intrusion dips ~40 degrees to the north west and overlies a footwall succession of sulphidic metasediments and mafic amphibolite. The hangingwall contact is a mylonite which contains intercalated mafic to felsic rock types derived from mixed mafic to felsic intrusives and metasedimentary rocks. The Gonneville intrusion is cut by post-mineral granitoid intrusives and the entire succession is cut by a swarm of broadly N-S orientated mafic dolerite-gabbro dykes which affect the entire western margin of the Yilgarn craton.

U-Pb zircon dating of a pegmatitic gabbro subunit of the Gonneville intrusion yielded a magmatic age of 2668 +/- 4Ma which defines an entirely new age of ultramafic magmatism and orthomagmatic Ni-Cu-PGE mineralisation in the Yilgarn.

Revealing Australia's lithospheric architecture for exploration targeting: Advances from the $225 M Exploring for the Future program (2016–2024)

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Many forecast demand is set to outstripping the rate of new resource discoveries, therefore improvements in exploration are needed to meet net zero targets. To position Australia, the Australian Government initiated the $125 M Exploring for the Future program (2016–2024), focused on establishing an integrated resource prospectus for minerals, energy and groundwater resources. The unprecedented diversity and volume of new data collection and analysis is transforming exploration undercover in Australia and is being emulated globally. Since the beginning of the program over one hundred companies have picked up new exploration tenements covering over 300,000 km^2 using new and legacy exploration tenements. Here, key advances in continental scale characterization of the lithosphere and insights into mineral systems and exploration targeting are showcased including:

- quantitative insights into the global predictive power of passive seismic tomography and long-period magnetotellurics for mineral exploration and progress on the respective national data acquisition program AusArray and AusLAMP
- establishment of a new national coverage of xenocryst to benchmark interpretations of deep lithospheric features
- discovery of new basins and major crustal boundaries based on deep reflection seismic profiles and common conversion point assessment
- identification of fertile regions for exploration using isotope mapping (Nd, Hf, Pb, U-Pb, Ar)
- unprecedented imaging of the near surface through the world's largest airborne electromagnetic survey (AusAEM) coupled with the world's best potential field and radiometric coverage
- delineation of the undercover exploration frontier through systematic mapping to and of subsurface geology along four mega-sequence unconformities
- geochemical and petrological characterisation of the surface using surface geochemistry, heavy mineral studies and satellite data.

These datasets and more are integrated within a mineral systems framework to infer mineral potential undercover benchmarked by rock sampling and drilling programs, often reducing the search space for new deposits by 70–90%. Furthermore, Economic Fairways are mapped to lower the risk of mineral exploration and renewable energy generation by taking into account mining costs given the spatial distribution of cover-thickness, energy and transport infrastructure. All these datasets and new decisions support tools are available for communities, government, industry, and through the Exploring for the Future Data Discovery Portal (https://portal.ga.gov.au/).

How magnetotelluric data from multiscale surveys can help to image the footprint of mineral systems in covered terranes

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The footprint of a mineral system is potentially detectable at a range of scales and lithospheric depths, reflecting the size and distribution of its components. Magnetotellurics is one of a few techniques that can provide multiscale datasets to understand mineral systems. The Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) is a collaborative national survey that acquires long-period magnetotelluric data on a half-degree grid spacing (about 55 km) across Australia. This project aims to map the electrical conductivity/resistivity structure in the crust and mantle beneath the Australian continent. We have used AusLAMP as a first-order reconnaissance survey to resolve large-scale lithospheric architecture for mapping areas of mineral potential in Australia. AusLAMP results show a remarkable connection between conductive anomalies and giant mineral deposits in known highly endowed mineral provinces. Similar conductive features are mapped in greenfield areas where mineralisation has not been previously recognised. In these areas we can then undertake higher-resolution infill magnetotelluric surveys to refine the geometry of major structures, and to investigate if deep conductive structures are connected to the near surface by crustal-scale fluid-flow pathways.

We summarise the results from a 3D resistivity model derived from AusLAMP data in Northern Australia. This model reveals a broad conductivity anomaly in the lower crust and upper mantle that extends beneath an undercover exploration frontier between the producing Tennant Creek region and the prospective Murphy Province. This anomaly potentially represents a fertile source region for mineral systems. A subsequent higher-resolution infill magnetotelluric survey revealed two prominent conductors within the crust whose combined responses produced the lithospheric-scale conductivity anomaly mapped in the AusLAMP model. Integration of the conductivity structure with deep seismic reflection data revealed a favourable crustal architecture linking the lower, fertile source regions with potential depositional sites in the upper crust. Integration with other geophysical and geochronological datasets suggests high prospectivity for major mineral deposits in the vicinity of major faults.

This study demonstrates that the integration of geophysical data from multiscale surveys is an effective approach to scale reduction during mineral exploration in covered terranes.

The use of zircon and apatite as metallogenic fertility indicators in Archean orogenic gold systems

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The utility of accessory minerals as metallogenic fertility indicators, particularly zircon and apatite, has shown great promise in Phanerozoic porphyry Cu ± Mo ± Au systems. For example, fertile Phanerozoic porphyry systems can be distinguished from similar suites of "barren" rocks using geochemical signatures recorded in the mineral zircon — particularly those signatures shown to provide useful proxies for magmatic hydration and oxidation states (e.g., Loucks et al., 2020). In comparison to Phanerozoic porphyry systems, less attention has been paid to accessory minerals as metallogenic fertility indicators to Au systems in Archean terranes. This may represent a lost exploration opportunity, as a growing body of research is demonstrating that magmatic-hydrothermal fluids (besides metamorphic) do contribute to the Au-Cu budget in orogenic Au deposits within the Yilgarn and other Archean cratons.

