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Lithogeochemistry and chemostratigraphy of the Rosemont Cu-Mo-Ag skarn deposit, SE Tucson Arizona: A simplicial geometry approach

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A B S T R A C T

The Rosemont skarn deposit contains resources exceeding 1 billion tons of Cu-Mo-Ag mineralization. The deposit comprises three major structural-stratigraphic domains informally named Lower Plate, Upper Plate, and West Block. The Lower Plate is composed dominantly of Paleozoic chemical sedimentary rocks forming an east dipping homoclinal sequence. The Upper Plate overlies the Lower Plate and is composed dominantly of Mesozoic and Cenozoic siliciclastic sedimentary rocks. The West Block is dominated by Precambrian granitoids structurally interleaved with panels of Paleozoic chemical and siliciclastic sedimentary rocks. Most of the economic mineralization is hosted in the Lower Plate.

Lithological variability, structural complications of the stratigraphy, and calc-silicate metasomatism complicates the visual identification of lithologies resulting in uncertain stratigraphic domains based on drill core observations. To circumvent this problem, a deposit-scale lithogeochemical and chemostratigraphic model was developed using multivariate statistics following a compositional data analysis approach to respect the relative scale and multivariate nature of geochemical compositions. Accordingly, hierarchical cluster analysis of variables using the variation matrix as a measure of similarity, and principal component analysis on centered logratio coefficients (clr) were used to explore relationships between variables and to reduce dimensionality. Simplicial projections including centered tetrahedral and ternary diagrams were used to develop a lithogeochemical classification for the sedimentary rocks of the Rosemont deposit. A ternary diagram, or 3-part simplex with vertices Ca, Mg, and a composite variable given by the geometric mean of Cr, Ni, Co, V, P, Hf, Zr, Th, Ti, Al, Nb, Sc, Ta, Y, Ce, and La contains a rich data structure for lithogeochemical classification.

The lithological attributes of the Rosemont deposit can be subdivided into 7 lithogeochemical classes evident on the ternary diagram. Limestone, dolostone, and siliciclastic-crystalline classes are key end members. The remaining 4 classes represent mixed chemical-siliciclastic lithogeochemical attributes discriminating complex lithological variations induced by the incorporation of siliciclastic component in chemical sedimentary rocks. The lithogeochemical classification derived from the ternary diagram is supported by *K*-means clustering applied to two balances representing isometric logratio (ilr) coordinates of the 3-part simplex.

The geospatial distribution of the lithogeochemical classes allows the simplification of the stratigraphy of the Lower Plate into three relevant chemostratigraphic units, namely a Lower Limestone Unit and an Upper Dolostone Unit separated by a Mixed Unit of chemical-siliciclastic sedimentary rocks. It is noteworthy that ore grades are controlled by the relative proportion of chemical to siliciclastic component of the mineralized rocks. Higher metal grades are characteristic of relatively pure chemical sedimentary rocks in the Lower Limestone and Upper Dolostone Units; whereas low metal grades characterize the Mixed Unit with a large proportion of siliciclastic component. As a corollary, the lithogeochemical classification can be used as a skarn fertility tool to predict the economic potential of chemical-siliciclastic sedimentary sequences in geological environments permissive of skarn mineralization.

1. Introduction

Skarn deposits are explored and mined for their economically valuable metals including Cu, Mo, Ag, Au, W, Fe, Pb, Zn, U, REE, F, B, In, and Sn (Einaudi et al., 1981; Einaudi and Burt, 1982; Meinert, 1992; Meinert et al., 2000). Although skarn deposits have been extensively

