Time in porphyry Cu-Au development – exploration implications

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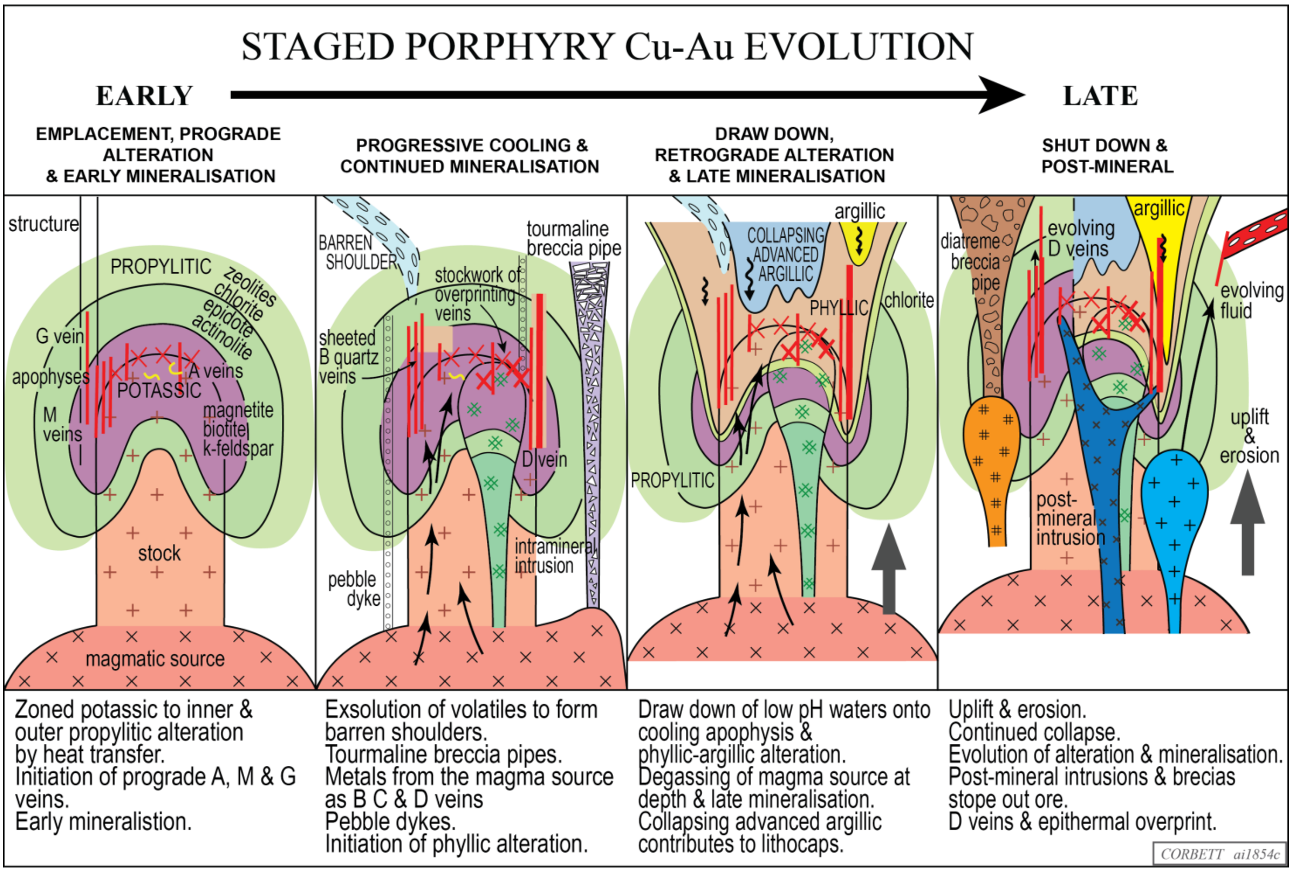
Porphyry Cu-Au deposits develop by a complex series of overprinting events of intrusion emplacement, hydrothermal alteration and mineralisation, which by development to varying degrees in each system, contribute towards great variations between individual porphyry deposits. While most porphyry geological models represent the end result of these overprinting processes, porphyry deposits can be better understood in the exploration environment by the consideration of time, such as in the staged model for porphyry development (figure 1). Exploration of the Philippine magmatic arc geothermal systems in the 1980's provided Terry Leach with the opportunity to view many porphyry Cu-Au intrusions at varying stages of development, including the relationship with magmatic arc epithermal Au-Ag mineralisation (Mitchell and Leach, 1991). The application of those geothermal studies to Cu-Au mineral exploration in the SW Pacific rim in the early 1990s facilitated initial development of a staged model for porphyry Cu-Au development (Corbett and Leach, 1998), which further evolved by application to the exploration of porphyry systems there an in other magmatic arcs (Corbett, 2008, 2009; 2017 & 2018).