To test the applicability of accessory mineral data for Archean metallogenic fertility, we present results from an ongoing study of zircon, and particularly apatite, from a large and lithologically diverse suite of igneous samples collected from both the Pilbara and Yilgarn cratons. Many of these samples represent "barren" igneous rock suites— those not associated with any known Au mineralization — which allows establishing the geochemical signature of barren Archean zircon and apatite. We compare the accessory mineral geochemical signatures of our barren suite to those of a fertile suite of samples collected from several intrusion-related Au deposits, albeit some that have been potentially overprinted by orogenic style gold mineralization. Our results show that geochemical signatures in zircon that are useful for distinguishing fertile Phanerozoic magmas, such as elevated Eu/Eu* (> 0.4), which is suggestive of hydrous magmas, and higher DFMQ (> +1) which is indicative of more oxidized magmas, can also be used to distinguish fertile and barren Archean igneous samples. In addition, zircon from the fertile Archean suite have more depleted mantle-like Hf isotope signatures compared to the barren suite. Apatite from the fertile suite also has depleted mantle-like Sm-Nd isotope compositions, as well as a distinct trace element inventory compared to apatite from the barren suite. Notably, fertile apatite has smooth rare earth element profiles, with high La/Yb and no Eu/Eu* anomaly, strikingly similar to those from traditional bulk-rock geochemical signatures of fertile magmas from Phanerozoic Cu-Au systems. Further, fertile apatite contains anomalously high Sr contents, far greater than their host rock, suggesting early crystallization during plagioclase suppression, and supporting the hydrous nature of fertile Archean magmas.

Ongoing work is aimed at understanding the petrologic and geodynamic processes operating in the Archean that produce "fertile" magmas. However, the results to date demonstrate the promise of zircon and apatite geochemical signatures (trace elements, Lu-Hf and Sm-Nd and potentially Rb-Sr isotopes) as a cost-effective exploration tool in Archean terranes.

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New horizons in predictive science

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Current exploration and extraction strategies are largely based on empirical knowledge reproducing analogues of known mineral systems and are not fit to deliver supplies of critical resources to meet rapidly increasing global demand. Increasing social and environmental constraints will require mineral exploration and mining operations to minimise their environmental footprints, and ore processing and metallurgical plants to be made more efficient and sustainable to maximise metal recovery and minimise waste disposal.

Challenges exist, especially on the education front. Tomorrow's industry professionals need interdisciplinary expertise that crosses traditional disciplines. We need to train and sustain the skilled future workforce to drive the required step change in practice and innovation in the resources sector. The direct outcome will be a more efficient way to target, characterise and process critical resources to sustain our future; this means transforming the fundamental science that underpins exploration for, and processing and extraction of critical resources.

The exploration process focusses on predictive and detective strategies, which are used sequentially from the global to the prospect scale (McCuaig et al., 2010). However, whereas in recent times detective techniques have made substantial advances, there is a perception that predictive tools have not experienced the same success. This discrepancy may be largely due to the perception that detective techniques are based on sound knowledge of chemical and physical parameters, which can be accurately and precisely measured by technology that is becoming increasingly advanced. Conversely, predictive techniques are often deemed to be largely flawed or at least fortuitous, because they are based on models that cannot be easily tested and often rely on outdated scientific paradigms.

As an example, there is no doubt that the focus on craton margins for magmatic Ni-Cu-PGE has increased since the 1993 discovery of Voisey's Bay, and the 2000 discovery of Babel-Nebo. The focus on these lithospheric domains has been well-articulated over the last decade (e.g., Begg et al., 2010), which may have resulted in further discoveries (e.g. Nova, Julimar). Furthermore, the focus on Trans-Lithospheric Faults is widely used in industry, with numerous deposits discovered globally. However, despite various aspects of mineral systems being encapsulated within the targeting methodologies of many teams and the science of Prediction having enormous upside, it is still entrenched in the mind of many that this has much less certainty than Detection. In this talk I would like to show that new scientific knowledge necessary for a leap change in the predictive power of exploration already exists, but simply not implemented as fast as it should.

Revolutionary advances in the knowledge of fluido-dynamics, chemo-physical behaviour of elements and nano-particles at P-T conditions that were unattainable until recently, petrophysics, as well as in the imaging of the thermal and compositional architecture of the lithosphere combined with the power of super-computing applications, machine learning and AI have laid out an exciting new series of opportunities that need to be tackled. A series of case studies that support this inference will be presented, highlighting how the discovery of new Tier 1 deposits and successful identification of greenfield areas, which is of paramount importance for the future of the planet and the implementation of the energetic green revolution, largely depends on a leap change in the predictive exploration of critical resources. Scientific advances can largely lower the risk associated with prediction as long as they are implemented correctly, thus boosting exploration success of ore deposits of the future, which will then be exploited in efficient and sustainable ways.

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