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researched, most studies have traditionally aimed at understanding the petrology of skarn-related intrusions, field characteristics, tectonic setting, ore forming fluids, ore genesis, mineral chemistry, geochronology, and metasomatic evolution (Einaudi and Burt, 1982; Gaspar and Inverno, 2000; Lieben et al., 2000; Meinert et al., 2000; Deng et al., 2015; Wang et al., 2015a; Baghban et al., 2016; Li et al., 2017; Park et al., 2017; Soloviev and Kryazhev, 2017; Yang et al., 2017; Zhou et al., 2017). However, a practical problem relevant to exploration and mining is the reconstruction of the stratigraphy of skarn deposits given that intense calc-silicate metasomatism and recrystallization complicate visual discrimination of rock types. Also, lithological differences among chemical sedimentary rocks, for instance limestone versus marlstone, are subtle, which complicate the identification of lithological boundaries. These geological challenges are manifested as inconsistent lithological and stratigraphic observations within and between drill holes rendering the delineation of stratigraphic domains highly uncertain. Establishing a reliable mine-scale stratigraphy is critical for mineral resource estimation, and of economic significance for mining operations given that metallurgical parameters such as metal grades, grinding efficiency, deleterious minerals, deleterious elements, and metal recoveries are spatially related and controlled by primary lithologic and stratigraphic features (cf., Gregory et al., 2013; Lund et al., 2013; Amer et al., 2014; Pownceby and Johnson, 2014; Yildirim et al., 2014; Wang et al., 2015b; Maydagán et al., 2016; Wang et al., 2016a, 2016b).

The goal of this study was to devise a lithogeochemical and chemostratigraphic framework for the Rosemont deposit to increase the certainty of mine-scale stratigraphic domains. To achieve this goal, multivariate statistical analysis was conducted on whole-rock multi-element geochemical data of approximately 33,000 samples distributed throughout the Rosemont deposit. The systematic data analysis presented in this paper follows a compositional data analysis approach to respect the multivariate relative structure of geochemical data (cf., Aitchison, 1986; Tolosana-Delgado et al., 2005; Egozcue and Pawlowsky-Glahn, 2006; van den Boogaart and Tolosana-Delgado, 2013; Barceló-Vidal and Martín-Fernández, 2016). We demonstrate that by applying mathematical transformations that are consistent with the simplicial geometry of compositional data, simple ternary diagrams can be developed for lithogeochemical classification of chemical-siliciclastic sedimentary sequences. The lithogeochemical classification is consistent within and between drill holes, which facilitates the recognition of key stratigraphic boundaries and the simplification of complex stratigraphy into relevant chemostratigraphic units that capture the most relevant lithological and geochemical variations of the Rosemont skarn deposit.

2. Geology, stratigraphy, and mineralization

The Rosemont deposit, Hudbay Minerals Inc., is a Cu-Mo-Ag skarn located in the Laramide porphyry belt of Arizona, 40 km to the southeast of Tucson. The deposit contains over 1 billion tons of mineralized rocks hosted dominantly within a Paleozoic chemical sedimentary sequence (Fig. 1). Three major structural-stratigraphic domains characterize the deposit, namely (1) the Lower Plate, (2) the Upper Plate, and (3) the West Block (Figs. 2–3).

The Lower Plate forms an upright, east-dipping, homoclinal sequence composed dominantly of Paleozoic chemical sedimentary rocks with minor interbedded siliciclastic rocks. Several Paleozoic formations form the Lower Plate of the Rosemont skarn deposit. From bottom to top, these are the Mississippian to Permian Escabrosa, Horquilla, Earp, Colina, Epitaph, and Scherrer Formations (Fig. 3) (cf., Johnson and Ferguson, 2007; Ferguson, 2009; Ferguson et al., 2009; Rasmussen et al., 2012).

The Escabrosa and Horquilla Formations comprise dominantly thickly-bedded limestone (Fig. 4A–B). However, marlstone, calcareous siltstone, mudstone, and siltstone become more abundant towards the upper parts of the Horquilla Formation (Rasmussen et al., 2012; this study). The Earp Formation is a mixed chemical-siliciclastic sedimentary sequence composed of bedded marlstone, calcareous sandstone, calcareous siltstone, fine-grained sandstone, siltstone, and mudstone (Fig. 4C). The Colina and Epitaph Formations, called the Epitaph Group in the Rosemont deposit, comprise dominantly dolostone and limestone (Fig. 4D). The occurrence of the Scherrer Formation in the Lower Plate is controversial given the paucity of drill holes higher up in the stratigraphy and outside of the economic ore body. The Scherrer Formation is composed of interbedded siltstone, calcareous siltstone, calcareous sandstone, dolostone, and limestone.

