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# Anatomy of porphyry-related Au-Cu-Ag-Mo mineralised systems: Some exploration implications

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## Summary

Analyses of exploration and mining case studies as well as magmatic arc geothermal systems have facilitated an understanding of the implications to explorationists of the anatomy of porphyry related Au-Cu-Mo-Ag mineralising systems. Deeply eroded magmatic source rocks tend to host sub economic mineralisation, which may become focused in the highly prospective in overlying apophyses to spine-like polyphasal intrusions. Buried targets may be identified by analyses of zoned alteration and mineralisation developed by complex overprinting relationships. Mineralised fluids may exit from the magmatic source migrating to higher crustal levels to form epithermal deposits. High sulphidation epithermal Au ± Cu ± Ag deposits display characteristic alteration and mineralisation zonation which aids target generation and in some instances evolve to host marginal and overprinting lower sulphidation ores which display improved metallurgy and metal grades. Low sulphidation epithermal Au-Ag deposits are categorised as a number of styles, linked on an overall anatomy, which display considerable variation in metal grade, size, form and metallurgy, typically governed by setting and crustal level of formation, as well as controls to vein formation such as: host rock competency, structure, and mechanism of Au deposition. All these controls and zonation pattern vectors provide valuable tools to explorationists in the search for hidden ores.

## Introduction

We have developed an understanding of porphyry-related ore systems by the analyses of many mines and exploration case histories during the post-WWII increase in demand for Cu and Mo, and rise in the price of precious metals since the late 1970's, aided by the use of magmatic arc active geothermal systems as modern analogies. Porphyry-related mineralisation systems under consideration here contain variable Au, Cu, Mo, and Ag, which are interpreted to have been derived from magmatic source rocks at considerable depth and focused into intrusion apophyses as porphyry Cu occurrences, or migrated into higher crustal levels to form high and low sulphidation epithermal Au-Ag deposits in the upper 1 km or so of the crust. In broad terms, many porphyry Cu deposits with accessary Mo occur in the western (north and south) Americas within calc alkaline magmatic arcs (Titley, 1993; Sillitoe 1993), while porphyry Mo deposits are associated within more siliceous quartz monzonite and alkali granite intrusions (White et al., 1981), commonly in regions characterised by a greater input of continental crust. In the SW Pacific porphyry Cu-Au deposits occur within now eroded island arcs emplaced into oceanic crust, and very Au rich porphyry deposits are recognised in association with shoshonitic magmatism (Cadia, Australia; Didipio, Philippines), especially in environments of interpreted (Solomon, 1992) remelting of oceanic crust (Lihir Is., Papua New Guinea).

## Geological settings

Quality porphyry-related deposits typically occur within variably eroded calc-alkaline magmatic (island) arcs developed as linear belts overlying subducting oceanic plates and may be coupled with back arc rifts (figure 1). While porphyry and high sulphidation epithermal Au

± Cu ± Ag deposits dominate within magmatic arcs, low sulphidation deposits display variations from more intrusion-related styles within the arc, intra arc rifts host carbonate-base metal Au (in the SW Pacific) and polymetallic Ag-Au vein (in the Americas) mineralisation, and chalcedony-ginguro banded epithermal Au-Ag veins occur within back arc environments (figures 1 & 2). Porphyry-related deposits display considerable variation in form and metal type and abundances, partly dependent upon the setting of formation. In this classification (figure 2) porphyry Au-Cu deposits form as deepest crustal levels rising to about 1 km below the surface as caps to deeper, large (commonly batholitic), buried magmatic source rocks and are overlain by high sulphidation and different styles of low sulphidation Au developed with variable relationships to the intrusion source at depth described herein.

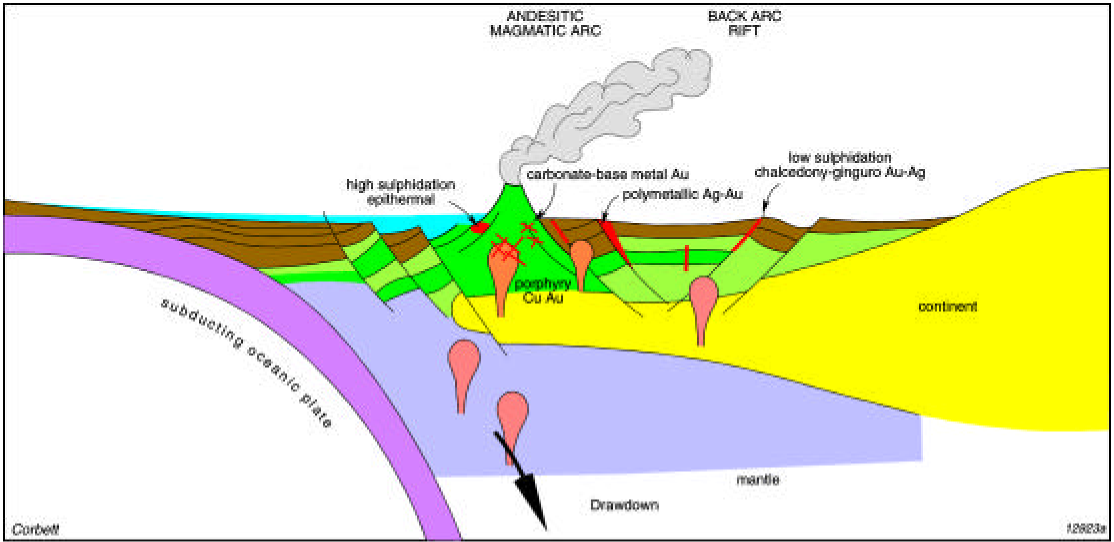

Figure 1. Cartoon illustrating the settings of different porphyry related mineral occurrences in relation to a subduction zone tectonic setting.

