EXPLORATION OF EPITHERMAL Au-Ag and PORPHYRY Cu-Au DEPOSITS

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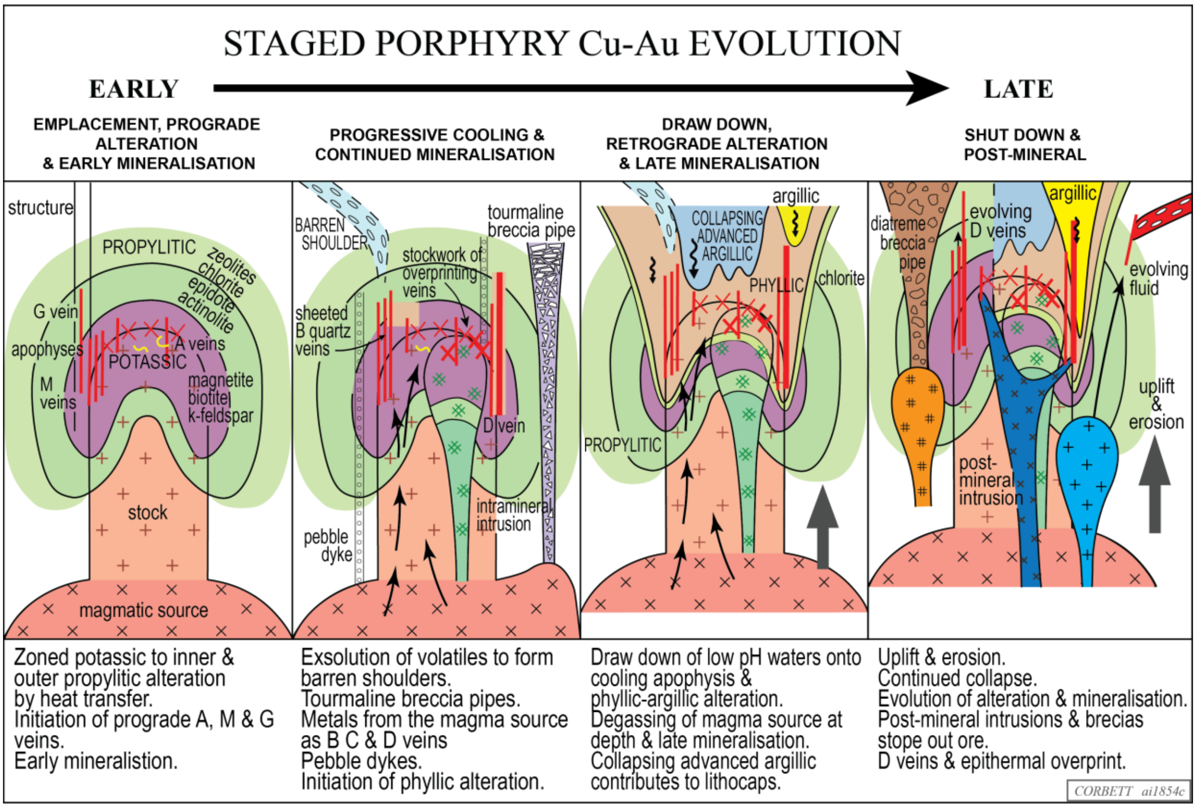
Porphyry and epithermal deposits form in subduction-related magmatic arcs, extending into back arc and rift environments. These deposits are characterised by many features which provide vectors towards the identification of ‘blind’ ore systems. Magmatic sources for mineralisation are commonly localised by dilatant settings within regional arc-parallel (Chuquicamata & La Escondida, Chile) and arc-normal (Yanacocha, Peru; Porgera, Papua New Guinea) structures, although conjugate fractures are also recognised (Pascua-Lama, Chile-Argentina; Veladero, Argentina).

Porphyry Cu-Au deposits are best understood if considered using the staged model of development (figure 1) which accounts for overprinting relationships and provides the many “out of porphyry features”, used by explorationists as vectors towards hidden ore bodies. Although in many traditional models, porphyry deposits develop at 1-2 km depths below andesitic stratovolcanoes, dilatant settings for porphyry development also include rifts (Resolution, USA; Stavely, Australia), while associated Cu lodes (below) developed within adjacent dilatant structures (Butte & Magma, USA and Cayley lode, Stavely). Porphyry intrusions cap more deeply buried batholitic magmatic sources which account for most of the metals focused into the porphyry apophysis.



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 development of porphyry Cu-Au deposits.

