



Characterization of ore-forming systems – advances and challenges

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Abstract: Economically viable concentrations of mineral resources are uncommon among the predominantly silicate-dominated rocks in Earth's crust. Most ore deposits that were mined in the past or are currently being extracted were found at or near Earth's surface, often serendipitously. To meet the future demand for mineral resources, exploration success hinges on identifying targets at depth, which, on the one hand, requires advances in detection and interpretation techniques for geophysical and geochemical data. On the other hand, however, our knowledge of the chain of events that lead to ore deposit formation is limited. As geoscience embraces an integrated Earth systems approach, considering the geodynamic context of ore deposits can provide a step change in understanding why, how, when and where geological systems become ore-forming systems. Contributions to this volume address the future resources challenge by: (i) applying advanced microscale geochemical detection and characterization methods; (ii) introducing more rigorous 3D Earth models; (iii) exploring critical behaviour and coupled processes; (iv) evaluating the role of geodynamic and tectonic setting; and (v) applying 3D structural models to characterize specific ore-forming systems.



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Economically viable concentrations of mineral resources are not common among the predominantly silicate rocks that formed Earth's crust: rock is everywhere, but ore deposits are rare! Exploration for mineral resources and their extraction has been an essential aspect of human society since pre-historic times, whether, nomadic, agrarian rural or urban: archaeological insights into early civilizations depend largely on the discovery and analysis of stone, ceramic and metal implements, and residential dwellings and monuments. The overwhelming majority of mineral deposits that were mined in the past, or are being extracted currently, were found at or near the Earth's surface, and only very few discoveries resulted from a structured search underpinned by scientific methods (e.g. Hronsky & Groves 2008). With a growing global population aspiring to the same levels of material affluence enjoyed by prosperous post-industrial societies, it is inevitable that demand for mineral resources in energy generation, building and manufacturing will continue to increase (Sykes *et al.* 2016; Ali *et al.* 2017; Arndt *et al.* 2017). There is, therefore, an urgent need to improve exploration success and

delineate new mineral reserves, while developing resource projects responsibly from economic, environmental and social perspectives (e.g. Herrington 2013; Vidal *et al.* 2013; Nansai *et al.* 2014; Sahu *et al.* 2015; World Economic Forum 2015; Nurmi 2017).

Accordingly, future exploration targeting will need to focus on either novel pathways for exploiting lower-grade and complex or previously intractable deposits, or improving technologies for detection and discovery at depth. In the former case, competing and, in some cases, conflicting priorities for land, energy and water access can be anticipated, compounded by environmental concerns, as the mining of lower-grade ores will typically require large-scale open-pit operations. Conversely, the search for high-grade mineral resources at depth requires more informed integration of data in mature mining districts (e.g. Grunsky 2010), as well as exploration techniques facilitating deep discovery in areas where the signatures of prospective targets are obscured beneath overlying rock units, such as regolith or sedimentary basins (Butt *et al.* 2000; Schodde 2014).

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Although the development of high-tech methods in exploration, production and mineral processing is likely to have a significant impact on exploration success and production economics, the geological understanding of how, when and where dynamic Earth systems become ore-forming systems poses a formidable scientific challenge in itself. Ore deposits are often the product of a complex interplay between coupled physical processes with evolving geological structure (Gessner *et al.* 2009; Ord *et al.* 2012). A number of ‘mineral system’ studies have explored the genetic links between the dynamic Earth systems that shape and modify the composition and structure of lithospheric domains and the mineral deposits that formed within them. In the mineral systems approach, the spatial extent of heat and mass transport is considered from the perspective of geodynamic driving processes of magmatism and crustal-scale hydrothermal fluid flow (Wyborn *et al.* 1994; McCuaig & Hronsky 2014; Huston *et al.* 2016; Occhipinti *et al.* 2016). This geodynamic perspective is warranted, as fluids in tectonic settings such as subduction and rifting can be part of planetary-scale transport cycles (e.g. Kelemen & Manning 2015; Foley & Fischer 2017). Furthermore, lithospheric domains and the structures bounding them can be important for melt and fluid fertility (e.g. Bierlein *et al.* 2006; Griffin *et al.* 2013; McCuaig & Hronsky 2014; Mole *et al.* 2014). Overall, the more ‘deterministic’ mineral systems approach complements more traditional, ‘empirical’, deposit-type-based approaches that use mineralogical, geochemical and structural characteristics to classify deposits (e.g. Cox & Singer 1986; Hedenquist *et al.* 2005). This Special Publication contains contributions to five research themes on the frontiers of mineral exploration: (i) advanced microscale geochemical detection and characterization methods; (ii) development of more rigorous 3D Earth models; (iii) critical behaviour and coupled processes; (iv) the role of geodynamic and tectonic setting; and (v) the application of 3D structural modelling to characterize specific ore-forming systems.

