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Influence of magmatic arc geothermal systems on porphyry-epithermal Au-Cu-Ag exploration models

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Summary

Work that Terry Leach began in the 1970s on the Philippine magmatic arc geothermal systems provides valuable insights into the complex overprinting patterns of alteration and mineralisation recognised in porphyry Cu-Au systems, and the progression to intrusion-related high and low sulphidation epithermal Au-Ag mineralisation. Terry's use of magmatic arc geothermal analogies is most pertinent as much of the existing geological literature on epithermal Au-Ag has been derived from studies of rift environments which are analogous to only a small portion of epithermal low sulphidation epithermal Au deposits.

Many significant porphyry Cu-Au deposits occur as spine-like intrusion apophyses capping deeper magmatic sources for polyphasal emplacement of intrusions carrying metals and volatiles to higher crustal levels. Porphyry deposits can display distinct stages of development of hydrothermal alteration, veins and mineralisation. Initial intrusion emplacement and hornfels formation is followed by prograde alteration as: potassic (Kfeldspar, biotite, magnetite), grading outwards to inner propylitic (actinolite, epidote), and outer propylitic (chlorite, zeolites). Early barren A veins (ptygmatic high temperature quartz) form while the intrusion is cooling, and are overprinted by mineralised M veins (quartz, magnetite with pyrite-bornite) which are associated with potassic alteration. Later B veins (open comb quartz with later pyrite-chalcopyrite) display stronger associations with retrograde phyllic (silica, sericite, pyrite) alteration. Sheeted quartz veins develop in dilatant structural sites and favour wall rock porphyry formation, while laminated veins occur in settings of reactivated dilational structures, and stockwork quartz veins may result from polyphasal porphyry emplacement with potential to host elevated Cu-Au grades.

Advanced argillic grading to marginal argillic alteration, are interpreted to form by several processes and display varying relationships to porphyry and epithermal Cu-Au-Ag mineralisation, and also contribute towards the development of lithocaps, interpreted by some workers as vectors towards buried porphyry mineralisation. Early ascending vapour-dominated magmatic fluids react with wall rocks to form barren advanced argillic alteration. This differs from alteration associated with high sulphidation epithermal Au deposits, which may be capped by steam heated alteration zones. Collapsing cool low pH waters react with wall rocks to higher temperature and more acidic collapsing waters result in the development of retrograde phyllic alteration, which may also contain advanced argillic portions, and grade to marginal argillic alteration.

There is a continuous progression from porphyry Cu-Au, including marginal D veins, to low and high sulphidation epithermal Au-Ag deposits. Low sulphidation Au-Ag mineralisation is deposited from dilute near neutral fluids varying in composition

from meteoric to magmatic dominant. Terry's detailed petrological studies contributed towards a classification which divides low sulphidation deposits into a variety of types formed in magmatic arc or rift settings. High sulphidation epithermal deposits display characteristic zoned advanced argillic alteration which is overprinted by sulphide mineralisation.

Introduction

There are two main end member tectonic settings for geothermal systems discussed in the geological literature as analogues for porphyry-epithermal Cu-Au-Ag mineralisation:

- Rifts typically develop behind the magmatic arcs as regions of crustal thinning where they occur as topographically depressed areas (Henley and Ellis, 1983) and are characterised by permeable commonly felsic, to locally bimodal, volcanic host rocks, which may favour deep circulation of meteoric-dominant waters (Taupo Volcanic Zone, New Zealand; Argentine, Patagonia). Rift environments host low sulphidation epithermal quartz vein deposits commonly without evidence of significant proximal magmatic input and classed as chalcedony-ginguro Au-Ag style low sulphidation epithermal (Corbett, 2007a).
- Magmatic arcs occur as chains of upstanding dominantly andesitic volcanos developed as linear belts above subduction zones (Mitchell and Garson, 1981; Mitchell and Leach, 1991) and favour the development of large magma chambers at depth (Philippines, Andes). Porphyry Cu-Au deposits develop not only below these volcanos, but also within dilational portions of major structures removed from associate volcanism. Porphyry intrusions may display genetic associations with nearby intrusion-related low and high sulphidation epithermal Au-Ag deposits. Styles of low sulphidation epithermal Au-Ag deposits are zoned in styles moving away from magmatic source rocks.

Much of the early research and subsequent geological literature concerning geothermal systems was carried out on the rift related geothermal systems in New Zealand (Weissberg et al., 1976; White, 1967; Ellis and Mahon, 1977; Henley and Ellis, 1983) which are analogues to only a small portion of the low sulphidation epithermal Au deposit group, now classed as the banded chalcedony-ginguro Au-Ag epithermal veins (Corbett and Leach, 1998; Corbett 2005, 2007a). A separate group of low sulphidation epithermal deposits formed within magmatic arcs display stronger associations with intrusion source rocks (figure 1; Corbett and Leach, 1998; Corbett, 2002, 2005, 2007a, 2007b). Note in figure 1 there are two low sulphidation epithermal end members, the chalcedony-ginguro Au-Ag (formerly adularia-sericite) banded quartz veins deposited from meteoric-dominant hydrothermal fluids in rift environments, and the epithermal quartz Au-Ag mineralisation developed as the last stage, lowest temperature end member of the intrusion related magmatic arc mineralisation series most, formed distal to intrusion source rocks (below). Work by Terry Leach in the 1980's on the Philippine geothermal systems (Mitchell and Leach, 1991) provides valuable insights into porphyry Cu-Au and an overlying intrusion-related group of low sulphidation epithermal Au-Ag deposits, which dominate in magmatic arcs (Corbett and Leach, 1998). Prominent in these deposits are the carbonate-base metal Au systems of the SW Pacific rim (Leach and Corbett, 1994), and the related Andean polymetallic Ag-Au veins, which are respectively the dominant epithermal Au and Ag producers in those regions.

Time in Porphyry Cu-Au-Mo deposit models

In the 1970's and 1980's mainly empirical observations contributed to the development of quality geological models for porphyry systems by several workers (Kalamazoo, Lowell and Guilbert, 1970: Philippine porphyries; Sillitoe and Gappe, 1984: El Salvador, Chile; Gustafson and Hunt, 1975). However, only the latter includes a significant analysis of time derived from overprinting alteration, mineralisation, intrusion and breccia events. In fact the SCC (sericite-clay-chlorite) alteration commonly described in porphyry systems (Sillitoe and Gappe, 1984) comprises earlier higher temperature sericite and later lower temperature clay alteration and so represents a composite of two events. One of the key outcomes of Terry Leach's work on the Philippine geothermal systems was his recognition, and inclusion of, a paragenetic sequence in geological models for intrusion-related Cu-Au-Ag mineralisation. In the course of routine geothermal exploration and development in the Philippines geological studies identified porphyry intrusions, as analogues to mineralised systems, during emplacement, followed by progressive degassing and cooling, and exsolution of volatiles which locally condensed and collapsed back into the porphyry environment (Mitchell and Leach, 1991). Terry correlated each of these stages recognised in active magmatic arc geothermal systems with overprinting events of alteration and mineralisation within porphyry Cu-Au and associated high and low sulphidation Cu-Au-Ag epithermal deposits (Corbett and Leach, 1998). This work therefore complemented the earlier studies (Henley and Ellis, 1983 and references therein) on epithermal Au-Ag developed in rift environments (analogous to low sulphidation chalcedony-ginguro Au-Ag epithermal veins) to provide a fuller analysis of porphyry-epithermal ore environments. Throughout the 1990s, the resultant mineral exploration models were presented in short courses (Corbett and Leach, 1998) and progressively enhanced by the application to additional ore systems.

Paragenetic sequences in porphyry-related Au-Cu-Ag deposits

A staged model for the development of porphyry Au-Cu and associated intrusion-related high and low sulphidation epithermal Au-Ag mineralisation includes:

1. Intrusion emplacement

Many porphyry Cu-Au deposits occur in the upper portions (apophyses) of spine-like polyphasal intrusions, which rise to crustal levels of 1-2 km below surface, and overlie much larger more deeply buried magma chambers. Overprinting intrusions are commonly emplaced into the centre of the apophyses from the deeper source. Importantly, in mineralisation models used herein, the deeper magma chamber is interpreted to represent the source for the majority of metals and volatiles, which form porphyry Cu-Au style mineralisation and hydrothermal alteration developed within the cooler overlying spine-like polyphasal intrusion and extending into the adjacent wall rocks. Some of the better porphyry Cu-Au intrusions (Bingham Canyon, U.S.A.), including those with spine like forms (Grasberg, West Papua), do not appear to have associated extrusive volcanism, possibly suggesting metals and volatiles have concentrated within the deeper magma chamber rather than vented with volcanic rocks.

