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Data fusion and porphyry copper prospectivity models, southeastern Arizona

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A B S T R A C T

Mineral exploration programs commonly use a combination of geological, geophysical and remotely sensed data to detect sets of optimal conditions for potential ore deposits. Prospectivity mapping techniques can integrate and analyse these digital geological data sets to produce maps that identify where optimal conditions converge. Three prospectivity mapping techniques – weights of evidence, fuzzy logic and a combination of these two methods – were applied to a 32,000 km^2 study area within the southeastern Arizona porphyry Cu district and then assessed based on their ability to identify new and existing areas of high mineral prospectivity. Validity testing revealed that the fuzzy logic method using membership values based on an exploration model identified known Cu deposits considerably better than those that relied solely on weights of evidence, and slightly better than those that used a combination of weights of evidence and fuzzy logic. This led to the selection of the prospectivity map created using the fuzzy logic method with membership values based on an exploration model. Three case study areas were identified that comprise many critical geological and geophysical characteristics favourable to hosting porphyry Cu mineralisation, but not associated with known mining or exploration activity. Detailed analysis of each case study has been performed to promote these areas as potential targets and to demonstrate the ability of prospectivity modelling techniques as useful tools in mineral exploration programs.

1. Introduction

The integration of different digital geoscientific datasets into an information-rich model is a key component of any mineral exploration program. Remotely-sensed surveys that provide gravity, aeromagnetic and satellite data can be used in conjunction with solid geology, geochemical survey and fault maps to determine an optimal set of conditions for a targeted mineral deposit (Behn et al., 2001; Bonham-Carter et al., 1989; Richards, 2003). Typically, data integration is performed using geographic information system (GIS) applications that allow identification of optimal conditions, their location and where they may be spatially correlated to indicate areas of high prospectivity (Carranza, 2011; Costa et al., 2012; Fallon et al., 2010; Feltrin, 2008; Ford and Hart, 2013; Joly et al., 2012; Nykänen et al., 2011; Raines and Bonham-Carter, 2006).

One of the challenges faced by geoscientists when producing meaningful mineral prospectivity maps is that the process can be labour-intensive, complicated and subjective, especially where regional programs are concerned. Also, how data are used and interpreted depends on the opinions and observations of the individual carrying out the study, which can cause highly variable non-repeatable results. Additionally, when new or updated datasets become available, their integration requires re-assessment of the model and can further complicate relationships between existing datasets and potentially extend timelines.

The development of statistical and expert-driven analysis methods has provided efficient and objective ways of producing meaningful prospectivity maps from digital geoscientific datasets (Agterberg et al., 1990). In this contribution we assess weights-of evidence (Bonham-Carter et al., 1989) and fuzzy logic (An et al., 1991; Zadeh, 1965) methods to delineate areas of high prospectivity in the established porphyry Cu deposit mining district in southeastern Arizona, USA. Weights-of-evidence is a data-driven approach that requires information from a set of data points representing known mineral deposits or occurrences (Agterberg et al., 1990; Bonham-Carter et al., 1989; Tangestani and Moore, 2001). Each data point is used to generate a set of weights that represent their association with a particular condition or pattern in different geoscientific data-sets. The fuzzy logic method is knowledge-driven and based on fuzzy set theory (Bonham-Carter, 1994; Tangestani and Moore, 2003; Zadeh, 1965). A set of data points are not required for this

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approach, as each spatial object is considered in terms of its membership to a diagnostic feature, such as the proximity of a felsic intrusion to a particular fault. We also apply a 'combination' approach that utilises data- and knowledge-driven methods to produce prospectivity maps.

Southeastern Arizona, together with areas in New Mexico and northern Mexico, form a larger region that has one of the highest concentrations of porphyry Cu deposits in the world (Barra et al., 2005). This region provides an excellent laboratory to assess the effectiveness of these methods. Data quality and coverage are sufficient as this mining district has been the subject of many exploration programs for over a century (Manske and Paul, 2002; Richards, 2003). The cylindrical geometry these deposits exhibit suits the recognition of mineralisation, alteration and structural control in plan-view images (Meju, 2002), increasing the potential for locating Cu deposit structures using GIS and supporting these prospectivity methods. We incorporate geophysical and satellite remote-sensing data into the prospectivity study to assist exploration in regions of poor outcrop as these can delineate aspects of the subsurface architecture favourable for the development of porphyry Cu deposits (Behn et al., 2001; Clark and Schmidt, 2001; Oldenburg et al., 1997).

Whilst these methods have been shown to be effective for prospectivity mapping for porphyry Cu mineralisation (Abedi et al., 2012; Carranza, 2004; Carranza and Hale, 2002; Tangestani and Moore, 2001, 2003; Ziaii et al., 2011; Zuo et al., 2009), they have also been effective for other deposit types such as Fe formations and base-metals (An et al., 1991; Lisitsin et al., 2013), Carlin-type Au deposits (Raines and Bonham-Carter, 2006; Turner, 1997), orogenic Au (Ford and Hart, 2013; Joly et al., 2012; Nykänen et al., 2011) sediment-hosted Au (Cassard et al., 2008), epithermal Au (Carranza and Hale, 2000, 2001) and sediment hosted Pb–Zn deposits (Feltrin, 2008; Porwal et al., 2001, 2003, 2004, 2006).

In this contribution we present prospectivity results from approaches using weights-of-evidence, fuzzy logic and a combination of the two methods. Sensitivity analysis is carried out to find the most effective method for identifying porphyry Cu deposits. Further, key datasets, information sources and their requirements will be identified providing guidance to future studies. Statistically validated regions of high potential are assessed using Landsat satellite imagery and stream sediment geochemistry to identify possible Cu prospects.

