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Reducing subjectivity in multi-commodity mineral prospectivity analyses: Modelling the west Kimberley, Australia

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ABSTRACT

Predicting realistic targets in underexplored regions proves a challenge for mineral explorers. Knowledge-driven prospectivity techniques assist in target prediction, and can significantly reduce the geographic search space to a few locations. The mineral prospectivity of the underexplored west Kimberley region was investigated following interpretation of regional gravity and magnetic data. Emphasis was placed on identifying geological structures that may have importance for the mineral prospectivity of the region. Subsurface structure was constrained through combined gravity and magnetic modelling along three transects. Crustal-scale structures were interpreted and investigated to determine their depth extent. These interpretations and models were linked to tectonic events and mineralization episodes in order to map the distribution of minerally prospective regions using a knowledge-driven mineral systems approach. A suite of evidence layers was created to represent geological components that led to mineralization, and then applied to each mineral system where appropriate. This approach was taken to provide a more objective basis for prospectivity modelling. The mineral systems considered were 1) magmatic Ni-sulphide, 2) carbonate-hosted base metals, 3) orogenic Au, 4) stratiform-hosted base metals and 5) intrusion-related base metals (including Sn–W, Fe-oxide–Cu–Au and Cu–Au porphyry deposits). These analyses suggest that a geologically complex belt in the Kimberley Basin at the boundary to the King Leopold Orogen is prospective for magmatic-related hydrothermal mineral systems (including Ni, Au and Cu). The Lennard Shelf is prospective for carbonate-hosted base metals around a feature known as the 67-mile high, and parts of the King Leopold Orogen are prospective for stratiform-hosted base metals. These results show that knowledge-driven mineral system modelling is effective in identifying prospectivity in regional-scale studies of underexplored areas, as well as drastically reducing the search space for explorers working in the west Kimberley.

1. Introduction

Mineral prospectivity modelling is a commonly used technique used to identify areas of high potential to host mineral deposits (Bonham-Carter, 1994a; Carranza, 2009). A wide range of mineral system types can be investigated with mineral prospectivity modelling, from deposit- to continental-scales. Crucially, the aim of these regional analyses is to not necessarily delineate drill targets, but to integrate diverse datasets to map conceptual geological favourability for ore genesis (Hronsky and Groves, 2008; McCuaig and Hronsky, 2000).

Two broad approaches to mineral prospectivity modelling can be taken: data-driven and knowledge-driven. Data-driven approaches use empirical observations of mineralization, usually in the form of spatially located mineral occurrences and deposits to determine their association with various geological features to develop a particular prospective 'signature' of a mineral system. These signatures are then used to identify regions of prospectivity that are not already highlighted by the existing (mapped) mineral deposit or occurrence data. Data-driven approaches rely upon a large dataset of well-described mineralised locations. Data-driven techniques include weights-of-evidence (Ford and Hart, 2013; Porwal et al., 2001), logistic regression (Carranza et al., 2008; Costa e Silva et al., 2012) and neural networks (Nykänen, 2008; Porwal et al., 2004). Conversely, knowledge-driven analyses use conceptual understanding of mineral system components as inputs into modelling (Joly et al., 2012, 2013; Lindsay et al., 2014). Knowledge-driven techniques include fuzzy logic (An et al., 1991; Knox-Robinson and Wyborn, 1997) and evidential belief functions (An et al., 1994a,b). Training data points (e.g., known mineral deposits or occurrences) are not required in knowledge-driven techniques, as the

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associations of various components of the mineral system are determined by the operator, as well as their relative importance to the mineralization process.

The mineral systems approach (MSA) (Knox-Robinson and Wyborn, 1997; Wyborn et al., 1994) has been used as a unifying conceptual framework in order to provide a platform for effective exploration targeting methods (Joly et al., 2012, 2013; McCuaig et al., 2010). The MSA recognises that ore deposits are expressions of multi-scale Earth-systems that focus mass and energy flux (McCuaig et al., 2010). Knowledge-driven mineral prospectivity modelling within the MSA framework is especially powerful in greenfields regions where few economic mineral deposit data points are available. Multiple mineral system models are also easily analysed for a given region using knowledge-driven methods (Aitken et al., 2014; Joly et al., 2013), and operators can easily update models and prospectivity maps as new or updated information becomes available. Data ambiguities and a desire for consistency and flexibility in the prospectivity modelling influenced the decision to use a knowledge-driven approach.

The west Kimberley region in northern Western Australia is a greenfields region and ideal for mineral prospectivity modelling using the MSA. Pre-competitive, publically available data have been used exclusively in this study. All relevant information used in developing the mineral systems model in the west Kimberley was extracted from public-domain sources. Geophysical interpretation, which forms a significant basis for many of the geological features used as inputs into the mineral prospectivity maps, was performed using data available from the Geological Survey of Western Australia (GSWA) 'GeoView' internet interface (http://warims.dmp.wa.gov.au/GeoView).

While some publically available mineral occurrence data points are available for this region, they are not considered reliable predictors of economic deposits, and preclude the use of data-driven techniques. The majority of data points in the region are classed as 'occurrences', meaning that concentration values only slightly above background were measured, and not at economic levels. Using such data would be inappropriate for this study as it would only predict other occurrence locations, and not those potentially hosting economic deposits. Further, the reliability of some historical data has been questioned by Hassan (2004), where 'a mountain of tin' reported by A. W. Sergison in the Sunday Times (1908) cannot be attributed to a single source or location. Cross-validation of historical data with locations in public datasets is made difficult due to lack of geographic co-ordinates. The lack of appropriate point and historical data led to the decision to avoid data-driven techniques.