Initial emplacement of the hot porphyry magma produces zoned prograde hydrothermal alteration within the wall rocks which is used as a vector towards blind porphyry intrusions, grading inwards from propylitic to potassic alteration. A paragenetic sequence of quartz veins which begins to form a this stage is progressively overprinted by Cu-Au mineralisation within bornite-chalcopyrite-pyrite derived from the magmatic source at depth. D veins, the last formed quartz veins, extend greatest distances into the wall rocks from buried porphyry intrusions, and so represent important exploration vectors towards blind porphyry deposits. Barren shoulders of advanced argillic alteration develop at this stage from the reaction with wall rocks of low pH fluids formed by the evolution of rising SO_2 volatile-rich magmatic fluids. Other over-pressured volatiles venting up structures propel intrusion and wall rock clasts upwards to form pebble dykes, which are also used as vectors towards blind porphyry deposits. Boron-bearing aqueous melts may rise to cool at high crustal levels, but become depressurised in rapidly eroded and uplifted arcs and so commonly explode as tourmaline breccia pipes which may represent significant Cu ores (Rio Blanco–Los Bronces, Chile).

Hot porphyry intrusions drive circulating cells of magmatic-meteoric fluids which draw volatiles, derived from cooling intrusions and veins, into the upper porphyry environment, where they mix with ground waters to form low pH fluids which react with the wall rocks to produce phyllic (silica-sericite-pyrite) alteration. Strongly acidic fluids provide advanced argillic wall rock alteration (Tantahuatay, Peru; Chimborazo, La Escondida, Chile; Onto, Indonesia). As the porphyry cools, the circulating cells stall and reverse, drawing the low pH fluids down into porphyry environment to overprint the earlier prograde alteration with retrograde phyllic alteration. Overprinting argillic alteration develops as additional meteoric waters enter the porphyry environment, locally termed sericite-clay-chlorite (SCC) alteration. Fluid mixing promotes the development of some additional mineralisation at this stage. As the best porphyry deposits feature multiple events of porphyry emplacement and mineralisation, recognition of these events is important. However, explorationists must be mindful that some late stage intrusions and phreatomagmatic breccias may stope-out ore and reduce the economic potential of a porphyry.

Following the cessation of mineralisation, during uplift and erosion oxidation of sulphides in the supergene environment, in particular of pyrite within phyllic and advanced argillic alteration, provides acidic ground waters which remobilise Cu from the leached cap to form deeper zones of chalcocite enrichment.

<u>Cu sulphide lodes</u> (Magma & Butte, USA; Queenstown & Stavely, Australia) are locally recognised within dilatant structural settings in the porphyry-epithermal transition where, they represent important Cu ores and act as vectors towards blind porphyry Cu deposits (Resolution, USA). A rising ore fluid, initially apparent as a typical pyrite-chalcopyrite D vein, progressively evolves to a lower pH and so deposits overprinting Cu sulphide minerals zoned in time an locally space as: chalcopyrite → bornite → chalcocite → covellite → enargite.

Epithermal Au deposits which develop above the porphyry environment at depths up to 1 km below the surface and at temperatures less than 300°C, are distinguished as low and high sulphidation.

<u>Low sulphidation epithermal Au-Ag deposits</u> were categorised by Leach and Corbett in the early 1990's as different styles, with variable exploration implications, in two fluid flow trends within magmatic arcs and back arcs, respectively.

<u>Magmatic arc</u> low sulphidation epithermal Au deposits (path A in figure 2) develop, from early to late, and to some extent deep to shallow, as:

<u>Quartz sulphide Au + Cu</u> low sulphidation epithermal mineralisation is characterised mostly as Au within pyrite varying to include chalcopyrite at depth, while pyrite passes to marcasite and arsenian pyrite at low temperature shallow crustal level settings. Coarse grained ores represent sources of easily leachable low grade Au (Round Mountain, USA; Nolans, Mt Rawdon, Mt Wright, Australia), especially if subject to near surficial supergene oxidation. However, Au may be encapsulated in fine grained arsenian pyrite (Lihir, Papua New Guinea). Explorationists must be careful that elevated near surficial supergene enriched Au grades may not be supported in deeper hypogene settings.

