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 active porphyry Cu-Au style 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 porphyry systems in other magmatic arcs (Corbett, 2008, 2009; 2017 & 2018).

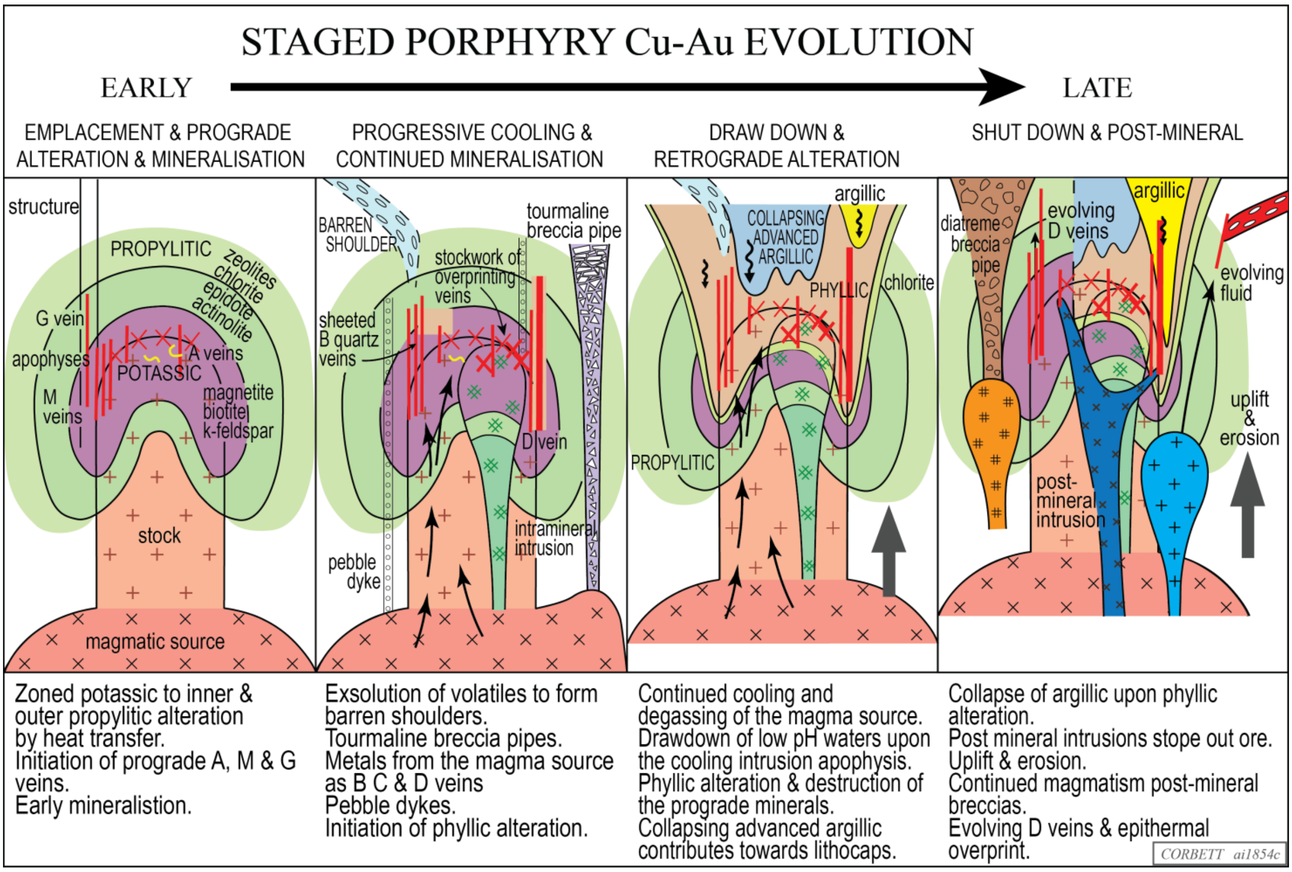

Figure 1. Staged model for porphyry development modified from Corbett (2018).

