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Advances in Mineral Systems Analysis: Integrated Interpretation, Sulfur Isotopes and Geodynamic Modelling

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ABSTRACT

The mineral system concept has evolved since its first formal introduction to a holistic attempt to represent the necessary geological components to forming a mineral deposit. The earliest formulation of the concept in the mid-90s adapted components from the oil and gas industry "source-pathway-trap" approach to include 'energy', 'ligands' and 'outflow', to one that now defines 'geodynamic throttle', 'lithospheric architecture', 'fertility', 'deposition site' and 'preservation'. Initially, it may appear that the evolution of the mineral systems concept is mainly semantic as these component labels essentially describe very similar theme, however a deeper examination of the newer labels reveals an expanded understanding of Earth processes and improvement of our ability to measure and image them. In particular, the availability of high-quality geophysical data from some government agencies has greatly enhanced definition of lithospheric architecture beyond that of simply identifying a potential 'pathway' for metals to migrate to a site of mineralization. The simultaneous interpretation of different geophysical data allows identification of deep-crustal scale features that may be connected to the mantle (e.g. seismic and magnetotelluric data), trace them up through the lower crust (e.g. gravity data) to form a fault network at the surface that defines a prospective mineral belt. Age relationships defined by radiogenic isotope geochronology are vital to understand whether the mineral belt belongs to an age bracket that is permissive for economic deposits (e.g gold in Archean rocks). Recent advances in stable isotope geochemistry can reveal source and age of sulfur, with Archean sources linked to fertility for gold mineralization. Growing expertise in supercomputing in the geosciences, combined with a greater understanding of large-scale geodynamic processes allows numerical modelling to be performed to simulate the tectonic evolution of a region, and, most importantly, help to identify triggers for mineralization (e.g. mass transfer of metalliferous fluids during post-collisional relaxation) and estimate metamorphic grades as proxies for preservation of the crust. The value of the mineral systems concept is providing a framework in which to guide the explorationist to test data, interpretations and models and develop a hypothesis from which mineralization may be revealed. Integration of multiple concepts is central to this, as is integration of multiple data sources when developing the inputs. This presentation provides a summary of recent developments with examples from Western Australia.

MINERAL SYSTEMS

The mineral systems concept was developed in response to the increasingly complex task of locating economic mineralization (Wyborn et al., 1994). Many diverse criteria can be used to characterize a deposit, however these criteria become so numerous that each deposit becomes unique, and a systems approach to mineral exploration becomes untenable (Wyman et al. 2016). Many criteria may be also common to unmineralized regions, so the overlap of criteria common to a mineral system must then be identified in a holistic manner (McCuaig et al. 2010). The interdependent components of a mineral system, once identified, can then be modelled to understand how their interaction leads to mineralization.

While the components of a mineral system have generally been agreed upon, their relative importance, definition and interaction have tended to provoke controversy. Wyborn et al. (1994) and Knox-Robinson and Wyborn (1997) specified 'energy', 'ligands', 'source', 'transport', 'trap' and 'outflow', adapted from the 'source-pathway-trap' paradigm adopted by the oil and gas industry during the 1970s. Various iterations have since been offered, and summarized by Hagemann et al. (2016), some highlighting permeability (for example, Skirrow, 2009), others advocate for energy gradients (Dulfer et al. 2016), however the major themes remain consistent. Occhipinti et al. (2016) propose the framework shown in Figure 1. The necessity of considering the multiscale temporal and spatial characteristics of mineral systems are reflected in all the proposed frameworks, highlighting the importance that data and model resolution has to play in our ability to represent mineral systems.

Mineral Systems Versus Prospectivity Modelling

Wyborn et al. 1994 proposed a workflow that allowed the mineral systems criteria to be represented in a GIS in order that spatially coincident indications of mineralization could be shown. This approach augmented the knowledge- and data-driven approaches described by Bonham-Carter (1994). This process of 'prospectivity modelling' is distinct from developing a mineral system model, though each term tends to be inappropriately interchanged. Specifically, prospectivity modelling is the act of translating the mineral systems model into digital form and subject to modelling to provide a quantitative estimate of prospectivity. Weights-of-evidence, fuzzy logic, neural networks, logistic regression and their hybrid methods are the main forms employed by practitioners to model prospectivity, and are necessary to communicate the spatial representation of the mineral system to explorers who desire to use it. Both the definition of a mineral system and prospectivity modelling activities require quite different experience and

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expertise, and likely requires a team approach. However each practitioner needs to be aware that while many mineral system criteria can be defined, they must also be mappable (McCuaig et al. 2010) and thus restricts which can be used. Recent advances in technology and method have expanded which criteria can be included. Further, as mineral systems comprise a series of interdependent criteria, it now generally acknowledged that an integrated approach to interpreting and modelling geoscientific data is necessary to ensure criteria are represented as appropriately as possible.