The rapid and forceful emplacement of the hot intrusions results in the development of hornfels mineral assemblages in the adjacent wall rocks by conductive heat transfer

(contact metamorphism). Biotite hornfels may be transitional to cooler hydrothermal potassic alteration and so mark the initiation of prograde alteration described below. Early A veins described in the geological literature (Gustafson and Hunt, 1975) as high temperature, locally massive, ptymatically folded quartz veins, with saline fluid inclusions, form early within cooling intrusions, and so are derived from entirely magmatic material and often dismembered during intrusion emplacement and cooling. As the hydrothermal system has not yet developed, these veins are barren.

The forceful emplacement of spine-like intrusions within overall compressional magmatic arcs may result from the transient changes in the nature of kinematics which facilitate the development of local dilatant sites of intrusion emplacement, commonly associated with major arc parallel or high angle structures (Corbett, 1994; Corbett and Leach, 1998). These dilatant structural settings, evidenced by sheeted quartz veins, concentrate metals by focusing mineralised fluids from larger magmatic source bodies at depth.

2. Heat transfer

Following initial intrusion emplacement, heat radiating from the cooling intrusion apophysis dissipates into the wall rocks by conductive heat transfer, while the deeper magma chamber cools more slowly. Initially, magmatic fluids exsolve from the magmatic source at depth and gather in intrusion apophyses, where they may participate in prograde alteration of intrusions and wall rocks as well as mineralisation processes. The magma heat source at depth drives convective rise of initially magmatic-dominated hydrothermal fluids and so sets up circulating hydrothermal cells which develop as meteoric-dominated waters are drawn to deeper levels, where they may entrain magmatic volatiles to form magmatic-meteoric hydrothermal fluids (figure 9). These convective fluids, initiated at this stage, continue to be active over a protracted period of time (below) as important mechanisms of heat and metal transfer. Depending upon host rock permeability and structure, the composite magmatic-meteoric waters may migrate into the wall rocks and beyond the porphyry environment, as hydrothermal cells circulate to elevated crustal settings. Here these hydrothermal fluids may be responsible for hydrothermal alteration and formation of epithermal Au-Ag deposits. Permeable volcanic host rocks often host broad alteration zones while underlying less permeable and brittle basement rocks might host high Au grade veins (Hishikari, Japan).

3. Prograde hydrothermal alteration

At the porphyry level, intrusion emplacement and initial heat transfer results in the hornfelsing of wall rocks followed by cooling and the development of prograde hydrothermal alteration, which grades outwards from a core of potassic (magnetite, Kfeldspar, biotite), to inner propylitic (actinolite, epidote), and then to more marginal outer propylitic (chlorite, carbonate, zeolite) alteration. These form as essentially concentric cells best developed at the apophysis to the intrusion, and locally distorted by dilational structures (figure 2). Veins described as M veins, comprising quartz, magnetite, bornite, pyrite and lesser chalcopyrite, are intimately associated with potassic alteration and overprint A veins. In addition to pervasive alteration flooding, potassic alteration minerals (biotite, magnetite, Kfeldspar and actinolite) may occur as discrete veins or as selvages to quartz veins. The M veins which may form sheeted (linear parallel or unidirectional), or more random stockwork vein arrays, and are commonly laminated by repeated vein growth. The M veins represent the initial event

of prograde Cu-Au mineralisation intimately associated with potassic alteration and account for a substantial portion of Cu-Au in many porphyry deposits. The magnetite present mainly within potassic alteration and locally also propylitic alteration halos can be detected by aeromagnetic surveys in the exploration for porphyry Cu-Au systems under cover.

4. Cooling and additional vein formation

During progressive cooling of spine-like porphyry intrusions, volatiles are focused from the larger magma sources at depth into the carapace, which is generally constrained within a skin of harder hornfelsed host rocks. Traditional retrograde boiling models describe a volume increase in the cooling intrusion carapace, which cracks when fluid pressure exceeds lithostatic pressure and tensile rock strength resulting in a sudden pressure drop which promotes quartz vein deposition (Phillips, 1973). Alternatively, the overpressured intrusion carapace may be fractured by continued movement on structures which have focused polyphasal intrusion emplacement and migration of volatiles from the magma source at depth into the apophysis. The resulting sheeted (parallel or unidirectional) porphyry-related quartz veins display a strong structural control and may extend considerable distances into the wall rocks (figure 3). The sheeted quartz veins at Cadia Hill display little change over a 700 metre vertical distance within interpreted wall rocks (Newcrest Mining Staff, 1996). Dilational sheeted quartz veins transport as well as host Cu-Au mineralisation from magmatic source rocks at depth into higher crustal level cooler intrusion apophyses and marginal wall rocks.

5. Continued quartz vein development

Random stockwork or sheeted quartz veins with open, centrally terminated comb quartz textures described as B veins as recognised at El Salvador, Chile (Gustafson and Hunt, 1975) and elsewhere, commonly overprint earlier A and M veins. The central terminations in B veins are exploited by later sulphides (pyrite, chalcopyrite and lesser bornite) interpreted to be derived from the cooling intrusion at depth. High temperature molybdenite commonly occurs at or close to the vein margins and B veins, which are often characterised by retrograde alteration (below) halos overprinting prograde alteration. Sulphides which exploit the central terminations may also cross-cut B veins are termed C veins by some workers. Sheeted B veins such as those recognised at Cadia Hill and Dinkidi, Didipio, Philippines, represent important dilatant mediums for the transport of mineralised fluids from higher temperature magmatic source rocks at depth to higher crustal level cooler sites for the deposition of Cu-Au mineralisation where wall rock porphyry deposits form (figure 3). Careful attention should therefore be paid to the orientation of drill testing in porphyry systems where sheeted quartz veins are evident.

6. Multiplicity

The reactivation of the controlling structural elements may result in repeated porphyry emplacement to form the spine-like polyphasal porphyry intrusions and associated overprinting vein systems. Similarly, repeated activation of dilatant structures, which facilitate evolution of ore fluids from the deep magmatic source to higher crustal levels of metal deposition, results in the development of higher metal grade banded or laminated veins. Overprinting sheeted, laminated, stockwork quartz-sulphide or gangue vein arrays may be related to specific events of porphyry emplacement (figure 4). It is important for explorationists to recognise evidence of multiplicity such as

overprinting intrusions, variations in intrusion type, xenoliths and contact of different alteration types as well as overprinting veins, as repeated porphyry and breccia emplacement may result in the formation of elevated metal grades (Ridgeway, Australia; Grasberg West Papua; Oyu Tolgoi, Mongolia). Each event of overprinting porphyry intrusion emplacement may contribute additional quartz veins to the complex stockwork vein array, as well as additional events of Cu-Au mineralisation (figure 4). Later intrusions are often emplaced into the centre of the spine-like form and may continue as post-mineral events which stope out earlier vein mineralisation and so lower the value of any resource (figure 11).

7. Early magmatic advanced argillic alteration

It is imperative explorationists correctly distinguish this barren advanced argillic alteration from alteration with mineralogical similarities associated with mineralisation including: porphyry Cu-Au as intense phyllic alteration, zoned high sulphidation epithermal Au alteration, (mostly Andean) steam heated alteration overlying high sulphidation Au-Ag deposits, or acid sulphate caps which overlie low sulphidation epithermal Au-Ag veins. Early examples of this advanced argillic alteration described in the SW Pacific rim form structurally controlled topographically prominent features in the vicinity of porphyry intrusions (Lookout Rocks, New Zealand; Horse Ivaal, Frieda Copper, and Oro Prospect, Bilimoia, Papua New Guinea; Nash's Hill, Goonumbla, Australia) and were originally termed barren shoulders (Corbett and Leach, 1998), and also represent a component of wider lithocap alteration model (Sillitoe, 1995).

While aspects may arise which remain unresolved, analysis of data from active Philippine magmatic arc geothermal systems (Reyes et al., 1993), facilitates the development of geological models to account for the formation of these alteration zones and their use in exploration for buried porphyry Cu-Au intrusions (Corbett and Leach, 1998). At Alto Peak in the Philippines, geothermal wells penetrated a hot (>400°C), very saline, 1 km wide and 2-3 km deep magmatic vapour-dominated fluid 'chimney' linked to specific quartz diorite dykes (Reyes et al., 1993). These workers document zoned prograde potassic alteration at depth grading upwards to propylitic alteration (biotite-actinolite-epidote) associated with the deeper portions of the chimney, terminating upwards as fracture controlled alteration comprising quartz-alunite-pyrophyllite and diaspore-anhydrite with minor apatite, zunyite and topaz (figure 2.7 in Corbett, and Leach, 1998).