<u>Carbonate-base metal Au</u> mineralisation (subsequently rebadged as intermediate sulphidation by some workers) overprints quartz-sulphide ores as quartz-pyrite-sphalerite > galena with local chalcopyrite and Ag sulphosalts. Sphalerite temperature as a function of Fe:Zn ratios, styles of Fe sulphide minerals, and zoned illite crystallinity within wall rock alteration, all provide an indication of the depth of formation and locally vector to blind deposits. The mixing of rising pregnant ore

fluids with oxidising bicarbonate waters promotes Au deposition which declines in Au grade as carbonates grade in composition with rising fluid pH as: Fe → Mn → Mg → Ca. These include many important Pacific rim Au deposits (Frute del Norte, Ecuador; Porgera, Morobe goldfield, Misima, Papua New Guinea; Cowal, Australia; Cripple Creek, USA; Acupan, Antamok, Victoria, Philippines). MnO formed by the weathering of rhodochrosite represents a useful prospecting tool. Many are associated with phreatomagmatic breccias (Mt Leyshon, Australia; Cripple Creek, USA; Acupan, Philippines; Rosa Montana, Romania)

Epithermal quartz Au mineralisation overprints quartz-sulphide and carbonate-base metal Au deposits, typically at shallow crustal levels where it may host bonanza grade high fineness Au with variable quantities of quartz gangue (Sleeper, USA; Porgera Zone VII, Papua New Guinea; Frute del Norte, Ecuador) and local tellurides (Emperor, Fiji).

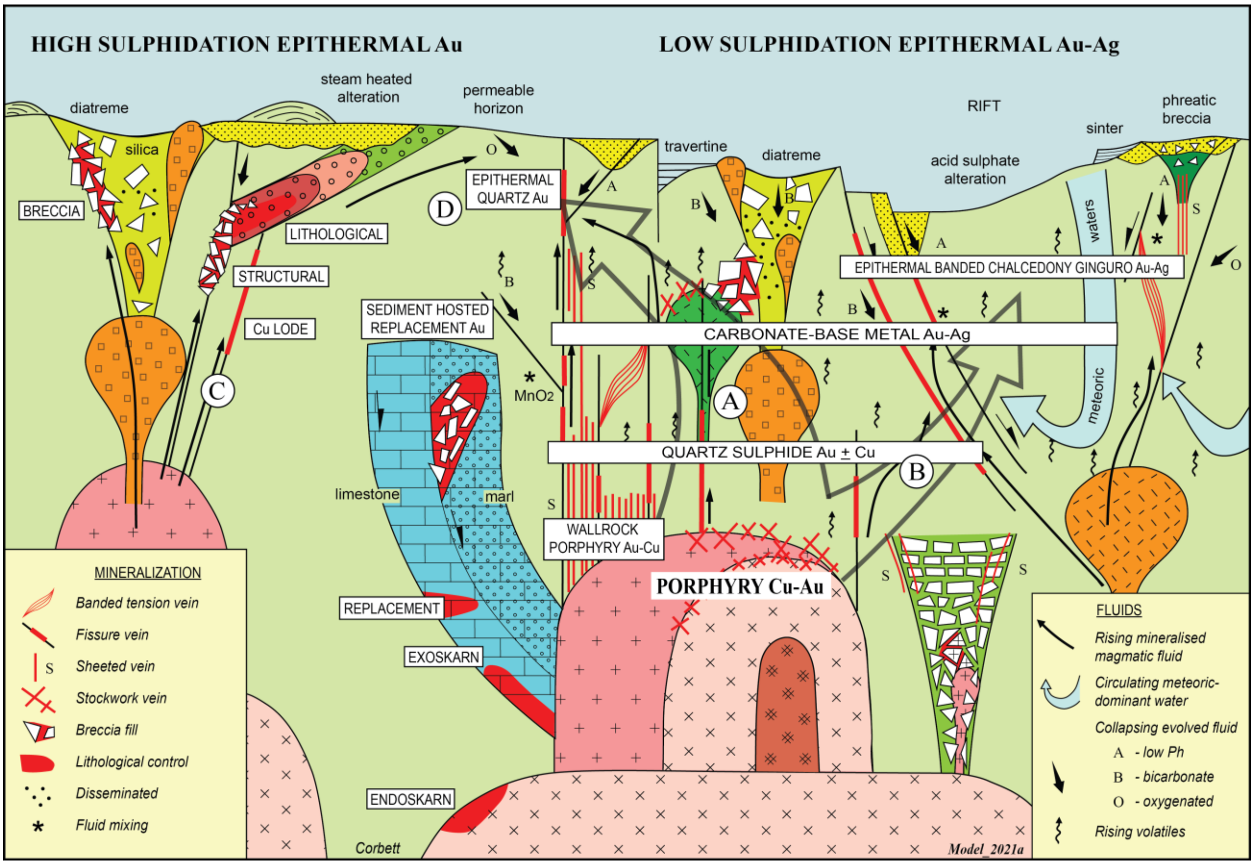


Figure 2 Styles of porphyry and epitheraml Au mineralisation showing fluid flow paths.