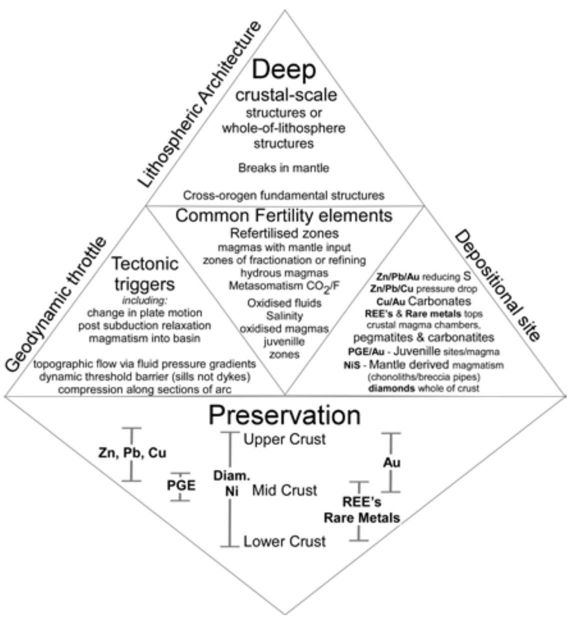

Figure 1: A schematic representation of a mineral system illustrating the main components required to form and preserve the listed mineral deposits (after Occhipinti et al. 2016).

MAPPABLE CRITERIA

Recent advances in data collection, analytical techniques and computing facilities have allowed us to represent three key elements from the framework shown in Figure 1. Lithospheric architecture can be more completely defined with a wide range of high resolution geophysical data. The cycling of sulfur in the crust has a critical role in crust formation and ore deposit formation and can represent fertility in a mineral system. The isotopic signature of this volatile agent can be traced through isotopic analysis, and give insight to either a Proterozoic or Archean source of sulfur, which is especially important for gold (Groves et al. 2005). Geodynamic numerical modelling has benefitted from increased availability of supercomputing platforms, and advances in code now allow the tectonic evolution of a region to be modelled, and geodynamic throttles identified. Changes in melt sources, composition of magmas and identification of P-T-t paths can be recorded in these numerical models, highlighting the type of mineral system that can form, as well as the potential for their preservation.

Lithospheric Architecture and Integrated Structural Interpretation

Lithospheric architecture is analogous to a 'pathway', and defines the conduits that supply metals to the depositional site in the crust. Integrated interpretation of magnetic, gravity and 3D magnetotelluric data has reveal a comprehensive view of the architecture of the east Kimberley region in northern Western Australia (Figure 2a).

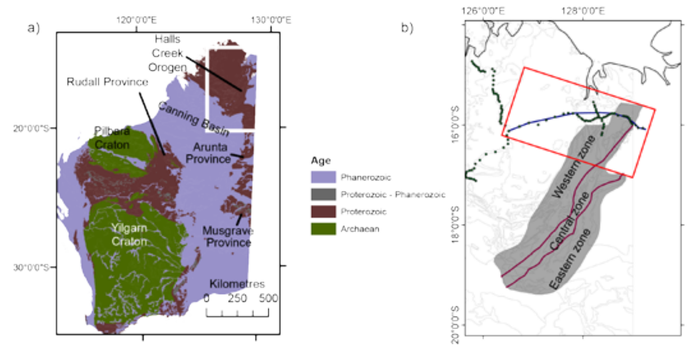

Figure 2: a) Location of the east Kimberley in northern Western Australia is indicated with the white rectangle. b) Location of MT recording station locations (points), forward model profile location (blue line) and the extent of the view shown in Figure 3 (red rectangle). Modified from Lindsay et al. (2017).

Integrated potential field structural interpretation and modelling has long been conducted to define lithospheric architecture and is now considered to be a key part of any mineral systems analysis. 3D MT data has only recently been incorporated into the process (Lindsay et al. 2017) due to the high computing requirements for inversion. The benefit of this can be seen in Figure 3.