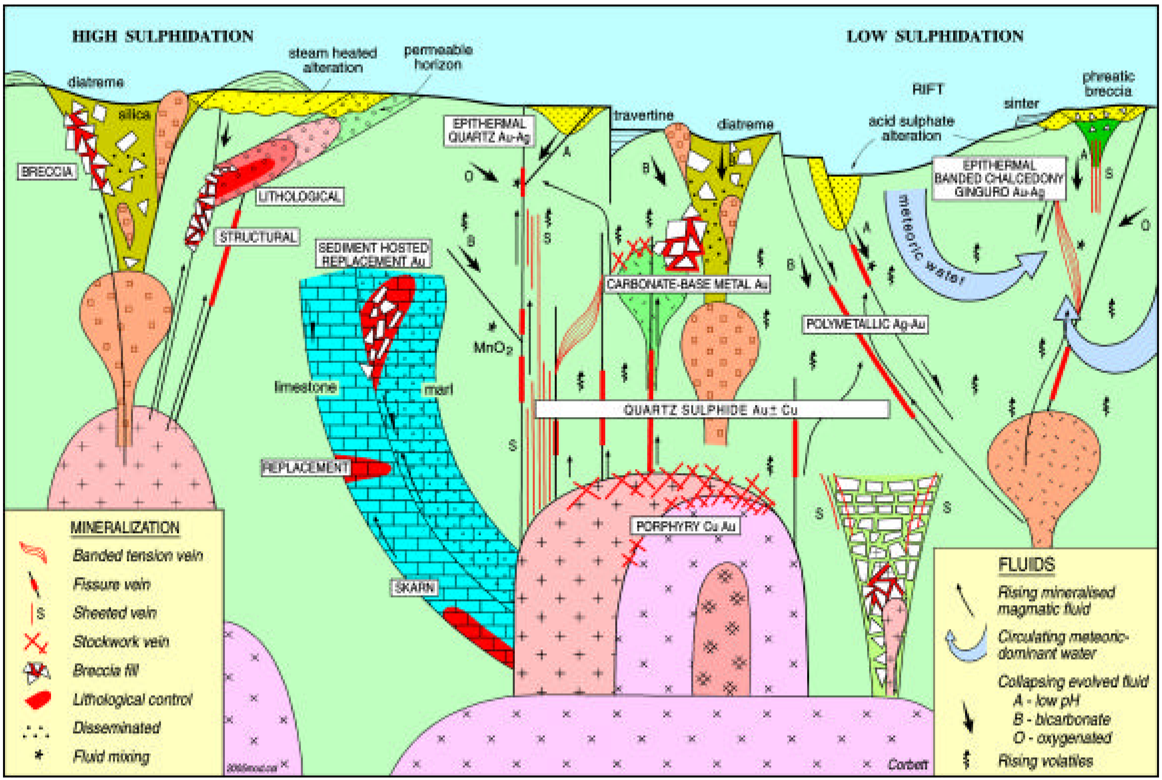

Figure 1. Conceptual model illustrating different styles of magmatic arc porphyry and epithermal Cu-Au-Mo-Ag mineralisation discussed herein (from Corbett, 2008 and modified from Corbett 2002, 2004).

Active geothermal systems exploited for the production of electrical energy provide analogies with porphyry-epithermal mineralisation. Our early (1970-1990) understanding of epithermal deposits benefited from the use of the analogies drawn from the study of geothermal systems, dominantly the back arc rift geothermal systems such as the Taupo Volcanic Zone in New Zealand (Weissberg et al., 1976; Henley and Ellis, 1983). However, more recently it has become apparent that these comparisons apply to only a small group of low sulphidation epithermal deposits classed as the chalcedony-ginguro banded epithermal Au-Ag (formerly adularia-sericite) veins, and studies of magmatic arc geothermal systems such as those in the Philippines (Mitchell and Leach, 1991; Corbett and Leach, 1998) provide better analogies to many porphyry and epithermal deposits (Corbett, 2008). Studies of the Philippine geothermal systems have allowed us to apply time to porphyry systems and better understand their staged evolution as well as the evolved hydrothermal fluids which participate in low sulphidation epithermal vein formation (figure 3).

## Porphyry Au-Cu-Mo

Although porphyry Au-Cu-Mo deposits display considerable variation, some broad generalisations are possible.

The terrain into which porphyry intrusions are emplaced varies. While traditional models place porphyry development in the root zones of upstanding calc-alkaline stratovolcanoes (Titley, 1982) and mineralisation must be exposed by considerable later uplift and erosion, many quality porphyry Cu-Au (Grasberg, West Papua; Bingham Canyon, US) and intrusion-related Au deposits (Porgera, Papua New Guinea) do not occur in association with related volcanic rocks. In these instances mineralisation and volatiles may have been concentrated by retention within the magma chamber and concentrate in apophyses localised on major structures or adjacent subsidiary dilatant structural sites. Active geothermal systems are recognised in dilatant settings along the Philippine Fault, which lie within flat terrains rather than within upstanding stratovolcanoes (Corbett and Leach, 1998). Dilatant settings in relation to major regional arc parallel and arc normal structures therefore represent favourable sites for porphyry Cu-Au exploration (Corbett, 1994; Corbett and Leach, 1998).

In the deeper portions of the porphyry-related anatomy, where the magmatic source might be exposed by deep erosion, primary disseminated mineralisation often occurs as chalcopyrite-pyrite confined within miralithic cavities (Yeoval, Australia), locally concentrated at intrusion margins (Timbara, Australia: Caspiche, Chile). These intrusions typically display sub economic metal grades but represent mineraliser source rocks for hydrothermal fluids which may become concentrated in higher level settings in appropriate conditions. Localised high Cu grade structurally controlled lodes (± magnetite-quartz) which developed in the vicinity of these intrusions may attract exploration attention but are commonly too small and isolated to provide economic resources (Goodrich at Yeoval, Australia). Similarly, the batholitic intrusions are unfavourable exploration targets.

