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Comparing prospectivity modelling results and past exploration data: A case study of porphyry Cu–Au mineral systems in the Macquarie Arc, Lachlan Fold Belt, New South Wales

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ABSTRACT

Mineral exploration is undertaken in stages, with each stage designed to get to the next decision point of whether or not to keep exploring a particular area based on the results at hand. As a general rule, each consecutive exploration stage is more expensive due to the progressively more drill- and study-intensive nature of the work required, in particular after discovery of a potentially economic mineral deposit. As such, the distribution of exploration activities and related expenditures essentially serve as a spatial measure of prospectivity as perceived by mineral exploration companies. In this study we compare historic (1980 to 2002) porphyry Cu–Au exploration activities and expenditures in part of the Ordovician to Early Silurian Macquarie Arc, Australia's most significant porphyry province with total resources greater than 80 Moz of Au and 13 Mt of Cu, to prospectivity modelling results from a weights of evidence (WofE) model. The outcomes of this spatial and statistical comparison indicate that at 2002 the Macquarie Arc was by no means a mature exploration destination and that past exploration investment outside the main mining areas was not necessarily effective. Moreover, no spatial correlation was apparent between areas of higher exploration expenditure and greater geological potential. For example, of the 692 km^2 of highly prospective ground covered by the exploration licences examined in this study, only 89 km^2 (c. 13%) have been explored effectively in that they received some form of drilling. Interestingly, the remaining area (603 km^2 or c. 87%) had not yet been effectively tested. As such, our analysis confirmed that despite a greater 100 year exploration and mining history, much of the prospective ground within the study area remained untested. Taken as a whole, the results of our spatial and statistical comparison are important inputs for assessing the effectiveness of exploration investment and explanation maturity and, therefore, future exploration decision-making. The outcomes also have implications for strategic planning of future government legislation helping to manage and maximise the benefits from exploration investment.

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1. Introduction

Mineral prospectivity modelling with GIS (Bonham-Carter, 1994; Carranza, 2009) is increasingly being used by geoscientists in government and academia who, over the past 25 years, have significantly improved the various computational modelling techniques (e.g., weights of evidence, fuzzy logic, artificial neural networks: Porwal and Kreuzer, 2010) and applied them (i) to a wide range of mineral deposit types worldwide (González-Álvarez et al., 2010; Herbert et al., 2014; Lindsay et al., 2014; Porwal et al., 2010), (ii) to data-rich and data-poor areas (Fallon et al., 2010; Ford and Hart, 2013; Lusty et al., 2012), and (iii) at scales typically ranging from district to continent (Billa et al., 2004; Feltrin, 2008; Nykänen et al., 2008). More recently the scope and capabilities of mineral prospectivity modelling have been significantly extended to include, for example, three dimensional analysis (Apel, 2006; Feltrin et al., 2008; McGaughey et al., 2009; Mejía-Herrera et al., 2014), fractal analysis (Ford and Blenkinsop, 2008; Wang et al., 2012), and economic risk analysis (Partington, 2009; Partington, 2010).

Regardless of these improvements and successes, uptake of GIS-based prospectivity modelling by industry has been slow (Partington and Sale, 2004); perhaps because the technique is (i) perceived as a

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black box technology that requires expert knowledge to operate, (ii) essentially interpolative and constrained by known data whilst most important exploration success has come from extrapolating patterns into environments of poor data coverage (Porwal and Kreuzer, 2010), (iii) typically applied to two-dimensional datasets whereas mineralisation processes operate in three-dimensional space (Porwal and Kreuzer, 2010), and (iv) rarely presented by its advocates as a practical tool for decision-making and problem-solving in mineral exploration. Whilst methodological and technical aspects of GIS-based prospectivity modelling have been dealt with comprehensively and published widely, demonstration of its practical applications has been very limited apart from the showcasing of mineral potential maps. These maps are very useful and informative but should not be regarded as the be-all and end-all of the modelling but as a starting point for further investigations.

Here we present an example of how a GIS-based prospectivity model may be used as input for further analysis. In this study, we compare prospectivity modelling results to real-world exploration data that essentially serve as a spatial measure of prospectivity as perceived by the minerals exploration industry (cf. Cowley et al., 2009). The outcomes of this spatial and statistical comparison have implications for assessing the effectiveness of exploration investment and exploration maturity, which are important inputs for future exploration decision-making. The outcomes also have implications for strategic planning of future government legislation helping to manage and maximise the benefits from exploration investment.

The area selected for the case study covers part of the Ordovician to Early Silurian Macquarie Arc (Fig. 1), a now dismembered intra-oceanic island arc most widely exposed in the Lachlan Fold Belt of New of South Wales (Crawford et al., 2007; Glen, 2005; Hough et al., 2007). The Macquarie Arc is Australia's most fertile and productive porphyry province with an endowment of greater than 80 Moz of Au and 13 Mt of Cu (Clancy Exploration Limited, 2009; Cooke et al., 2007). The study area, which is defined by the Narromine, Dubbo, Forbes, Bathurst, Cootamundra, and Goulburn 1:250,000 scale map sheets, was selected to match an area investigated by a previous, unpublished study of historic porphyry Cu–Au exploration activities and expenditure commitments undertaken at the ARC National Key Centre for Geochemical Evolution and Metallogeny of Continents (GEMOC), Macquarie University, Sydney. A weights of evidence (WofE) model of porphyry Cu–Au prospectivity was developed by Kenex Limited in the framework of a mineral systems approach (Hronsky and Groves, 2008; Kreuzer et al., 2008; McCuaig et al., 2010; Wyborn et al., 1994). The model, which covers the entire Lachlan Fold Belt in New South Wales, was clipped to the study area, allowing direct comparison of the prospectivity model and the historic exploration and expenditure data.

