Epithermal and Porphry Gold — Geological Models

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ABSTRACT
Geological models for the exploration and evaluation of epithermal Au and porphyry Cu-Au deposits rely upon a classification of different deposit styles and an understanding of the evolutionary processes of deposit formation. These models guide the interpretation of subsurface deposit anatomy in order to target drill testing and assist the explorationist to focus on the more prospective projects. It is important for the explorationist to distinguish between different styles of magmatic arc Au deposits as each style displays distinctive characteristics with exploration implications.

Magmatic arc Au deposits are distinguished as porphyry Cu-Au formed at depths of 1 - 2 km at the apophysis to larger, buried, magmatic sources which are also the ultimate metal sources for the varying styles of shallower level epithermal Au deposits. Low sulfidation epithermal Au deposits characteristically develop from dilute circulating meteoric waters and are distinguished as the group with a closer relationship to intrusive source rocks, and slightly higher sulfide contents (still generally <10 per cent), which are classifyed with decreasing crustal level as: quartz-sulfide Au ± Cu, carbonate-base metal Au (including polymetallic Au-Ag), and epithermal quartz Ag-Au, and contrast with the low sulfidation adularia-sericite banded epithermal Au-Ag quartz veins. Sediment hosted replacement Au deposits result from the reaction of a quartz-sulfide style fluid with reactive carbonate host rocks. High sulfidation Au deposits develop from strongly acidic evolved magmatically-derived fluids with characteristic zoned alteration and pyrite-eprite mineralisation.

INTRODUCTION
Our understanding of epithermal Au deposits has advanced considerably since the first Pacrim conference in 1987, and many important contributions to our understanding have been presented at subsequent Pacrim meetings. While we still draw on the outstanding work on porphyry Cu-Au deposits prior to the 1980s new data enables the refinement of porphyry Cu-Au mineralisation models. This study outlines some important features of these deposits discernible to the field geologist and demonstrates the benefit to explorationists of an understanding of the styles of magmatic arc Cu-Au-Ag mineralisation, and the processes of ore formation. It provides an update of the Australian Institute of Geoscientists President’s Lecture ‘Epithermal Gold for Explorationists’ (Corbett, 2002a), and draws on earlier studies (Corbett and Leach, 1998; Corbett, 2002b), which are therefore not extensively quoted in this text.

Geological models characterise different styles of magmatic arc Au mineralisation in the exploration environment, and so aid the explorationist in either the more rapid identification of economic mineralisation, or rejection of unsuitable projects. It is important for explorationists to be able to envisage the subsurface anatomy of an exploration project, and comprehend the exploration implications of different deposit styles. However, the use of geological models in mineral exploration is a mixed blessing. While models provide a framework for the expeditious use of precious exploration resources, it is imperative to maintain flexibility in the use of any model. As the database emerges, explorationists should be ready to modify any existing exploration model, or change to another which is more appropriate. The science we use is constantly developing, and so we must always be ready to accommodate geological scenarios which do not fit our existing framework. Careful preservation of the original factual data is essential in order to later apply interpretive geological models in mineral exploration.

STYLES OF MINERALISATION
Magmatic Arc Cu-Au-Ag deposits are distinguished mainly on the basis of ore and gangue mineralogy in order to characterise varying deposit styles which are derived from dramatically different fluids, at varying crustal levels. Deposits are initially divided between porphyry Cu-Au and skarns, developed at crustal depths of 1 - 2 km, and epithermal Au-Ag ± Cu which form at shallower crustal levels, and are categorised as high and low sulfidation styles (Figure 1). In the latter class it is possible to further distinguish between the adularia-sericite style banded epithermal Au-Ag quartz veins, and a group of more sulfide-rich deposits with common associations with intrusive source rocks, which vary with often continuous progressions from deeper to shallower crustal levels as: quartz-sulfide Au ± Cu, carbonate-base metal Au, (including the Andean polymetallic Au-Ag veins), and epithermal quartz Au-Ag deposits. Sediment hosted Au (Carlin-style) deposits develop from the interaction of quartz-sulfide style fluids with reactive calcareous rocks. The class of intermediate deposition may be promoted by mild cooling (Sillitoe and Hedengquist, 2004) in part corresponds to the earlier documented carbonate-base metal Au association (Leach and Corbett, 1993, 1994, 1995; Corbett and Leach, 1998; Corbett, 2002a). High sulfidation Au deposits develop from a characteristic evolved strongly acidic magmatically-derived fluid described below in detail.

LOW SULFIDATION EPITHERMAL GOLD DEPOSITS
Low sulfidation epithermal Au-Ag ± Cu deposits develop from near neutral dilute fluids, which are dominated by meteoric waters within cells of circulating hydrothermal fluids, commonly driven by the intrusive source rocks for metals, at considerable depth. Low sulfidation deposits therefore tend to dominate in reactivated dilational structural settings, and so are commonly characterised by banded veins comprising many individual events of hydrothermal mineral deposition. Some events of mineral deposition will be dominated by Au-bearing fluids derived from the magmatic source, deep circulating meteoric waters will entrain a magmatic component and so may exhibit lower grade Au mineralisation, while shallow circulating meteoric waters are sometimes barren. Groundwaters may collapse into the hydrothermal system or otherwise interact with the hydrothermal cells as an important feature of the ore deposition process (Figure 2). Varying mechanisms of mineral deposition are apparent within multi-generational veins. While boiling or phase separation by rapid pressure drop has long been proposed as a possible mechanism of mineral deposition, detailed character sampling has often failed to identify the bulk of Au-Ag mineralisation in the minerals deposited at this stage — adularia, bladed calcite, quartz pseudomorphing calcite and to a certain extent chalcedony. Rather, these minerals constitute much of the gangue mineralogy. Some workers (Corbett and Leach, 1998) have proposed that Au deposition may be promoted by rapid cooling of the ore fluid, enhanced by wall rock reaction, or mixing with varying ground waters. Rapid cooling of an ore fluid, which promotes high-grade Au deposition, is often evidenced by the presence of Au within chalcedony, while fluid mixing is apparent from the presence of kaolin for low pH acid sulfate waters, manganese oxide for bicarbonate waters, and hypogene haematite and jarosite for oxygenated ground waters.

