The geological characteristics, geochemical signature and geophysical expression of porphyry copper-(gold) deposits in the circum-Pacific region

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SUMMARY

Porphyry deposits of the circum-Pacific region contain a large amount of the world's copper, molybdenum and gold. These deposits are formed from calc-alkaline and potassic magmas characterized by varying oxidation states (fO_2), which contribute to different ore mineral assemblages and contrasting relationships to hydrothermal alteration zones. Gold-rich porphyry copper deposits are typically characterized by hydrous and highly oxidized causal magmas. Variations in the styles of geology and mineralization contribute to differing geochemical expressions and geophysical signatures of the porphyry deposits. Exploration programs that integrate high-quality geological mapping and drill-core logging with a three-dimensional understanding of geochemical and geophysical data will facilitate the path to discovery.

Key words: porphyry copper-gold, geology, geochemistry, geophysics.

INTRODUCTION

Porphyry deposits are the world's leading source of copper and molybdenum. This deposit type also contains a great abundance of gold and silver. Gold-rich porphyry deposits occur in both continental and island-arc orogenic settings. Classic provinces in continental settings include the northern and central Andes, western USA and New Guinea, whereas volcanic island-arc deposits occur throughout the western Pacific.

Porphyry deposits are characterized by disseminated, veinlet- and fracture-controlled copper-iron sulphide minerals distributed throughout a large volume of rock in association with potassium silicate, sericitic, propylitic and, less commonly, advanced argillic alteration in porphyritic plutons and in the immediate wall rocks. In porphyry systems, there exists a close spatial and temporal link between volumetrically-small causative intrusions and broadly dispersed magmatic-hydrothermal alteration and mineralization. Porphyry copper deposits are large (commonly hundreds to thousands of million tonnes) and low to medium in grade (0.3 to 1.5% copper). The majority of gold-rich porphyry deposits occur in the circum-Pacific and commonly contain 0.3 to 1.6 g/t gold.

The general characteristics of porphyry systems include:

1) small diameter (<2 km) causative intrusions of intermediate to felsic composition,
2) shallow levels of emplacement (typically 1-4 km beneath the paleosurface),
3) porphyritic texture of causative intrusions, where feldspar, quartz and mafic phenocrysts are contained in a fine-grained to aplitic groundmass,
4) multiple phases of intrusions, pre-, syn-, late- and post-ore; late-stage diatremes are common in western Pacific volcanic-arc settings,
5) several stages of hydrothermal alteration associated with each mineralizing intrusion,
6) extensive development of fracture-controlled alteration and mineralization in both porphyritic intrusions and adjacent wall-rock,
7) a progression from early, discontinuous and irregular veins and veinlets ("A veinlets") through transitional, planar veins ("B veins") to late, through-going veins ("D veins") and breccia bodies (vein terminology follows that of Gustafson and Hunt, 1975),
8) a progression in hydrothermal alteration from early, central potassium silicate and distal propylitic styles through transitional intermediate argillic to late sericitic/phyllic, and advanced argillic alteration types,
9) sulphide and oxide minerals which vary from early magnetite-(bornite) through transitional chalcopyrite-pyrite-(hematite) to late pyrite, pyrite-bornite-(digenite) or pyrite-enargite-(covellite),
10) fluid inclusion studies which indicate that early alteration and copper mineralization are generated by magmatic fluids with 30 to >60 wt%NaCl equivalent over a temperature range of 400º to >700˚C under lithostatic pressure; whereas the fluids related to late alteration and mineralization may include a meteoric component and are more dilute (<15 wt% NaCl equiv.), lower in temperature (200˚ to 400˚C) and under hydrostatic pressure.

PORPHYRY DEPOSIT TYPES AND MAGMA CHEMISTRY

Two major types of porphyry copper-(gold) systems are discussed in this extended abstract. The first of these systems is characterized by early, high-temperature magnetite and bornite-(digenite-chalcocite)-chalcopyrite-bearing ore assemblages in the general absence of pyrite (Type I, Einaudi et al., 2003). The majority of the copper-(gold) ores in these deposits are hosted by potassium silicate alteration (e.g. biotite and secondary feldspar). Late-stage, feldspar-destructive, phyllic and advanced argillic alteration types, characterized by abundant pyrite, are less significant in this type of deposit.

Examples of large Type I deposits include Batu Hijau, Panguna, Endeavour 26N, Yerington, Bajo de la Alumbrera, Christmas, Dinkidi-Didipio and Cadia-Ridgeway.

In contrast, Type II deposits are characterized by chalcopyrite-pyrite-(hematite) introduced during transitional-stage, chlorite-sericite-clay (intermediate argillic) alteration, which is typically magnetite-stable, and late-stage sericitic/phyllic alteration, where magnetite has been converted to pyrite-(hematite). This deposit style is characterized by abundant pyrite, locally in equilibrium with bornite-digenite and covellite-enargite; anhydrite is common. Advanced argillic alteration is more abundant than in Type I deposits. Type II deposits typically contain greater amounts of copper and gold than do Type I. It is inferred that Type II deposits are formed by magmatic-hydrothermal fluids created from causal intrusions that are highly oxidized (high *f*O2) with abundant SO_2, where sulphur saturation has been delayed to produce copper-bearing sulphide mineral assemblages at lower temperatures than in Type I systems. Examples of large Type II deposits include Bingham Canyon, Chuquicamata, El Salvador, Silver Bell, Alpala-Cascabel, Almalyk, Grasberg and Oyu Tolgoi (Hugo Dummett).

