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Editorial

Primary geochemical characteristics of mineral deposits — Implications for exploration

The old adage 'mineral exploration is like finding a needle in a haystack' recaps the difficulty of finding economic mineral deposits near or beneath the surface. In general, two main approaches can be used to detect the presence of mineral deposits near or beneath the ground surface. One employs a mineral deposit model and the other aims at the identification of a primary halo about a mineral deposit. A mineral deposit model provides systematic empirical (descriptive) and/or theoretical (genetic) descriptions of the essential geological, geochemical and geophysical features of a type of mineral deposits (cf. Cox and Singer, 1986; Roberts et al., 1988). The primary halo of a mineral deposit, as defined originally by Safronov (1936), is 'an area including rock, surrounding mineral deposit (ore bodies) and enriched elements that make up that deposit'. Thus, descriptions of primary haloes may form part of a mineral deposit model, but both deposit model and primary halo approaches to mineral exploration are based on studies of primary geochemical characteristics of mineral deposits because chemical processes during mineralization are the ones that ultimately bring about metal precipitation or mineral formation. However, a deposit model approach to mineral exploration is apt for identifying 'which haystacks contain a needle' whereas a primary halo approach to mineral exploration is proper for deducing 'where in a needle-bearing haystack is the needle located'.

Because mineral deposit models provide only empirical and/or theoretical guidelines but not diagnostic criteria for exploration, the identification of 'which haystacks contain a needle' requires lithogeochemical studies using major/trace element data to distinguish between mineralized and barren rocks of certain types (e.g., Makkonen et al., 2008; Zhao et al., 2011). However, deposit model descriptions of regional geochemical features of a mineral deposit type have been used traditionally as reference 'expert knowledge' for preparing geochemical evidence maps, which are integrated with other thematic evidence maps in a geographic information system (GIS) for creating regional-scale mineral prospectivity maps (e.g., Bonham-Carter, 1994; Carranza et al., 1999; Cassard et al., 2008). Nowadays, adoption of a mineral system approach to delineation of exploration targets is advocated (McCuaig et al., 2010) because of the recognition that mineral deposits are focal points of much larger systems of energy and mass flux (Hronsky and Groves, 2008). In contrast to the deposit model approach, which relies mainly on using certain geological, geochemical and geophysical features as empirical or conceptual evidence of mineral prospectivity, the mineral system approach to delineation of exploration targets relies on a 5-question paradigm (Walshe et al., 2005). The five questions, which relate to processes of geologic controls on mineralization, are: (i) What is the architecture and size of the system?; (ii) What is the P–T and the geodynamic history of the system?; (iii) What is the nature of the fluids and fluid reservoirs in the system?; (iv) What is the nature of fluid pathways and processes driving fluid flow?; and (v) What is the chemistry of metal transport and deposition in space as well as time? Each of these questions certainly requires studies of primary geochemical characteristics of mineral deposits at various geographic scales. In particular, geochemical studies of primary haloes of mineral deposits can provide important insights to mineral systems as well as significant implications for mineral exploration (e.g., de Almeida et al., 2010; Goldberg et al., 2003; Kekelia et al., 2008; Zhang et al., 2011).

Primary haloes of mineral deposits, which are results of interactions between country rocks and mineralizing fluids, are characterized by element/metal enrichment/depletion (e.g., Goldberg et al., 2003; Govett, 1983; Safronov, 1936) and/or mineral alterations (e.g., Bierlein et al., 1998; Hannington et al., 2003; Lovering, 1949). These features, which are usually contemporaneous with mineral deposition, occur as envelopes around individual mineral deposits. Geochemical characteristics of primary haloes of mineral deposits are quite predictable and explicable, and thus generally provide better exploration targets. Certain elements/metals forming primary haloes about mineral deposits potentially play the role of pathfinders for ore zones (e.g., Kekelia et al., 2008). However, the choice of pathfinder elements/metals depends on factors such as consistency of association with the ore deposits sought, characteristics of primary dispersion and ease with which geochemical analysis can be performed (Levinson, 1974; Rose et al., 1979). Vertical element/metal zonations about certain mineral deposits have led to the notion of supra- and sub-ore haloes, defined by certain elements/metals, which have been used as guides in mineral exploration (cf. Beus and Grigorian, 1977; Distler et al., 2004; Gundobin, 1984; Ziaii et al., 2011).

Depletion, enrichment and conservation of particular elements/metals in primary haloes of certain mineral deposits provide a basis for development and application of certain element/metal ratios for vectoring toward ore zones (e.g., Goodell and Petersen, 1974; Jones, 1992; Pirajno and Smithies, 1992). Variations in major element compositions related to mineral alterations in rocks (e.g., during mineralization) can also be described using Pearce element ratios (Pearce, 1968), which aid in the exploration for certain deposit-types (McQueen and Whitbread, 2011; Stanley and Madeisky, 1994; Urqueta et al., 2009). Moreover, intensities of mineral alterations in rocks associated with certain types of mineralization have been represented by alteration indices using mainly major element data (e.g., Barrie, 1993; Date et al., 1983; Ishikawa et al., 1976; Kishida and Kerrich, 1987; Large and McGoldrick, 1998; Large et al., 2000, 2001; Piché and Jébrak, 2004; Prendergast, 2007).