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Fig 1 - Conceptual model illustrating the styles of Pacific rim porphyry to epithermal Cu-Au mineralisation (modified from Corbett, 2002a).

Fig 2 - Conceptual model for the generation of fluids in high and low sulfidation epithermal Au deposits (modified from Corbett 2002a).
Varying styles of low sulfidation epithermal Au deposits, which commonly form in different geological environments, are distinguished on the basis of vein mineralogy, and display sufficiently different characteristics to warrant distinction by explorationists. The group of low sulfidation Au-Ag deposits with higher sulfide contents, although in many instances only in the order of one to two per cent, display a closer association with intrusive source rocks. These display transitional relationships and vary spatially and temporally from early to later in a vein paragenetic sequence, and generally from deeper to shallower levels from: quartz-sulfide Au ± Cu, to carbonate-base metal Au, and epithermal quartz Au-Ag deposits. Mechanism of mineral deposition provides one of the important distinguishing characteristics, and is of interest to the explorationist as a significant influence upon precious metal grades.

Quartz-sulfide Au + Cu deposits
Quartz-sulfide Au + Cu deposits characteristically contain iron sulfides with a quartz-rich gangue, varying to Kfeldspar-rich in the silica-poor alkaline intrusion-related deposits, and demonstrate pronounced mineral zonation with varying crustal levels of formation. Barite is present in many Andean examples. At deepest crustal levels these deposits may contain pyrite, pyrrhotite and chalcopyrite, with lesser specular haematite and magnetite. At lower levels or drusy quartz gangue. Gold is deposited with sulfides, typically by fluid boiling, and so slow cooled coarse-grained veins often display lower Au grades, but good metallurgy, especially where oxidised. While most quartz-sulfide Au deposits contain pyrite as the main iron sulfide, at elevated crustal settings this may pass to marcasite and arsenian pyrite, in combination with opal to chalcedony as the silica component. Many high level deposits are therefore characterised by an arsenian pyrite bearing Au-As-Ag anomalous ‘grey silica’ (‘silica gris’ in Latin America), which commonly displays poor metallurgy as Au is encapsulated in the silica lattice. The refractory ores at the Ladolam deposit Lihir Island, Papua New Guinea, are of this style. Here, Kfeldspar alteration dominates in the alkaline host rocks.

As the quartz-sulfide Au ± Cu deposits form at deeper crustal levels they tend to exploit pre-existing structures and commonly display a close relationship to porphyry Cu-Au intrusions, locally representing the porphyry-epithermal transition. Many quartz-sulfide Au ± Cu vein systems fit into the D vein classification of the early porphyry Cu literature (Gustafson and Hunt, 1975). In dilational structural settings often evidenced by the presence of sheeted veins, ore fluids may migrate considerable distance from source porphyry Cu-Au intrusion to form wall rock porphyry Au deposits. Consequently, sheeted veins in some Marcungas Belt (Chile) porphyry Au deposits are typical of quartz-sulfide Au ± Cu mineralisation. Similarly, the giant Cadia Hill wallrock porphyry, Australia, displays significantly higher Au than Cu contents, than is typical of porphyry Cu-Au deposits, and so represents a transition between quartz-sulfide and porphyry mineralisation. At La Arena in Peru, quartz-sulfide Au mineralisation occurs as a fracture coating pyrite in a quartzite immediately overlying a porphyry intrusión. Sector collapse at Ladolam initiated the change from porphyry Au to epithermal Au mineral deposition (Corbett et al., 2001).

Many quartz-sulfide Au ± Cu deposits occur as steeply dipping lodes (Mineral Hill) and Adelong, Australia; Bilimoria (Iranian Timur) (Papua New Guinea; Gaing Cha Ling, China; Rawas, Indonesia) while fracture vein networks (Nolans, Australia; deeper parts of Porgera, Papua New Guinea) may vary to more dilational sheeted veins (Kelian, Indonesia). Flat structures may host ore where collapse of volcanic edifices is interpreted as a trigger for ore formation, such as the flatmaks at Emperor Gold Mine, Fiji, initiated as a reactivation of a bedding plane during caldera collapse, or the listric faults at Ladolam formed by Mt St Helens style sector collapse, and where ores vary from a deeper structural, to higher level lithological control. At both these deposits most ore is hosted within fine variably arsenian pyrite deposited as the ore fluid has rapidly cooled by contact with the wall rocks. Quartz-sulfide Au ± Cu deposits are not restricted to magmatic arcs and provide a link to other intrusion-related mineralisation styles, such as the Paulsens PreCambrian quartz-pyrite lodes formed adjacent to a granite batholith in the Ashburton district of Western Australia.

Exploration implications
Gold is readily liberated from oxidised coarse-grained quartz-sulfide Au ± Cu ores and so very low metal grades may be worked as bulk low-grade heap leach operations (San Cristobal, Chile). However, explorationists should be aware that quartz-sulfide Au deposits are notorious for surficial supergene enrichment, particularly in steeply dipping structures as sites of chemical and mechanical concentration. Elevated assay results of surficial samples should be treated with caution. Supergene settings are evidenced by boxworks after pyrite, or Au anomalous jarosite at the surface, base of oxidation and deep within faults. Many cases where soil geochemical anomalies cannot be substantiated during drill testing, are accounted for by supergene enriched quartz-sulfide Au ± Cu mineralisation, even in association with other deposit styles such as adularia-sericite banded epithermal Au-Ag quartz vein deposits. Fine grained Au-rich ores (Lihir and Kerimenge in Papua New Guinea), formed by fluid quenching display poor metallurgy, and high As contents in these ores may prove to be an environmental liability. However, the ‘silica gris’ may be used as a vector to buried ores in Andean settings where extreme topographic variations allow direct access to much deeper level, and possibly more prospective, vein portions where higher precious metal grade polymetallic ores might occur.

