WORLD GOLD

PACIFIC RIM EPITHERMAL Au-Ag

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ABSTRACT

Epithermal Au-Ag deposits form in the upper 1 km of the crust and are therefore best preserved in the less eroded Pacific rim arcs, although also recognised elsewhere. Two profoundly different ore fluid types give rise to low and high sulphidation styles apparent as variations in ore and gangue mineralogy as well as characteristic zoned wall rock alteration. Low sulphidation epithermal Au deposits are derived from near neutral composite magmatic-meteoric fluids and divided into a group with a stronger intrusion association within arcs grading in time and space from: quartz-sulphide Au + Cu, to carbonate-base metal Au, and the epithermal quartz Au + Ag, whereas in strongly extensional settings the influx of meteoric waters promotes the development of chalcedony-ginguro banded Au-Ag epithermal veins. In the presence of continental crust particularly in Latin America polymetallic Ag-Au veins represent a Ag-rich equivalent of carbonate-base metal Au and passes upwards to chalcedony-ginguro Au-Ag style. By contrast high sulphidation epithermal deposits are deposited from an acidic magmatic fluid which provided characteristic hydrothermal alteration by reaction with wall rocks grading outwards as mineral assemblages dominated by: vughy silica, alunite, pyrophyllite-diaspore, dickite-kaolin and then illite-smectite neutral clays. Au mineralisation is commonly refractory with enargite deposited dominantly later within the silica zone.

Exploration for epithermal Au deposits benefits from an understanding of the controls to mineralisation which commonly give rise to the development of ore shoots with widest and highest Au grade ore zones. In low sulphidation systems a combination of competent host rocks, dilatant structures, higher grade styles of mineralisation and efficient mechanism of Au deposition, contribute towards ore shoot formation. High sulphidation epithermal Au systems occur in permeable volcanic and breccia host rocks which are linked by major structures to the magmatic source.

INTRODUCTION

Epithermal Au-Ag deposits form attractive bulk low grade open pit and high grade underground mines which are localised about the ‘Pacific rim of fire’ by subduction-related island arcs (SW Pacific floored by oceanic crust) and magmatic arcs (east Pacific floored by continent crust), although also present in other complex arcs (Turkey). Ages vary from Ordovician for the deeply eroded Tasmanides of eastern Australia, to the Cretaceous Okhotsk-Chukotka arc in Far Eastern Russia, and Tertiary age for the majority of systems in the western and southwestern Pacific rim, including many active examples. An understanding of the processes involved in the formation of intrusion-related deposits has been
enhanced by the late Terry Leach’s studies of active arc systems in the Philippines (Corbett and Leach, 1998), while the back arc New Zealand active geothermal examples provided early concepts applicable to smaller group deposits. While the current era of elevated Au price (since 1980) has promoted a vast increase in research on epithermal Au-Ag deposits, this study draws upon field analyses of Pacific rim mines and exploration projects to discuss the exploration implications of the variations in styles of epithermal Au-Ag deposits and the controls to Au mineralisation of interest to explorationists (Corbett, in prep.).

Figure 1. Conceptual model for varying styles arc style porphyry and epithermal Cu-Au-Ag mineralisation (updated from Corbett, 2009; Corbett, in prep., and references therein).

DEFINITION

Epithermal Au-Ag deposits form in the top 1 km of the crust and so dominate in more youthful, less eroded crustal settings. Nevertheless, tectonic processes have preserved many examples in the Tasmanides of eastern Australia. While the original Lindgren (1922) definition restricted these deposits to 300m depths, ‘anything above the porphyry environment’ presently tends to be regarded as epithermal, although the term ‘deep epithermal’ is locally employed to replace Lindgren’s ‘mesothermal’ term in order to avoid confusion with orogenic deposits. Au-rich wallrock porphyry deposits (Cadia Hill, Australia) provide a transition between porphyry and epithermal deposits, in the low sulphidation regime (figure 1). The distinction between low and high sulphidation epithermal (figure 1; Corbett and Leach, 1998 and references therein; Corbett, 2009) is best considered for explorationists as two quite different hydrothermal fluids which prove varied ore and gangue mineralogies and zoned wall rock hydrothermal alteration, along with practical features such as metallurgical characteristics and precious and base metal ratios. It is therefore critical for explorationists to recognise the individual deposit types in order to access how to explore for epithermal deposits and evaluate any discoveries.
LOW SULPHIDATION EPITHERMAL