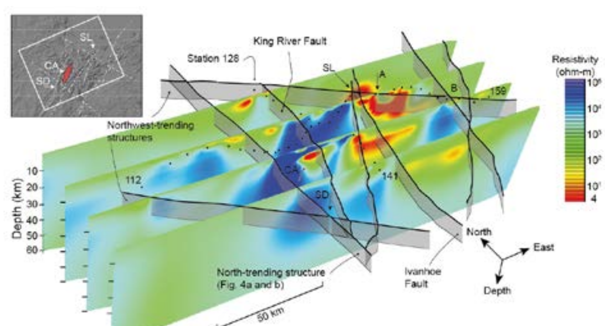

Figure 3: Isometric view from the south of inverted 3D MT data with structures interpreted and modelled using potential field data. Resistivity colour scale is shown at right - blue colours represent resistive areas and the warm conductive areas. The heavy black lines indicate the position and geometry of large-scale structures defining lithospheric architecture important for mineral systems analysis. These structures have been extended down vertically to help visualise where each structure may intersect the conductivity structure of the region. Dip or dip-direction is not indicated. The inset map shows the approximate extents of the view in the main part of the figure. Dashed grey lines indicate the position of the large-scale structures (heavy black lines in the main figure). From Lindsay et al. (2017).

The introduction of MT data to interpretation allows the conductivity structure to be viewed at an equivalent scale to the magnetic and density structure. Conductivity can be seen as an indicator for alteration and potential mineralization, and steep gradients can be interpreted to be structures. An example in Figure 3 is the King River Fault, which has a conductive anomaly located in the hanging wall and when traced to the surface, is linked with carbonate-hosted base metal mineralization (Lindsay et al. 2017). The conductive anomaly can also appears to extend along strike of the King River Fault, highlighting that structure should be included in prospectivity modelling (see Occhipinti et al. 2016).

Fertility and Sulfur Isotopes

Chemical and isotopic variations in sulfur-rich mineral systems record the interaction of different fluid reservoirs, some of which may be fertile and have supplied metalliferous fluids to mineralization sites along pathways defined with geophysics. Specifically, the mass independent fractionation of sulfur (MIF-S) is unique to the Archean sedimentary rock record and is quantified as $\Delta^{33}S$ and $\Delta^{36}S$. Sulfur reservoirs that interacted with the oxygen-poor atmosphere prior to the Great Oxidation Event at 2.4 Ga display a MIF-S signature. Granitoids formed from melting of these Archean sedimentary rocks will retain this signature, and may indicate a fertile Archean source of sulfur, and thus potential for gold and other metal deposits (LaFlamme et al. 2016). Sampling across a prospective mineral belt can then reveal gradients in the MIF-S signature, and thus provide a vector to mineralization, potentially concentrated along large crustal scale faults, or at the smaller scale, in zones of geological complexity and depositional sites.

Geodynamic Throttles and Numerical Modelling

The importance of understanding the geodynamic evolution of a region has long been accepted as an important aspect of any mineral system. Geodynamics will define at the regional scale what type of commodity is prospective and where, what structures were active during one or multiple mineralization episodes, and whether the appropriate throttles were in place to transport and then trap metals in the crust (McCuaig et al. 2010). Up until recently, understanding the geodynamic evolution has been limited to mental models, nonetheless constructed through rigorous geological account and years of research, but not testable in an objective manner.

A recent study in the east Kimberley has taken the I2VIS numerical modelling code (Gerya and Yuen, 2003) to test the hypotheses of the evolution of the Halls Creek Orogen (Figure 2a; Kohanpour et al. 2017). Two hypotheses have been proposed, one where a prospective rock package (the Tickalara Metamorphics) has formed as an oceanic arc, the other where the Metamorphics formed in a back-arc basin, with implications for prospectivity for base metal and gold systems respectively.

Results of the study reveal that a back-arc scenario is more feasible (Figure 4a). The model records the changes in melt production showing that by the end of collision and the last major tectonic episode in the region, the dominant signature is of a mafic source, consistent with analytical work on rocks samples (Bodorkos et al. 2002). The P-T-t paths for various markers through in the model (Figure 4c) also show consistency with analytical studies (Bodorkos et al. 2000). The geodynamic component of the mineral systems model for east Kimberley at this time can now be applied with more confidence knowing that it is more likely to be a back-arc basin.

CONCLUSIONS

The concept of a mineral system is not new, however a desire to provide a holistic and flexible framework is now seeing benefit. Earth processes that could not be imaged when mineral systems were first proposed in the mid-90s are now possible 20 years on. Integrated interpretation of 3D MT with potential field data gives comprehensive insight into the architecture of a prospective region. Sulfur isotopes combine well with the geophysics, and provide mappable criteria presenting the fertility of the region. Geodynamic numerical modelling gives the opportunity to test tectonic hypotheses and test the results against analytical results. These advances are important to forming a more complete and consistent mineral system from with explorers can discover new economic deposits.