Higher hypogene grade ores are recognised in settings of fluid quenching, either by wall rock reaction, or by mixing with varying ground waters as evidenced by kaolinite (low pH waters), or more commonly manganese oxides (bicarbonate waters), as a reflection of the transition to higher crustal level carbonate-base metal Au mineralisation. Overprinting epithermal quartz Au-Ag mineralisation also provides higher Au-Ag grades.

Carbonate-base metal Au
As the group of sulfide-bearing low sulfidation intrusion-related Au deposits display a fluid evolution from quartz-sulfide Au ± Cu, to carbonate-base metal Au, and later epithermal Au-Ag, many deposits are characterised by all three deposit styles either grading temporally in overprinting events (Porgera), laterally (Kelian, Indonesia), or vertically (Kerimenge), while others display telescoping into single lodes (Tuvatu, Fiji), or fracture networks (Mt Kare, Papua New Guinea). Similarly, district scale vertical zonation may be evident, such as in the Morobe Goldfield in Papua New Guinea, where the Hamata quartz-sulfide Au deposit occurs at deepest level, Hidden Valley, Kerimenge and Upper Ridges carbonate base metal Au deposits lie at intermediate levels, and the Edie Creek bonanza grade epithermal Au deposit is mined at an elevated crustal setting. Furthermore, Kerimenge displays a vertical zonation over several hundred metres from quartz-sulfide Au ± Cu, to carbonate-base metal Au and highest and lateral epithermal Au-Ag mineralisation, all localised at the contact of a fault with the margin of a diatreme breccia pipe. Although most deposits display some transitional relationships, a significant portion of the Au in many southwest Pacific rim Au deposits is clearly of the carbonate-base metal Au affiliation, as these represent the most prolific producers in the region. In older more deeply eroded terranes such as the Ordovician Lachlan Fold Belt of eastern Australia, quartz-sulfide Au systems attain economic status due to the overprinting carbonate-base metal Au mineralisation (Kidston, Lake Cowal and London-Victoria in Australia). Carbonate-base metal deposits display more efficient
mechanisms of Au deposition than the quartz sulfide and so commonly display higher precious metal grades.

Carbonate-base metal Au deposits are characterised by one to ten per cent sulfides, commonly as pyrite > sphalerite > galena with a gangue of carbonate and variable quartz and display pronounced zonation (Corbett and Leach, 1998). At deeper levels the transition to quartz-sulfide style may reflect minor pyrrhotite (Porgera, Kelian). Vertical zonation in sphalerite type is evident as a composition-controlled colour change related to temperature (depth), varying from black, Fe>Zn, high temperature at depth, through brown, red, yellow and locally clear, Zn>Fe, low temperature sphalerite, at highest crustal levels. Carbonates are zoned as the collapsing weakly acidic bicarbonate fluids undergo a progressive rise in pH with depth by wall rock reaction, and so vary with increasing depth from carbonates dominated by Fe (siderite) at higher crustal levels, to Mn (rhodochrosite), Mg (ankerite, dolomite) at intermediate levels, and Ca (calcite) at deepest crustal levels. Much of the mineral deposition results from the mixing of rising ore fluids with bicarbonate waters, often derived from high level felsic intrusions.

The form of carbonate-base metal Au deposits varies considerably from banded veins (Antamok and Acupan, Phinmen, Cikoto and Pongkor, Indonesia), or composite lodes (Eddie Creek and Woodlark Island in Papua New Guinea, and Tavatu), fracture vein networks (Porgera, Mt Kale, Lake Cowal), sheeted vein systems (Kelian, Kidston), and matrix to diatreme breccias (Mt Leyshon, Australia; Montana Tunnels, USA, Rosia Montana, Romania), or brecciated intrusion margins (Bulawau, Philippines). This association with phreatic magmatic (diatreme) breccias commonly provides a link to magmatic source rocks (frequently dacite and rhyolite). At higher crustal levels the clay altered diatreme breccias are incompetent and so fracture mineralisation occurs in the adjacent host rocks (Kelian, Kerimenge), or at the diatreme-host rock contact (Acupan), and only at deeper crustal levels does mineralisation reside in the diatreme matrix (Mt Leyshon, Montana Tunnels), including cross-cutting fracture systems (Cripple Creek, USA). Elsewhere, pre-mineral phreaticmagmatic breccia dykes exploit structures and provide ground preparation (Woodlark Island).

While in many instances carbonate-base metal Au deposits occur in the same terranes as high sulfidation deposits (Rio de Medio at El Indio in Chile, Victoria at Lepanto in the Philippines), it is also possible, but only rarely noted, for the fluids responsible for the formation of high sulfidation Au-Ag deposits to undergo progressive cooling and neutralisation by rock reaction to evolve to low sulfidation mineralisation. Consequently, the Link Zone Prospect provides a higher grade and better metallurgy Au mineralisation as quartz-sulfide veins with a carbonate overprint, recognised on the margin of the Wafi high sulfidation deposit, Papua New Guinea.