Low sulphidation epithermal Au deposits are derived from dilute reduced hydrothermal fluids which contain S as $\text{H}_2\text{S}$ and display variable interplays of magmatic and meteoric fluid components. Zoned wall rock hydrothermal alteration, classed as neutral chloride, grades outwards from illite to smectite, and many deposits are capped by acid sulphate alteration zones characterised by cristobalite, kaolin and minor alunite. The several different deposit styles (figure 1) are classified from changes in ore and gangue mineralogy (including metal contents) and progressively develop in time and space as ore fluids evolve. Deep magmatic sources for heat, metal and volatiles drive circulating cells of hydrothermal fluids which travel to higher crustal levels within dilatant structures. During this migration fluids evolve from magmatic-dominant at depth to meteoric-magmatic at elevated crustal levels, where higher precious metal grade deposition typically occurs. Consequently, some veins deposited from dominantly shallow circulating meteoric, waters which have not come in contact with the magmatic source for metals and may contain only barren quartz and possibly adularia while most Au-Ag is considered (Corbett, 2008) to occur in the less volumetrically significant sulphide-bearing magmatic component.

Two groups of deposits result from divergent fluid flow trends for the mineralised magmatic component (figure 1). One trend typically within arcs (mainly SW Pacific rim) occurs as: quartz-sulphide $\text{Au} + \text{Cu}$ -> carbonate-base metal $\text{Au} ->$ epithermal quartz $+\text{Ag}$. In strongly extensional settings (e.g., Mexico; Peru; Deseado Massif, Argentine Patagonia) the progressive introduction of quartz and lesser adularia from meteoric waters is associated with a trend of ore styles classed as: quartz-sulphide $\text{Au} + \text{Cu}$ -> polymetallic Ag-Au -> chalcedony-ginguro Au-Ag. and more extensional inter-arc extension or back arc settings hosted by volcanic sequences commonly underlain by continental crust in Latin America ( ). These fluid flow paths (figure 1) are the arc-related and in extensional settings and so the individual styles of low sulphidation epithermal Au deposits include:

Quartz sulphide $\text{Au} + \text{Cu}$ deposits develop early in the paragenetic sequence as the ore fluid exsolves from the magmatic source and typically comprise quartz with auriferous pyrite varying to include chalcopyrite, pyrrhotite and specular haematite at deeper crustal level high temperature conditions, or marcasite, opal and ‘grey silica’ at shallow crustal level low temperature conditions (Corbett and Leach, 1998) At deeper levels ore fluids typically exploit pre-existing structures or breccias, but at elevated crustal settings may occur within dilatant structures, commonly as sheeted veins. Mineral deposition by cooling provides modest Au grades ( <2 g/t), although high grade examples are locally recognised (300g/t at Kencana Gosowong, Indonesia, below) where other mechanisms of Au deposition prevail. Gold is generally high fineness with typical Ag:Au ratios >1. The common coarse pyrite hosts free Au on fractures and grain boundaries and so this group of deposits generally display good metallurgy forming ideal heap leach operations (Round Mountain & Sleeper, Nevada; San Cristobal, Chile) which might facilitate exploitation of low Au grade ores. ‘Grey silica’ comprises chalcedony with microfine pyrite formed by rapid quenching of the ore fluid and, as Au may be encapsulated in microfine pyrite and so this group of deposits commonly host refractory ores (Kerimenge & Lihir, Papua New Guinea). Some other examples of quartz-sulphide Au ore systems include Mineral Hill, Adelong, Mt Wright, Paulsens, Australia; Hamata & Bilimoia, PNG; Emperor and Crianiu, Fiji. Caution is required as quartz-sulphide ore systems are notorious for near surface supergene Au enrichment (below).