Advanced microscale geochemical detection and characterization methods

The development of new microscale analytical methods and their application is an important contribution to better characterize ore-forming systems. In their paper ‘Microscale data to macroscale processes: a review of microcharacterization applied to mineral systems’, Pearce *et al.* (2017) explore how innovations in microanalytical procedures and techniques, including synchrotron X-ray fluorescence, electron backscatter diffraction and X-ray computed

tomography, combined with trace-element mapping can be applied to ore deposit studies to constrain macroscopic processes within mineral systems. Based on case studies of mineralization at Sunrise Dam Gold Mine and the Mount Keith Ni-sulphide deposit in Western Australia, the authors find that an increasing use of microanalysis and the combination of micro- and macroscale datasets in ore deposit geology allow constant reassessment of established models for ore genesis.

Development of more rigorous 3D Earth models

To target mineralization and develop resource projects requires accurate models of the Earth’s crust and the ore-forming systems within it. Such models can never be exact due to inherent data paucity, but they do need to be consistent with all available geological and geophysical information. In addition to containing the best available spatial information, models should include an understanding of the time dimension. One important problem is the inherent uncertainties in these models.

In ‘Uncertainty estimation for a geological model of the Sandstone greenstone belt, Western Australia – insights from integrated geological and geophysical inversion in a Bayesian inference framework’, Wellmann *et al.* (2017) provide a novel quantitative approach explicitly addressing uncertainty and optimization by integrating structural, geological and geophysical data using probabilistic programming. In an application to a gold-bearing greenstone belt in Western Australia, they show that additional data integration significantly reduces uncertainties in the final model.

In their paper ‘Geologically driven 3D modelling of physical rock properties in support of interpreting the seismic response of the Lalor volcanogenic massive sulphide deposit, Snow Lake, Manitoba, Canada’, Schetselaar *et al.* (2017) generated lithofacies and physical rock property models to interpret 3D seismic data from the Lalor volcanogenic massive sulphide deposit, Manitoba, Canada. The authors found that kriging of P-wave velocity and density conditioned by curvilinear grids generated seismic synthetics that better matched the acquired data than properties forward-modelled in Cartesian space. They also found the physical rock property modelling methodology useful to assess the limitations of their discrete model.

Critical behaviour and coupled processes

Ore-forming systems contain many types of feedback, and are thus inherently non-linear. Chemical and mechanical systems are involved, making a

INTRODUCTION

complete analysis a formidable task. However, these problems are now being tackled through more unified non-linear thermodynamic approaches. This holds out the promise of a true systems approach to mineralization. Practical aspects of this approach may focus on identification and quantification of multifractal patterns in ore systems. In their contribution, ‘Coupling of fluid flow to permeability development in mid- to upper crustal environments: a tale of three pressures’, **Hobbs & Ord (2017)** consider the principles involved in the coupling between fluid flow and dilatant plastic deformation. They first review how elastic and plastic volume changes affect the fluid, mechanical and thermodynamic pressures, and then provide numerical examples of this hydromechanical process coupling. These authors also explore the role of critical behaviour in influencing the hydraulic architecture in open-flow-controlled systems at the crustal scale.

