Geochemistry of Hydrothermal Alteration Associations in Porphyry Copper Deposits: Applications to Geometallurgical Modeling

Brian Townley¹,²,³, Rodrigo Luca⁴, Luis López⁵, Marcia Muñoz⁵ y Pamela Castillo¹
¹Departamento de Geología, Universidad de Chile, Plaza Ercilla 803, Santiago, Chile
²Advanced Mining and Technology Center (AMTC), Universidad de Chile, Av. Tupper 2007, Edificio AMTC, Santiago, Chile
³Geoanalytical Vision S.A., Av. Ricardo Lyon No. 3547, Nuñoa, Santiago

* email: btownley@ing.uchile.cl

Abstract. We discuss the value of multi-element geochemistry in ore modeling which has important applications to geometallurgical processes. In mine production of porphyry copper deposits much effort is placed on geological modeling which is the base for mine planning, applied for predictive mineral processing behavior, from blasting, comminution, leaching or flotation, down to waste disposal and environmental management. High confidence geological models are commonly based on geological mapping of drill core, and surface/ underground exposures, combined with mineral characterization techniques (e.g., petrography, QEMSCAN®, XRD, spectroscopy, etc.). Unfortunately these are expensive and can only be applied to limited numbers of samples thus lacking sufficient representativity. In addition, geological mapping always presents a degree of uncertainty, based on qualitative and semi-quantitative estimates. The combination of information usually provides geological models that are hard to combine with geometallurgical data, much less with mineral processing predictive behavior. The advent of multi-element geochemistry, at low cost, has allowed many companies to employ such tool, yet little use is given to the data. Geochemistry reflects the mineral composition of rocks, thus allowing characterization of lithology, alteration types and intensities, and mineralization. As an example of such applications we present a generic classification based on aqua regia geochemistry.

Keywords: Geochemistry, Geometallurgical Modeling, Geological Modeling, Porphyry Copper

1 Introduction

A rock represents a mineral aggregate, these of primary (lithology), endogenous secondary (hydrothermal) and/or of secondary supergene origin, among others. Minerals are constituted by chemical elements, mineral associations, be them of lithologic, hydrothermal alteration and mineralization and/or of supergene origin will be represented by specific geochemical compositions and chemical element combinations, major, minor and trace. Multi-element geochemical data base processing and interpretation may allow characterization and determination of lithology, hydrothermal alteration (type and intensity) and mineralization, and supergene alteration. The previous procedures allow characterization of all above mentioned parameters in a quantitative manner at a resolution scale equal to that of sample support, being of assistance in detailed determination of ore deposit geologic models, applied to exploration and/or geo-mineral metallurgic models.

The potential application of multi-element geochemistry to mineral characterization in porphyry copper deposits, or any other type of deposit, requires data processing and interpretation, and final calibration of geochemical classification parameters to mapping and mineral characterization data. Classification parameters may be determined as element combinations (e.g. resulting from multivariate statistical analysis), element ratios or combinations of additive variables and ratios, in some cases, multiples. The objective of synthetic variables is to test mass transfer processes that occur during hydrothermal alteration and mineralization, and later, during supergene alteration (if applicable). As mass transfer processes introduce geochemical modifications and ion exchange in rocks, ratios may commonly discriminate alteration processes that individual elements do not. The compositional variance of an individual element will usually depend on lithology, alteration and mineralization, hence the sources of variance do not respond to a single or specific process. As opposed to single elements, synthetic variables, in particular those that include ratios, will detect and discriminate those rocks in which one or more elements have been added or depleted as a result of a mass transfer process, this, respect to those ions participating in equilibrium reaction exchange during hydrothermal alteration and mineralization. Another discrimination variable that may be recognized from data processing and interpretation could result from element groups associated with specific hydrothermal alteration assemblages, all elements associated to the same specific mineral association, having similar variance behaviors, as determined from multivariate statistics.

As testing of geochemical classification criteria may be crossed respect to geological mapping and/or mineral characterization, the level of confidence obtained for classification can be measured, hence confidence of any specific parameter, in the ability to discriminate, may be evaluated numerically. It must be noted that there are no
specific recipes to determine geochemical characterization parameters, as these may vary from one deposit to another, depending on combinations of host rock lithology, hydrothermal alteration type and intensity, mineralization, and superposition of multi-stage hydrothermal events.

2 Hydrothermal Alteration Characterization in porphyry copper deposits: A generic example

The procedures followed for the determination of geochemical mineral association classification parameters are summarized on figure 1. Data processing usually includes full statistical univariate, population and multivariate analysis of all valid geochemical data. Univariate statistics, depending on data distributions, may be carried out in arithmetic or log normal base, depending on nature of statistical distributions. Such nature must be established during the univariate statistical analysis.