Many quartz-sulphide veins, particularly with the addition of base metal sulphides and carbonate, might be included within the D vein classification of Gustafson and Hunt (1975) and so are used by explorationists as vectors towards porphyry intrusions (Corbett, in press). Some workers (Thompson, et al., 1999) place quartz-sulphide Au deposits in the ‘intrusion-related Au’ class.
Carbonate-base metal Au deposits (Leach and Corbett, 1993; Corbett and Leach, 1998, Corbett, in prep.) are some of the most prolific Au producers in the SW Pacific rim (Porgera Waruwari, Hidden Valley, Misima, Woodlark, Waifi Link Zone, Papua New Guinea; Cowal, Kidston, Mt Leyshon, Mt Rawdon, Australia; Gold Ridge, Solomon Islands; Acupan, Antamok, Victoria, Bulawan, Philippines; Kelian, Mt Muro, Cikotok district, Indonesia, and many others). Examples are recognised in the Americas (Frute del Norte, Ecuador; Golden Sunlight, Montana Tunnels, Cripple Creek, USA; Rio de Medio, San Cristobal, Chile). Carbonate-base metal Au deposits are characterised by early pyrite + quartz (of the quartz-sulphide Au stage) followed by sphalerite>galena and local chalcopyrite or Ag sulphosalts followed by variable carbonate, but dominated by Mn-carbonates (typically rhodochrosite, below), and locally additional quartz. There is a considerable vertical range of formation evidenced by a change in ore mineralogy, particularly sphalerite colour varying with decreased depth of formation form deeper level Fe>Zn black, through brown, to red, and yellow and white Fe<Zn sphalerite formed under low temperature conditions at elevated crustal settings. Fe sulphides also vary from pyrrhotite and chalcopyrite at depth, through central pyrite, to marcasite at elevated settings. Au deposition by the mixing of rising sulphide-bearing hydrothermal fluids with oxidising bicarbonate waters provides Au grades in the 2-10 g/t range with Ag:Au ratios >1 (below). Ores typically occur as stockwork fractures (Porgera, Cowal) disseminations (Gold Ridge, Woodlark), sheeted veins (Kidston) and breccia matrix (Mts Leyshon & Rawdon), while fissure veins are well represented (Cikotok, Antamok, Misima) and there is a common association with phreatomagmatic (diatreme) breccias (Acupan, Bulawan, Montana Tunnels, Cripple Creek, Kelian) or deeper level magmatic hydrothermal breccias (Kidston, Golden Sunlight), or domes (Drake, Australia; Porgera). Many individual mines display quite variable metallurgy, Au grade and Ag:Au ratios, generally associated with a variety of mineralisation styles and controls to mineralisation. Deposits commonly pass in style from quartz-sulphide Au ± Cu, to carbonate-base metal Au and then epithermal quartz Au ± Ag through time and space.

Epithermal quartz Au ± Ag (modified from epithermal quartz Au-Ag in Corbett and Leach, 1998) mineralisation is characterised by gangue-poor, high fineness, high to locally bonanza grade, free Au, which commonly overprints quartz-sulphide (Round Mountain & Sleeper, USA; Emperor, Fiji; Thames, New Zealand) or carbonate-base metal Au ore systems (Porgera Zone VII, Mt Kare, Edie Creek, Papua New Guinea). The addition of chalcedony-adularia from circulating meteoric waters may provide banded veins with high fineness free Au in contrast the ginguro bands described below (Sleeper; Gosowong, Indonesia). The main characteristic of these ores is to provide extremely irregular Au grades and of course considerably improve the economics of some projects.