Cooling of vapour-dominated fluids within the chimney results in the development of acidic fluids (Gigginbach, 1992, 1997), which are then progressively neutralised by wall rock reaction to produce distinctively zoned advanced argillic alteration. Massive silica cores to the zoned alteration, which develop by reaction with wall rocks of the more acidic waters, may form linear bodies (termed ledges) where the flow of ascending acidic fluids is governed by (commonly steep and at deeper crustal level) structures, or (commonly flat and at shallower crustal level) permeable volcanic lithologies. These alteration zones may coalesce as large alteration zones as part of lithocaps (figure 5). Zoned advanced argillic alteration resulting from reaction with wall rocks of the progressively neutralised and cooled acidic fluids is characterised by mineral assemblages, grading outwards from the central massive silica core, to marginal alteration progressively dominated by minerals including alunite, pyrophyllite-diaspore, dickite, and outermost kaolinite and possibly more marginal

illite (Corbett and Leach, 1998). The central highly resistive massive silica core is an important characteristic of this alteration style and contributes towards the development of elevated topography. The massive silica here contrasts with distinctive residual vuggy silica formed in the cores of high sulphidation epithermal Au ± Ag alteration zones, by reaction with wall rocks of rapidly ascending extremely acidic fluids developed from more evolved magmatic fluids at higher crustal level cooler (epithermal) settings (below). Marginal neutral (illite) alteration develops after complete neutralisation of the acidic fluid. Alteration zones need not display the complete zonation described above. Those formed from less acidic fluids may lack silica cores, and so occur as alunite-pyrophyllite-dickite or pyrophyllite-kaolin alteration zones. The aerial extent of alteration zones may depend upon the plumbing system for hydrothermal fluids. At near porphyry settings structurally controlled systems tend to be smaller than those developed in permeable wall rocks over large areas, typically at higher crustal levels. At Thames, New Zealand, adjacent structurally (Lookout Rocks) and lithologically (Roadshow) controlled alteration systems may be related to the same magmatic source as the nearby Ohio Creek porphyry Cu-Au system (Corbett and Leach, 1998). Intrusion-related magmatic hydrothermal or phreatomagmatic breccias are generally not recognised.

Some features which aid in the identification of the barren shoulder advanced argillic alteration zones include:

- Halogen-bearing minerals zunyite and topaz, not common in other styles of advanced argillic alteration (above), develop from the vapour dominant fluid.
- There appears to be a greater degree of pyrite flooding than other alteration styles, which often oxidises to provide extensive FeO including leiser gang rings. Arsenic anomalies are probably associated with pyrite.
- As these alteration zones are developed at hot near porphyry levels, many alteration minerals (alunite, topaz, diaspore, pyrophyllite) display coarse grained fabrics not present in other styles of advanced argillic alteration.
- Ledges of massive silica rimmed by alunite-pyrophyllite are a common form of these alteration zones.

Explorationists should be aware barren shoulders are common in the vicinity of anomalous Au, including pannable Au, derived from associated porphyry and epithermal sources with only indirect relations to this advanced argillic alteration which is NOT an exploration target in itself, but aids in vectoring towards mineralisation ONCE the entire system is understood (Bilimoia & Frieda, Papua New Guinea; Vuda, Fiji, Lookout Rocks, New Zealand; Bulahdelah, Australia).

Several factors may contribute towards the lack of Au-Cu-Mo mineralisation within the barren shoulder advanced argillic alteration. The vapour from which the acid fluids have been derived does not transport metals, and appears to have vented the porphyry before much of the metal component has focused in the intrusion apophysis. There is a possibility of Hg transport by the vapour fluid and this alteration is As anomalous. High sulphidation epithermal Au ± Ag-Cu deposits are interpreted to evolve from intrusion source rocks later once the liquid metal-bearing fluid phase has concentrated in the upper portion of the cooling magma chamber.

8. Retrograde alteration

Volatiles, in particular H₂S and SO₂, of magmatic origin from the degassing of cooling intrusions (with disseminated sulphides), as well as veins, condense in the reservoir rocks to form hot acid hydrothermal fluids which react with the wall rocks to produce: initially phyllic (silica, sericite, pyrite, chlorite, carbonate) alteration, grading to marginal argillic (kaolin, chlorite, pyrite) alteration as the hot acidic fluids are progressively cooled and neutralised by wall rock reaction. Therefore argillic alteration overprints and occurs marginal to phyllic alteration. On the scale of entire hydrothermal systems with sufficient permeability, acid waters developed in the upper portions may collapse upon the intrusions due to drawdown as the intrusion apophysis cools (figure 6). At a local scale, retrograde alteration forms within faults, fractures and crackle breccias and at vein margins where it overprints and downgrades prograde alteration. The replacement of magnetite by non-magnetic haematite reduces the magnetic intensity discernible on aeromagnetic images. Consequently, the aeromagnetic signatures of prograde and variably retrograde altered porphyry Cu-Au systems vary widely and geological knowledge is required in order to correctly evaluate of geophysical data. The high levels of disseminated pyrite in phyllic-argillic alteration are easily detected as chargeability anomalies in induced polarisation geophysical surveys. Drawdown of hot acid condensate waters along the fractured margins of porphyry systems where they may overprint the lateral transition from potassic to propylitic alteration, contributes towards the development of alteration zonation patterns originally described by Lowell and Guilbert (1970), as the progressive transition outwards from potassic, to (overprinting) phyllic, and more marginal propylitic alteration (figure 6). This alteration zonation is now more easily understood with the aid of a paragenetic sequence for overprinting alteration (Corbett and Leach, 1998). Of interest to explorationists is that contact of rising ore-bearing hydrothermal fluids with the acidic condensate waters promotes mineral deposition, typically within B veins or breccias developed at that stage, in part providing a correlation between phyllic alteration and Cu-Au mineralisation.

CO₂ rich volatiles which also exsolve from cooling intrusions condense to form blankets of bicarbonate waters recognised in the upper portions of geothermal systems (Henley and Ellis, 1983; Corbett and Leach, 1998; figure 10). Reaction of these weakly acidic waters with rising ore fluids promotes Au deposition to form carbonate-base metal Au deposits (below; Leach and Corbett, 1994).

As recognised in some geothermal systems (Corbett and Leach, 1998) and ore deposits (Gustafson and Hunt, 1975), the development of extremely acidic condensate waters in the upper portions of intrusion-related hydrothermal systems react with wall rocks to produce advanced argillic alteration characterised by minerals such as alunite, pyrophyllite, and diaspore, grading to marginal and deeper level phyllic (silica-sericite-pyrite) alteration and more marginal lower temperature acid argillic (kaolin-pyrite), grading laterally to neutral argillic (illite-smectite) alteration (figure 7). This alteration zonation results from the progressive cooling and neutralisation of the hot acid fluids by wall rock reaction. At El Salvador Gustafson and Hunt (1975) recognised advanced argillic (pyrophyllite-diaspore) overprinting phyllic (sericite) alteration. A similar pattern has been recognised at the Bacon-Manito geothermal system in the Philippines (figure 2.14 in Corbett and Leach, 1998) where advanced argillic alteration (alunite ± diaspore/pyrophyllite) grades laterally to argillic alteration (kaolinite, illite/smectite) and overprints phyllic-argillic alteration (sericite-illite/smectite) overlying a porphyry intrusion. The zonation of upper advanced

argillic alteration and lower level phyllic and argillic alteration is different to the alteration resulting from reaction with wall rocks of the rising magmatic volatiles described earlier (figure 5). These two styles of advanced argillic alteration can both occur in large porphyry-related alteration systems (figures 8 & 11), and are grouped together in the lithocap model of Sillitoe (1995).

9. Porphyry Cu-Au to Epithermal low sulphidation Au-Ag transition

The deeper level magma chamber cools more slowly than the intrusion apophysis and collapsing thermal gradients result in the local drawdown of cooler acidic surficial waters. These fluids facilitate retrograde alteration as an overprint upon prograde earlier formed higher temperature mineral assemblages. Although the upper portion of the porphyry environment has cooled during the development of porphyry Cu-Au mineralisation, the deeper level major heat source still has the capacity to drive circulating cells of hydrothermal fluids, which can result in the formation of later low sulphidation epithermal vein systems at shallow crustal levels. In suitable conditions, ore fluids, which continue to exsolve from this deep cooling major magmatic source, may become entrainment and diluted within circulating cells of ground waters and ascend through the cooling fractured (commonly spine-like) intrusion apophysis, as meteoric-magmatic waters, to form intrusion-related low sulphidation epithermal Au-Ag mineralisation within the wall rocks.