**Exploration implications**

Carbonate-base metal Au deposits are important Au producers but vary considerably, with resultant metallurgical implications, especially where overprinting relationships are recognised with other styles of low sulfidation Au mineralisation (Kelian, Porgera). Explorationists should be aware that carbonate-base metal Au deposits often display very irregular Au distribution which must be taken into account in ore reserve estimation, particularly within oxide zones, or where overprinted by telescoped epithermal quartz Au-Ag mineralisation. Carbonate-base metal Au deposits display highly variable forms requiring an estimation of the sub surface three dimensions and ore controls prior to drill testing. It is imperative that drilling transect sheeted veins or lodes at the best possible angles, and that kinematic analyses attempt to determine the setting of structurally controlled ore shoots within throughgoing veins. While high level diatreme breccia systems may be barren at surface, Au mineralisation may occur at breccia pipe margins at this level, or within the breccia matrix at depth. The characteristic Mn wad formed by the weathering of common Mn carbonates provides a ready tool for the recognition of these deposits, but may scavenge Au.

**Epithermal quartz Au-Ag**

Epithermal quartz Au-Ag deposits form at the highest crustal levels and late stage in the paragenetic sequence of intrusion-related low sulfidation Au deposits. They consequently overprint both quartz-sulfide Au (Ladolam, Emperor), and carbonate-base metal Au deposits (Porgera Zone VII, Mt Kale, parts of Eddie Creek). So larger marginal to porphyry Cu-Au deposits (Thames, New Zealand), or at periphery of carbonate-base metal deposits (Kelian and Kerimenge). Most display a strong structural control as they form at great distances from the magma source as fluids deposit to cooler epithermal crustal settings. Consequently, much of the higher grade ore commonly occurs in ore shoots formed at preferential sites of fluid flow or Au deposition (Porgera). One of the most notable features of these deposits is that the characteristic bonanza grade often overprint existing veins with little new gangue material deposition. Many deposits contain anomalous exotic metals such as tellurium (Emperor) or selenium (Selene, Peru) and minerals such as telluriumsulfosaltiate are a common associate with Au (Bilimoria). Mineral deposition is considered to be promoted by rapid fluid cooling, which may be enhanced by the mixing of ore fluids with groundwaters entering the deposits at elevated crustal settings.

Recent age data for the Porgera Au deposit (Ronacher et al, 1999) provides a 5.9 m.y. age for two contrasting mineralisation events, with a very small age separation (0.26 m.y. within the error estimation). The initial (Stage I) bulk low-grade quartz-sulfide grading to a late stage carbonate-base metal Au event currently being mined at the Waruwaro open pit, is predominantly formed at a deep crustal level as evidenced by the presence of high temperature pyrrhotite and dark sphalerite. The later (Stage II) low temperature epithermal quartz Au-Ag mineralisation well developed in the Zone VII underground is associated with renewed more felsic magmatism (Corbett et al, 1995), and probably formed with at least 600 m less overburden. Recent exposures from the deepest portion of the mine demonstrate that the (Stage II) epithermal mineralisation grades rapidly through quartz-sulfide and low temperature carbonate-base metal alteration, as a renewed mineralisation associated with the later felsic magmatism. Thrusting exposed within the Porgera open pit and common throughout the region, is suggested to account for the rapid unroofing of the Porgera Intrusion Complex and provision of a trigger for renewed epithermal mineralisation.

**Exploration implications**

The free milling bonanza Au has led to the ready identification of many epithermal Au-Ag deposits by panning (Porgera, Eddie Creek), but may also promote the presence of artisan miners (Mt Kale, Kelian). The improved metallurgy and high metal grades within epithermal quartz Au-Ag mineralisation have enhanced the economics of other lower Au grade or metallurgically difficult quartz-sulfide Au and carbonate-base metal Au deposits (Porgera, Emperor). Great care must be exercised in the drill testing of these deposits to ensure that vein ores are intersected at the best possible angles, and maintenance of good core recoveries is essential within mineralised fault zones. Similarly, in careful drill core sampling, a geologist should mark where core should be sawed, and so allowance made for best possible sample returns. The bonanza Au grades, commonly with only minor gangue minerals, are difficult to recognise and so may provide challenges in ore reserve determinations. Explorationists must
also be aware that most ore and higher precious metal grades commonly occur in ore shoots formed as dilatant structural sites (flexures or fault jogs) of enhanced fluid flow (Porgera Zone VII), or enhanced metal deposition at cross structures (Thames), or hanging wall splits (Porgera Zone VII).

**Sediment hosted replacement Au**

Sediment hosted replacement Au (Carlin style) deposits are well documented as major Au producers in the western US (Carlin, Goldstrike, Cortez), and although less important Au producers in the southwest Pacific (Messel, Indonesia; Bau, Malaysia; and Sepon, Laos), remain as important exploration targets worldwide, and are well represented in emerging provinces such as China. They are also recognised in rocks of varying ages including the Precambrian of the Asburton District of Western Australia.

These deposits develop from the interaction of an ore fluid typical of quartz-sulfide Au style deposits, with reactive host rocks, typically impure calcareous sediments (marls of the Popovich Formation, Nevada). Regional scale extensional structures facilitate the transport of ore fluids from magmatic source rocks at depth to elevated crustal settings, where mineral deposition occurs. Deposits of the Carlin trend are localised along the Post Fault system, and Mesel occurs within a smaller scale fault jog, where dilatant fractures have focused ore fluid flow. Sediment hosted replacement Au deposits display important internal variations from structurally controlled feeder structures at deeper levels, commonly with higher Au grades, to lithologically controlled lower grade ores at higher crustal levels. At Mesel Au contents decline rapidly moving away from dilatant feeder structures, and in the Carlin trend structurally controlled higher grade deposits such as Meikle are mined underground, while the lithologically controlled ores (Carlin, Goldstrike) represent large open pit mines.

Sediment hosted replacement Au deposits are characterised by the dolomite-silica-kaolin alteration associated with the introduction of auriferous arsenic pyrite, with anomalous Hg and Sb. The early dolomitisation of calcite creates open space and so provides secondary permeability for ore fluid flow associated with local silicification. This dissolution is commonly evidenced as collapse breccias. Silicification is also apparent as barren jasperoid alteration, common in the upper portions of these deposits.