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 to explore for blind porphyry deposits and the interplay between mineralised and barren events (figure 1). Variable geophysical signatures which result from overprinting events of porphyry intrusion, alteration and mineralisation are better interpreted in a context of time.

EMPLACEMENT AND PROGRADE ALTERATION AND MINERALISATION

Changes in the tectonic conditions, often evidenced by vein kinematics as transient episodes of extension within overall compressional arc environments, 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).

Prograde hydrothermal alteration developed within the cooling intrusion apophysis is zoned outwards from the porphyry to the host wall rocks. A variable mix of magnetite, silica, K-feldspar, secondary biotite, albite, anhydrite, pyrite, chalcopyrite and bornite, within the innermost potassic alteration provide a geophysical signature of a magnetic, resistive and moderately chargeable body. As most mineralisation lies within the potassic alteration, wall rock mineral zonation which grades outwards to inner (actinolite, epidote, calcite) and then outer propylitic (chlorite, haematite, carbonate) prograde alteration, provides an important vector towards blind porphyry intrusions (figures 1 & 2). The earliest barren high temperature ptygmatic A veins (in the classification Gustafson and Hunt, 1975) develop within the cooling magma and so display the contorted and dismembered form. The EDM veins (Rusk et al. 2008), characterised by biotite (locally retrogressed to chlorite) selvages to a central crack, which may host anhydrite and mineralised chalcopyrite (with pyrite) extending into the selvage, also form early, possibly in association with potassic alteration.

Initiation of porphyry mineralisation is most commonly represented by the development of linear A style massive quartz veins with disseminated and fracture chalcopyrite-bornite and prograde alteration selvages. A veins may evolve into laminated quartz-magnetite veins, termed M veins, which host most sulphides deposited later during a reopening of the laminations. Consequently, it is possible for some porphyry deposits to host barren M veins. Au-rich porphyry deposits (commonly high temperature and oxidised) develop where bornite dominates over chalcopyrite in A and M veins, as bornite hosts more substantially Au than chalcopyrite, especially at higher temperatures. Linear B veins, defined with centrally terminated quartz, overprint A and M veins with prograde or retrograde alteration selvages and so straddle the prograde-retrograde divide. These three vein styles may develop as multi-directional stockworks especially due to multiple vein events associated with overprinting porphyry intrusions, or form parallel sheeted veins capable, in dilatant structural settings, of transporting ore fluids considerable distances away from the source intrusion into the overlying wall rocks.

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, while the prograde alteration selvages and variations in vein mineralogy 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 low pH fluids with wall rocks then provides barren shoulders of zoned wall rock advanced argillic alteration typically developed above, and marginal to, many porphyry deposits early in the paragenetic sequence (Corbett and Leach, 1998; Corbett, 2008, 2018). 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. Barren shoulders are important elements of the ‘out of porphyry’ features used to vector towards blind intrusions.

Boron-bearing magmas may rise to elevated crustal settings and erupt to form ‘out of porphyry’ breccia bodies in which shingle breccia clasts are indicative of collapse following volatile escape. Open space is then filled by later sulphides with quartz-tourmaline gangue.

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 to elevated crustal settings within dilatant sheeted quartz veins. Chalcopyrite-dominant C veins represent important sources of late stage sulphide mineralisation as fracture/veins, filling central open space within earlier B style quartz veins and the partings of laminated M veins. These sulphides are interpreted to have been derived from the degassing magma source at depth.

Late stage pebble dykes, characterised by the presence of rounded clasts milled during propulsion up structures by degassing magmatic volatiles, transect porphyry deposits and the overlying wall rocks. Pebble dykes are cut by D veins where both exploit the same structures as both are likely to have been derived from the deeper level magmatic source at depth.

RETROGRADE ALTERATION

Cooling magmatic volatiles oxidise to form low pH fluids which react with wall rocks to produce retrograde phyllic, argillic and advanced argillic wall rock alteration.