The Upper Plate is composed dominantly of Mesozoic and Cenozoic siliciclastic and volcanic rocks overlying the Lower Plate (cf., Johnson and Ferguson, 2007; Ferguson, 2009; Ferguson et al., 2009; Rasmussen et al., 2012; this study). A low angle fault, an unconformity that has been structurally overprinted, bounds the Lower and Upper Plates (Fig. 2). The Upper Plate includes the Jurassic-Cretaceous Glance Formation, and the Cretaceous Willow Canyon Formation (Fig. 3) (Drewes, 1971; Johnson and Ferguson, 2007; Ferguson, 2009; Ferguson et al., 2009; Rasmussen et al., 2012). The Glance Formation is a thickly-bedded, clast-supported, polymictic conglomerate with abundant limestone clasts and carbonate-rich matrix. In the Rosemont deposit the limestone conglomerate and some structural panels of limestone and minor dolostone, inferred to represent the Permian Concha and Rain Valley Formations, are informally called the Glance Group (Figs. 2–3). The Willow Canyon Formation is a succession of cross-stratified arkose, silty sandstone, and mudstone. A stratigraphic marker within the Willow Canyon Formation is a volcanic unit comprising lava flows and volcaniclastic rocks of andesitic composition (Figs. 2–3). The siliciclastic sedimentary rocks of the Willow Canyon Formation and the andesitic volcanic rocks are informally named the Arkose Group in the Rosemont deposit.

The most distinctive Cenozoic unit in the Upper Plate is the Pliocene-Miocene Gila Conglomerate (Drewes, 1972a, 1972b; Johnson and Ferguson, 2007; Ferguson, 2009; Ferguson et al., 2009; Rasmussen et al., 2012; this study). This unconsolidated conglomerate is polymictic with clasts ranging from granitoid, arkose, andesite, and minor limestone deposited within a normal-fault-bounded basin.

The West Block is bounded to the Lower Plate by the steeply-dipping backbone fault system (Fig. 2). The dominant lithological unit of the West Block is the Precambrian Granitoids (Johnson and Ferguson, 2007; Ferguson, 2009; Ferguson et al., 2009; Rasmussen et al., 2012). However, the contact with the Lower Plate comprises structurally interleaved panels of the Precambrian Granitoids, and sedimentary formations including the Cambrian Bolsa Quartzite and Abrigo Formations, and the Devonian Martin Formation (Figs. 2–3). The Bolsa Quartzite Formation is distinctively composed of coarse-grained quartz sandstone. The Abrigo Formation consists dominantly of interbedded limestone, fine-grained sandstone, siltstone, and mudstone, whereas the Martin Formation is dominated by dolostone.

Tertiary quartz-feldspar porphyries intrude the Lower Plate below the low angle fault (cf., Keith and Wilt, 1986). These porphyritic intrusions are economically mineralized with Cu, Mo, and Ag and are thought to be the source of mineralization and calc-silicate metasomatism of the Rosemont skarn deposit (Figs. 1 and 3).

Calc-silicate alteration in the Lower Plate and chemical sedimentary rocks of the West Block are characterized by fine to very fine-grained skarn facies such as garnet, pyroxene, wollastonite, and serpentine skarn. In contrast, metasomatism in the Upper Plate is dominated by massive fine-grained epidote alteration.

Most of the economic mineralization is hosted in the Lower Plate (Fig. 2). The highest Cu grades are hosted in the upper part of Escabrosa, Horquilla, and Epitaph Group; whereas lower metal grades are typical of the Earp Formation. Some low-grade economic mineralization is hosted in the Upper Plate Arkose Group (Figs. 2–3). The West Block contains some economic mineralization, mostly hosted in structurally interleaved chemical sedimentary rocks of the Abrigo and