In back arc and rift settings (path B in figure 2), dilatant environments draw additional meteoric waters into the ore environment, to deposit substantial quantities of essentially barren quartz and locally adularia as the low temperature form of K-feldspar.

The carbonate-base metal Au-Ag deposits in extensional settings of Latin America, developed as Ag-rich banded quartz-carbonate-sulphide fissure veins (southern Peru, Arcata, Caylloma; Deseado Massif of Southern Argentina- Chile, Cerro Negro, Cerro Moro, Cerro Bayo; Sierra Madre of Mexico, Fresnillo, Palmarejo and central western USA, Comstock), and have therefore been termed ‘polymetallic Ag-Au’ veins (Corbett, 2002, 2005). Silver mostly occurs within tennantite-tetrahedrite minerals, especially freibergite, varying at low temperatures to argentite-acanthite in combination with low-Fe white sphalerite and local marcasite. This ore type evolves to the ginguro material described below.

Chalcedony-ginguro epithermal Au-Ag deposits typically occur as low temperature banded veins which host most Au-Ag mineralisation within the black sulphidic ginguro bands (including breccia fill or clasts) which are made up of argentite-acanthite, pyrite and electrum, along with local cinnabar, tellurides and rare chalcopyrite (Hishikari, Japan; Waihi, New Zealand; Pajingo, Australia;

Ares, Peru; Midas, USA). Gangue in these low sulphidation epithermal veins includes low temperature quartz (chalcedony) and K-feldspar (adularia) interlayered with quartz pseudomorphing platy calcite. Dilatant structural settings contribute towards the formation of banded veins deposited from pulsing fluids which vary from magmatic-dominant for deposition of the mineralised sulphidic ginguro component, to meteoric-dominant for much of the poorly mineralised gangue. Consequently, it is common for meteoric-dominant fluids to deposit barren banded veins of quartz, adularia and quartz pseudomorphing platy calcite, which lack the mineralised ginguro component. Some veins in Latin America, cap banded carbonate-base metal Au-Ag deposits formed as quartz polymetallic Ag-Au veins, while in the western Pacific rim others terminate downwards as quartz-carbonate veins (Kupol, Far Eastern Russia; Waihi, New Zealand). Surficial sinter, acid sulphate caps, phreatic breccias and zoned wall rock alteration, act as vectors towards blind deposits. Highest Au grades result from the mixing of rising pregnant fluids with oxidising acid sulphate, oxygenated and bicarbonate waters, evidenced by the presence of hypogene kaolin (Waihi, New Zealand; Sleeper, Nevada), hypogene haematite and Mn carbonate (Karangahake, New Zealand) in the ore assemblage, respectively.

High sulphidation epithermal Au deposits are characterised by zoned advanced argillic alteration and Cu-Au-Ag typically associated with enargite-pyrite, grading to covellite-chalcocite at depth and luzonite at shallow crustal levels. Ore fluids rise from buried magmatic source rocks and during depressurisation and cooling, exsolve SO_2 volatiles which undergo disproportionation to form H_2SO_4 in a progressively more acidic fluid, most pronounced below 300°C (path C in figure 2). This fluid typically breaks into a faster moving volatile-rich phase that creates the zoned advanced argillic alteration by reaction with the wall rocks, followed by a slower moving liquid-rich phase which deposits sulphide mineralisation with gangue of additional alunite, barite and local sulphur. The zoned advanced argillic hydrothermal alteration provides an excellent exploration vector towards mineralisation which lies within the core of vughy silica, although more marginal wall rock hosted As, Sb and Hg geochemistry may be useful. As the refractory hypogene enargite ores commonly display problematic metallurgy, many high sulphidation epithermal Au deposits are only worked as oxide ores, unless an evolution to lower sulphidation provides bonanza Au grades (below). Smelted ores may yield Cu (Lepanto, Philippines; El Indio, Chile).

There is a progression from high to lower sulphidation mineralisation recognised in some high sulphidation epithermal Au deposits, as the hot low pH fluids are rapidly cooled and neutralised by entrainment of substantial meteoric waters and reaction with permeable wall rocks (path D in figure 2). In these conditions ore fluids deposit mineralogies typical of carbonate-base metal Au and epithermal quartz Au deposits with associated bonanza grades of high fineness free Au (El Indio, Chile; La Zanga, Orcopampa, Peru; Mt Carlton, Australia). The high Au grades and good metallurgy make these attractive exploration targets.

In conclusion, variable fluid types contribute towards the development of distinct Cu-Au-Ag deposit styles, formed at different crustal levels with characteristic metal grades and metallurgy. All these deposits are associated with features within the nearby wall rocks which aid in the exploration for blind ore deposits.

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