Minerals Engineering 69 (2014) 91–96

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Development of an effective and practical Process Alteration Index (PAI) for predicting metallurgical responses of Cu porphyries

Baris G. Yildirim [a,*], Dee Bradshaw [a], Malcolm Powell [a], Cathy Evans [a], Alice Clark [b]

[a] *Julius Kruttschnitt Mineral Research Centre (JKMRC), Sustainable Minerals Institute, The University of Queensland, Australia*
[b] *CdeK Geological and Mining Services, New South Wales, Australia*

ARTICLE INFO

Article history:
Received 4 December 2012
Accepted 4 July 2014

Keywords:
Processing alteration index
Predictive modelling
Copper
Porphyry
Ore forming system
Geometallurgy

ABSTRACT

Approximately two thirds of the world's copper comes from porphyry deposits. These deposits have many distinct attributes, including multiple events in their formation, which affect the reaction series between the hydrothermal fluid and its host rock. This, in turn, defines the alteration and main causes of ore formation. Many porphyry copper deposits are hosted in quartz feldspar porphyries, where the alteration–mineralisation is zoned from barren early sodic–calcic, through potentially ore-grade potassic, chlorite–sericite, and phyllic, to advanced argillic. Chalcopyrite ± bornite mineralisation in many porphyry copper deposits is largely confined to potassic zones (Sillitoe, 2010). This paper discusses the initial development of a Process Alteration Index (PAI) that focuses on understanding the formation of copper porphyry mineralisation, and supports predictive comminution and metallurgical modelling studies. The PAI can be determined using analytical techniques and focuses on the role of plagioclase and quartz during porphyry deposit formation. Samples from the Highland Valley Copper Mine in British Columbia were selected from a single lithology which displayed a range of degrees of alteration advancing from weak to intense. The samples were analysed using X-ray Diffraction Analysis (XRD) with Rietveld refinement, and the ore hardness determined using the Julius Kruttschnitt Rotary Breakage Tester (JKRBT). A relationship between key alteration parameters which underpin copper ore formation and the ore hardness was observed in the limited dataset available for this research and further work is recommended to determine whether this relationship could be used in predictive mill throughput modelling studies.

1. Introduction

Porphyry copper deposits are well known as the world's primary source of copper and many also contain important sources of molybdenum and gold. Some of these deposits are gigantic, with several deposits of over 1 billion metric tons with ore grades greater than 0.5% copper; e.g. Bingham Canyon in Utah, USA; Collahuasi, Chuquicamata, La Escondida, El Teniente, Los Bronces in Chile. These deposits are formed in association with subduction-related magmas and are found sporadically in magmatic arcs worldwide. Their formation involves the exsolution of metalliferous and sulphur rich hydrothermal fluids from calc-alkaline arc magma, and deposition of ore minerals in response to fluid phase separation, cooling, wall-rock reaction, and mixing with external fluids (Richards, 2003). This deposition process occurs mostly in igneous and volcanic lithologies, and more than 50% of the world's porphyry copper deposits are hosted by quartz feldspar porphyry (QFP) as shown in Fig. 1.

The general mineralogical composition of quartz feldspar porphyry (hereafter referred to as the "original form") consists of quartz, plagioclase, potassium-feldspar, hornblende, and biotite. In ore forming systems the mineralisation is complimented by chalcopyrite, bornite, and other secondary copper minerals, with accessory pyrite, magnetite, apatite, and other minerals. In porphyry deposits these mineral assemblages are replaced by alteration minerals such as quartz, potassium-feldspar, illite, kaolinite, sericite, chlorite, dickite, biotite, calcite, zunyite and other minerals, in accordance with a chemical reaction series (hereafter referred to as the "alteration form"). Put simply the copper minerals are introduced during the changes from the "original" to the "alteration" forms. Table 1 (after Sillitoe 2010) summarises the key geological and mineralogical characteristics of the main alteration types of copper porphyry deposits and Fig. 2 shows the location of these alteration zones in a typical porphyry copper deposit. The main ore contributor alteration types are listed as 1–4 and in Table 1 and the expected processing behaviour of such alteration types are noted. Rock which

---

[*] Corresponding author.
E-mail address: b.yildirim@uq.edu.au (B.G. Yildirim).

http://dx.doi.org/10.1016/j.mineng.2014.07.009
0892-6875/© 2014 Elsevier Ltd. All rights reserved.

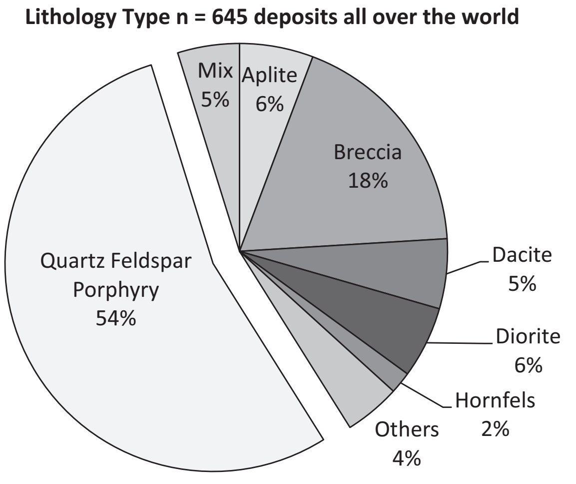

Fig. 1. Lithology distribution of the world Cu Porphyries * modified from 2010 USGS Database (USGS, copper porphyry deposit model, 2010).

has undergone potassic alteration is harder than other ore contributor alteration types and the effect of this on the mill throughput is high. This same degree of alteration has consistent and non-complex copper mineralogy and therefore the expected effect on flotation is low. In general, porphyry copper deposits which have undergone potassic alteration exhibit low mill throughput and high flotation recovery. Advanced argillic alteration has mainly soft clay minerals, and therefore the expected effect on mill throughput is low while the more complex copper mineralogy, with various alteration minerals, is expected to have a greater, deleterious effect on flotation.