**Exploration implications**

At the reconnaissance exploration stage, the resistant jasperoid rocks, which are commonly preserved in the float train, are an indication of this style of mineralisation within a region. While barren in outcrop these rocks may provide indicators of mineralisation at depth (Mesel). Because sediment hosted Au deposits are commonly termed classic ‘no see ‘em’ gold deposits, gold panning may not be reliable, and so advocated geochemical tools include BLEG stream sediment sampling, followed by analyses of soil samples for elements such as As, Sb, W, and Hg.

During evaluation, analysis of structural controls may allow explorationists to target higher grade ores within feeder structures at depth, which will compensate for the additional costs of dealing with these metallurgically difficult fine As-rich pyritic ores. Consequently, oxide ores are favoured for mining operations. The environmental aspects of the As, Sb and Hg bearing ores should be taken into account.

**Adularia-sericite banded epithermal Au-Ag quartz vein deposits**

The adularia-sericite banded epithermal Au-Ag quartz vein deposits are the most extensively documented low sulfidation Au-Ag deposits, particularly using the parallels with the New Zealand geothermal systems. While many of these deposits are well developed in back arc environments (Drummond Basin, Australia; Taupo Volcanic Zone, New Zealand; Artigen Patagonia; Japan; western US), or some are noted within intra-arc rifts (Tolukuma, Papua New Guinea), other individual deposits occur within magmatic arcs (El Peñón, Chile; Ares, Peru), or other linear magmatic arcs are dominated by these deposits (Coromandel Peninsula, New Zealand; Kamchatka Peninsula, Eastern Russia). This style of mineralisation is also recognised in the mid oceanic ridge hotspot environment at Iceland. All these environments display characteristic of bimodal volcanism, commonly as an interpreted association of Au-Ag mineralisation with felsic magmatism, commonly hosted with andesitic or basaltic rock sequences.

The low sulfidation adularia-sericite banded epithermal Au-Ag quartz veins typically comprise fine interlayers of chalcedony varying to opal, with lesser adularia, quartz pseudomorphing platy calcite, and black sulfidic ginuro bands (named by the nineteenth century Japanese miners). Most genetic interpretations suggest that meteoric dominant waters rise rapidly up dilatant fracture systems hosted within competent rock packages and boil to deposit much of the vein mineralogy. Comparisons with geothermal systems link adularia and quartz pseudomorphing platy calcite to boiling fluids. However, these mineral assemblages tend not to contain Au-Ag mineralisation, which dominates in the ginuro bands and to a lesser extent chalcedony and so, as discussed above, some workers therefore invoke rapid cooling, locally aided by mixing of the ore fluid with varying groundwaters, as a mechanism for deposition of bonanza Au-Ag mineralisation.

Adularia-sericite banded epithermal Au-Ag quartz vein deposits display pronounced vertical zonation. At surficial levels eruption breccias (Champagne Pool and Puhipuhi in New Zealand; Toka Tindung, Indonesia; Twin Hills, Australia), represent sites of venting hydrothermal fluids which form laminated sinter deposits. Although anomalous in toxic elements (Hg, As, Sb, W) many silica sinter deposits are barren with respect to Au, unless proximal to fluid up flows (Champagne Pool). Sheeted veins often extend into the deeper portions of eruption breccias (Twin Hills; McLaughlin, USA) and also cap the upper portions of some fissure vein systems (Golden Cross and Karangahake in New Zealand). Most ore systems occur within deeper fissure veins, commonly localised by dilatant fractures with competent host rocks (Pajingo and Vera Nancy, Australia; Tolukuma; Hishikari and Sado in Japan; Waihi, New Zealand; Asacha; Eastern Russia). Wall rock clay alteration varies from illite at deeper levels marginal to fissure veins and grades vertically and laterally to assemblages dominated by illite-smectite and thence smectite. Acid sulfate alteration (alunite, cristobalite, kaolin) forms at near surficial settings by the reaction with wall rocks of low pH condensate waters, which may also collapse into the ore system to promote mineral deposition.

Factors which influence the localisation of higher grade ore systems include, structure, hot rock competency, and mechanism of Au-Ag deposition. In many vein systems most ore, including of higher grades, occurs in ore shoots developed as preferential sites of mineralised fluid flow within flexures in otherwise poorly mineralised throughgoing structures (Vera Nancy; Sims, 2000), fault jogs between structures, or splays. Structures dominated by strike-slip fault movement host steeply plunging ore shoots (Vera Nancy), while those within listric faulting with display flat plunges (Sierra Madre, Mexico; Arcata, Peru). Rock competency influences the manner in which host rocks fracture during vein formation and less competent sequences may cap ore. At Hishikari, the Shimanto Group shale, which hosts vertical quartz veins, is overlain by volcanic breccias, and preferred mineral deposition of bonanza ores has occurred at the intersection of these veins with the lithological contact, resulting
in the development of flat plunging higher grade ore zones. At Karangahake, the andesite-hosted mineralised fissure veins become a less well mineralised stockwork in overlying incompetent rhyolite. While the Chon Aike ignimbrite hosts veins in the Cerro Vanguardia region, Argentine Patagonia, elsewhere veins are limited to the competent margins of felsic domes at Ares and Asacha (Kamchatka). Enhanced Au-Ag deposition often occurs at sites of fluid mixing where ground waters come in contact with ore fluids such as at splay faults (Tolukuma), hanging wall splits (Asacha), or changes in host rock competency (Hishikari). These may be recognised by the presence of kaolin (Ares) or manganese oxide (Karangahake) in the upper and better mineralised portions of the vein systems.

Exploration implications

Adularia-sericite banded epidemeral Au-Ag quartz vein deposits provide attractive exploration targets, which commonly contain bonanza Au-Ag grades, and are amenable to mining in semi urban areas (Hishikari, Waihi) or in difficult terranes (Tolukuma lacks a road link and is wholly supplied by helicopter).