2. Regional geology

Southeastern Arizona (Fig. 1) records almost two billion years of tectonic activity (Drewes, 1981). The regional basement comprises accretionary, back-arc and arc terranes of the Proterozoic Yavapai and Mazatzal Provinces (Eisele and Isachsen, 2001; Karlstrom and Bowring, 1988; Swift and Force, 2001). Movement along major strike-slip fault systems formed Proterozoic rift basins (Drewes, 1981; Larson et al., 1994; Stewart et al., 2001). Reactivated Proterozoic northwest trending faults control the emplacement of magmatic intrusions associated with the ca 270 Ma–245 Ma Sonoma Orogeny (Drewes, 1981). The Cretaceous andesitic and rhyolitic volcanic successions of the Temporal and Bathtub Formations were emplaced during the Sevier Orogeny (DeCelles and Coogan, 2006; Zaleha, 2006), which continued until the Late Cretaceous (75–70 Ma). The Tertiary Laramide Orogeny (Anthony, 2005) resulted in regional uplift and orogenic activity along NW-trending faults during east-northeast-west-southwest directed crustal shortening (English et al., 2003). Laramide-age intrusions and faults are often spatially and genetically linked with porphyry Cu mineralisation (Barra et al., 2005; Titley, 1995). Following the Laramide Orogeny, southeastern Arizona was subjected to east–west Basin and Range extension (Wernicke and Burchfiel, 1982). Extension-related volcanism, dominated by rift-related alkaliac basaltic volcanism, uplift and erosion resulted in the development of low-angle detachment faults, exhumation of metamorphic core-complexes (Frassetto et al., 2006; Henry and Aranda-Gomez, 1992; Kempton et al., 1990). Further extensional episodes were accommodated by listric and N–S trending planar normal faults, expressed at the surface as a complex arrangement of half-graben of the Basin and Range (Wernicke and Burchfiel, 1982).

3. Porphyry copper deposits

Porphyry Cu deposits are a primary source of the world's Cu, Mo, and Au (Lowell and Guilbert, 1970; Manske and Paul, 2002; Richards, 2003; Sillitoe, 1972). Porphyry Cu deposit ore bodies typically occur as disseminations within a stockwork of large veins or small fractures. Ore formation occurs via magmatic–hydrothermal transport of metals along fractured conduits before deposition within porphyritic intrusions and wall-rocks (McMillan and Panteleyev, 1988). The main characteristics of porphyry Cu deposits are: (1) the intrusive core of the deposits are generally felsic to intermediate in composition, such as granodiorite, diorite or andesite; (2) genesis occurs from multiple igneous intrusive events; (3) dyke swarms and brecciation are common and (4) are hosted in any type of rock, from distinctly unrelated country rock to syngenetic extrusive magmas; (5) extensive fracturing within and around the intrusions; (6) large areas of alteration and mineralisation that display lateral zoning; and (7) temporal relationships with the timing of mineralisation, regional or orogenic uplift and erosion patterns (Behn et al., 2001; Candela, 1986; Cline and Bodnar, 1991; Francis et al., 1983; Gow and Walshe, 2005; Lowell and Guilbert, 1970; McMillan and Panteleyev, 1988; Padilla Garza et al., 2001; Richards, 2003; Robb, 2007; Rosenbaum et al., 2005; Sillitoe, 1972, 1988, 1997).

Porphyry Cu deposits display distinctive lateral alteration zones which can indicate the different magmatic environments in which they formed. Simplified alteration models show that, from the core to the margin, a zonation pattern characterised by potassic, phyllic, agrillic to propylitic alteration (Francis et al., 1983; Gutscher et al., 2000; Harris and Golding, 2002; Padilla Garza et al., 2001). Robb (2007) outlines three main types of mineralisation: hypogene sulphides; supergene sulphides and Cu oxides. Hypogene mineralisation is recognised by varying amounts of chalcopyrite, bornite, molybdenite and pyrite within fracture fillings, disseminations and quartz veins. Zoning patterns can differ slightly between individual deposits. Supergene blankets are typically seen to have three zones, the upper being a barren leached zone, underlain by a Cu "oxide" zone comprising chrysocolla, brochantite, antlerite and atacamite, that overlies a Cu sulphide zone of chalcocite.

4. Porphyry copper deposit exploration model

An exploration model that combines knowledge of the ore deposit and geological setting of the study area is important to help identify the geological characteristics that are associated with or near the targeted deposit, and can then be represented as evidence layers and combined to develop the prospectivity maps (Tangestani and Moore, 2001). The exploration model used in this contribution is based on the characteristics of southwestern US porphyry Cu deposits as defined by Hildenbrand et al. (2000), Lowell and Guilbert (1970), McMillan and Panteleyev (1988), Manske and Paul (2002) and Seedorff et al. (2005). Deposit characteristics adapted for use as evidential layers in our method are: (1) most deposits are hosted within Laramide age (80–55 Ma) felsic to intermediate igneous intrusions and (2) hosted within Late Cretaceous sedimentary and meta-sedimentary wall rock; (3) deposit emplacement is mostly controlled by northeast and northwest trending regional faults; (4) the intersection of regional magnetic lows, likely due to the low magnetic response exhibited by fault systems controlling the emplacement of host intrusions; (5) high-response gravity lineaments that possibly identify re-activated Proterozoic basement faults; (6) host orebodies have an oval to pipelike