Consequently, three low sulphidation epithermal hydrothermal fluid end member types, which are interpreted to develop above and adjacent to the porphyry environment (Corbett, 2007a), driven by the magma chamber heat source at depth, include (figure 9):

- Shallow supra-porphyry circulating meteoric water-dominant systems, which have not come in contact with intrusion sources for metals, may deposit barren quartz vein portions,
- Deeper circulating meteoric water systems may entrain a magmatic component (metals and volatiles) to form mixed meteoric-magmatic hydrothermal fluids which may deposit low grade Au-Ag bearing quartz-sulphide vein/breccias while,
- Magmatic water-dominant systems can deposit higher grade Au-Ag quartz-sulphide mineralisation.

Investigations of Philippine geothermal systems identified those with dilute near neutral mineralised hydrothermal fluids which are probable analogues to intrusion-related low sulphidation epithermal Au-Ag mineralisation at a higher crustal levels than porphyry Cu-Au mineralisation (Mitchell and Leach, 1991; Corbett and Leach, 1998). Careful petrological work by Terry Leach (Leach and Corbett, 1995; Corbett and Leach, 1998) demonstrated the paragenetic relationships of earlier and typically deeper level, low sulphidation epithermal Au-Ag mineralisation styles overprinted by later, higher level mineralisation styles (figures 1 & 10) as:

9.1, *Quartz-sulphide Au ± Cu*

Close to the porphyry environment Cu-Au bearing quartz-sulphide veins, formed late in the porphyry paragenetic sequence and originally termed D veins by Gustafson and Hunt (1975), have more recently become important Au ores included within the low sulphidation quartz-sulphide Au ± Cu style of mineralisation (figures 1 & 10; Nolans, Adelong, Charters Towers district, Jacks Hut Lode at Mineral Hill, Australia). D veins

overprint pebble dykes (El Salvador, Chile, Gustafson and Hunt, 1975; Bilimoia, Papua New Guinea, Corbett et al., 1994; Corbett and Leach, 1998) as well as A, M and B style porphyry veins and may be difficult to distinguish from C veins. D veins are commonly thick and banded with a variety of sulphide styles and are characterised by extensive halos of silica-sericite-pyrite (phyllic) alteration. While low sulphidation D veins are dominated by pyrite and chalcopyrite with lesser galena, sphalerite and bornite, a high sulphidation equivalent is describe below (Section 10). Quartz-sulphide Au \pm Cu veins deposited from a slow cooling fluid typically comprise quartz and Au within coarse pyrite-chalcopyrite, and are commonly anomalous in Bi. Similar to D veins quartz-sulphide Au \pm Cu mineralisation may locally grade to become Pb-Zn-Ag rich (Parkers and Iodide lodes at Mineral Hill, Conrad, New England, NSW) in more distal settings to the source intrusion (Leach and Corbett, 1995; Corbett and Leach, 1998) evolve to form polymetallic Ag-Au and carbonate-base metal Au style mineralisation.

Quartz-sulphide mineralising fluids may become rapidly quenched at elevated crustal settings, and so deposit auriferous arsenian pyrite with anomalous Ba, Sb and Hg (Ladolam at Lihir Is., Papua New Guinea). Reaction of quartz-sulphide Au fluid with reactive impure limestone at elevated crustal settings results in the development of sediment hosted replacement Au or Carlin-style Au deposits (Leach, 2004). Both these groups of quenched quartz-sulphide ores deposited from quenched hydrothermal fluids, commonly display difficult Au recoveries to standard leach treatment where Au is encapsulated within arsenian pyrite.

Exploration implications of the coarse grained quartz-sulphide Au \pm Cu mineralisation style (Corbett, 2004) include the good metallurgy which allows these commonly low grade ores to be worked by heap leach operations (Round Mountain and Sleeper, Nevada; San Cristobal, Chile), although explorationists are cautioned that quartz-sulphide veins are notorious for near surficial supergene Au enrichment.

9.2. Carbonate-base metal Au

Magmatic fluids with metals and volatiles exsolve from intrusions at depth and progressively migrate further into the overlying wall rocks, commonly via dilational structures and become entrained in convective cells of circulating meteoric-dominant waters to form meteoric-magmatic ore fluids (figures 1 & 10). The blankets of bicarbonate waters developed by condensation of magmatic CO₂ are weakly acidic and mix with rising ore fluids to oxidise and destabilise complexes carrying Au, and so as a more efficient mechanism of Au deposition, provide elevated Au grades. The resulting intrusion-related low sulphidation epithermal mineralisation termed carbonate-base metal Au (Leach and Corbett, 1994; Corbett and Leach, 1998), are some of the most prolific Au producers in the SW Pacific (Cowel, Australia; Porgera & Misima, Papua New Guinea; Kelian & Mt Muro, Indonesia; Acupan & Antamok, Philippines) and are recognised in other magmatic arcs (Rosa Montana, Romania; Cripple Creek & Montana Tunnels, US). Carbonate-base metal Au mineralisation generally features initial quartz-sulphide Au \pm Cu style quartz-pyrite deposition followed by sphalerite greater than galena, and later carbonate and may evolve further to the epithermal quartz Au-Ag style (below), as part of the continuum of intrusion-related low sulphidation epithermal mineralisation styles (Corbett and Leach, 1998).

Variation in acidity of the bicarbonate waters influences Au grade and carbonate type. Highest Au with Fe carbonate (siderite) are deposited by mixing of ore fluids with more acid bicarbonate waters, progressively declining through Mn (rhodochrosite), mixed MnMgFe (kuthahorite & ankerite), to CaMg (dolomite), and finally Ca (calcite) carbonate, the latter with low Au deposited by mixing ore fluids with near neutral waters. Sphalerite colour changes with Fe:Zn ratios, governed by temperature, from: white-yellow, low temperature Zn>Fe sphalerite, deposited at low temperature elevated crustal settings, through brown and red, to black, Fe>Zn sphalerite, deposited at deeper crustal level higher temperature conditions. The low temperature end member of the carbonate-base metal Au series characterised by yellow Fe-poor sphalerite has recently been termed intermediate sulphidation (Sillitoe and Hedenquist, 2003). However, the original Leach and Corbett (1994) carbonate-base metal Au terminology is preferred here to encompass the wider deposit style within the continuum of intrusion related low sulphidation mineralisation.

Carbonate-base metal Au deposits are characterised by higher Au grades than the early quartz-sulphide Au ± Cu, with higher Ag:Au ratios, and may display extremely irregular Au distribution if overprinting bonanza epithermal quartz Au-Ag mineralisation is present (Corbett and Leach, 1998; Corbett, 2004).

9.3. *Low sulphidation polymetallic Ag-Au*

Low sulphidation polymetallic Ag-Au veins occur as the Andean Ag-rich equivalents of the SW Pacific rim carbonate-base metal Au deposits (figures 1 & 10). They have been major Ag sources in Mexico and Peru and are emerging as important Au-Ag producers in new terrains (El Penon, Chile; Argentine Patagonia), while others are recognised in older SW Pacific rim terrains (Hadleigh Castle & Mungana, Queensland; Conrad, NSW). These deposits vary to Sn veins marginal to granitic intrusions (Cornwall, England) and locally display associations with early advanced argillic alteration (Cerro Potosi, Bolivia). Of interest to explorationists, these veins which have been rejected by major mining companies for many years as too small, can now represent company makers for many junior explorers (Palmarajo & Fresnillo, Mexico; Arcata & Corani, Peru; San Cristobal, Bolivia; El Penon, Chile; Cerro Negro, San Jose (Huevos Verde) & Cerro Moro, Argentine Patagonia). Banded veins (figure 9) comprise barren quartz which may be deposited from meteoric-dominated waters, in combination with sulphides, deposited from magmatic-rich fluids and including, pyrite, galena, sphalerite, chalcopyrite and Ag sulphosalts (including Ag rich tetrahedrite, freibergite) along with carbonate, derived from blankets of bicarbonate waters, and display highly varied controls to Ag mineralisation (Corbett, 2007a).

The intrusion-related low sulphidation carbonate-base metal Au and polymetallic Au-Ag deposits are clearly related, although the former Au-rich style dominates in the SW Pacific rim within magmatic arcs underlain by oceanic crust, and the latter Ag-rich style dominates in settings of continental crust, typically central and South America. Whereas polymetallic Au-Ag deposits occur almost exclusively as fissure veins, many carbonate-base metal Au deposits are also hosted by phreatomagmatic and other breccias and fracture networks.