2. Geology of the Macquarie Arc

The Ordovician to Early Silurian Macquarie Arc (Fig. 1) is an intra-oceanic island arc that is most-widely exposed in the New South Wales section of the Lachlan Fold Belt, one of five Palaeozoic orogenic belts in eastern Australia that together form the Tasman Fold Belt System (Foster and Gray, 2000; Glen, 2005; Hough et al., 2007; Suppel and Scheibner, 1990; Walshe et al., 1995).

The Macquarie Arc performed a key role in the development of the Lachlan Fold Belt, which formed by complex accretionary processes from Cambrian to Carboniferous times. These processes were triggered and sustained by the closure of the Wagga back-arc basin and associated collision of the Macquarie Arc with the proto-Pacific margin of Gondwanaland during the Late Ordovician to Early Silurian Benambra Orogeny. Post accretion, the Macquarie Arc was dismembered largely by E–W extension, with arc-parallel strike-slip faulting mainly restricted to the southern end. The overall tectonic development of the Macquarie Arc is commonly linked to its position above and interaction with a west-dipping subduction zone underneath the Gondwana plate, although a more complicated setting with multiple switches and intermittent cessation of subduction is likely (Cooke et al., 2007; Fergusson, 2009; Glen et al., 2007a; Holliday et al., 2002).

Igneous and volcaniclastic rocks of the now-dismembered Macquarie Arc are exposed in four structural belts:

- The Junee–Narromine Volcanic Belt in the west;
- The central Molong Volcanic Belt;
- The Rockley–Gulgong Volcanic Belt in the east; and
- The Kiandra Volcanic Belt in the south.

These belts, which formed by fragmentation of the Macquarie Arc post accretion, are separated by younger Silurian to Devonian rifts but can be correlated based on stratigraphy and major and trace element chemistry (Glen et al., 2007b, 2011).

Geochronological, stratigraphic and geochemical evidence is compatible with episodic evolution of the Macquarie Arc over a period of approximately 50 million years. The arc-related magmatism can be divided into four principal, partly overlapping phases that range in age from Early Ordovician to Early Silurian (Cooke et al., 2007; Crawford et al., 2007; Fergusson, 2009; Glen et al., 2007b):

- Phase 1 (Early Ordovician; c. 490 to 475 Ma): Produced mainly high-K calc-alkaline and shoshonitic intrusions and lavas that are only represented by relatively restricted outcrop in the Junee–Narromine and Molong volcanic belts.
- Phase 2 (Middle Ordovician; c. 466 to 450 Ma): Produced widespread, mainly high-K calc-alkaline and shoshonitic intrusions and lavas across all four structural belts of the arc.
- Phase 3 (Late Ordovician; c. 450 to 445 Ma): Produced shoshonitic intrusions and widespread but voluminously small, mainly felsic intrusions with distinctive medium-K calc-alkaline compositions; coincided with a five million year hiatus in magmatism in the western part of the arc that was accompanied by uplift, erosion and establishment of a widespread carbonate platform; resulted in the emplacement of porphyries and related Cu–Au mineralisation at Copper Hill, Cargo and possibly at Marsden.
- Phase 4 (Late Ordovician to Early Silurian; c. 458 to 437 Ma): Produced dominantly shoshonitic intrusions and lavas; coincided with crustal thickening during the Benambran Orogeny; resulted in the emplacement of the economically most significant Cu–Au mineralised porphyries in the Macquarie Arc.

Arc-related magmatism ceased in the Early Silurian during the protracted Benambran Orogeny (Cooke et al., 2007).

The Macquarie Arc is well endowed with large porphyry, skarn and epithermal deposits (cf. Table 1 in Cooke et al., 2007) containing more than 80 Moz of Au and 13 Mt of Cu (Clancy Exploration Limited, 2009). A spatial, temporal and genetic relationship is evident between many of the porphyry, skarn and epithermal deposits and Late Ordovician to Early Silurian shoshonitic intrusive complexes in the Macquarie Arc (Holliday et al., 2002; Gray et al., 1995; Lickfold et al., 2003; Forster et al., 2004; Lawrie et al., 2007; Glen et al., 2007b; Cooke et al., 2007; Wilson et al., 2007; Forster, 2009).

3. Macquarie Arc porphyry Cu–Au deposits

3.1. Alkalic porphyry Cu–Au deposits

The discovery of Cu and Au in the Macquarie Arc dates back to 1851. However, alkalic porphyry Cu–Au systems were only recognised in the Macquarie Arc in 1976 when wide-spaced drilling by Geopeko Limited intersected the Endeavour 22 deposit (Lye et al., 2006). Since then, two well-endowed clusters of Au-rich alkalic porphyries have been delineated in the Cadia (c. 40 Moz Au, 8 Mt Cu: Holliday et al., 2002; Thomas and Moorehead, 2011) and Northparkes (c. 2.1 Moz Au, 1.5 Mt Cu: Lickfold et al., 2003, 2007) districts. Combined, these districts

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