Sillitoe (2010) describes the structure of porphyry copper deposits as follows: "the volumes of the different alteration types vary markedly from deposit to deposit. Phyllic alteration may project vertically downward as an annulus separating the potassic and propylitic zones as well as cutting the potassic zone centrally (as shown in Fig. 2). Phyllic alteration tends to be more abundant in porphyry copper–molybdenum deposits, whereas chlorite–sericite alteration develops preferentially in porphyry copper–gold deposits. Alteration–mineralisation in the lithocap is commonly far more complex than shown, particularly where structural control is paramount". Hydrothermal alteration is extensive and typically zoned both on a deposit scale and around individual veins and fractures. The alteration is defined by the following mineral associations: potassic zone (1) characterised by biotite and/or potassium-feldspar (±amphibole ± magnetite ± anhydrite), an outer zone of chlorite – sericite (2) that consists of (quartz + sericite + chlorite + pyrite) and the outermost zone is propylitic alteration (5) that consists of quartz, chlorite, epidote, calcite and, locally, albite associated with pyrite. Porphyry deposits may also include zones of phyllic alteration (3) (quartz + sericite + pyrite) and advanced argillic alteration (4) (quartz + illite + pyrite ± kaolinite ± smectite ± montmorillonite ± calcite) and lastly zones of sodic–calcic alteration (6) consisting of (albite + calcite + oligoclase + actinolite).

2. Alteration indices

Alteration indices using oxide and molecular ratios were first introduced by Ishikawa et al. (1976), Spitz and Darling (1978), and Saeki and Date (1980). Mass balance calculations were also used (Gresens, 1967; Kranidiotis and MacLean, 1987; Pearce, 1968; MacLean, 1990), element ratios have been tentatively applied (Stanley and Madeisky, 1994). In a more recent study Piché and Jebrak (2004) used five fundamental mineral forming rules based on a whole rock analysis technique.

The Alteration index proposed by Ishikawa et al. (1976), measures the alteration intensity by using the whole rock chemical analyses and represent the degree of alteration in terms of the relative depletion of alkali elements using the following equation:

$$\text{Alteration Index} = (K_2O + Na_2O)/(K_2O + MgO) + (Na_2O + CaO) \tag{1}$$

The potassium oxide and magnesium oxide quantities increase, whereas sodium oxide and calcium oxide content decrease based on the alteration intensity and the index reaches 100 when alteration intensity is at its maximum.

The approach proposed by Piché and Jebrak, (2004) is a normative technique (Normat) that quantifies hydrothermal alteration of rock in metamorphic terranes using normative mineral ratios. The technique was developed for the volcanogenic massive sulphide (VMS) exploration and is sensitive to alkali element depletion associated with hydrothermal alteration; Normat uses five petrologic rules which are listed in order of priority:

1. Silica saturation is increased.
2. Divergent and reversed Bowen series are used for calculations.
3. Mineral assemblages are calculated according to Greenschist facies.
4. Calculations done according to VMS – type hydrothermal alteration.

Table 1
Characteristics of principal alteration–mineralisation types in porphyry copper systems, modified from Sillitoe, 2010.

	Alteration type (alternative name)	Position in system (abundance)	Key minerals	Principal sulphide assemblages (minor)	Economic potential	Expected effect on mill throughput	Expected effect on flotation
1	Potassic (K-silicate)	Core zones of porphyry Cu deposits	Biotite, K-feldspar	Pyrite, chalcopyrite, bornite, digenite and chalcocite	Main ore contributor	High	Low
2	Chlorite–Sericite (sericite–clay–chlorite)	Upper parts of porphyry Cu core zones	Chlorite, sericite/illite, hematite	Pyrite, chalcopyrite	Common ore contributor	Moderate	Moderate
3	Sericite (phyllic)	Upper parts of porphyry Cu core zones	Quartz, sericite	Pyrite, chalcopyrite, enargite, tennantite, bornite, sphalerite	Weak to moderate ore contributor	Moderate	Moderate
4	Advanced argillic	Above porphyry Cu deposits, constitutes lithocaps	Quartz, alunite, pyrophyllite, dickite, kaolinite	Pyrite, enargite, chalcocite, covellite	Locally constitutes ore	Low	High
5	Propylitic	Marginal parts of systems below lithocaps	Chlorite, epitode, albite, carbonate	Pyrite, sphalerite, galena	Barren, unlikely be ore grade	N/A	N/A
6	Sodic–calcic	Deep, including below porphyry Cu deposits (uncommon)	Albite/oligoclase, actinolite, magnetite	Typically absent	Barren, unlikely be ore grade	N/A	N/A