Phyllic alteration, developed in moderately low pH (7-4.5) conditions over a considerable temperature range >250^{o}C, is characterised by mainly sericite-pyrite with variable additions of silica, carbonate (typically siderite), anhydrite and chlorite, the latter commonly as pseudomorphs after mafic minerals, which passes to sericite with more intense alteration (figure 2). Sericite crystallinity varies with depth to higher temperature muscovite and passes to less ordered illite at lower temperatures. Settings of phyllic alteration include: selvages to B, C and D veins which locally coalesce; pervasive alteration as a progression of cooling prograde alteration and mineralisation as well as a collapsing overprint upon earlier prograde alteration.

The drawdown process, apparent in magmatic geothermal systems (Corbett and Leach, 1998), helps to explain the setting of phyllic alteration in the upper portion of the porphyry environment and the collapsing overprint upon prograde alteration, best developed within faults and permeable portions of the porphyry environment, such as intrusion margins. The hot porphyry apophysis contributes towards the development of circulating convective hydrothermal cells which draw meteoric waters in from the margins and transport magmatic volatiles within magmatic-meteoric to the upper porphyry environment. Here, the magmatic volatiles oxidise and mix with ground waters and form sinks of hot low pH waters. As the porphyry apophysis cools the circulating cells stall and reverse and the hot low pH waters are drawn down upon the deeper porphyry environment, particularly down the fractured intrusion margins. Consequently, phyllic alteration displays a molar tooth shape at the top of the intrusion (figure 1; Corbett and Leach, 1998). Near neutral Cu and Au bearing fluids continue to vent from the cooling hot magmatic source at depth into the overlying apophysis and mix with the collapsing oxidising low pH waters responsible for phyllic alteration, to promote high grade metal deposition. Here, the phyllic alteration is expected to contain bornite grading outwards to chalcopyrite as the fluids have been cooled and neutralised as described by Pollard et al. (2017) from Ak-Sug, Russia.