Zoned potassic to inner & outer propylitic alteration by heat transfer.
Initiation of prograde A, M & G veins.
Early mineralistion.

Exsolution of volatiles to form barren shoulders.
Tourmaline breccia pipes.
Metals from the magma source as B C & D veins
Pebble dykes.
Initiation of phyllic alteration.

Draw down of low pH waters onto cooling apophysis & phyllic-argillic alteration.
Degassing of magma source at depth & late mineralisation.
Collapsing advanced argillic contributes to lithocaps.

Uplift & erosion.
Continued collapse.
Evolution of alteration & mineralisation.
Post-mineral intrusions & brecias stope out ore.
D veins & epithermal overprint.

Figure 1. Staged model for porphyry development (from Corbett, 2018).

The exploration implications of the understanding and application of this staged model for porphyry Cu-Au development lie in the use of vectors within wall rocks towards blind porphyry deposits and the interplay between mineralised and barren events. The temporal geological context provides a better understanding of the variable geophysical signatures which result from overprinting events of porphyry intrusion, alteration and mineralisation.

EMPLACEMENT AND PROGRADE ALTERATION AND MINERALISATION

Changes in the tectonic conditions, evidenced by vein kinematics, may act as triggers to initiate the forceful, rapid, upward emplacement of vertically attenuated porphyry apophyses above deeper magma source bodies (Corbett and Leach, 1998; Corbett, 2018). Pre-mineral, early, barren, high temperature ptygmatic A veins (Gustafson and Hunt, 1975) develop within the cooling intrusion.

Prograde hydrothermal alteration developed within the cooling intrusion apophysis is zoned outwards from the porphyry to the host wall rocks. The magnetite, silica and variable sulphides, along with K-feldspar, secondary biotite and anhydrite, within the innermost potassic alteration provide a geophysical signature of a magnetic, resistive and moderately chargeable body. As most of this initial mineralisation lies within the potassic alteration, the surrounding zoned inner and then outer prograde propylitic alteration within the wall rocks provides an important vector towards blind (potassic altered) porphyry intrusions, with associated prograde Cu-Au mineralisation (figure 1). Biotite-rich EDM veins with anhydrite and local chalcopyrite may form at this stage.

Porphyry vein mineralisation is initiated as development as linear A and laminated M veins with prograde alteration selvages, commonly overprinted by B veins which straddle the prograde-retrograde divide. High temperature oxidised magnetite-bearing porphyries may grade from central early bornite with high Cu and Au contents, outwards to chalcopyrite-pyrite, and so are regarded as attractive exploration targets. This stage therefore represents the main mineralising event within many Au-rich porphyries, which because of the high bornite content are Au-rich.

G veins and lodes are distinguished from laminated M veins as wall rock hosted more massive magnetite-bearing veins and lodes with additional combinations of quartz, haematite, pyrite, chalcopyrite and bornite. These wall rock hosted veins provide vectors towards blind porphyry intrusions and prograde alteration selvages help to distinguish them from later retrograde D veins.

PROGRESSIVE COOLING AND CONTINUED MINERALISATION

Initial degassing of the porphyry intrusion may allow a plume of hot magmatic volatiles to vent from the intrusion and evolve to form strongly acidic fluids during depressurisation and cooling associated with the rise to elevated crustal settings. Reaction of these acidic fluids with wall rocks then provides barren shoulders of zoned wall rock advanced argillic alteration formed above and marginal to many porphyry deposits early in the paragenetic sequence (Corbett and Leach, 1998). These resistive and topographically obvious features are commonly more structurally controlled at depth and lithologically controlled at higher crustal levels, and are essentially barren of Cu-Au unless cut by later low or high sulphidation epithermal events. Deeply eroded structurally controlled barren shoulders may vector towards blind porphyry deposits.