In this contribution, we present prospectivity modelling results using knowledge-driven modelling techniques for a wide-range of generic mineral system types. These are: intrusion-hosted Sn and W; orthomagmatic Ni-sulphide; stratiform-hosted base metals (both volcano- and sedimentary-hosted base metals); porphyry-related and orogenic Au; and carbonate-hosted base metal (Mississippi Valley Type) deposits. We adopt a new approach where a set of prospectivity model inputs are generated, and then applied to each mineral system where appropriate. This is in contrast to similar multisystem studies where a unique set of model inputs are generated for each mineral system. The intended aim in taking this new approach is to reduce the inputs to those that are essential, avoid overfitting the model results, reduce subjectivity, incorporate uncertainty and produce a consistent set of models that reveal realistic areas of prospectivity in the underexplored west Kimberley.

1.1. The geology of the west Kimberley region

The west Kimberley includes the King Leopold Orogen and Lennard Shelf, forming a ~360 km by ~180 km ESE–WNW striking region that separates the southern margin of the Kimberley Basin from the northern margin of the Canning Basin (Fig. 1a). The dominantly Paleoproterozoic King Leopold Orogen can be divided into two distinct tectonic regions: (1) layered mafic and ultramafic sills, I-type granitoid intrusions, metasedimentary rocks, felsic volcanics and migmatites of the Western Zone to the Lamboo Province (Tyler et al., 1995); (2) the deformed sedimentary and mafic volcanic rocks of the Paleoproterozoic Kimberley Basin (Fig. 1a,c). The 1870–1850 Ma Hooper Orogeny, 1835 Ma Halls Creek Orogeny, the <1000–800 Ma Yampi Orogeny and the c. 560 Ma King Leopold Orogeny are recorded in the rocks of the King Leopold Orogen (Griffin et al., 2000; Sheppard et al., 2012; Tyler and Griffin, 1990). The relatively undeformed hills of Frasnian to Famennian (Late Devonian) reef complexes of the Lennard Shelf strike parallel to the southern edge of the King Leopold Orogen (Playford et al., 2009). Reefs surrounded the Neoproterozoic islands of the now Pillara and Oscar Range Complexes. The current day position of the reefs is thought to be controlled by the basement to the Lennard Shelf, considered to be a southward extension of the King Leopold Orogen (Fig. 1c) (Lindsay et al., 2015).

Several rock units are important for mineral prospectivity within the King Leopold Orogen (Fig. 2). The oldest unit is the metaturbiditic Marboo Formation, deposited c. 1872 Ma (Tyler et al., 1999), and the intruding sills of the Ruins Dolerite (Griffin et al., 1993; Tyler and Griffin, 1992). Magmatism related to the Hooper Orogeny is linked to the 1865–1850 Ma Paperbark Supersuite and c. 1855 Ma Whitewater Volcanics (Griffin et al., 2000; Sheppard et al., 1999, 2001). These units form the bulk of the King Leopold Orogen.

The c. 1835 Ma Speewah Group unconformably overlies the northern margins of the King Leopold Orogen and was possibly deposited in a retro-arc foreland basin during the Halls Creek Orogeny (Griffin et al., 1993; Tyler and Griffin, 1992). The c. 1800 Ma Kimberley Group, including the extrusive basaltic rocks of the Carson Volcanics disconformably overly the Speewah Group (Tyler et al., 2006). The c.1797 Ma Hart Dolerite intrudes the Speewah and Kimberley groups forming thick (up to 1.8 km) sills. The Carson Volcanics and Hart Dolerite comprise a large igneous province and cover an area > 160,000 km^2 with an estimated total volume of 250,000 km^3 (Griffin et al., 1993; Tyler et al., 2006). At the western extent of the study is the c. 1740 Ma Wotjulum Porphyry which intrudes the Kimberley Group as a series of sills (Sheppard et al., 2012; Tyler and Griffin, 1992). The youngest rocks examined for mineral prospectivity are the carbonate Late Devonian reef complexes of the Lennard Shelf, which overlie Ordovician rocks, and formed along shorelines of the Kimberley Craton and islands formed by the low-grade metasedimentary rocks of the Oscar Range.

1.2. Existing and possible west Kimberley mineral deposit types

A variety of mineral occurrence types are expressed in the west Kimberley, either as previously mined, sub-economic deposits or as prospects. These include base metal deposits (e.g., Yampi Sound, Grants Find), orogenic Au (e.g., Mount Broome, Robinson River, Oombulgurri), Sn–W (e.g., King Sound), Ni-sulphides (e.g., Camden Sound prospect) and more widely known Mississippi Valley-type Pb–Zn deposits (e.g., Pillara) and diamonds (e.g., Ellendale). The variety of occurrences, deposits and mines recorded in reports (Hassan, 2004) and the GSWA database 'Minedex' indicate the presence of different mineralising systems. While these data sources provide little constraint on the spatial distribution of favourable geological conditions for mineralization, they do provide some guidance in developing mineral system models applicable to the west Kimberley.

1.3. Orthomagmatic Ni sulphide mineralization

Possible orthomagmatic occurrences of Cu and/or Ni are associated with the Hart Dolerite (Lyndon, 1988a) and Noril'sk style, flood basalt-related Ni–Cu–PGE mineralization is suggested by the Australian Mines Atlas (http://www.australianminesatlas.gov.au, Model 5b). A mineral system involving the Hart Dolerite as a source rock and west-northwest trending dykes as fluid pathways was analysed for Ni–Cu–Co mineralization (Hassan, 2004), similar to the Voiseys Bay deposit,