In some settings volatiles and metals, which concentrate in the upper portions of batholitic bodies, may erupt as breccia pipes characterised by initial volatile exsolution, followed collapse and then later Cu-Au introduction and deposition from a liquid-dominated fluid. Examples include the Cu ± Au tourmaline breccia pipes common in the coastal batholitic of Chile-Peru or the Kidston Au breccia pipe. In the latter case geological mapping and gravity data provide evidence of a buried magma source for mineralisation (Corbett and Leach, 1998). While breccia pipes display highly variable anatomies, marginal sites of collapse should be of immediate interest to explorationists, noting the importance of the post-breccia timing of Au mineralisation (Kidston, Australia).

Many quality SW Pacific rim porphyry Cu-Au occurrences develop in the upper portions of spine-like polyphasal intrusion systems which cap deeper magmatic source rocks. Here, repeated intrusion emplacement provides multiple events of mineralisation while post-mineral intrusions may also stope out earlier mineralisation. Volatiles and metals derived from the major magmatic source at depth are interpreted to concentrate at the cooler apophysis to the elongate stocks and extend into the adjacent wall rocks where further mineral deposition occurs. Most Cu-Au mineralisation occurs within stock work quartz veins and breccias (El Teniente, Chile) while local disseminations may be more concentrated at intrusion apophyses than at deeper levels. Intact intrusion apophyses and the immediately adjacent wall rocks represent the most favoured portion of the porphyry anatomy for the development of Cu-Au mineralisation of considerable size and metal grade (Oyu Tolgoi; Mongolia: Ridgeway, Australia). Consequently, explorationists should seek to identify buried intrusion apophyses not yet exposed by erosion as the most favoured targets. Vectors discussed below provided by alteration zonation, marginal mineralised D veins and structure, as well as geophysical tools such as magnetics and electrical conductivity studies (IP chargeability) may assist in target generation.

Mineralised fluids may exit from high level porphyry Cu-Au intrusion as a number of several forms. Porphyry-style mineralisation formed marginal to the source intrusion are sheeted quartz-sulphide veins which may exploit dilatant fracture systems and migrate significant distances into the wall rocks, and are termed wall rock porphyry systems. For instance the Cadia Hill wall rock porphyry veins display little change over several hundred metres, localised wholly within earlier intrusion wall rocks outside the interpreted source intrusion. Sheeted veins therefore host and transport mineralisation and provide a structural grain which must be considered during drill testing. Although the transitional relationship of the wall rock porphyry to low sulphidation epithermal mineralisation commonly provides higher Au contents relative to Cu, wall rock porphyry systems tend to be large but display low metal grades (Gaby Au-Cu, Ecuador, some Maricunga belt Au systems, Chile and Whitewash porphyry Mo Rawbelle, Australia), and so only represent favoured exploration targets in settings of good logistics or close to other higher Cu-Au grade mineralisaiton (i.e. Ridgeway adjacent to Cadia Hill).

While endoskarns occur within the source intrusion, exoskarn deposits also represent mineralisation formed outside the source intrusion by reaction of magmatic hydrothermal fluids with reactive wall rocks commonly characterised by prograde alteration followed by hydrous retrograde alteration and metal deposition.

## Zonation patterns and time in porphyry Cu-Au deposits

Porphyry Cu-Au deposits display complex patterns of zonation in alteration and mineralisation which result from the overprinting of many prograde and retrograde events. These patterns are best analysed in the light of the model for the overprinting stages of porphyry evolution (figure 3; Corbett, 2008) as:

- Emplacement of the porphyry intrusion, commonly as an apophysis to a larger underlying magmatic source, results in the development of progade hydrothermal alteration derived from mainly conductive heat transfer characterised as potassic (magnetite, secondary biotite, Kfeldspar) grading outwards to inner propylitic (actinolite, epidote) and outer propylitic (chlorite, calcite) alteration, formed at progressively cooler conditions with more marginal relationships to the source intrusion. Barren high temperature ptygmatic and disjointed A style quartz veins developed while the intrusion is cooling may be overprinted by stock work and linear sheeted Au veins which vary to locally wormy A style quartz-sulphide, or stock work and sheeted M style quartz-magnetite-sulphide veins. These veins and lesser disseminated sulphides represent the main pyrite-chalcopyrite-bornite ± Au mineralisation developed during prograde hydrothermal alteration, preferentially concentrated close to the intrusion apophyses, extending into the adjacent wall rocks.