Boron-bearing magmas may rise to elevated crustal settings and become rapidly depressurised to erupt and form tourmaline breccias, including pipes, typical of environments above intrusive source including batholiths. Breccias are characterised by a paragenetic sequence of: volatile injection, followed by collapse and the later introduction of sulphides into open space.

While the magma associated with the (polyphasal) porphyry apophysis is expected to contain considerable metal deposited upon initial cooling, much of the Cu-Au mineralisation within better porphyry Cu-Au deposits has been derived from cooling of the magmatic source at depth, commonly transported within dilatant features such as sheeted fracture/quartz veins arrays.

Chalcopyrite-rich C vein sulphides locally contribute towards the Cu-Au mineralisation by using the plumbing system provided by earlier veins such as open space B style quartz veins and may deposit sulphides within fractured competent quartz veins. Much of the sulphide mineralisation within laminated quartz-magnetite M veins was introduced by reopening of the laminations after initial vein formation. Consequently, some porphyry deposits host essentially barren M vein packages which did not benefit from this later event.

In strongly dilatant structural settings prograde sheeted porphyry veins may extend well into the wall rocks and form wallrock porphyry Cu ± Au ± Mo deposits, such at the 1 km deep Cadia East, Australia and Llurimagua, Ecuador, and smaller Cadia Hill systems.

Late stage pebble dykes, characterised by the presence of rounded clasts milled during propulsion up structures by degassing volatiles, are recognised within porphyry deposits and the overlying wall rocks, and are used as vectors towards blind intrusions. Both pebble dykes and D veins cut porphyry intrusions and extend into the wall rocks, and so are interpreted to have been driven by the deeper magmatic source as well as the porphyry apophysis. D veins are formed late in the vein paragenetic sequence and may overprint pebble dykes by exploitation of the same structures.

RETROGRADE ALTERATION

Cooling magmatic volatiles form acidic fluids which react with wall rocks to produce retrograde phyllic alteration, varying from disseminations to flooding and selvages to B and D veins, which may coalesce, including with altered faults, to form larger alteration zones dominated by silica-sericite-pyrite±chlorite. During cooling of the porphyry apophysis, outward circulating convective hydrothermal cells of magmatic-meteoric waters transport these volatiles into the upper portion of the porphyry environment to mix with ground waters and form sinks of hot acidic waters. In the process of drawdown, recognised in geothermal systems, the apophysis cools sufficiently for these cells to reverse and the hot acidic waters to collapse upon the porphyry apophysis, particularly down the intrusion margins. Here, retrograde phyllic alteration by wall rock reaction overprints the prograde mineral assemblages as well as adjacent fresh rocks. Sericite formed by the destruction of prograde minerals displays variation in crystallinity with temperature of formation from the cooler and uppermost of marginal illite to deeper level more ordered muscovite with associated locally abundant pyrite. Dickite and pyrophyllite develop in more acidic conditions while corrundum-andalusite are recognised in high temperature phyllic alteration (Corbett and Leach, 1998). In strongly acidic conditions, as pH declines to 1-2, phyllic alteration may contain cores of silica-alunite bearing advanced argillic alteration, as an important component of lithocaps, which may extend laterally within permeable host rocks. Conversely, the progressive cooling of the hydrothermal system results in the overprint of phyllic alteration by lower temperature retrograde argillic alteration characterised by illite-kaolinite(including local dickite)-chlorite-pyrite, termed SCC (sericite-clay-chlorite) by some workers.

Many porphyry deposits host significant Cu±Mo±Au mineralisation in association with phyllic-argillic alteration (Corbett and Leach, 1998), although the timing relationships of mineralisation and several mechanisms of retrograde alteration are not always clear. Comparisons with districts such as Bingham Canyon (Porter et al., 2012), support rise of metals sourced from the deeper magma source, although drawdown may have already facilitated collapse of low pH waters onto the exposed uppermost portion of the vertically attenuated porphyry apophysis. Consequently, in some instances Cu-Au mineral deposition is promoted by the mixing of rising pregnant magmatic ore fluids with collapsing low pH waters associated with phyllic-argillic alteration. Elsewhere, the ore fluids responsible for mineralisation may have attained a low pH character during cooling to promote retrograde phyllic-argillic alteration synchronous with mineralisation. Local outward zonation from bornite to chalcopyrite (Ak-Sug, Pollard et al., 2017; Bingham Canyon; Porter et al., 2012) supports cooling as a mechanism of metal deposition, while the evolution to lower pH conditions may cause bornite to overprint the generally more abundant chalcopyrite. In progressively lower pH conditions covellite-chalcocite may become the dominant sulphide species (Central porphyry Oyu Tolgai, Crane and Kavalieris, 2012) grading to marginal later enargite.