Gold panning (Tolukuma; Chatree, Thailand), and BLEG stream sampling, continue as useful first pass prospecting tools, aided by the recognition of characteristic banded quartz as stream float downstream (Tolukuma), or at prospect scale (Chatree, Cerro Vanguardia). Resistive geophysical techniques (CSAMT) have targeted quartz veins for drill testing (Hishikari), locally within throughgoing structures (Vera Nancy). PIMA now replaces slower XRD to readily provide studies of clay alteration zonation to target higher temperature illite alteration close to veins (see Golden Cross in Corbett and Leach, 1998).

Explorationists should be conscious of the importance of ore shoots as sites of bonanza Au grades within vein systems. While many ore shoots display steep plunges (Vera Nancy), flat plunging ore shoots occur in settings of listric fault control, or changes in host rock (Hishikari), and the intersection of hanging wall splits with main the fault (Asacha). Often unmineralised erosion breccias and acid sulfate alteration may cap mineralised vein systems and so vector towards mineralisation.

Careful geological mapping is essential in order to plan drill testing at the best possible angle, and the angle of veins to the core axis should be monitored to ensure optimum drill direction is maintained. As bonanza ores comprising ginguro sulfide vein portions locally occur with clays, and are commonly fault-controlled, good drill core recoveries are essential for accurate ore reserve determinations. Poor ore recoveries sometimes downgrade Au contents.

BARREN HIGH ADVANCED ARGILLIC ALTERATION

Many varying styles of alteration result from the interaction of acid waters with host rocks, and while some alteration systems clearly vector towards Au mineralisation, it is imperative for the explorationist to distinguish prospective from barren hydrothermal alteration. There is clearly great benefit for explorationists to adequately understand varying styles of barren advanced argillic alteration.

Magmaic-derived advanced argillic alteration

Magmaic arcs contain common bodies of barren advanced argillic alteration which typically outcrop as resistive ledges developed by alteration within structures or permeable lithologies, and extending from porphyry to epithermal crustal levels. While these alteration systems display characteristic zonation outwards from silica cores, mineral assemblages vary with depth such that at deeper levels mineral assemblages are dominated by alunite, pyrophyllite and diaspore grading laterally to dickite and kaolin clays, and may contain minerals such as corundum and andalusite, formed in very high temperature settings. By contrast, at epithermal crustal levels, silica cores grade to mineral assemblages dominated by alunite and more marginal dickite and kaolin clays. Erosion of the softer marginal clays commonly facilitates formation of prominent topographic highs by preservation of the relict silica cores which are resistant to erosion.

These alteration zones are interpreted to have developed from the reaction with host rocks of magmatic volatiles venting directly from intrusive source rocks early in their evolution, and are compared to magma plumes in geothermal systems (Reyes et al, 1993). Alteration zones are recognised outcropping on the margins of porphyry Cu-Au systems where they have been termed barren shoulders (Corbett and Leach, 1998). Importantly, the fluids responsible for these alteration zones were rising at the time of alteration, but have not evolved as the volatile-rich high sulfidation fluids, and so are not mineralised.

Explorationist should note that these alteration zones are common in the vicinity of porphyry Cu-Au deposits and other intrusion-related manifestations such as low sulfidation quartz-sulfide veins. Many exploration case histories include instances where Au anomalies derived from low sulfidation epithermal veins has been attributed to these topographically obvious alteration zones which are themselves barren.

Exploration implications

The early recognition of these barren alteration zones may aid in prioritisation of exploration programs to focus upon more fertile alteration systems. These bodies of zones magnetically derived advanced argillic alteration might commonly be recognised by the explorationist by the presence of massive rather than vugly silica, typical of high sulfidation epithermal Au deposits. At deeper crustal levels high temperature minerals such as corundum and andalusite are characteristic, and minerals such as alunite and diaspor may display very coarse-grained shapes indicative of slow formation at near porphyry levels. The distinction of this non-fertile alteration at epithermal crustal levels is less definitive. Higher temperature dickite clays dominate over kaolin. They commonly form in settings such as within eroded volcanic edifices, and contain ledges of structurally or lithologically controlled silica in intense clay-pyreite alteration, which anomalous derived to provide distinctive liegegang rings and ferricrete deposits. Any Au mineralisation may be in later cross-cutting veins or breccias and importantly generally occurs outside to core of actual alteration zone.

HIGH SULFIDATION Au - Ag - Cu DEPOSITS

High sulfidation epithermal Au deposits result from the interaction with host rocks of magmatically-derived ore fluids, which have evolved to attain a characteristic very acidic character. In simple terms, a volatile-rich fluid (dominantly SO2, but also containing CO2, H2S, HCl) leaves the magmatic source and becomes depressurised during the rapid migration to epithermal crustal levels, causing the volatiles to come out of solution and oxidise (as O2 and H2O also evolve from the same depressurising fluid) to form a hot acidic fluid. The fluid has not interacted with host rocks or groundwaters during rapid upward migration. Consequently the fluid has evolved during rapid ascent, from a near neutral fluid in the porphyry environment, to strongly acidic at epithermal levels, where host rock reaction results in the development of the characteristic high sulfidation alteration zonation and mineralisation. High sulfidation deposits commonly develop without the repeated activation of dilational structures, which in low sulfidation systems drive hydrothermal cells of
meteoric-dominated waters to facilitate banded quartz vein formation. Rather, the development of high sulfidation deposits might be promoted as single magmatically dominated hydrothermal events during transient relaxation in compressional magmatic arcs. The kinematics of individual deposits therefore commonly contrast with observed regional tectonics.