Potassic-rich magmas are inferred to be related to gold-rich porphyry- and epithermal-deposits (Muller and Groves, 2019). However, calk-alkaline magmas make for a greater abundance of global porphyry systems. About 5-10% of igneous rocks are high-K, yet these magmas are associated with approximately 25% of the combined Cu+Au+Ag US dollar value of global porphyry and epithermal deposits. The largest and richest gold-bearing, global porphyry systems are related to potassic magmas. About 60% of the gold that is contained in the 25 largest porphyry copper-gold deposits in the world, as ranked by gold content, occurs in nine potassic magma-related deposits (Garwin, 2019). In approximate order of decreasing gold contents, these gold-rich potassic porphyry deposits include Grasberg, Almalyk, Bingham Canyon, Oyu Tolgoi, Pebble East, Cadia-Ridgeway, Pebble West, Ok Tedi and Bajo de la Alumbrera. Most of the richest and largest of these deposits are of Type II affinity, characterized by oxidized and hydrous causal melts and ore assemblages that contain significant chalcopyrite-pyrite.

GEOLOGICAL CHARACTERISTICS

The key geological characteristics of porphyry copper-(gold) systems include distal to proximal intrusive dykes and small causal porphyritic stocks, with hornblende occurring as phenocrysts and in the groundmass, which is characteristic of a hydrous magma. Quartz eyes (resorbed quartz phenocrysts) provide evidence of rapid magma ascent and disequilibrium related to a drastic reduction in confining pressure. Many deposits show a structural focus, forming along the margins of pre-mineralization plutonic complexes or within uplifted fault blocks or horsts. Peripheral dyke swarms, vein systems and fracture systems often increase in abundance/intensity and converge toward the porphyry centres. The increase in the abundance of porphyry-related, sugary to granular, A- and B-type quartz veins are one of the best indications of proximity to a porphyry centre. These key geological indicators are best identified through careful geological mapping techniques, such as the ‘Anaconda Method’ (Einaudi, 1996; Brimhall et al., 2006; Garwin, 2018).

Hydrothermal alteration exhibits well documented zoning, characterized by early-stage, central biotite-secondary feldspar (potassic-sodic metasomatism) overprinted by transitional, sericite-chlorite-clay (intermediate argillic), which is typically magnetite-stable. Late-stage, feldspar-destructive, phyllic and advanced argillic alteration zones (pyrite-stable) often coalesce towards, and overprint, central potassium silicate and distal propylitic zones. Actinolite and epidote provide indicators of increased temperatures towards the porphyry centre. The use of ASD spectrometry in the analysis of rock- and drill-samples may assist in the determination of hydrothermal alteration assemblages, particularly when properly integrated with critical observations made by geologists using a 20x hand lens.

Sulphide minerals typically show an increase in the chalcopyrite-pyrite ratio towards the porphyry centre, which is flanked by zones of increased pyrite (pyrrhotite) abundance. Late-stage bornite and covellite provide good indications of a robust system, rich in copper and sometimes gold. The oxidation of the sulphide minerals produces goethite, hematite, jarosite and secondary copper minerals. The goethite-jarosite ratio is a good proxy for the chalcopyrite-pyrite ratio in arid weathering environments.

GEOCHEMICAL SIGNATURE

There is a common zoning of geochemical elements in global systems, with local variations related to differing styles and intensity of late-stage alteration, and varying fluid activities of H_2O, CO_2 and S. This style of zoning has been well documented for the Yerington deposit in Nevada, which is applicable to many circum-Pacific porphyry systems (Cohen, 2011 and Halley et al., 2015). Characteristic metal zoning includes: a central and deep zone of Cu-(Au)-(Mo), proximal and intermediate Mo-W-Sn, and distal and high-level As-Sb-Li-Th-(Au). Within porphyry centres, there is a common depletion of Mn, Pb, Zn, As, Tl, Li and other related elements. Certain elements, such as Bi, Te, Se and Mo (low-levels) form a plume that extends from the top of the Cu-(Au)-(Mo) ore zone to high-levels in the paleo-system. As a consequence of the depletion of some elements in the central part of many deposits, there is an enrichment in Pb, Zn, Mn, Ag, Au and other related elements in the peripheral portions of porphyry systems. These distal zones commonly show Pb-Zn-Ag-(Cu)-bearing epithermal gold veins.