In their paper ‘Episodic modes of operation in hydrothermal gold systems: Part I. Deformation, mineral reactions and chaos’, **Ord & Hobbs (2018)** explore orogenic gold systems from the perspective of non-linear, non-equilibrium, dynamical, open-flow systems, for which they consider the coupling of aseismic, non-adiabatic processes. The authors suggest that localized changes in temperature at periods of less than 1–2 myr can control episodic temperature and fluid pressure behaviour, and cause gold deposition without external forcing by seismic events. In the related paper ‘Episodic modes of operation in hydrothermal gold systems: Part II. A model for gold deposition’, **Hobbs & Ord (2018)** discuss the physical and chemical coupling of deformation and simultaneous endothermic and exothermic reactions with fluid flow in highly localized gold deposition. The authors argue that episodic and localized variations of temperature, fluid pressure and the activity of H₂S are recorded in the deformation history, and in multifractal paragenetic sequences of alteration and ore minerals.

In ‘Spatial organization of gold and alteration mineralogy in hydrothermal systems: wavelet analysis of drillcore from the Sunrise Dam Gold Mine, Western Australia’, **Munro *et al.* (2018)** use wavelet analysis of hyperspectral drillcore logs to document and quantify the multifractal spatial distributions of mineralization and alteration in the Sunrise Dam gold mine in Western Australia. The authors suggest that the multifractal spatial organization of primary Au mineralization, calcite and ankerite veins, sericite and chlorite alteration, and metamorphic amphibole result from deterministic dynamical processes rather than from random stochastic processes.

With ‘Textural changes of graphitic carbon by tectonic and hydrothermal processes in an active

plate boundary fault zone, Alpine Fault, New Zealand’, **Kirilova *et al.* (2017)** present a microstructural study on graphitization in relation to fault rock properties and orogenic gold mineralization. The authors use optical and scanning electron microscopy and Raman spectroscopy to document a complex microtextural record of graphite mobilization during the temperature-retrograde deformation history of Alpine Schist samples from Deep Fault Drilling Project (DFDP) drillcore. This paper has significant implications for understanding the textural, mechanical and hydraulic properties of fault zones.

Role of geodynamic and tectonic setting

There has been a long history of relating geodynamics and tectonic settings to specific styles of mineralization, even to the extent that the characteristics of mineral deposits have been used to infer geodynamic settings. However, a potential pitfall of that approach is revealed by some studies of older mineral deposits, for which the tectonic setting can be contentious. Nevertheless, models that integrate lithospheric-scale processes with mineralization may have important large-scale implications for exploration.

In ‘Tropicana translated: a foreland thrust system imbricate fan setting for *c.* 2520 Ma orogenic gold mineralization at the northern margin of the Albany–Fraser Orogen, Western Australia’ **Occhipinti *et al.* (2017)** investigate the geodynamic setting of the Tropicana gold deposit at the margin of the Neoproterozoic Yilgarn Craton in Western Australia. The authors document the tectonic evolution of the Tropicana Zone, which they interpret as a fold-and-thrust belt that exhumed lower crustal rocks; thus producing the context of the Tropicana gold deposit. The sequence of events proposed in this paper suggests that deformed margins of Archean cratons may be prospective for gold deposits.

Lindsay *et al.* (2017) present an integrated interpretation of geological field observations and geophysical data in northern Western Australia in their paper ‘Identifying mineral prospectivity using 3D magnetotelluric, potential field and geological data in the east Kimberley, Australia’. This study uses the interpretation of magnetotelluric and potential field data to distinguish between deep crustal domains, and identifies the King River Fault as a crustal-scale, west-dipping structure that may have significance for exploration for graphite and base metals in the east Kimberley region.