The volatile portion of the high sulfidation fluid travels more rapidly than the fluid-rich portion, and reacts with the host rocks to produce the characteristic alteration zonation. At the core of the alteration zone the host rocks undergo intense leaching by the extremely acidic fluid to produce a rock composed almost entirely of silica, termed residual or vughy silica, indicative of the characteristic open space texture. As the hot acidic fluid is cooled and neutralised by rock reaction the zoned alteration grades outwards through alteration assemblages characterised by alunite, pyrophyllite, diaspore, and dickite/kaolin, to neutral clays such as illite/smectite, and eventual marginal porphyritic alteration (chlorite-carbonate). Alteration zonation also varies according to, proximity to the fluid up flow, host rock permeability, and crustal level (eg dickite at deeper levels passes to kaolin in higher level cooler settings).

High sulfidation fluid flow is influenced by permeability controls classed as structural, lithological and breccia. While many deposits are localised either on major throughgoing structures (Gidginbung, Australia, on the Gilmore Suture; Wafi, Papua New Guinea on a transfer structure; Mt Kasi, Fiji), or on dilational fractures between throughgoing faults (Lepanto and Nena each lie on splays; El Indio occurs within a sigmoidal loop), the contacts of these structures with permeable lithologies (Sipan, Peru; El Guanaco, Chile; Nena and Gidginbung), or diatreme breccias (Lepanto), provide suitable settings for development of alteration zones. Other deposits are wholly controlled within permeable lithologies in volcanic sequences (Pierina, Peru; La Coipa Chile). Many high sulfidation deposits are associated with phreatomagmatic breccias (Wafi; Pascua, Chile; Veladero, Argentina; Miwah, Indonesia), which no doubt facilitate the rapid rise of ore fluids from porphyry to epithermal levels, and so some high sulfidation deposits also occur within felsic domes (Mt Kasi), or dome/breccia complexes (Yanacocha, Peru). Felsic domes are an important link to magmatic source rocks at depth, and therefore commonly associated with high sulfidation Au deposits. Some deposits occur as veins (El Indio) while other deeper level systems collapse upon porphyry Cu-Au deposits (Monywa, Myanmar; Tampakan, Philippines).

A liquid-dominated fluid component enters the zoned alteration via the same plumbing system as supplied the volatile portion of the ore fluid, and so deposits sulfides comprising pyrite, enargite (including the low temperature polymorph luzonite) and additional alunite, along with barite and late stage sulfur, mainly within the vughy silica, locally extending into the adjacent silica-alunite portion of the zoned alteration. High sulfidation deposits display a zonation from Cu-rich at deeper levels, grading to Au-rich at higher crustal levels. Ores occur as veins, breccia matrix, or filling vughy silica. While most southwest Pacific deposits contain very little Ag, many Andean deposits are Ag-rich and higher level deposits may contain Hg and Te.

Exploration implications
The characteristic siliceous float provides a ready prospecting tool, which may be recognised in the float train well downstream and traced to source (Miwah). Covered silicification is discernible on resistivity geophysical studies such as CSAMT (Mt Kasi; Maragorik, Papua New Guinea), most apparent in higher level systems where there is a strong contrast with the adjacent conductive clay alteration. The high sulfidation clay alteration may be identified on geophysical studies as regions of magnetic destruction and coincident electrical conductivity, or

in remote sensing imagery as colour anomalies, and more recently using multispectral clay analyses.

The enargite ores often display difficult metallurgy and so many deposits are preferentially worked in the oxide zone (Sipan, El Guanaco, La Coipa) and the bulk low-grade ores are conducive to extraction as heap leach operations (Sipan, Yanacocha). Acid mine waters produced by weathering of the pyritic clay alteration, and the high As content of sulfide ores, and local Hg by products, may all provide environmental concerns.

One of the most important exploration procedures is the use of careful PIMA studies to supplement field identification of the alteration zonation in order to vector to the central vughy silica which hosts most mineralisation. It is possible for silica-alunite to form resistant barren caps and so mask mineralised vughy silica. In some cases the barren alteration has previously been mined for industrial minerals (pyrophyllite at Peak Hill, Australia). The Nansatsu high sulfidation deposits in Japan have been mined for silica flux and the Gidginbung silica was initially used for road construction.

POPHRYY COPPER-GOLD

Porphyry Cu-Au deposits develop as a result of focusing of the mineralising fluids at depths of 1-2 km in the cooler apophyses to magmatic sources at greater depths, and so extend from intrusion host rocks into the wall rocks. Some of the better ore systems (Grasberg, Indonesia; Oyu Tolgoi, Mongolia; Ridgeway and Goonumba in Australia) are characterised by multi phase intrusion emplacement into spine-like vertically attenuated intrusion complexes. Overprinting intrusions provide multiple events of mineralisation and locally recyle ore minerals into settings with higher metal grades, but may also overprint and obliterate mineralisation related to earlier porphyry Cu-Au intrusions, therefore downgrading the total ore system (Figure 3).
In generally compressional subduction-related magmatic arcs, changes in the nature of convergence may act triggers to facilitate the emplacement of vertically attenuated intrusions from magmatic source rocks at depth, into higher crustal level dilational structural settings (Corbett and Leach, 1998; Corbett, 2002b). Ore fluids then continue to evolve from the magmatic source into higher level ore settings utilising dilational fracture systems such as sheeted quartz veins. Many quality porphyry Cu-Au deposits are not linked to associated extrusive volcanic rocks (Grasberg; Oyu Tolgoi; Bingham Canyon, USA) suggesting volatiles and mineralisation may have been retained within the cupola rather than vented.