The use of elemental ratios, such as Cu-Zn, Pb-Zn, Mo-Mn, Au-Ag and Cu-S (as a sulphide species) often indicate increasing values towards the hotter and more central portions of many porphyry systems. However, exceptions do occur. In less oxidized (lower fO_2) porphyry systems, which may exhibit pyrrhotite halos and peripheral Au-Bi-Te-As-bearing vein- and fracture-systems, the Au-Ag ratio typically decreases towards the porphyry centres.

Elements that are deposited by oxyanion complexes, such as Mo, W, Bi, Te, As and Sb are more stable in the weathering and oxidation of porphyry systems than are those elements carried by chloride complexes, characterized by Cu, Pb, Zn, Au and Ag. The zoning patterns of the oxyanion-complexed elements typically provide a better vector to the porphyry centre in regions that have undergone oxidation than do the more mobile chloride- and bisulphide-complexed elements.

Loucks (2014) has developed geochemical indications of hydrous and fertile magmas, which may contribute to the formation of productive porphyry deposits. These indices include Sr/Y>35, which signifies early and abundant crystallization of hornblende and delayed and reduced production of plagioclase, both in response to elevated H_2O in the melt. High V/Sc (>10) is related to elevated H_2O in the magma and/or elevated pressure. This facilitates hornblende crystallization with respect to titanomagnetite. This process favours the incorporation of V in the residual melt, rather than in magnetite, with Sc extracted from the magma into hornblende (Loucks, 2014). Least-altered, magmatic rocks that exceed these thresholds are considered to have potential to produce copper-(gold)-rich porphyry deposits. However, some large and rich porphyry deposits are characterized by causal intrusions with Sr/Y and V/Sc that lie below these thresholds.

GEOPHYSICAL EXPRESSION

Porphyry deposits often are well expressed by contrasts in magnetic-, resistivity-, chargeability- and gravity-responses (Hoschke, 2011). The more oxidized porphyry systems, which are characterized by abundant primary (rock) and secondary (hydrothermal) magnetite, typically indicate a central airborne- or ground-magnetic high with an annular low or zone of subdued magnetic response. In contrast, those systems that are less oxidized, characterized by a smaller abundance of magnetite, may show a central magnetic low with an annular magnetic high that is related to a pyrrhotite-bearing halo to the porphyry centre. Linear zones of demagnetization, due to the replacement of magnetite by pyrite, may delineate structurally-controlled, feldspar-destructive clay-mica alteration zones that coalesce with proximity to the porphyry centre.

Deep-sensing magnetotelluric (MT) surveys exhibit a major resistivity low to coincide with some large porphyry deposits, which probably is a reflection of the increased conductivities associated with elevated sulphide-mineral abundance and feldspar-destructive clay-mica alteration. Induced polarization-resistivity results may indicate a chargeability (IP) halo that typically coincides with >2% pyrite and lower chalcopyrite-pyrite ratios. Elevated chargeability may also occur in porphyry centres that are characterized by abundant copper sulphide minerals (e.g. bornite-chalcopyrite zone at Batu Hijau, Indonesia; Garwin, 2002) but this typically shows a lower IP response than that expressed by the pyrite-rich halo. Resistivity is often elevated in the propylitic halo and potassic core. In contrast, resistivity lows are more common in the surrounding and overlying mica-and clay-rich, phyllic and argillic zones. Silica-rich zones of advanced argillic alteration can be highly resistive.

The gravity signature of porphyry systems is variable with the intrusions typically showing a density contrast to adjacent wall-rocks. In some systems, the intrusions are denser than the wall-rocks, producing a gravity high, and in others, the intrusions are less dense, resulting in a gravity low. The geological basement is typically denser than overlying volcanic sequences and expressed as a gravity high in horst blocks and anticlines.

Topography serves as the ‘poor man’s geophysics’ and is readily acquired from satellite data, such as SRTM (Shuttle Radar Topographic Mission). The processing of this data to enhance topographic gradients and disruptions at a range of wavelengths can assist in the delineation of favourable structural settings for porphyry emplacement. This type of analysis is particularly effective in regions where geology is well manifested in the topographic expression. Some porphyry systems are characterized by a rim of hard propylitic rocks and subdued topography associated with softer phyllic and argillic zones. Quartz-rich veins and silica ledges typically form resistant ridges. Porphyry centres show variable topographic expression, dependant on the abundance of A- and B-type quartz veins (harder) and varying extent of the mica-clay alteration (softer) overprint to the potassic and propylitic zones.

CONCLUSIONS

The integration of good field observations, geological mapping and drill-core (or drill-chip) logging with geochemical-, ASD spectrometry- and geophysical-data is a good start to a successful porphyry exploration program (Garwin, 2018). Three-dimensional visualization software and the creation of serial cross-sections and level-plans are particularly helpful in the integration of large and diverse geoscientific databases. The use of a 20x hand lens allows for the identification of early- and prolific-crystallization of hornblende, characteristic of hydrous magmas, and magnetite, which may provide evidence for oxidized systems. The visual determination of sulphide- and oxide-mineral assemblages and the relative timing of their development to intrusion stages, vein paragenesis and hydrothermal alteration will assist the explorer in the recognition of the distal- to proximal-indicators of porphyry copper-(gold) ore.

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