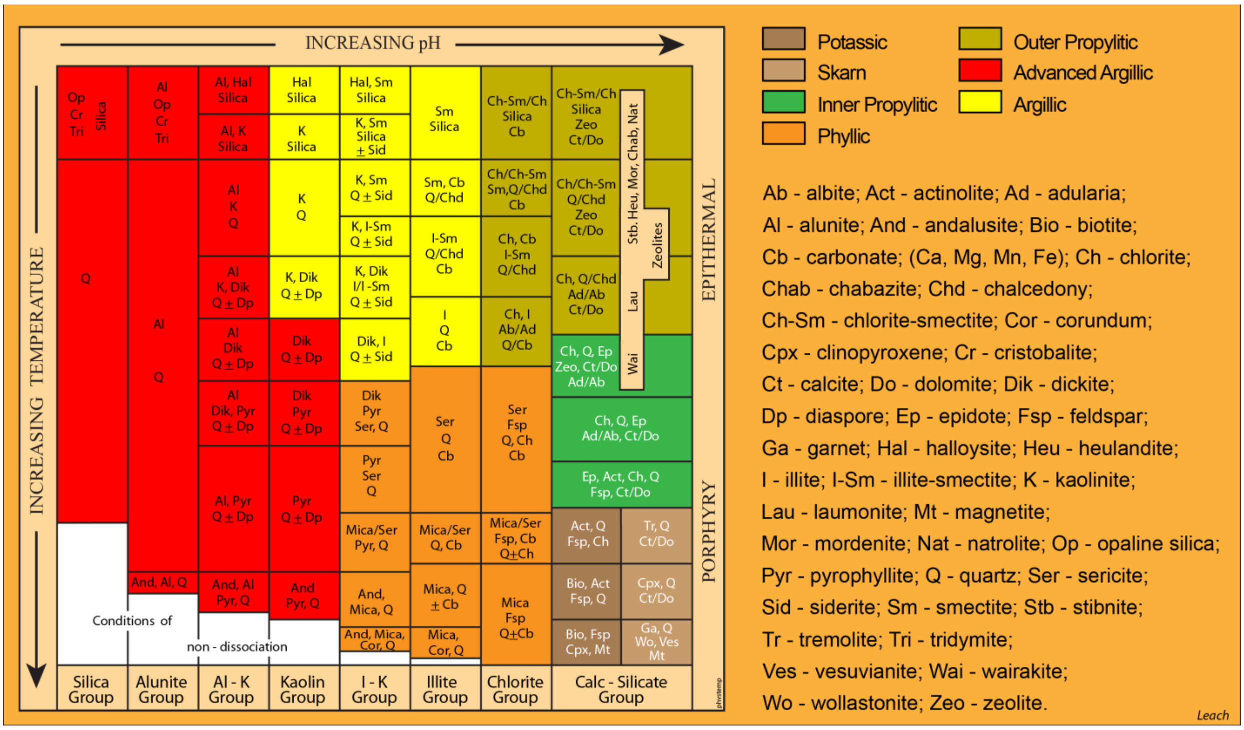

Figure 2 Minerals associated with different styles of hydrothermal alteration plotted as pH against temperature from Corbett and Leach (1998). Potassic alteration cools at constant pH passing to inner and then propylitic alteration (at the right hand side), or is overprinted by phyllic alteration as the pH conditions decline. Phyllic alteration may host cores of advanced argillic alteration lithocaps developed in conditions of even lower pH, or become overprinted by argillic alteration at lower temperatures, commonly associated with the greater influx of meteoric waters. Fluid flow paths which contribute to the development of zoned hydrothermal alteration are shown in Corbett (2018).

In more acidic conditions (<pH 4.5) dickite and pyrophyllite and high temperature corrundum-andalusite are present within phyllic alteration (Corbett and Leach, 1998), and as the pH declines further phyllic alteration may also contain cores of zoned advanced argillic alteration as silica-alunite grading out to pyrophyllite and dickite, commonly referred to as lithocaps, which may extend laterally within permeable host rocks (figure 2). Here, higher sulphidation state Cu minerals may include chalcocite and covellite passing to enargite in lowest pH conditions.

As meteoric waters enter the porphyry environment, cooling and neutralisation of the low pH waters responsible for the development of phyllic alteration promotes the development of argillic alteration at the outer margins of the phyllic alteration, dominated by chlorite with higher temperature dickite passing to lower temperature kaolinite and then illite in more neutral conditions. Similarly, aided by the entry of meteoric waters, later stage argillic alteration may overprint upon the earlier phyllic alteration as phyllic-argillic alteration, termed SCC (sericite-clay-chlorite) by some workers (figure 2).

Phyllic alteration is characterised by the destruction of secondary magnetite produced during potassic alteration to provide regions of irregular and subtle magnetic response. The abundant pyrite provides induced polarisation chargeability anomalies with variable resistivity. However, this collapsing phyllic alteration need not be directly associated with Cu-Au mineralisation, especially if drill intercepts remain in the overlying wall rocks.

SHUT DOWN AND POST-MINERAL

Continued uplift and erosion are an integral part of the porphyry process which may provide an important trigger for emplacement of porphyry intrusions as a whole, or individual intra-mineral and post-mineral intrusions. Shallower crustal level epithermal mineralisation is commonly telescoped upon uplifted originally deeper level earlier porphyry systems, such as the low sulphidation epithermal overprints on earlier porphyries at Gosowong, Indonesia and Lihir, Papua New Guinea. While sector collapse of a volcanic edifice is discernible in this latter case, thrust erosion in compressional settings (Porgera-Mt Kare in Corbett, 2018), or regional scale normal faults active during uplift, may also promote tectonic erosion. Shallow crustal level diatreme breccia pipes vent to the surface from rising intrusion sources related to renewed magmatism at depth and locally stope out porphyry mineralisation (Dizon, Philippines; El Teniente, Chile).