Initial intrusion emplacement is characterised by zoned prograde alteration grading outwards as potassic (magnetite, secondary biotite and Kfeldspar), to inner propylitic (actinolite, epidote), and outer propylitic (chlorite, carbonate) alteration (Figure 3). In sodic rocks albite alteration may dominate over potassic-propylitic alteration assemblages. The early disjointed, high temperature pytmgic A-style quartz veins (in the terminology of Gustafson and Hunt, 1975) develop within the cooling intrusion, while quartz-magnetite (M-style) quartz veins dominate within the prograde magnetite-bearing alteration, and locally contain chalcopyrite-borneite-pyrite mineralisation.

As also recognised in active geothermal systems (Reyes et al., 1993), volatiles venting from intrusions early in the cooling history react with host rocks to produce barren advanced argillic alteration, often migrating laterally as altered ledges, described above.

Hydrothermal fluids accumulate at the apophyses of cooling intrusions which become overpressured and eventually fracture. The resulting pronounced pressure drop promotes the development of B-style quartz veins in the termination of Gustafson and Hunt, 1975). Whereas traditional geological models utilise an excess of fluid pressure over rock tensile strength to promote fracture development, structural systems which localise intrusions may also crack an overpressured caparace. Consequently, sheeted (parallel) quartz veins display dilational tensile fracture/vein relationships, and so may transport ore fluids from magmatic sources at depth, to the cooler caparace, and extending into the wall rocks where mineral deposition occurs. At Cadia Hill, Australia, wall rock hosted sheeted quartz veins vary little through 700 m vertical extent.

Low pH condensate waters develop in the upper portion of the hydrothermal system and react with the host rocks to promote retrograde alteration of the prograde assemblages, including demagnetisation, typically as phyllitic (sericite-silica-pyrite) grading to kaolinitic (chlorite-kaolin-carbonate) alteration, as the collapsing fluids are progressively cooled and neutralised by rock reaction (Figure 3). Strongly acid fluids will also promote the development of advanced argillic alteration, which contains additional alunite-pyrophylite in addition to the phyllitic alteration assemblage. This, and early venting magmatic volatiles, contribute towards the development of lithocaps recognised in the upper levels of porphyry systems. Cooling of the intrusion apophysis promotes collapse of the hydrothermal system and re-entry of ground waters into the porphyry environment and development of extensive pyrite-bearing acid alteration.

While sulfides may be exsolved from the major intrusion source at depth throughout the life of the cooling porphyry, mineral deposition is promoted as the apophysis cools in the at later stages of the porphyry evolution, especially if ore fluids come in contact with low pH condensate waters collapsing into the hydrothermal system. Consequently, sulfides (chalcopyrite-borneite-pyrite) commonly cross-cut or occur in the central portions of quartz veins, and are focused within breccias. Dilational structural settings promote the evolution of ore fluids from the intrusion source at depth to form intrusion-related epithermal deposits (including D veins) at higher crustal levels.

**Exploration implications**

Explorationists need to gain an understanding of the subsurface anatomy of the overprinting intrusion-hydrothermal system to target ore, generally best developed in stockwork and sheeted quartz veins about the intrusion caparace and wall rocks. The magnetic and zoned prograde alteration provides vectors towards the intrusion caparace. However, magnetite destruction and chargeability anomalies recognised in association with the strongly pyritic retrograde phyllilic-argillic and advanced argillic alteration styles need not display a direct relationship with mineralisation, and require an understanding of the overprinting events. Regional structural analysis may be projected into the ore environment combine with careful geological mapping in order to plan the best direction for drill testing of preferentially oriented sheeted vein systems, which both host and transport ore as tension veins. While multiple intrusion events may upgrade some systems, post-mineral intrusions can also stope out ore and so explorationists should carefully consider the implications of barren drill holes within mineralised zones.

Explorationists should not neglect the importance of skarns in porphyry exploration. Many important porphyry systems (Frieda River and Ok Tedi in Papua New Guinea) were identified by follow up of skarn float well downstream, while the presence of skarns helped maintain interest in the Cadia alteration system during exploration, and eventual identification of the Ridgeway deposit, and the Grasberg discovery in West Papua, because during the mining of the Ertsberg skarn.

**CONCLUSION**

Geological models assist the in the prioritisation of exploration projects and play an important role in the estimation of the subsurface anatomy of hydrothermal systems in order plan effective drill testing.

Porphyry Cu-Au mineralisation is best developed at intrusion apophyses and high sulfidation Au mineralisation is focused in the central portions of zoned alteration. Once categorised, barren high zones of advanced argillic alteration can be avoided. An understanding of the different styles of porphyry and epithermal Au mineralisation allows the exploration implications of each style of mineralisation to be applied to individual projects, and so provide a framework for mineral exploration in magmatic arc settings. For instance, quartz-sulfide Au deposits often undergo surficial supergene enrichment and so surface assay data must be treated with caution. The alteration zonation in high sulfidation Au deposits varies according to crustal level, relationship to fluid up flow and style of host rocks. Similarly, the application of the understanding of the processes of ore formation assist in accessing whether an alteration system warrants continued evaluation, and locally aid in provision of vectors to guide further exploration. In low sulfidation gold deposits shallow circulating meteoric waters may deposit banded chalcedony veins which are essentially unmineralised.

While many exploration successes formerly relied upon the recognition of mineralised float during first pass prospecting (Tolukuma, Chatree, Mitwah), where ore systems have been exposed by erosion, it is often now necessary to focus upon techniques which aid in the identification of buried mineralisation, either not exposed by erosion (Nena, Ridgeway), or obscured by post-mineral cover (Rafferty’s Porphyry, Walli; Vera Nancy). It is hoped a better understanding of the nature of porphyry and epithermal Au mineralisation will assist in the evaluation of subsurface geology during exploration.

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REFERENCES


Ronacher, E, Richards, J P, Villeneuve, M E and Johnston, M D, 2002. Short life span of the ore forming system at the Porgera Gold Deposit PNG. Laser \(^{40}Ar^{39}Ar\) dated from rossellite, biotite and hornblende, Mineralium Deposita, 37:75-86.