Polymetallic Ag-Au veins dominate in Latin America as Ag-rich variants of the carbonate-base metal Au style (Corbett, 2008) and tend to occur mostly as quartz-rich fissure veins (Arcata, Cayalloma, Peru; Palmarine, Fresnillo, Pinos Altos, Mexico). As for carbonate-base metal Au there is a wide temperature range evident in sphalerite colour from white through yellow red brown and black (above). The mineralogy, which includes elements of quartz-pyrite Au ± Cu mineralisation deposited early in the paragenetic sequence, varies from carbonate-base metal Au with the addition of Ag sulphosalts minerals (e.g., argentite-acanthite, freibergite as the Ag-rich tennantite-tetrahedrite). In some instances, particularly at high crustal levels and late in the paragenetic sequence, entry of meteoric waters into the ore environment may result in the addition of substantial quartz (chalcedony), adularia and quartz replacing platy calcite to the ore mineralogy, as part of the transition from polymetallic Ag-Au to chalcedony-ginguro Au-Ag (figures 1 & 2). This transition, with associated rise in Au-Ag contents and local decline in Ag:Au ratio, is characterised by white low temperature sphalerite, argentite-acanthite and relatively coarse cubic pyrite or marcasite, which passes with additional fluid evolution to fine black sulphides.

Chalcedony-ginguro Au-Ag banded epithermal mineralisation (Corbett, 2008, 2009, in prep.) represents the most widely recognised form of low sulphidation epithermal Au mineralisation
discussed in the geological literature, where they may be termed adularia-sericite or quartz-adularia. Quartz is dominantly chalcedony, while the adularia alteration which might lie within the K-rich wall rocks is commonly confused as a vein adularia and wrongly cited as evidence of boiling, which is not an essential component in this model. Chalcedony-ginguro mineralisation comprises generally low temperature microfine chalcedony as the main form or quartz, although saccharoidal and crystalline quartz can also occur, with characteristic black sulphidic ginguro and local adularia, early quartz replacing platy carbonate or post-vein calcite. The word ginguro is derived from the 19th century Japanese miners who recognised the association of elevated precious metal grades with this material as bands, breccia clasts and matrix. Ginguro comprises fine pyrite, Ag sulphosalts, electrum, free Au, minor chalcopyrite and local components such as selanides (Midas, USA). Zoned marginal wall rock alteration grades laterally outwards from illite to smectite and may be used as a vector towards mineralisation (figure 3). Similarly, chalcedony-ginguro Au-Ag vein systems are vertically zoned (figure 3) from barren surficial acid sulphate caps, sinter and eruption breccias, downwards to sheeted (stockwork) veins which may be emplaced into the base of eruption breccias with low grade mineralisation, to fissure veins which host most economic Au-Ag mineralisation which may terminate downwards in quartz veins with elevated base metal contents but sub-economic Au-Ag. Most fissure veins occur in dilatant fractures which host wider and higher Au grade vein portions within ore shoots (below).

Figure 2. Transition from polymetallic Ag-Au to chalcedony-ginguro Au-Ag showing some of the controls to mineralisation in a typical Argentine Patagonia setting (from Corbett, in prep.).

Sediment hosted replacement Au or Carlin style Au deposits develop by the interaction of a low sulphidation quartz-sulphide Au style fluid with reactive marr (impure limestone or calcareous shale) host rocks, typically within strongly extensional settings (Corbett and Leach, 1998). The presence of anomalous Sb, Hg, Ba in addition to the strongly As-rich pyrite suggest an elevated setting of formation. Although dominant in in the Carlin and Battle Mountain trends, western USA, which reflects deep crustal source structures, these deposits are recognised throughout the Pacific rim (Mesel, Indonesia; Bau, Malaysia; Sepon, Laos). Many systems display a progression from steep plunging
feeder structures with elevated precious metal grades to higher crustal level lithologically controlled lower Au grade ores. The alteration and mineralisation process (Leach, 2004) proceeds as primary permeability in the host rocks and influences dolomitisation of the calcite to provide additional open space secondary permeability to aid hydrothermal fluid flow. Features such as stylolites and breccias testify to the dissolution of carbonate. Silicification is associated with the deposition of generally refractory Au within microfine arsenian pyrite. While favoured as oxide targets many sediment hosted replacement Au deposits have been of a sufficient size to justify the high cost treatment of the sulphide ore.