- During continued cooling of the porphyry intrusion, magmatic volatiles may exit the cooling magma chamber and become depressurisation as they rise rapidly to higher crustal levels. At this stage the cooling volatiles develop into strongly acidic fluids which react with wall rocks to develop zoned barren advanced argillic alteration described by Corbett and Leach (1998) as barren shoulders and included within the lithocap model of Sillitoe (1995). These alteration zones are not in themselves altered but are an important portion of the porphyry-related anatomy.
- Veins described in the geological literature (Gustafson and Hunt, 1975) as B style quartz-sulphide veins overprint earlier veins. These veins contain centrally terminated comb quartz in-filled by later sulphides (mainly pyrite-chalcopyrite). Some workers describe sulphide in-fill as C veins. Depressurisation due to fracturing of the overpressured intrusion carapace promotes quartz deposition and sheeted or linear vein arrays indicate the involvement of structural processes in the failure of the carapace and dilational sheeted veins may transport mineralised fluids. The porphyry intrusion acts as the source for volatiles and metals as well as heat responsible for the development of circulating cells of magmatic-meteoric hydrothermal fluids, which may extend some distance from the source intrusion into the wall rocks where they deposit epithermal veins (below).
- Volatiles ($H_2O$ and $SO_2$, but also $CO_2 > HF$) venting from cooling intrusions and vein mineralisation condense and acidify, locally forming large bodies of hot acid ground waters which promote the development of retrograde alteration varying from hot more acidic phyllic (silica, sericite, pyrite, chlorite, carbonate) to cooler and less acid argillic alteration (locally but commonly not combined: dickite, kaolinite, illite, pyrite, chlorite). These hot acid waters commonly collect in the upper portions of the hydrothermal systema and may collapse to deeper levels as drawdown results from the reversal of the initially outward circulating cells hydrothermal fluids during cooling of the intrusion apophysis and so earlier prograde mineral assemblages are overprinted by retrograde alteration (stage 3 in figure 3). Interaction of the acid fluids with mineralised fluids rising from the major magma source at depth (below the cooling apophysis) promotes enhanced Cu-Au deposition, typically within B style porphyry veins which commonly display halos of phyllic (silica-sericite-pyrite) alteration (Corbett and Leach, 1998).
- The last stage of vein formation typically occurs within the wall rocks outside the source porphyry intrusion as the development of D veins described in the old porphyry Cu literature (Gustafson and Hunt, 1975), and marks the progression from porphyry to both high and low sulphidation epithermal mineralisation described below. Marginal D veins might therefore provide explorationists with vectors to hidden porphyry deposits.
- While polyphasal intrusion emplacement and resultant repeated Cu-Au mineralisation provides an important mechanism for the development of elevated metal grades of many porphyry systems (Ridgeway, Australia; Grasberg, West Papua; Oyu Tolgoi, Mongolia), many polyphasal intrusion scenarios culminate in the emplacement of barren late to post-mineral intrusions, which may stope out mineralisation and lower the overall Cu-Au tenure of the deposit (Bajo del la Alumbrera). Elsewhere, diatreme breccia eruptions associated with the emplacement of deeper level intrusions may also stope out Cu-Au mineralisation (El Teniente, Chile; Dizon, Philippines).

There are profound exploration implications in the correct understanding of the staged alteration and mineralisation associated with polyphasal porphyry emplacement. For instance, magnetic signatures are governed by the overprinting of prograde magnetite by demagnetising retrograde alteration and many IP chargeability anomalies are derived from barren pyrite related to phyllic (silica-sericite-pyrite) alteration and not mineralisation. Most importantly, zoned prograde potassic-phyllic alteration and the presence of sheeted B or D veins may be used as vectors to explore for blind porphyry targets.

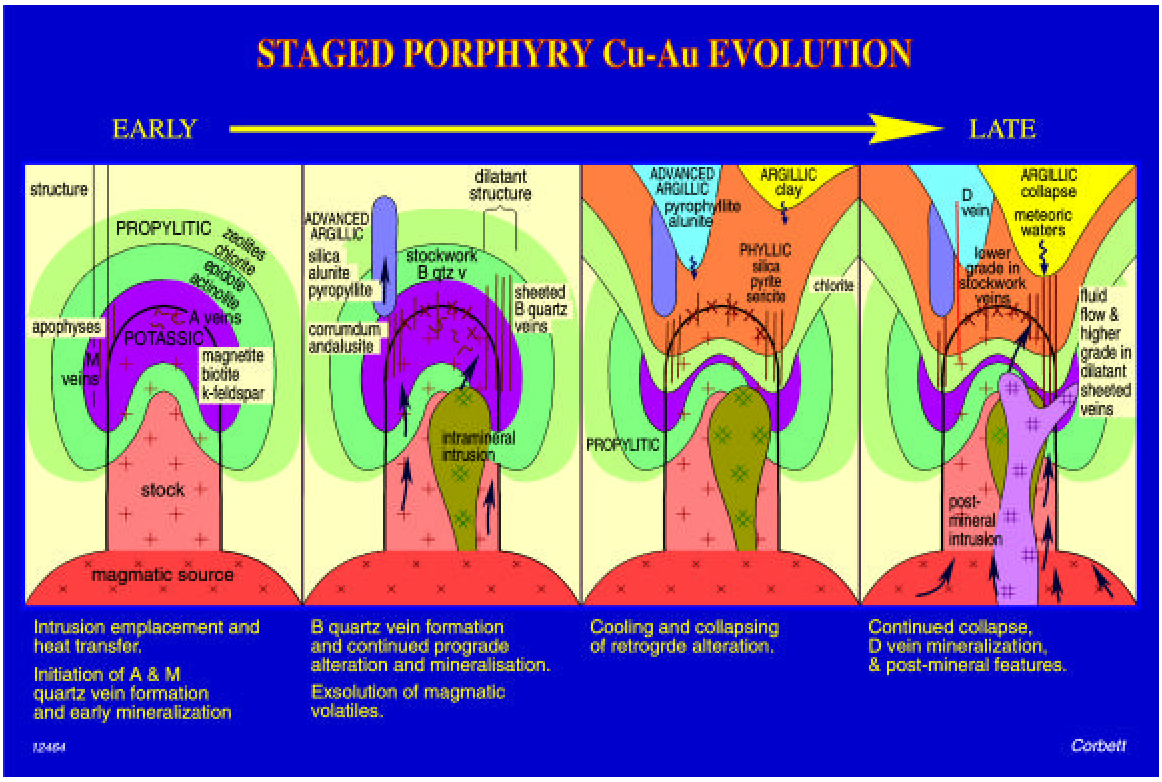

Figure 3. Conceptual model illustrating stages in the evolution of porphyry Cu-Au intrusions, mineralisation, alteration and vein types as discussed herein.