The above-cited studies illustrate the importance of multi-element lithogeochemical data to characterize mineral deposits in support of prospect- to deposit-scale exploration programs. However,

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lithogeochemical characteristics of potential host rocks can be useful in determining, at early stages of exploration programs, geological environments or petrogenetic signatures that are favorable for occurrence of certain types of mineral deposit (e.g., Barnes et al., 2004; Piercey, 2010). Effective use and interpretation of lithogeochemical data for regional-scale exploration programs can be achieved through applications of GIS (Harris et al., 1999, 2000, 2001). However, primary haloes of mineral deposits as well as favorable settings associated with mineral deposits can also be characterized by other means, such as analyses of isotopic compositions, fluid inclusions and mineral chemistry.

Fluid–rock interactions during mineralization are accompanied by isotopic exchange resulting in alterations in both the fluid and the rock, and the isotopic signature of haloes developed in altered rock may provide a larger exploration target and a vectoring capability. As examples, studies by Arehart and Donelick (2006), Benavides et al. (2008), Bierlein et al. (1998, 2004) and Hannington et al. (2003) on certain types of mineral deposits have shown that mineralized and barren areas are characterized by distinctive alteration indices and stable isotope values, and certain stable isotopes, depending on deposit-type, exhibit spatial distribution patterns that generally correlate with those of certain elements/metals in mineralized areas. Radiogenic isotope compositions may also exhibit broad correlations with metal contents in mineralized areas (e.g., Haest et al., 2009); however, radiogenic isotope data can provide useful petrogenetic constraints on host rocks, which can be important in the formulation of mineral exploration models for certain deposit-types (e.g., Harmer and Farrow, 1995; Zhang et al., 2011). Nevertheless, the effective application of isotope systematics in mineral exploration, especially when integrated with other exploration datasets (e.g., Criss et al., 1985), remains limited due to certain factors. These factors include complex and/or lengthy sample preparation and analytical procedures, access to mass spectrometer facilities, high costs and relatively long turn-around times.

During mineralization, fluid–rock interactions result in the release of certain gases from rocks to the mineralizing fluids. Thus, analyses of gas compositions of fluid inclusions in gangue and/or ore minerals provide useful insights into the chemistry of hydrothermal fluid and possible mechanisms of metal precipitation, which aid in vectoring toward ore zones of a mineral system. This has been demonstrated by several studies devoted mainly to investigate the potential of fluid inclusion gas analyses in exploration for hydrothermal vein mineralizations (e.g., Kesler, 1991; Kesler et al., 1986; Shepherd and Waters, 1984). Nevertheless, gas patterns from fluid inclusion analyses are relatively subtle and, therefore, their usefulness is limited unless they are used in conjunction with other geochemical or geophysical exploration data. However, petrographic examinations of fluid inclusion assemblages (e.g., Moncada et al., 2011; Rankin and Alderton, 1983) can also provide insights to mechanisms of metal/mineral precipitation from mineralizing fluids, which are useful information for mineral exploration, and are much simpler than fluid inclusion gas analyses.

Variations in chemical compositions and textures of particular minerals, either in ore zones or in primary haloes, are due to certain crystallo-chemical processes during mineralization (Stone and Crocket, 2003). Mineral chemistry can be determined by methods of lithogeochemical analysis and by means of infrared spectroscopy (e.g., Fakhry, 1974; Gemmell, 2007; Yang et al., 2011) or by electron microprobe analysis (e.g., de Almeida et al., 2010; Hannington et al., 2003; Large and McGoldrick, 1998). Like lithogeochemical data, mineral chemistry data can provide mineral and/or metal ratios for vectoring to ore zones (e.g., Baker et al., 2006; Barnes, 1990; Oyman, 2010; Stone and Crocket, 2003). Mineral chemistry data, in combination with petrographic and whole-rock composition data, are useful in the identification of least altered rock samples to support studies of vectoring toward ore (e.g., de Almeida et al., 2010). Mineral chemistry and element dispersion data combined with the known geology of a mineral deposit support the development of a primary halo model (e.g., Hannington et al., 2003; Large and McGoldrick, 1998), a chemostratigraphic model (e.g., Barrett and MacLean, 1994; Lentz, 1996; O'Connor-Parsons and Stanley, 2007) or an igneous stratigraphy model (e.g., Stone and Crocket, 2003) to assist exploration for certain types of mineral deposits.