CONTROLS TO LOW SULPHIDATION EPITHERMAL Au-Ag

Continued comparisons between many Pacific rim epithermal ore systems has enhanced suggestions (Corbett, 2007; in prep.) that best low sulphidation epithermal mineralisation (wider and higher Au grade veins) occurs in ore shoots developed by the coincidence of several controls defined as:

*Host rocks* for the development of quality epithermal mineralisation should be sufficiently competent to host throughgoing fractures. Quality hosts include andesite, basement metamorphics, or silicified non-reactive sandstone and locally welded tuff or intrusive domes, although some rhyolite domes form stockwork rather than fissure vein systems. The restriction of quality mineralised veins to the intersection of feeder structures and competent host rocks in interlayered volcanic sequences provides flat plunging ore shoots. Some important exploration successes include cases where incompetent clay altered permeable tuffs overlie competent mineralised hosts, and have not only acted as aquitards to impede upward vein formation to result in higher Au grade vein ores at depth, but obscure the underlying mineralised veins (Hishikari, Japan; El Peñón, Chile; Chatree Thailand [Cumming et al., 2008] and parts of districts at Palmarejo, Mexico; Arcata Peru; and Drake, Australia [Cumming et al., 2010]).
Structure influences vein formation as dilatant fractures which facilitate fluid flow and structural intersections act as sites of fluid mixing and efficient Au deposition. Several structural environments envisaged for vein formation (figure 4; Corbett, 2012 & in prep.) include:

- Listric or normal faults developed in strongly extensional settings host vein mineralisation only in the steeper dipping portions providing flat plunging ore shoots (figure 4; Arcata, Peru; Pinos Altos, Palmarejo, Mexico; Sleeper, Nevada).
- Oblique convergence contributes towards the development of dilatant structural sites within flexures or link structures (figure 4) commonly underlying pull-apart basins within negative flower structures (Waihi, New Zealand). Steep plunging ore shoots commonly develop where flexures overprint steep dipping portions of listric faults (Vera Nancy, Australia; Palmarejo, Mexico).
- In compressional settings flatter dipping portions of thrust faults may host shallow plunging ore shoots which may be blind at the surface (figure 4; Kencana at Gosowong, Indonesia; Hamata at Morobe Goldfield, Papua new Guinea). Elsewhere in compressional settings steeply dipping veins form within flexures close to parallel to the direction of compression within conjugate fractures. For instance in Argentine Patagonia most vein systems exploit NW and NE conjugate fractures with an emphasis upon the NW structures, with WNW-EW trending ore shoots.

Structure therefore represents the greatest influence upon the overall shape of ore shoots.

Mechanisms of Au deposition have the greatest influence upon Au grade as more efficient mechanisms of Au deposition contribute towards the deposition of elevated Au grades (Corbett and Leach, 1998; Leach and Corbett, 2008; Corbett, in prep.) as:

- Boiling often promoted in the geological literature as a mechanism of Au deposition, deposits gangue minerals such as adularia and quartz after platy calcite, possibly chalcedony and no doubt some Au-Ag. However, precious metals are not intimately associated with minerals that
are cited as evidence for boiling, but rather sulphides, for which other mechanisms of Au
deposition are preferred. Boiling is not preferred here as the universal mechanism of Au
deposition.

- Sulphidation reactions have been cited (T. Leach, unpubl.) as involved in Au deposition where
bisulphide complexes carrying Au are destabilised during the formation of pyrite through
reaction with Fe within volcanic (andesite) wall rocks to deposit Au (Lihir, Papua New
Guinea).

Figure 5. Fluid mixing as mechanisms of bonanza Au deposition (Corbett, in prep, modified
from Corbett, 2008).

- Cooling accounts for much of the Au deposition associated with sulphides throughout low
sulphidation epithermal veins where slow cooled coarse sulphides contain modest precious
metal grades (most quartz-sulphide Au + Cu deposits).
- Rapid cooling evidenced by fine grained sulphides is commonly associated with elevated Au
grades, but refractory ores (Lihir, Kerimenge, Papua New Guinea). Mixing of rising ore fluids
with deep circulating ground waters may provide elevated metal grades, evidenced by the
intergrowths of low temperature quartz (opal) with higher temperature sulphides (dark
sphalerite).
- Mixing of rising ore fluids with near surficial oxygenated ground waters destabilises bisulphide
complexes carrying Au and deposits elevate Au grade mineralisation evidenced by hypogene
haematite within the ore assemblage (Kencana at Gosowong, Indonesia; Kubaka, Eastern
Russia) or immediately overlying the ore (Fresnillo, Mexico).
- Mixing of rising ore fluids with bicarbonate waters, derived from the condensation of CO2
exsolved from cooling felsic intrusions and rising boiling fluids, destabilises bisulphide
complexes carrying Au and deposits elevate Au mineralisation in association with carbonate, typically within the carbonate-base metal Au – polymetallic Ag-Au deposits. Au grades are in part related to the type of carbonate declining from (uncommon) Fe through Mn, and mixed Mg-Ca carbonates, such that most better quality deposits feature rhodochrosite (Mn carbonate) and are evidenced in surface exploration by the presence of MnO.