9.4. *Two low sulphidation epithermal Au-Ag end members*

There are two highest crustal level low sulphidation epithermal Au-Ag end members; epithermal quartz Au-Ag and chalcedony-ginguro epithermal Au-Ag veins, which are

distinguished by mineralogy and Ag:Cu ratio, and display different relationships to magmatic source rocks.

9.4a. *Epithermal quartz Au-Ag*

Epithermal quartz Au-Ag mineralisation commonly overprints quartz-sulphide Au \pm Cu and carbonate-base metal Au mineralisation as the lowest temperature highest crustal level end member of the intrusion-related low sulphidation epithermal Au-Ag mineralisation series (figures 1 & 10), in which efficient mechanisms of Au deposition provide elevated Au grades (Leach and Corbett, 2008; Corbett, 2007a). This mineralisation commonly contains very little quartz gangue and so may be difficult to recognise overprinting quartz-sulphide Au \pm Cu and carbonate-base metal Au, which then display irregular Au distribution. Gold is typically of a high fineness as these deposits contain very little Ag. Many quartz-sulphide and carbonate-base metal Au deposits are therefore noted for later stage structurally controlled bonanza Au (Round Mountain & Sleeper in Nevada; Porgera, Edie Creek, Woodlark Is., Mt Kare in Papua New Guinea; Emperor & Tavatu in Fiji). Explorationists must exercise extreme caution in processing drill core and resource calculations in these bonanza deposits (Corbett, 2004).

9.4b. *Chalcedony-ginguro epithermal Au-Ag veins*

Chalcedony-ginguro Au-Ag epithermal veins typically comprise banded chalcedony, adularia, quartz pseudomorphing platy calcite and black sulphidic ginguro bands named by the nineteenth Japanese miners. The chalcedony-ginguro terminology is now regarded as more accurately descriptive than earlier terms such as adularia-sericite or quartz-adularia used for these veins (Corbett and Leach, 1998; Corbett, 2004, 2005, 2007a, 2007b). The adularia and quartz pseudomorphing platy calcite deposited from boiling mainly meteoric waters are generally barren and some Au may occur within banded quartz which contains fine sulphides. Mineralisation is commonly Ag rich and occurs within the ginguro black sulphidic bands or breccia in fill comprising fine pyrite, minor chalcopyrite, Ag sulphosalts, electrum and gold. Minor opening of dilatant structures may focus shallow circulating barren meteoric-dominated waters into veins which deposit chalcedony, whereas major openings of the same structures focus the ginguro-bearing mineralised magmatic fluids from distal intrusion source rocks at much greater depth (figure 9). Most bonanza Au is interpreted to have been deposited by fluid mixing reactions (Leach and Corbett, 2008; Corbett, 2007a). These deposits dominate in rift environments and generally do not show strong associations with intrusion source rocks and so are correlated with the geothermal systems on the Taupo Volcanic Zone, New Zealand, which were the subject of much early research into epithermal deposits (Henley and Ellis, 1983 and references therein).

Acid sulphate alteration

Acid sulphate alteration characterised by kaolin, cristobalite with minor alunite and sulphur forms by the interaction with country rocks of warm acidic ground waters typically developed above the water table by the oxidation of volatiles (H_2S). These alteration zones commonly cap feeder structures for low sulphidation epithermal mineralisation and the low pH waters may collapse to quite deep levels within epithermal ore environments (figures 1 & 10). Mixing of the low pH waters with ore fluids promotes elevated Au deposition (Corbett, 2007a; Leach and Corbett, 2008).

10. Porphyry Cu-Au - high sulphidation Au epithermal transition

In some instances D veins, (in the terminology of Gustafson and Hunt, 1975) formed marginal to porphyry intrusions, contain enargite (including the low temperature polymorph luzonite)-pyrite-alunite-barite mineral assemblages, typical of the root zones of high sulphidation epithermal Au deposits (La Coipa, Chile; Pierina, Peru), and may overprint earlier porphyry alteration and mineralisation (Yanococha district, Peru). Elsewhere, typically further from the source intrusion, enargite gives way to slightly lower (moderate) sulphidation minerals (tennantite-tetrahedrite) as the acidic fluids are cooled and neutralised by rock reaction (Viento vein system, El Indio, Chile) and more distal low sulphidation Au (Wafi, Papua New Guinea; Leach, 1999).

High sulphidation epithermal Cu-Au-Ag deposits develop in settings where volatiles and metal bearing fluids vent from magma sources at considerable depth (figures 1 & 10) and travel rapidly to elevated crustal settings, without reaction with wall rocks, or mixing with ground waters. During the rapid ascent, the volatile component becomes progressively depressurised and SO₂ in particular comes out of solution and in turn oxidises to form H₂SO₄, such that the rising and cooling fluid becomes increasingly acidic (to pH of 1-2) as it ascends to epithermal levels, where it reacts with wall rocks to produce advanced argillic alteration (Corbett and Leach, 1998). Because the progressive cooling and neutralisation of the hot acid fluid by wall rock reaction, the advanced argillic alteration is zoned outwards from a central core of vuggy or residual silica, from which everything apart from silica (and some rutile) has been leached by the strongly acidic waters, through alteration zones dominated by alunite, pyrophyllite, dickite, kaolin and then illite, as the acidic waters are progressively cooled and neutralised by reaction with the wall rocks. The shape and intensity of alteration vary according to crustal level and permeability of the host rocks. The liquid rich phase of the high sulphidation hydrothermal fluid generally follows the volatile rich portion, and so sulphides (enargite, luzonite, pyrite and locally covellite) with additional alunite and barite gangue overprint the earlier alteration.

Mineralisation most commonly occurs as sulphide breccia infill of competent vuggy silica and silica-alunite altered clasts. Permeability for the development of high sulphidation epithermal alteration and mineralisation (figure 1) is controlled by variations in dilational structures (El Indio, Chile), host rock permeability which is commonly provided by fiamme-bearing ignimbrites (Pierina, Peru; La Coipa, Chile), or breccias, most typically phreatomagmatic breccias, as many high sulphidation systems are associated with diatreme-flow dome complexes (Yanococha & La Virgin, Peru; Pascua, Chile; Lama & Veladero Argentina; Wafi, Papua New Guinea; Lepanto, Philippines). Many ore systems are localised at the intersection of feeder structures and permeable host rocks (Sipan, Peru; Nena & Maragorik, Papua New Guinea), which commonly develop sub horizontal pencil-like ore shoots at these intersections. While SW Pacific rim high sulphidation systems are generally Ag-poor compared to the locally Ag-rich Andean equivalents, most display variations from Cu-rich at depth to higher level Au-rich, and Te and Sb occur at very highest crustal levels within minerals such as goldfieldite (Corbett and Leach, 1998; Nena, Papua New Guinea; Goldfield, Nevada).

Explorationists should be aware that mining has commonly ceased at the transition from oxide to sulphide ores (Gidginbung & Peak Hill Australia; Sipan, Peru) as many high sulphidation systems display difficult sulphide metallurgy and these ores are commonly roasted to liberate Au (El Indio, Chile). Higher Au grades and improved

metallurgy are commonly associated with transitions to lower sulphidation at the margins of high sulphidation systems, or telescoped upon them (Wafi, Papua New Guinea; Leach, 1999; El Indio, Chile; Quimsacocha, Ecuador).

Steam heated alteration develops as locally laterally extensive blankets characterised by cristobalite, powdery alunite, kaolin and sulphur formed by reaction with wall rocks of acidic waters which result from the oxidation of volatiles (SO₂), typically above the water table (figure 10). These barren advanced argillic alteration zones overlie many high sulphidation deposits (Pascua & La Coipa, Chile; Veladero, Argentina; Pierina, Peru; Quimsacocha, Ecuador) where they may obscure blind mineralisation (Quimsacocha). Mixing of ore fluids with these intensely these near surficial oxidising, waters which locally collapse onto the high sulphidation mineralisation, may promote elevated Au deposition characterised by hypogene oxidation of the original sulphide mineral assemblages to form covellite (Pierina, Peru) or hypogene jarosite (Veladero, Argentina).