The following two papers extend tectonic/geodynamic models of mineralization and hydrothermal activity to include the asthenosphere. In ‘The relationship between mineralization and tectonics

at the Kainantu gold–copper deposit, Papua New Guinea’, [Blenkinsop *et al.* \(2017\)](#) put an epithermal gold–copper deposit in Papua New Guinea into geodynamic context. The authors propose that while the tectonic history of the region hosting the Kainantu gold–copper deposit is dominated by north–south shortening due to Tertiary convergence along the Australian–South Bismarck plate boundary, mineralization occurred during a different tectonic regime between 9 and 6 Ma that may have been related to lithospheric delamination. In ‘Crustal fluid flow in hot continental extension: tectonic framework of geothermal areas and mineral deposits in western Anatolia’ [Gessner *et al.* \(2017\)](#) review characteristics of geothermal fields and of Miocene mineral deposits in a continental tectonic domain that experienced rapid thinning of lithospheric mantle and crustal extension in a convergent plate tectonic setting. The authors find that although the Menderes Massif in western Anatolia has remained in a similar plate tectonic setting from the Miocene to the present, changes in mantle dynamics affected crustal-scale hydrothermal flow, resulting in the contrast between Miocene mineralization and present day non-volcanic geothermal activity.

Application of 3D structural modelling to characterize specific ore-forming systems

3D structural geological models that characterize the spatial relationship between lithologies and structural features have become a standard tool in the characterization of ore-forming systems. In ‘The Windimurra Igneous Complex: an Archean Bushveld?’, [Ivanic *et al.* \(2017\)](#) present a 3D model of the V–Ti mineralization hosting Windimurra Igneous Complex, a mafic–ultramafic layered intrusion that is part of a 2.81 Ma anhydrous tholeiitic intrusive suite in the Yilgarn Craton, Western Australia. The authors use a 3D model based on seismic surveys and potential field modelling to better constrain the genetic model for magma emplacement, and they show that at *c.* 11 km it is the thickest and among the volumetrically largest layered mafic–ultramafic intrusions on Earth. The authors also suggest that the Windimurra Igneous Complex may include a thick, subsurface Ultramafic Zone with economic Ni–Cr–PGE mineralization.

In their paper ‘Delineating the structural controls on the genesis of iron oxide–Cu–Au deposits through implicit modelling: a case study from the El Group, Cloncurry District, Australia’ [Case *et al.* \(2017\)](#) use implicit 3D modelling to document structural controls on strata-bound iron oxide–copper–gold (IOCG) mineralization in the Mount Isa inlier in Queensland. The results of their study

allow the authors to constrain the deformation history of the deposit, and to view its genesis in the context of regional tectonic and mineralization events with implications for other IOCG provinces.

[Bell *et al.* \(2017\)](#) in their paper ‘Assessment of lithological, geochemical and structural controls on gold distribution in the Nalunaq gold deposit, South Greenland using three-dimensional implicit modelling’, use field, drillcore and geochemical data to create a 3D implicit deposit model. The model allows the integration of gold assay data from the mine with structural observations, and enables the delineation of the mineralization extent beyond the currently mined areas.

Outlook and challenges

Research on ore-forming systems is progressing along several lines of investigation, including technological advances in detection and characterization, better integration with geodynamic concepts, and application of rigorous models of interactions between physical processes.

The availability of geophysical and geochemical data in larger quantities and at increasingly high spatial resolution is likely to challenge our ability to process and interpret these data. This is particularly the case when a non-equilibrium genetic perspective is adopted, which predicts that ore-forming systems have emergent properties with multifractal signals that we are only beginning to understand. Whereas first principles of the separate processes may be well known, the large variety of possible boundary conditions, chemical speciation and fluid-phase transitions introduces a large complexity, which can only be tackled at present for a limited scope of subsystems.

The challenge may lie in finding where the useful balance lies between identifying the chain of events and mechanisms in ore-forming systems, and acquiring increasingly large datasets. Other scientific disciplines face similar challenges of balancing empirical v. deterministic and reductionist v. emergent approaches, such as the integration of neuroimaging studies with cognitive behaviour (e.g. [Spunt & Adolphs 2017](#)). Aside from the fascination of studying such natural complexity, one can also ask the question: How much of this knowledge can be translated to successful treatment of patients with cognitive or neurological disorders – or to find new mineral deposits?

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INTRODUCTION

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