## Epithermal Au

The terminology for epithermal Au end members has evolved from early acid sulphate and adularia-sericite terms based mainly upon alteration (Bagby and Berger, 1985), to the current high and low sulphidation based upon the sulphidation state of ore minerals, as enargite for high sulphidation and chalcopyrite-galena-sphalerite for low sulphidation (White and Hedenquist, 1995). Low sulphidation deposits are divided between the group which dominates in magmatic arcs and display stronger associations with intrusions grading away from the intrusion source as; quartz-sulphide Au ± Cu, carbonate-base metal Au and epithermal quartz Au-Ag (Leach and Corbett, 1994, 1995), and the banded chalcedony-ginguro epithermal veins which dominate in rift settings. This latter group correspond to the widely studied deposits formerly termed adularia-sericite, but a description based on ore mineralogy is preferred (Corbett, 2007). Polymetallic Ag-Au veins occur throughout the pacific Rim (Mungana, Conrad, Australia) but dominate as West pacific (Mexico, Peru, Patagonia) equivalents of carbonate-base metal Au deposits, which are preferentially developed in extensional arc or near arc settings. In strongly dilational settings may pass upwards to banded chalcedony-ginguro Au-Ag ores. The term intermediate sulphidation (Sillitoe and Hedenquist, 2003) has recently been introduced to describe mineralisation equivalent to the lower temperature portion of the existing carbonate-base metal Au style.

### High Sulphidation

High sulphidation epithermal Au-Cu deposits develop in settings where volatiles rise rapidly from a magma source at depth without interaction with wall rocks or ground waters, and become depressurised to progressively develop as hot very acid hydrothermal fluids, which at epithermal levels react with wall rocks (Corbett and Leach, 1998 & Corbett, 2004; and references therein). The progressive cooling and neutralisation of the hot acid hydrothermal fluids by wall rock reaction produces zoned hydrothermal advanced argillic alteration which characterises high sulphation ore deposits, although most Cu-Au mineralisation deposition (typically associated with pyrite-enargite-barite-alunite) commonly post-dates alteration.

There are exploration benefits in an understanding of the anatomy of high sulphidation epithermal deposits. The porphyry-high sulphidation transition is discernible as the structurally controlled pyrite-enargite-alunite-barite veins which form marginal to many Andean porphyry intrusions and correspond to the veins recognised in the root zones of many mineralised high sulphidation epithermal Au-Cu deposits. These veins commonly represent the basis for small scale mines (La Coipa district, Chile), but are not the main targets. Deposit types are classified according to controls to alteration and mineralisation classed as: dilatant structures (Nena, Papua New Guinea; El Indio, Chile), permeable lithologies (Pierina, Peru; La Coipa Chile) and diatreme-flow dome breccia systems (Pascua-Lama-Veladero, Chile-Argentina), while the intersections of feeder structures and permeable lithologies are common settings (Sipan, Peru). Most mineralisation occurs in the vughy or residual silica core to the advanced argillic alteration which grades progressively and laterally outwards to mineral assemblages dominated by alunite, pyrophyllite, dickite-kaolinite and marginal illite, and vertically as pyrophyllite-diaspore-dickite might dominate at depth and alunite-kaolin occur at elevated settings with much sharper transitions between narrow alteration zones are recognised. These alteration patterns can be easily mapped by PIMA or ASD to vector towards the mineralised central portions where most mineralisation generally occurs. High sulphidation epithermal Au deposits commonly grade to Cu rich at deeper crustal levels and may be Te and Sb anomalous in the uppermost portions, while Ag is important in west Pacific systems and those in the SW Pacific are essentially barren of Ag. Sulphide mineralogy varies from higher level luzonite to cores of enargite-pyrite and deeper levels covellite in addition to enargite-pyrite.

## High-Low sulphidation Au transition

The progressive cooling and neutralisation of the hot acid fluids responsible for the development of high sulphidation epithermal deposits by wall rock reaction, especially if aided by the introduction of ground waters, may result in the transition from high to lower sulphidation mineral assemblages. Transitions are discernible changes from high to lower sulphidation mineralisation laterally (Wafi, Papua New Guinea; Viento, Chile; Mt Carlton Australia) or overprinting as changes in time (El Indio, Chile). Of great interest is that the later low sulphidation ores display higher Au grades and benign metallurgy as the high sulphidation enargite ores commonly exhibit refractory Au.

## Low sulphidation epithermal Au-Ag

Low sulphidation epithermal Au deposits are characterised by neutral chloride wall rock alteration developed by the interaction of wall rocks with near neutral hydrothermal fluids, which are often considered to result from the entrainment of a mineralised magmatic component by deep circulating meteoric waters. It is useful to the explorationist to consider the anatomy of individual veins in detail. Each mineral band of a typical banded epithermal vein represents a new episode of mineral deposition possibly promoted as renewed hydrothermal fluid flow by polyphasal opening of the host structure. In a model in which an intrusion at depth provides the source for heat and metals, hydrothermal fluids might be considered (Corbett, 2007, 2008) as the three end members (figure 4):

- Magmatic-dominant hydrothermal fluids may rise from intrusion source rocks at considerable depth during irregular yet pronounced opening of the host structure and then deposit Au-Ag bearing sulphides in addition to quartz with saline fluid inclusions. These locally thin bands contain most metals in many veins.
- Some circulating meteoric waters descend to deeper crustal levels and entrain a magmatic component and then rise as magmatic-meteoric hydrothermal fluids

capable of depositing quartz with only moderate salinities along with disseminated sulphides, which contain modest precious metal values.

- Shallow circulating meteoric-dominant waters do not come in contact with the metal-bearing intrusions at depth and so may deposit veins comprising locally well banded but essentially barren quartz (varying from chalcedony to saccharoidal and comb quartz) along with adularia and locally quartz pseudomorphing platy calcite from boiling fluids. These commonly well banded quartz vein portions lack sulphides and Au-Ag mineralisation, but may comprise the majority of some veins. Fluid flow has been promoted by regular shallow opening of the host structure.