11. Composite acid alteration

Acidic hydrothermal alteration (advanced argillic, acid argillic) and marginal neutral argillic alteration vary according to the temperature and pH of the acid waters, which react with wall rocks (figure 11). Advanced argillic alteration derived from high temperature acid waters contains minerals such as alunite, pyrophyllite, diaspore, and grades to more marginal acid argillic (sericite, dickite, kaolin) and then neutral argillic alteration (illite, smectite). Several styles of acid alteration derived from the reaction of acid waters with wall rocks discussed herein include:

1. Advanced argillic derived from interaction with country rocks of rising magmatic volatiles, described in section 7 herein, and may vector downward to porphyry intrusions,
2. Advanced argillic derived from collapsing very acidic condensate waters described in section 8 herein, is rootless,
3. Phyllic alteration formed marginal to advanced argillic alteration and derived from interaction with country rocks of moderately acid condensate waters. described in section 8 herein,
4. Zoned advanced argillic - acid argillic – neutral argillic alteration developed within mineralised high sulphidation epithermal Au-Cu-Ag deposits, described in section 10 herein,
5. Blankets of barren advanced argillic steam heated alteration developed overlying mineralised high sulphidation epithermal deposits, described in section 10 herein,
6. Acid sulphate caps formed overlying low sulphidation deposits are dominated by argillic alteration, but may contain alunite as portions of advanced argillic alteration described in section 9 herein,
7. Magmatic solfataras which form at the surface in volcanic edifices, and are locally mined for sulphur, display marginal advanced argillic - argillic alteration.

These styles of alteration display marked differences in relationship to mineralisation. For instance, some advanced argillic alteration (4 above) is intimately associated with high sulphidation epithermal Au mineralisation, while the porphyry styles (1 and 2) are barren but may overlie porphyry systems, and acid sulphate (6 above) or steam heated (5 above) alteration are each barren, but overlie high and low sulphidation

mineralisation, respectively. Analysis of acid sulphate alteration may provide an important exploration tool in the search for high Au grade low sulphidation epithermal Au veins (Leach and Corbett, 2008; Corbett, 2007a). These alteration styles may coalesce to form mixed alteration zones (figures 8 & 11) such as within lithocaps (Sillitoe, 1995). Correct analysis of these alteration zones and recognition of their relationship to Au-Cu-Ag mineralisation is vital in the efficient management of porphyry-epithermal exploration programs.

9. Post-mineral effects

Intrusion activity may continue during and following the development of porphyry systems and may be related to overprinting epithermal mineralisation. Of interest to explorationists is that later stage intrusions (Bajo de la Alumbrera) and phreatomagmatic breccias (El Teniente, Chile) may stope out ore and seriously downgrade the economics of porphyry Cu-Au systems (figure 12). Explorations must take care to identify these intrusions during resource estimations. Many post-porphyry Cu-Au phreatomagmatic breccias emplaced at higher crustal levels by renewed magmatism, commonly during rapid uplift and erosion, are sources of significant high sulphidation Au-Ag and carbonate-base metal Au low sulphidation epithermal mineralisation, and so represent attractive exploration targets (figure 1).

Conclusion

Whereas the rift-related geothermal systems are analogous to a small group of low sulphidation epithermal Au-Ag deposits (chalcedony-ginguro epithermal Au-Ag veins), analyses of magmatic arc geothermal systems by Terry Leach has aided in the understanding of the overprinting alteration and mineralisation events during the progressive evolution from porphyry Cu-Au to low and high sulphidation epithermal Au deposits. Different styles of advanced argillic alteration display varying relationships to mineralisation but may coalesce. Correct interpretation of these varying alteration styles aids porphyry-epithermal mineral exploration.

Like all Leach and Corbett science, the geological models presented herein have been developed, tested and progressively modified using empirical observations (including petrology and XRD/PIMA/ASD clay analyses) during the application to many mineral exploration and mining projects. These models are continuing to evolve and potential remains for researchers to apply techniques such as isotopes or theoretical considerations (thermodynamics) to the continued development of geological models which aid mineral exploration.

Acknowledgements

This work represents continued development of geological models which Terry Leach and this author presenting short courses during the 1990's, and so Terry has made an essential contribution. Ian Plimer and the late David Semple initiated the first short courses. I thank the many colleagues who generously shared their ideas and time in the pursuit of science in mineral exploration. I hope Terry and other colleagues who are no longer with us, will be fondly remembered. Mike Smith and Ray Merchant commented on this manuscript, Denese Oates proofread the text and drafted the figures and Peter Lewis prepared it for publication.

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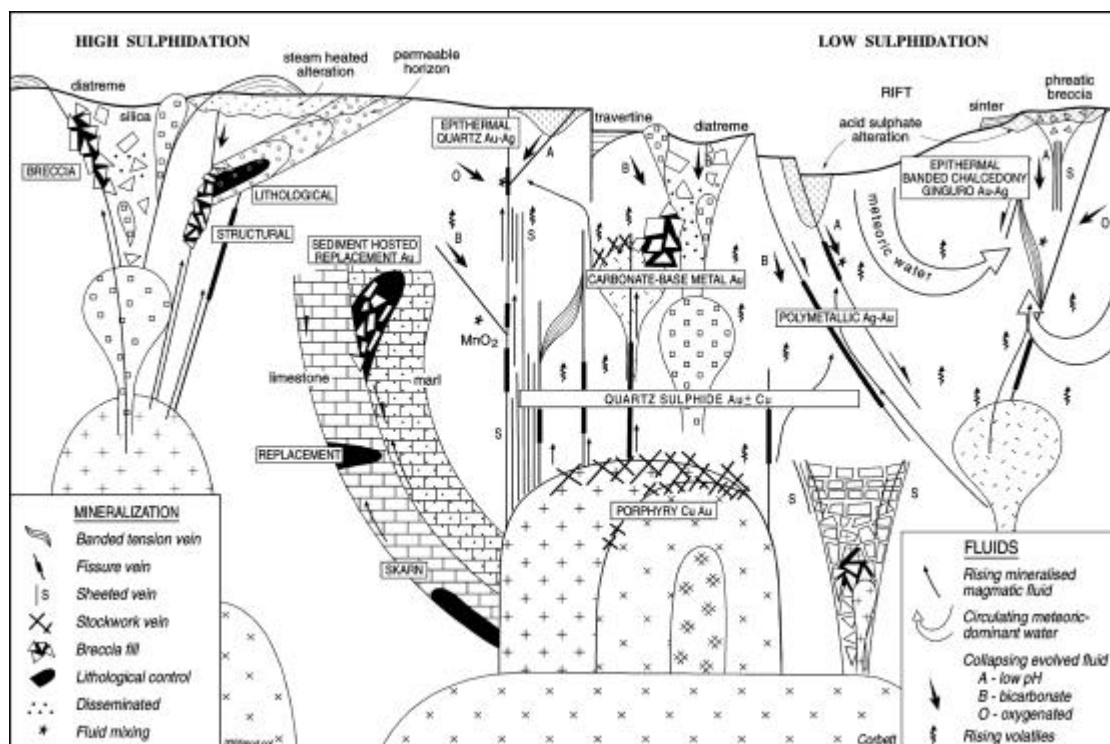


Figure 1. Conceptual model for styles of porphyry and epithermal Cu-Au-Ag mineralisation developed in magmatic arcs showing porphyry Cu-Au mineralisation developed at the apophysis to a spine-like polyphasal intrusion cap to a larger magmatic source at depth, and two groupings of low sulphidation deposits as the intrusion-related group developed within magmatic arcs (comprising quartz-sulphide Au \pm Cu, carbonate-base metal Au and epithermal quartz Au-Ag mineralisation), dominant in magmatic arcs, and another style (epithermal banded chalcidony-tinguro Au-Ag) formed in rift environments further from intrusive source rocks for metals. High sulphidation epithermal Au-Ag mineralisation also displays a relationship to buried intrusive source rocks (adapted from Corbett, 2004 and 2007b).

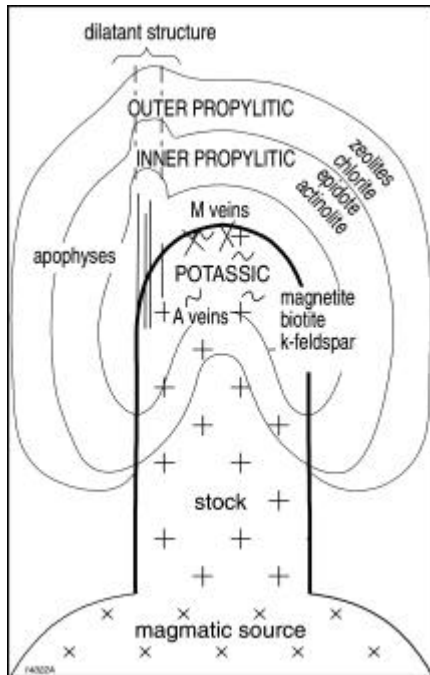


Figure 2. Conceptual model for zoned prograde alteration developed at the apophysis to a spine like intrusion cap to a larger magmatic source at depth. Note the influence of structures on the shape of the alteration zones and A quartz vein along with sheeted and stockwork M veins.