Results of statistical analysis and interpretation of results allows a first approximation for quantitative determination and classification of mineral associations, indicating lithology and hydrothermal environments. Discrimination and classification parameters can then be tested against geological mapping and any other mineral characterization technique, allowing crossed comparison respect to any particular geological feature, such as lithology, hydrothermal alteration, mineralization, among others.

A generic example for the characterization of hydrothermal mineral associations is shown on figure 2, multi-element geochemistry from an aqua regia digest ICP-MS data set. All individual elements and synthetic variables can be compared respect to core logging, allowing detection of those elements and/or variables that best discriminate one type of alteration respect to another. Cross comparison of all variables will finally determine those combinations that best discriminate, be it on first pass, or resulting from data sub-classifications and iteration of discrimination on data subsets.

![Figure 1](image1.jpg)

**Figure 1.** Work flow methodology followed for data processing and interpretation and determination of geochemical mineral association classification parameters.

![Figure 2](image2.jpg)

**Figure 2.** Examples of element concentration comparisons for Al, Ca, and synthetic variable KxAl, respect to hydrothermal alteration types. Pink, orange and green-brown colors represent mostly hydrolytic alterations (quartz-sericite, sericite, sericite-clay); green colors represent mostly chlorite and chlorite-sericite; yellow represents silicic alteration; dark brown and reddish brown represent potassic alteration, the first biotite dominant, the rest, K-feldspar dominant.
These concepts may be further tested by use of bi-variant or ternary diagrams, such as those shown on figure 3 and 4. On these discrimination diagrams samples plot along trends and fields that represent hydrothermal extremes and superposition trends. Also, in some cases, a specific mineral may cause a separate subset of data, parallel to a main trend. Such case is determined on figures 3 and 4, on which the presence of anhydrite in a portion of samples separates a parallel alteration trend, discriminating sulfate-rich environments from those sulfate-poor. Such discrimination allows detailed determination of an anhydrite sulfate roof, common in porphyry copper systems, and of important implications in mine design, mine planning, extraction, mineral processing and production.

Figure 3. Examples of bi-variant diagrams. Top, Mg vs. Fe, showing samples that plot along the biotite-chlorite trend (brownish and green colors), clearly discriminated from those samples that plot along the pyrite trend representing hydrolytic alterations (orange and yellow). Bottom, S vs. Fe, samples plotting along the pyrite trend (yellow-orange), discriminated from potassic and chlorite (browns-greens). Bottom trend is anhydrite absent; samples above the pyrite line are anhydrite-rich.

Figure 4. Example for ternary diagram data discrimination, Mg-Fe-S. Potassic and chlorite alterations (brown and green colors) are discriminated respect to hydrolytic alterations (quartz-sericite, sericite-clay; orange and yellow). Trend from dark brown to orange represents biotite dominant potassic, to K-feldspar dominant (light brown) to phyllic (orange), a transitional trend; on which phyllic overprint on potassic occur along the trend, as well as chlorite-sericite and chlorite. On the right, a parallel trend represents those samples that are anhydrite-rich, displaced respect to the others due to elevated S provided by the sulfate.

These are some examples of geochemical discrimination and classification parameters for hydrothermal alteration. Study and combination of all geochemical parameters, individual elements and synthetic, applied to massive data sets, allows discrimination of classification extremes and overprint trends, such as those shown on figure 5. It must be noted that large data sets, including multi-element geochemistry and combinations of synthetic parameters, may allow much more discrimination criteria, this as further data processing on multiple pass selection and classification is conducted.

Once any amount of geochemical single and/or synthetic parameters are defined, these, being quantitative, and spatially defined, may be used for 2 and 3D spatial models, using any geostatistical techniques desired, on any specific ore deposit modeling software. If sample support for multi-element geochemistry is similar to ore reserve estimate sample support, in addition to ore reserves, gangue mineralogy can be modeled with the same or similar accuracy as metal concentrations and ore mineralogy. On further applications, if gangue mineralogy is of known impacts to mineral processing, geometallurgical models may be derived as mineral characterization determinations are crossed to metallurgical tests.
3 Discussion and Conclusions

Once samples are classified by lithology, hydrothermal alteration type and intensity, and mineralization, these may be studied for spatial distribution. As a result, these geological features will be mapped on a resolution equivalent to sample support. These results may be applied to 2 and 3D ore deposit models for exploration and/or geo-mineral metallurgical models. Models may be based of thousands to tens of thousands of samples with multi-element geochemical analysis, which at present is usually analyzed by digestion ICP combination techniques, but that may soon migrate to analytical XRF, as these techniques allow ever better resolution and access to larger suites of elements. Based on the same concepts it is feasible to determine elements that discriminate lithologic types, especially immobile elements (e.g. Ti, Zr, Th, REE). Classifications based on immobile elements allow determination of lithologies, independent of alteration. It is important to note that these are only tools to assist geology, and by no means replace the basics, core logging and mapping!