Explorationists should be aware that as a consequence, thick veins of well banded epithermal quartz deposited from dominantly circulating meteoric waters may be barren, while thinner sulphide-bearing veins may be well mineralised, and so it is imperative to have a clear understanding of vein mineralogy of the vein being sampled.

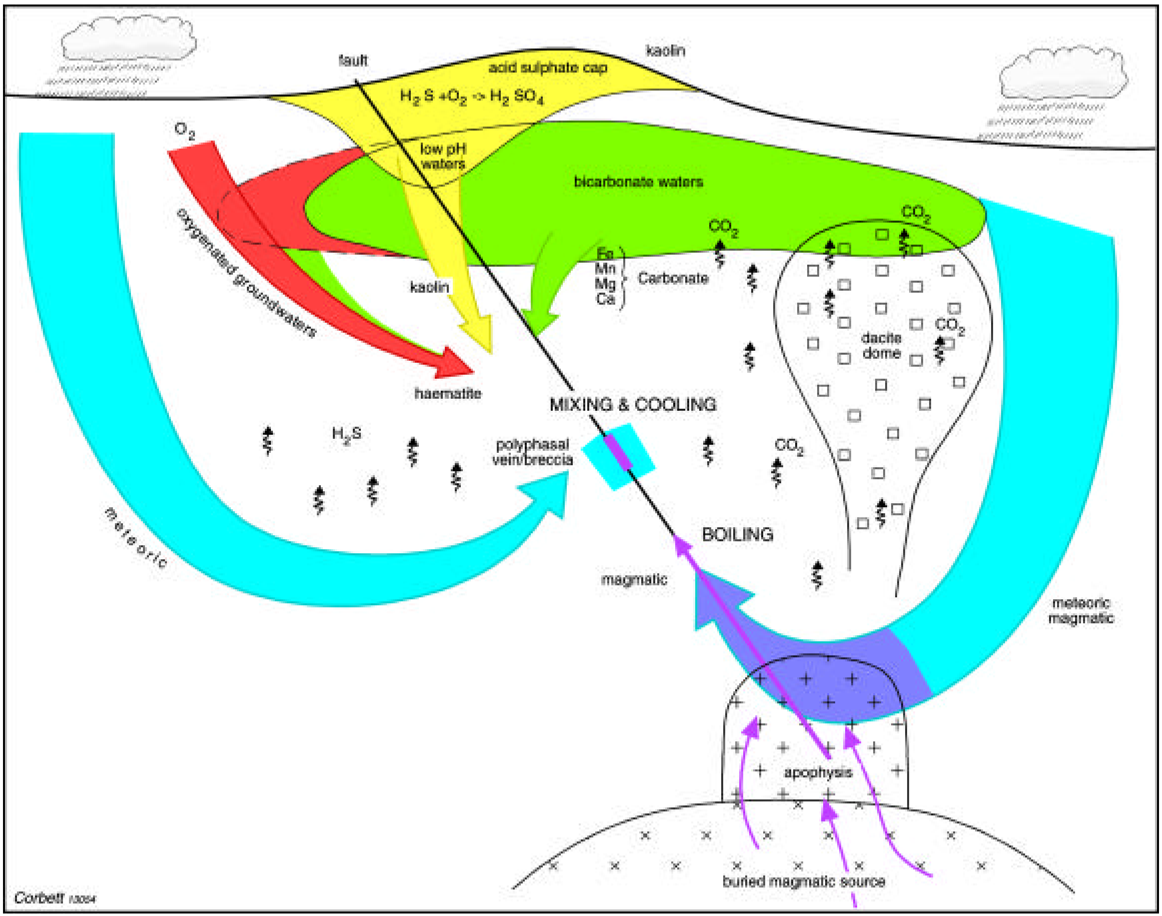

Figure 4. Illustration of the fluid end members involved in the development of banded veins discussed herein, along with evolved waters which contribute towards bonanza Au deposition discussed in Leach and Corbett (2008).

Low sulphidation epithermal Au veins host best mineralisation within ore shoots commonly controlled (Corbett, 2007) by:

- Competent host rocks which fracture well.
- Dilational structures localise fluid flow to provide flat ore shoots in normal and listric as well as compressional faults, or steep ore shoots in strike-slip conditions. Structural intersections may represent sites of fluid mixing and bonanza ore formation.

- Different styles of mineralisation described below display variations in Au and Ag grade as well as metal ratios and metallurgy.
- More efficient mechanisms of Au deposition, typically fluid mixing reactions (figure 4; Leach and Corbett, 2008), provide higher precious metal grades.

There is a progression of linkages in low sulphidation epithermal Au deposit types grading from deep to shallow levels away from the source intrusion (figure 2: Corbett and Leach, 1998; Corbett, 2002, 2004, 2008) as:

- Wall rock porphyry deposits typically comprise sheeted arrays of B style quartz-chalcopyrite veins formed marginal to source intrusions (Cadia Hill, Australia; Maricunga Belt, Chile; Gaby, Ecuador).
- Quartz-sulphide Au ± Cu mineralisation is characterised by veins comprising comb quartz in-filled by auriferous pyrite (Nolan's, Adelong, Australia; Bilimoia, Papua New Guinea; Round Mountain, Sleeper, Nevada; Emperor, Fiji). Deeper level deposits may contain chalcopyrite (Mineral Hill, Australia), specular haematite (Hamata, Papua New Guinea) or pyrrhotite (Porgera, Papua New Guinea; Kelian, Indonesia) and vary to lower temperature marcasite-opal assemblages at elevated crustal settings (Rawas, Indonesia; Chatree, Thailand). Rapid cooling or sulphidation reactions may result in the deposition of fine arsenian auriferous pyrite of questionable metallurgy (Kerimenge, Lihir, Papua New Guinea). Deeper level quartz-sulphide deposits are mined as Cu-Au ores and may be Bi–anomalous (Mineral Hill, Australia; Bilimoia, Papua New Guinea). Many contain bonanza Au grades within an epithermal overprint (Sleeper and Round Mountain, Nevada) and some in this class are Te anomalous (Bilimoia, Papua New Guinea; Emperor, Fiji).
- Reaction of quartz-sulphide Au style magmatic hydrothermal fluids at elevated crustal settings with impure limestone rocks (marls) may give rise to Carlin style (sediment hosted replacement) Au deposits in which most Au occurs in association with arsenian pyrite. These deposits display anatomies categorised by deeper level structural control with higher Au grades and higher level lithological controls with lower Au grades but locally very large ore systems. While Au is very fine and not pannable, Sb, As and Hg provide distinctive geochemical prospecting tools.
- Carbonate-base metal Au mineralisation contains early quartz-sulphide Au overprinted by sphalerite>galena with lesser chalcopyrite and tennantite-tetrahedrite, and late stage carbonate (Porgera, Morobe Goldfield in Papua New Guinea; Mt Muro, Kelian, Cikotok district in Indonesia; Acupan & Antamok in Philippines; Cowal, Australia). These deposits may evolve to contain overprints of low temperature epithermal quartz Au-Ag mineralisation (Porgera, Mt Kare; Papua New Guinea). Au is associated with the sulphide content and metal deposition is promoted by mixing reactions of ore fluids with bicarbonate waters derived from the cooling intrusion (Leach and Corbett, 2008). The Au grade therefore displays a relationship to style of carbonate governed by the acidity of the bicarbonate waters declining as Fe>Mn>Mg>Ca carbonates. Many quartz-sulphide Au deposits display economic Au contents at the transition to carbonate-base metal Au (Kidston, Australia), in the presence of improved mixing mechanisms of Au deposition.
- Polymetallic Ag-Au deposits comprise quartz-sulphide-carbonate banded fissure vein equivalents of the quartz-sulphide and carbonate-base metal Au deposits which are best developed in Central and South America, where they have been mined since Inca times as important Ag ores. Quartz and pyrite of the quartz-sulphide Au ± Cu mineralisation occur early in the paragenetic sequence, as also recognised in carbonate-base metal Au mineralisation, and polymetallic Ag-Au veins evolve to later stage higher crustal level epithermal equivalents characterised by high Ag contents (typically within argentite, freibergite [Ag tetrahedrite] and polybasite) in association with white low temperature sphalerite. Polymetallic Ag-Au veins may pass upwards to low sulphidation epithermal banded chalcedony-ginguro Au-Ag veins in dilational

structural settings where circulating meteoric waters deposit banded chalcedony and possible adularia. Of interest to the explorationist, is these systems display vertical zonation from Cu>Au at depth through to central Zn, Pb with Au-Ag and high grade Ag ≥ Au in the uppermost portions. Best Au-Ag grades occur below essentially barren acid sulphate caps where the mixing of rising ore fluids with low pH waters (Leach and Corbett, 2008) provides a superior mechanism of precious metal deposition (Guadalupe zone, Palmarejo Mexico; Arcata, Peru; San Jose Patagonia). These caps therefore represent favoured sites for exploration in poorly eroded terrains.

- Two end epithermal members developed at highest crustal levels comprise (figure 2):
  - Epithermal quartz Au-Ag mineralisation which contains high Au grade high fineness Au with little gangue and overprints quartz-sulphide Au ± Cu and carbonate-base metal Au mineralisation (Porgera Zone VII, Mt Kare, Edie Ck in Papua New Guinea; Emperor, Tavatu in Fiji; Sleeper, Round Mountain, Nevada). These deposits are preferentially developed within magmatic arcs (figure 1) and commonly contribute towards the development of bonanza Au grades in the systems described above.
  - Chalcedony-ginguro Au-Ag banded epithermal veins (formerly termed adularia-sericite or quartz-adularia) represent the low sulphidation epithermal veins most commonly described from around the Pacific rim in the geological literature. They are characterised by low fineness Au contained within the black sulphidic ginguro portion of banded veins which also contain chalcedony, quartz pseudomorphing platy calcite and adularia gangue (Pajingo-Vera Nancy, Australia; Waihi, New Zealand, Hishikari, Japan; Midas, US). The term ginguro is derived from the 19th century Japanese miners who recognised the elevated Au-Ag grades in these bands comprising fine pyrite, electrum Ag sulphosalts and Au. These deposits develop in strongly dilatant structural settings, commonly in back arc basins and pass downwards of polymetallic Ag-Au veins.

## Lithocaps

Lithocaps are regarded by most explorationists as zones of acid (advanced argillic grading to acidic argillic) alteration which comprise minerals such as silica, alunite, pyrophyllite, diaspore, dickite, with locally abundant pyrite. In most instances lithocaps are considered to develop overlying or adjacent to porphyry intrusions. However, different styles of acid alteration mineral assemblages, which some workers include within lithocaps, develop in many settings (Corbett, 2008) with highly variable relationships to Cu-Au mineralisation and source rocks (figure 5) such as:

- Acid sulphide caps to low sulphidation epithermal Au-Ag vein deposits which may obscure mineralised veins (Guadalupe zone Palmarejo, Mexico).
- As part of the zoned hydrothermal alteration which characterises high sulphidation epithermal Au deposits (Nena, Papua New Guinea; La Coipa, Chile; Pierina Peru), which may also locally collapse upon deeper level pre-existing mineral assemblages.
- Steam heated (cristobalite, powdery alunite, kaolin) alteration developes as blankets overlying high sulphidation epithermal deposits (Pascua-Lama-Veladero, Chile-Argentina).
- Zoned alteration described as barren shoulders (Corbett and Leach, 1998) is formed by the reaction of magmatic volatiles with wall rocks which may display structural or lithological permeability controls to fluid flow and contain high temperature minerals such as andalusite or corundum. Although barren these alteration zones occur in the vicinity of porphyry and epithermal mineralisation and so represent important aspects of the model of overall porphyry anatomy (Lookout Rocks New Zealand; Vuda, Fiji; Bulahdelah, Australia; Horse Ivaal, Papua New Guinea).