It is important for explorationists to distinguish between retrograde alteration and mineralisation. While phyllic (silica-sericite-pyrite) alteration is magnetite destructive and the abundant pyrite is highly chargeable, coincident subtle magmatism and induced polarisation chargeability anomalies derived from phyllic alteration may not always reflect Cu-Au mineralisation.

SHUT DOWN AND POST-MINERAL

Late stage barren intrusions may stope out mineralised intrusions and so must be accommodated in any geological model and resource determination. Cooling and neutralisation, of the collapsing fluids responsible for phyllic alteration provides a lower temperature argillic overprint of kaolinite-chlorite-pyrite±illite (locally within SCC alteration). Continued uplift and erosion may promote removal of the upper porphyry environment, including by sector collapse of volcanic edifices, and so promote the telescoping of 'above porphyry' features upon the existing porphyry, such as the development of cross cutting diatreme breccia pipes and epithermal mineralisation driven renewed magmatism at depth.

High sulphidation epithermal Au deposits which locally overprint porphyry deposits feature advanced argillic alteration developed by reaction with wall rocks of hot very acidic fluids developed by the evolution of rising magmatic volatile-rich fluids. In many cases vertically zoned sulphides dominated by enargite-pyrite overprint the alteration. While there is a common spatial association with the mineralised porphyry apophysis, many of these epithermal ore systems are interpreted to have been derived from the deeper magmatic source, and require a several hundred metre fluid flow path in which to evolve, rather than the porphyry apophysis.

Fluids responsible for the formation of Cu sulphide lodes including D veins may evolve during the substantial fluid rise and may also take on a high sulphidation enargite-bearing character, and then become progressively cooled and neutralised by wall rock reaction, to deposit later lower sulphidation mineralogies, commonly at higher crustal levels with paragenetic sequences including tennantite and later galena-sphalerite. Porphyry D veins may extend well into the wall rocks to become transitional to low sulphidation (deep) epithermal quartz-sulphide Au ± Cu mineralisation which grades to later stage and commonly overlying carbonate-base metal Au mineralisation. Similarly, early porphyry A veins may evolve to include epithermal mineral assemblages at elevated crustal settings. Studies of vein kinematics suggest the formation of many low sulphidation epithermal Au deposits is triggered by changes in the tectonic conditions and this mineralisation is derived from the magmatic source at depth. Therefore, it may not be feasible to place the formation of low sulphidation epithermal Au deposits within the porphyry paragenetic sequence. Nevertheless, there may be a strong association of epithermal mineralisation with porphyry apophyses, which commonly formed earlier and have been uplifted and eroded.

CONCLUSION

Porphyry deposits display paragenetic sequences of vein development as: ptygmatic A → EDM → linear A → M (including wall rock G) → B → C → D veins coincident with the overprinting of prograde potassic-propylitic alteration by retrograde phyllic-argillic alteration. This latter group of veins display the greatest variation, especially over extensive vertical wall rock exposure and pass into the epithermal regime.

Economic porphyry Cu-Au deposits develop by polyphasal events of intrusion emplacement with associated alteration and mineralisation. Interruptions to the normal vein sequence (described above) may provide valuable evidence for the existence of multiple, yet not recognised, intrusions.

Several different types of advanced argillic alteration, developed in the sequence of porphyry events, display different relationships to porphyry and epithermal mineralisation (Corbett, 2008), and so must be understood in order to be used as vectors towards mineralisation. As the fluids responsible for the development of high sulphidation epithermal Au mineralisation must evolve over some vertical distance outside the source intrusion, caution is urged where exploration scenarios suggest a source porphyry Cu-Au deposit may immediately underlie related epithermal Au mineralisation, although telescoping associated with uplift an erosion may promote these relationships.

Adequate interpretation of geophysical signatures, which vary from prograde to retrograde alteration and display different relationships to mineralisation, is required in order to vector towards porphyry targets and some knowledge of the geology is required to interpret the geophysical data.

Only porphyry deposits with extensive phyllic alteration host sufficient pyrite that will oxidise to form the acidic ground waters which promote leaching of Cu which is re-deposition to form supergene chalcocite enrichment blankets.

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