Patterns of element/metal concentrations in primary haloes of mineral deposits are often associated with zoning patterns of alteration mineral assemblages (e.g., Eilu and Mikucki, 1998; McQueen and Whitbread, 2011; Pons et al., 2010). Mineralogical data from primary haloes of mineral deposits can, together with or independent of lithogeochemical and/or mineral chemistry data, provide useful indicators of intensely mineralized parts of a mineral system. The alteration mineralogies of primary haloes of certain types of mineral deposits are commonly examined using X-ray diffractometry or XRD (e.g., Hannington et al., 2003; McQueen and Whitbread, 2011; Sun et al., 2001) and short-wave infrared spectroscopy or SWIR (e.g., Di Tommaso and Rubinstein, 2007; Sun et al., 2001; Yang et al., 2011). Applications of multi- and/or hyper-spectral remote images aid greatly in the detection and mapping of mineral alteration zones associated with certain types of ore deposits (e.g., Laukamp et al., 2011; Pour and Hashim, 2012; Rowan et al., 2000).

Most of the studies cited in the foregoing discussions focused on deposit-scale primary geochemical characteristics of mineral deposits, which are important for deducing 'where in a needle-bearing haystack is the needle located'. Similar studies can be focused, however, on regional-scale primary geochemical characteristics of mineral deposits to identify 'which haystacks contain a needle'. Perhaps the best examples of the latter type of studies are concerned with volcanogenic massive sulfide (VMS) deposits (e.g., Hannington et al., 2003; Huston et al., 1998). These studies showed good regional-scale spatial relationships between alteration mineralogies and stable isotope compositions associated with VMS mineralizations. However, fractal or scale-invariant properties are exhibited by spatial distributions of certain types of mineral deposits (e.g., Carranza, 2009; Gumiel et al., 2010; Raines, 2008) and deposit-related geochemical attributes (e.g., Allègre and Lewin, 1995; Bölviken et al., 1992; Zuo et al., 2009). Therefore, studies of the latter at any scale are a key to 'finding the needle in a haystack' at any scale. A recent example of this proposition is shown by Ziaii et al. (2011), who successfully applied vertical zonality coefficients, related to the notion of supra- and sub-ore haloes at deposit-scales, to regional-scale mineral prospectivity mapping.

In this special issue of Ore Geology Reviews, there are five papers about primary deposit-related geochemical characteristics of different deposit-types and at different geographic scales. The first two papers are about identifying 'which haystacks contain a needle' whereas the last three papers are about deducing 'where in a needle-bearing haystack is the needle located'. The first three papers are district- to regional-scale studies, whereas the last two papers are prospect- to deposit-scale studies.

In the first paper, Yuan et al. studied major/trace (including rare-earth and platinum group) element data from well-exposed and well-preserved continental flood basalts in the Keping area of the Tarim Basin (northwestern China) to discuss the plausibility of sulfide saturation history and magmatic Ni–Cu sulfide potential of the Tarim Permian mantle plume-related large igneous province.

In the second paper, Fogliata et al. studied major/trace (including rare-earth) element data and U–Pb geochronological data from various granites in the Sierras Pampeanas Orogen (northwestern Argentina) to discuss (a) geochemical trends, crystallization age and fertility of granitoids with respect to Sn–W mineralization and (b) pathfinder elements for Sn–W deposits in fertile granitoids.

In the third paper, Van Ruitenbeek et al. studied laboratory SWIR data and airborne hyperspectral imagery to characterize the

distribution of white micas in Archean submarine hydrothermal systems related to VMS mineralization in a well-exposed volcanic sequence of the Soansville greenstone belt in the Pilbara craton (Western Australia). Then, in conjunction with whole-rock geochemistry and temperature estimates from oxygen isotope studies of hydrothermally altered rocks, they compared and contrasted the abundances and distributions of white micas with published hydrothermal alteration maps. The integrated study allowed reconstruction of paleo-fluid pathways, which help to delineate sites of hydrothermal discharge where VMS mineralization has formed.

In the fourth paper, Sonntag et al. studied petrographic, SWIR and XRD datasets to investigate hydrothermal alteration related to low sulfidation epithermal Co–O deposits (eastern Mindanao, Philippines), and then they discussed the pros and cons of using SWIR and/or XRD datasets to define geochemical vectors to Au-rich rich zones in deposits similar to Co–O.

In the fifth paper, Andrada de Palomera et al. studied vein/alteration mineralogical data and major/trace element geochemical data from drillholes in the La Josefina low-sulfidation epithermal deposit (Deseado Massif, southern Argentina) to determine geochemical indicators of Au-rich zones in the deposit and to assess the effects of weathering on those indicators.

Therefore, the papers in this special issue demonstrate further the applications of some of the above-cited tools for analysis of primary geochemical characteristics of mineral deposits in order to derive information of exploration relevance. We hope that these papers will be useful for mineral explorationists and/or mineral deposit researchers to adopt/adapt the results and/or methods described for vectoring into undiscovered deposits or potentially mineralized areas.

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