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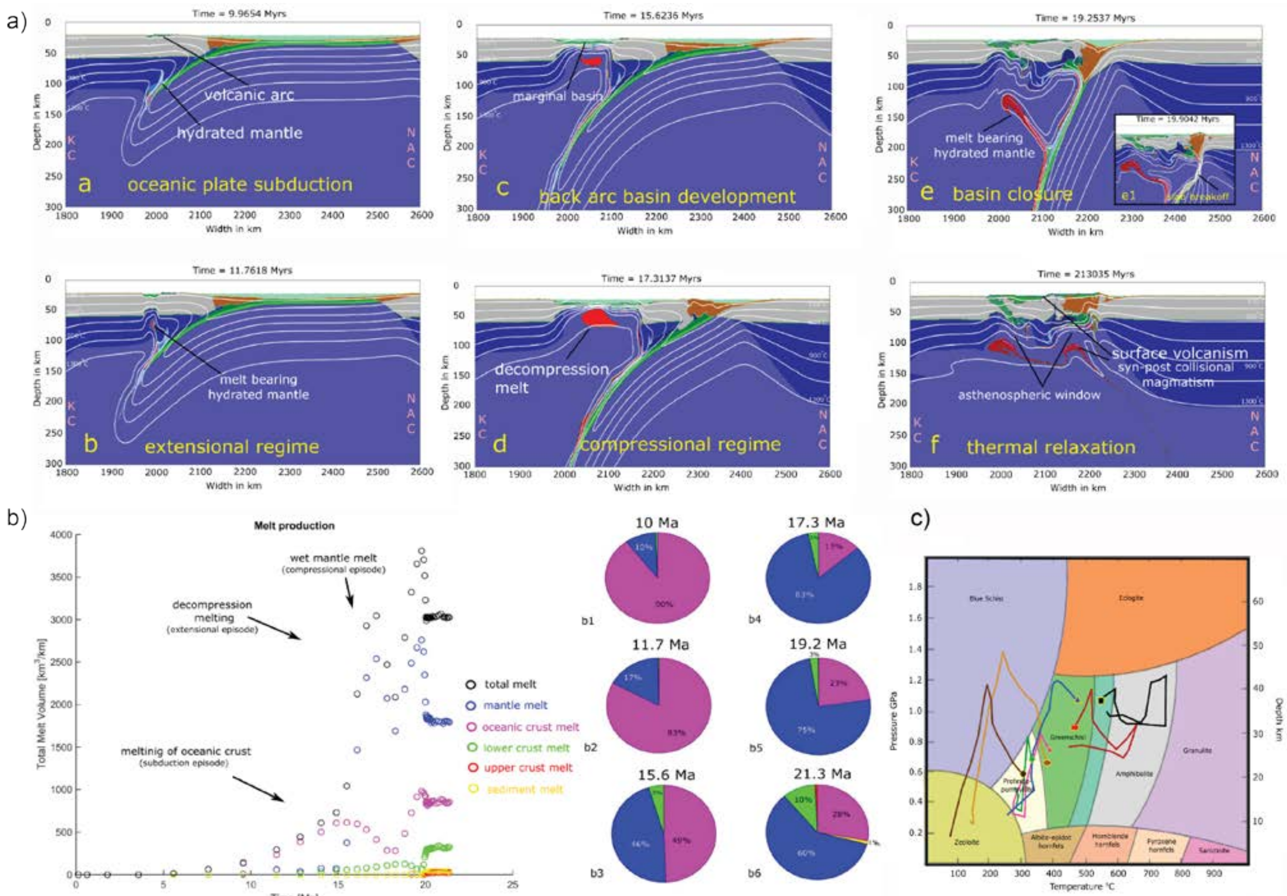

Figure 4: Numerical modelling results. a) The modelled tectonic evolution of the east Kimberley. Each section a-f (each viewed from the south) shows a time-slice from the start of modelling (~ 1.86 Ga). Different tectonic regimes are as labelled. b) The magmatic evolution of the numerical model – the graph shows time versus melt volume, colour-coded according to source. The pie charts show melt proportions at different time slices. c) P-T-t paths calculated from the numerical model, showing the highest metamorphic grade at upper amphibolite facies. Modified from Kohanpour et al. (2017).

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