D veins (in the classification of Gustafson and Hunt, 1975) represent the final vein event as veins or lodes dominated by combinations of quartz, pyrite, chalcopyrite, carbonate, anhydrite and local bornite with sericite-pyrite alteration selvages. Many D veins, derived from the magmatic source at depth, cut mineralised porphyry intrusions and extend considerable distances into the wall rocks, and so are used by explorationists as vectors to mineralisation. Mo-bearing D veins form part of the marginal halo of Mo anomalism used to vector towards blind porphyry intrusions. In the wall rock environment both low and high sulphidation D vein classes are discernible. Low sulphidation D veins are equivalent to (deep) epithermal quartz-sulphide Au $\pm$ Cu mineralisation (Corbett and Leach, 1998; Corbett, 2018) and may evolve to carbonate-base metal Au style with increases in galena, sphalerite and carbonate (commonly rhodochrosite). The low sulphidation D vein are one of the most important sources of supergene enriched Au worked by artisan miners. High sulphidation D veins are characterised by the presence of hypogene chalcocite, covellite and enargite (depending upon the sulphidation state) and advanced argillic alteration selvages (alunite, pyrophyllite, dickite). Pregnant near neutral, hot and reduced magmatic fluids vent from the magma source at depth and during the rise to higher crustal levels become depressurised and cool to exsolve volatiles (SO_2 in particular) and so progressively take on a lower pH character, to deposit higher sulphidation ore minerals within lodes marginal to the magmatic source and locally the porphyry (Magma vein, Resolution; Butte Montana). At epithermal crustal levels the hot acidic oxidising fluids may also form high sulphidation epithermal Au deposits or become cooled and neutralised by wall rock reaction to deposit zoned lower sulphidation mineral assemblages (Butte, Montana veins).

Argillic alteration (kaolinite-chlorite-pyrite$\pm$illite) continues to overprint the porphyry systems dominated by potassic-propylitic alteration during final cooling varying to more neutral zeolites (laumontite) and carbonate, particularly in fracture and fault zones. Gypsum is formed by anhydrite hydrolysis dominantly in the upper portions of cooling porphyry systems, and promotes rock expansion in mines.

Supergene weathering of sulphides within porphyry deposits such as those with abundant pyrite-bearing phyllic or advanced argillic alteration, produces low pH ground waters which promote the development of surficial leached caps dominated by silica, clay and iron oxides and from which Cu and Au may be remobilised. Supergene Cu is redeposited at depth below the base of oxidation upon pre-existing sulphide minerals within chalcocite blankets which become progressively thicker during uplift and erosion, locally with uppermost Cu oxide, as some chalcocite is lifted above the water table (Chávez, 2000; Taylor, 2011). Supergene Au typically deposits with FeO immediately above the base of oxidation. Mo is immobile in the supergene environment and any Ag commonly concentrates with Cu.

CONCLUSION

Zoned alteration and mineralisation in porphyry systems can only be utilised as exploration tools, such as vectors to blind porphyry intrusions, if there is a satisfactory understanding of the overprinting relationships. This understanding of overprinting alteration aids in the interpretation of geophysical data. Magnetic anomalies are created in potassic alteration and later destroyed in phyllic alteration, which along with advanced argillic alteration contains pyrite identified in induced polarisation surveys, but not necessarily mineralised.

Porphyry deposits display paragenetic sequences of vein development as: ptygmatic A → linear A → M (including wall rock G) → B → C → D veins. This latter group extend the greatest distance into the wall rocks as zoned low and high sulphidation vein mineralogies and associated wall rock alteration selvages.

Economic porphyry Cu-Au deposits develop by polyphasal events of intrusion emplacement with associated multiple episodes of alteration and mineralisation, often apparent as stockwork arrays of overprinting veins. Interruptions to the normal vein sequence (above) may provide valuable evidence of multiple intrusion emplacement. Consequently, porphyry intrusions characterised by only single events of intrusion emplacement and associated mineralisation are less likely to develop as economic systems.

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 and erosion may promote these relationships, the underlying porphyry is often older than the epithermal system.

Only porphyry deposits with extensive phyllic or advanced argillic alteration host sufficient pyrite that will oxidise to form the acidic ground in order to promote leaching of Cu which is re-deposited to form supergene chalcocite enrichment blankets.

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