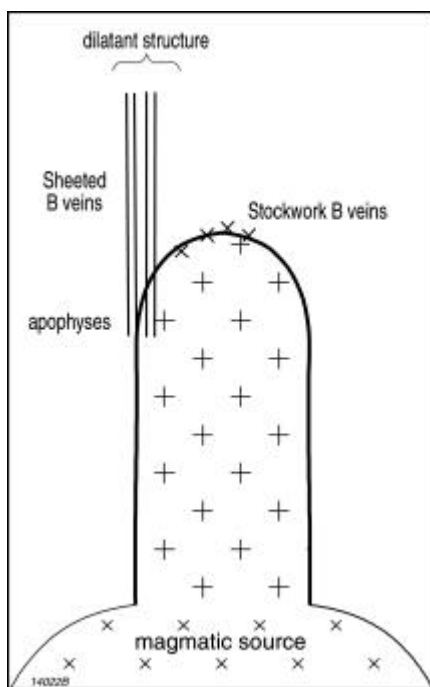


Figure 3. Sheeted and stockwork B veins developed at an intrusion carapace.

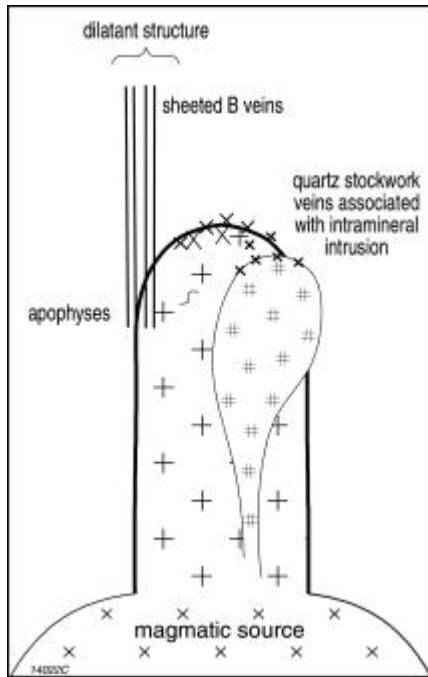


Figure 4. Overprinting of earlier A and M veins by polyphasal B veins related to two intrusion events.

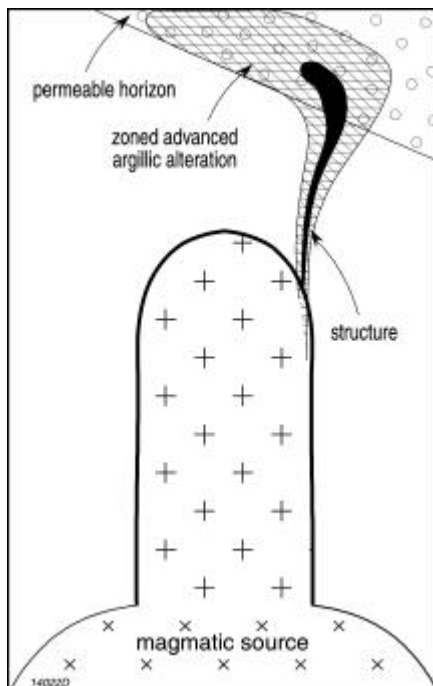


Figure 5. Advanced argillic alteration formed from the exsolution and acidification of magmatic volatiles is developed as deeper level structurally controlled zones likened to the barren shoulders of Corbett and Leach (1998) and at higher levels exploit permeable horizons to form larger blankets of alteration likened to the lithocaps of Sillitoe (1995).

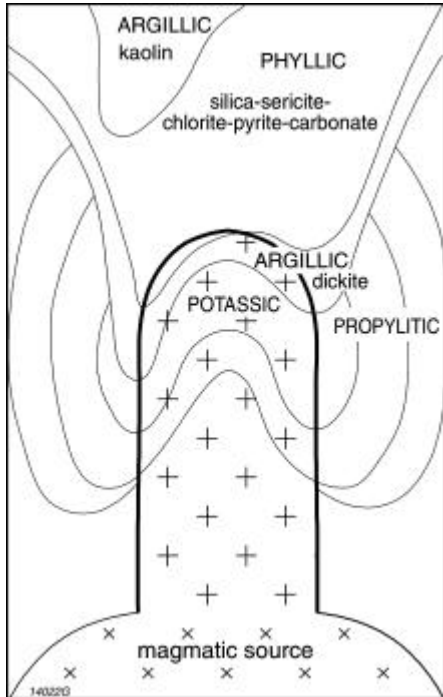


Figure 6. Collapsing condensate waters impose retrograde phyllic-argillic alteration upon earlier prograde potassic-propylitic alteration replacing many prograde minerals. Alteration of magnetite to haematite reduces the amplitude of the magnetic signature.

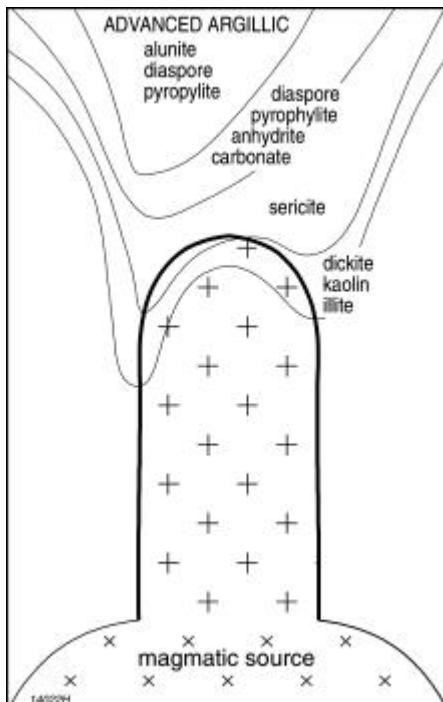


Figure 7. Hot very acid condensate waters result in a transition from advanced argillic to phyllic and argillic alteration, also recognised in geothermal systems (here without earlier prograde alteration shown).

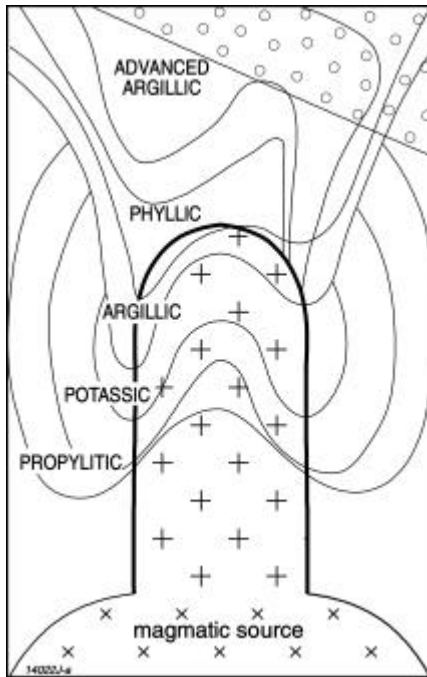


Figure 8. Composite retrograde advanced argillic-phyllic alteration overprinting zoned prograde alteration.