- Portions of phyllic alteration involving strongly acidic condensate hydrothermal fluids, commonly form pyrophyllite ± alunite alteration occur as a core to more extensive silica-sericite-pyrite alteration overlying porphyry intrusions (El Salvador, Chile).
- Magmatic solfataras result from the reaction with wall rocks of venting magmatic volatiles (White island, New Zealand).
- Supergene weathering is promoted by the development of strongly acidic ground waters, commonly formed by the oxidation of mainly pyrite and some other sulphides during weathering.

The correct recognition in the field of the nature of acid hydrothermal alteration, which is loosely included within the lithocap alteration style by some workers, and an understanding of its relationship to Au-Cu mineralisation, remains one of the continuing challenges for explorationists.

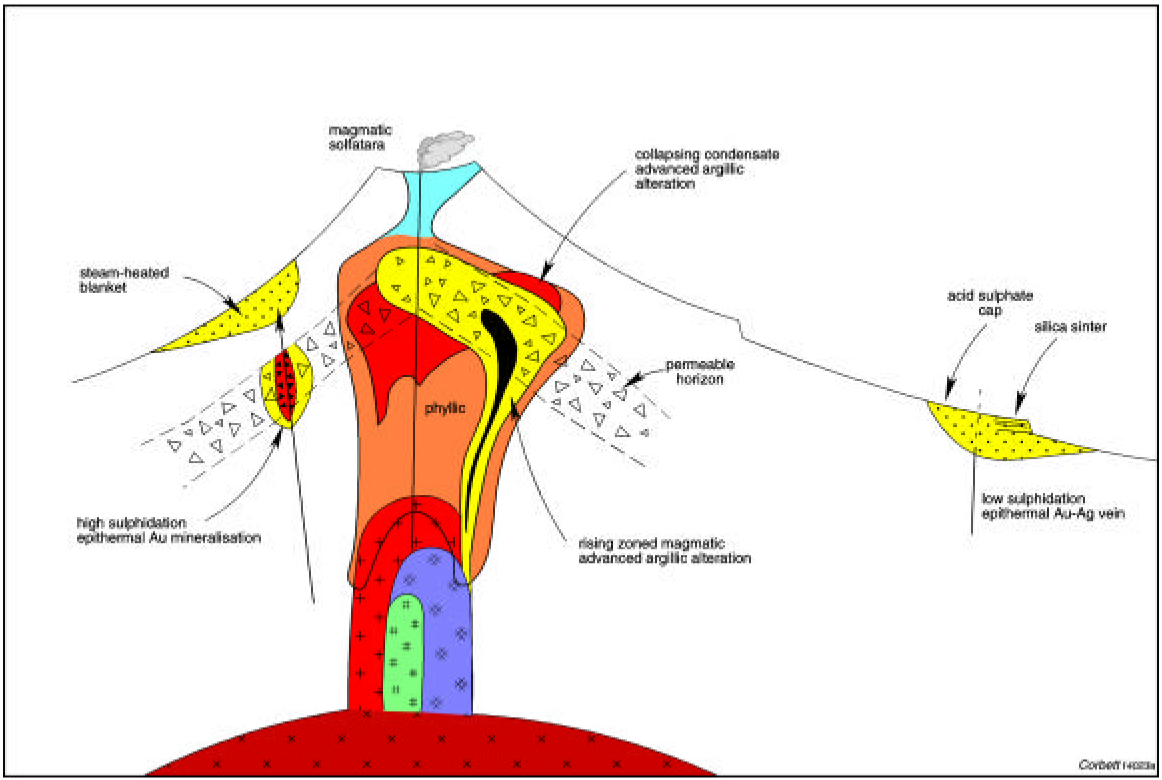

Figure 5. Common settings for the development of acidic alteration.

## Conclusions

After many years study of exploration, mining and magmatic arc geothermal case histories, it is possible to delineate the anatomy of intrusion-related ore systems grading from low metal grade batholitic magmatic source rocks at depth, though porphyry Cu-Au-Mo best developed at the apophyses overlying larger intrusions, and then overlying high and low sulphidation Au, the latter group distinguished as: a linked group of mineralisation styles developed within magmatic arcs and banded veins which dominate in back arc settings. All these deposits display zonation in alteration and metals which may be used by explorationists to target mineralisation.

Geophysical data might be better interpreted with an understanding of the anatomy of porphyry-related ore systems. Magnetic patterns result from the interaction of prograde processes of magnetite deposition and retrograde magnetite destruction. Many chargeability anomalies tested in exploration programs result from pyrite within barren phyllic (silica-sericite-pyrite) alteration and not mineralisation. PIMA and ASD studies might target mineralisation in both high and low sulphidation epithermal systems through the analysis of zoned alteration patterns.

Although high sulphidation epithermal deposits generally display low Au grades and refractory Au metallurgy, many evolve to host marginal and later lower sulphidation mineralogy with higher Au-Ag grades and better metallurgy and so then become more favoured exploration targets.

Explorationsists should understand the anatomy of veins even at hand specimen scale as the metal contents of different veins vary according to fluid source within banded veins as well as controls to mineralisation deposited within ore shoots such as host rock competency, structure, mineralisation style and mechanisms of Au deposition.

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