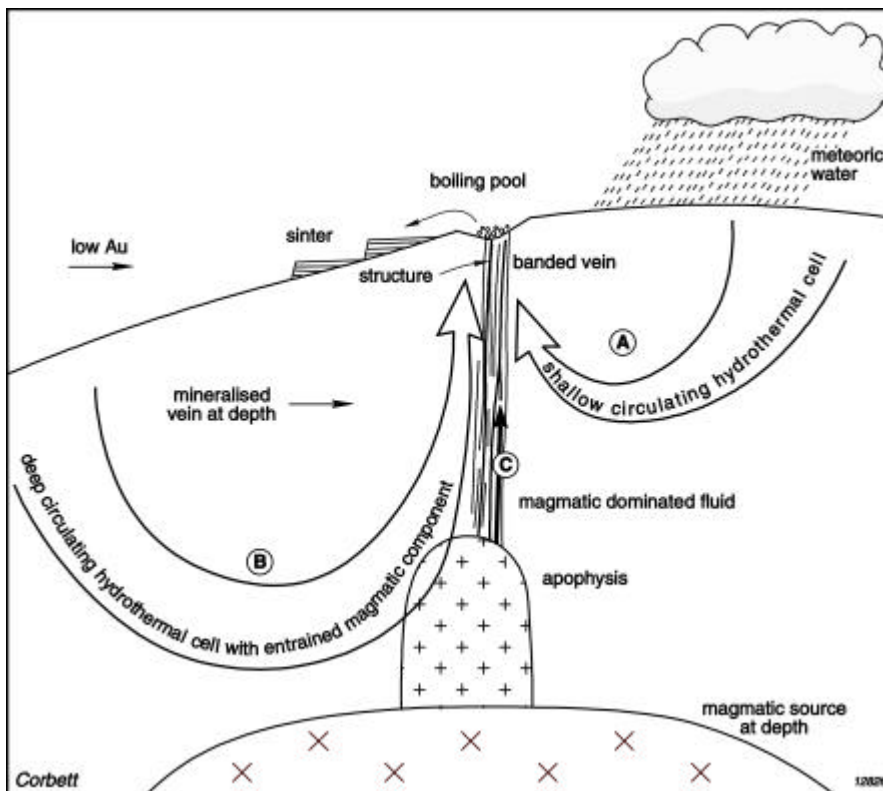


Figure 9. Conceptual model illustrating three end member fluid types recognised in low sulphidation epithermal deposits. The magmatic chamber at depth is the source for heat, metals and volatiles. Shallow circulating meteoric dominant waters deposit barren clean quartz. Deeper circulating meteoric waters entrain a magmatic component to form meteoric-magmatic waters which deposit low grade Au-Ag in quartz vein/breccias with disseminated sulphides. The majority of mineralisation is associated with sulphides derived from the magmatic source at depth.

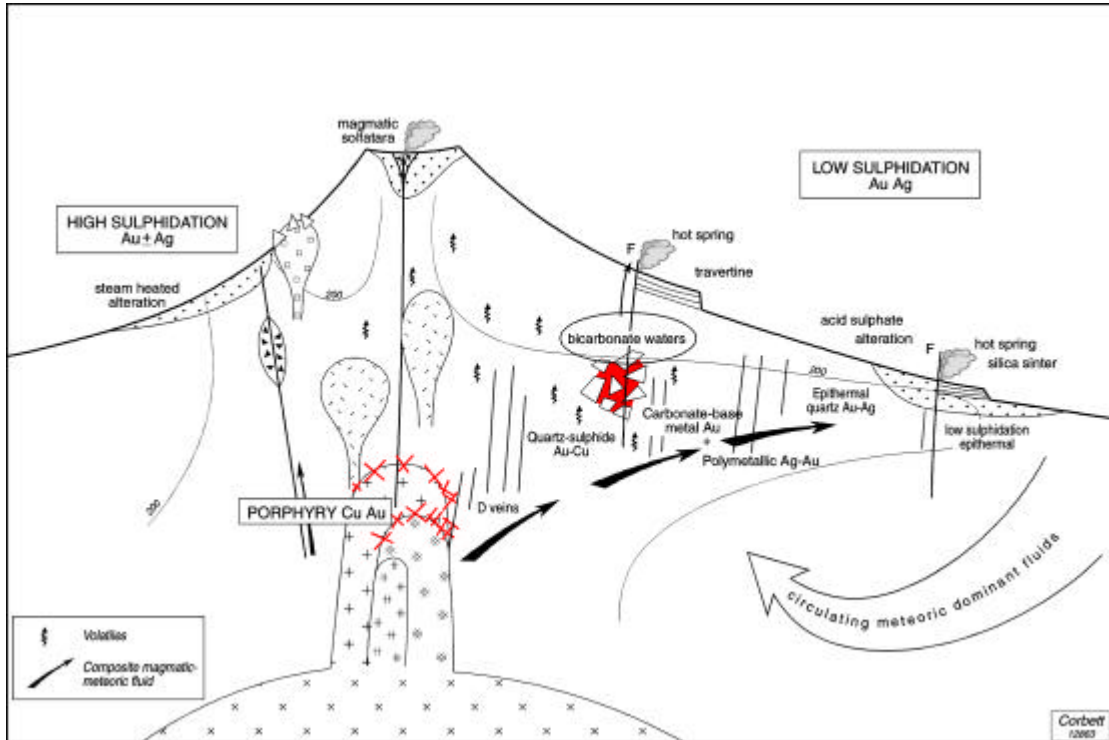


Figure 10. Varying styles of low sulphidation epithermal Au-Ag, porphyry Cu-Au and high sulphidation epithermal Au-Ag mineralisation Progression from porphyry to develop marginal to a volcanoplutonic centre characterised by volcano and deeply buried magma chamber.

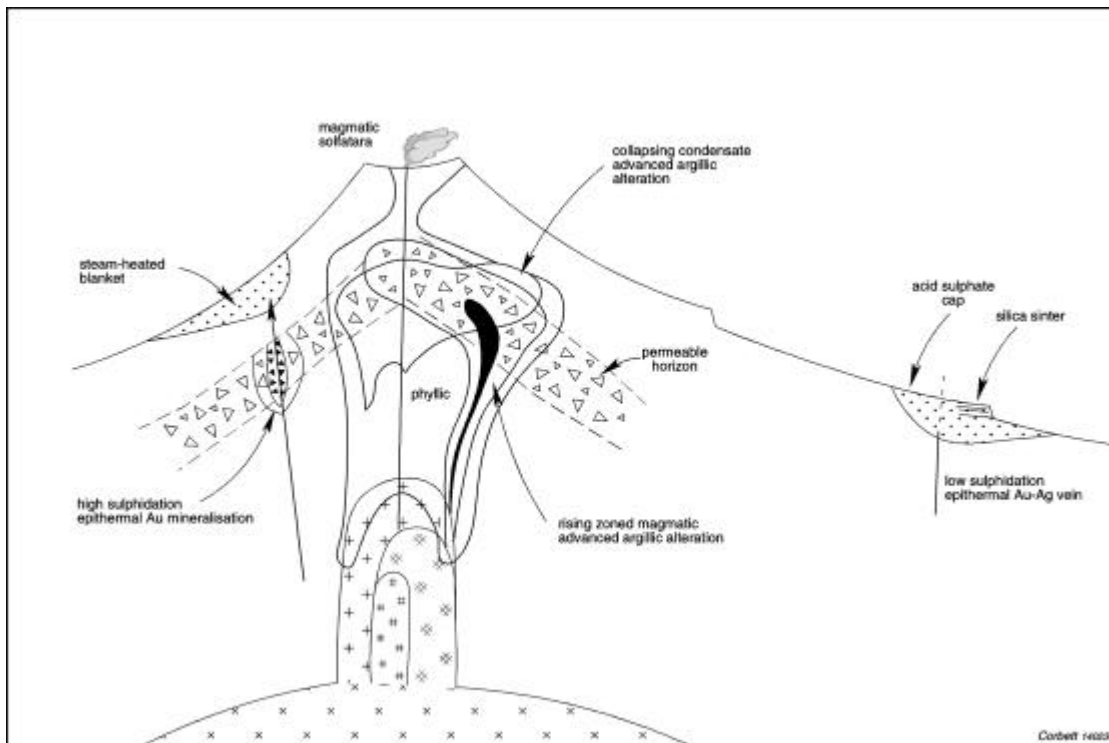


Figure 11. Conceptual illustration of varying styles of advanced argillic-argillic alteration developed within magmatic arcs.

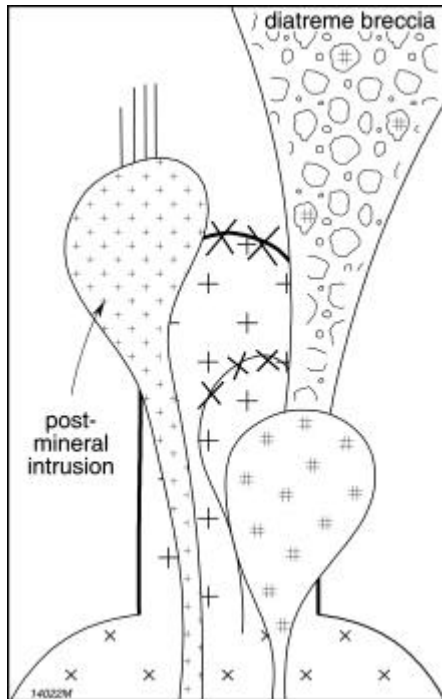


Figure 12. Post-mineral effects recognised in porphyry systems as intrusions and phreatomagmatic breccias, the latter commonly associated with high and low sulphidation epithermal ore systems.