- Mixing of rising ore fluids with near surficial low pH acid sulphate waters is a most efficient mechanism to destabilise bisulphide complexes and so is associated with some of the highest Au grades evidenced by hypogene kaolin (Sleeper, USA; Hishikari, Japan; San Jose, Cerro Moro, COSE, Argentine Patagonia; Guadalupe at Palmarejo, Mexico; Arcata, Peru; San Cristobal, Bolivia). Clay altered incompetent acid sulphate caps are incompetent and restrict upward development of veins which at depth might then display elevated Au grades (Guadalupe, at Palmarejo, Mexico).

**Dilution** downgrades precious metal contents such as:

- Post-mineral barren dykes (Chatree, Thailand).
- Post-mineral calcite (Golden Cross, New Zealand).
- Gangue minerals within the vein such as chalcedony deposited from meteoric waters. Epithermal veins are deposited from an interplay of barren meteoric waters (chalcedony) and a magmatic waters (mineralised sulphide component), and so some vein systems have been recognised passing downwards from barren chalcedony dominated in the upper levels to mineralised at depth (San Jose, Cerro Moro, Argentine Patagonia).

**Supergene enrichment** is most commonly recognised in systems with a component of quartz-sulphide style Au mineralisation, evidenced in oxide ores by FeO boxworks after weathered pyrite. Au concentrates at the surface in FeO after sulphides, base of oxidation and collapsing down faults, where it may be evidenced by a decline in Ag:Au ratios. While a disappointment for explorationists where surface anomalies are not substantiated by drilling, some ore bodies develop in the supergene environment (San Cristobal, Chile; Cirianiu, Fiji; McKinnons, Australia).

**Styles of Au mineralisation** discussed above contribute towards variations in Au grade and metal ratios in systems which are zoned spatially and temporally.

**HIGH SULPHIDATION EPITHERMAL Au ± Ag**

High sulphidation epithermal Au ± Ag mineralisation is deposited from oxidising, hot acidic fluids in which S occurs as SO₂ and so displays characteristic ore mineralogy and zoned hydrothermal alteration. The particular process of formation places a physical separation between the source intrusion and epithermal mineralisation (e.g., 1km between Far South East porphyry Cu-Au and Lepanto high sulphidation Au, Philippines; Corbett and Leach, 1998). The ore fluid commonly breaks into an initial fast travelling volatile-rich phase and later slower liquid-rich phase. As volatile-rich fluids vent from cooling intrusions and rise rapidly, within a structure without reaction with host rocks or ground waters, depressurisation results in exsolution of SO₂ which then becomes oxidised to progressively form a more acidic fluid as it rises to higher crustal levels. At epithermal crustal levels the hot acid fluids then become progressively cooled and neutralised by rock reaction, typically within permeable reactive volcanics or breccias, and so provide characteristic zoned hydrothermal alteration, grading outwards from the feeder structure as mineral assemblages dominated by: residual vughy silica, alunite, pyrophyllite-diaspore, dickite, kaolin to marginal illite.

The later liquid-rich phase commonly deposits Au-Ag mineralisation with enargite, including the low temperature polymorph luzonite, and pyrite along with gangue of alunite, barite and local sulphur. In most instances the later mineralisation brecciates the core vughy silica, and locally marginal silica-alunite, close to the feeder structure. This separation between volatile and liquid-rich events is not
always easily recognised where sulphides appear to be intergrown with vugly silica. While high sulphidation epithermal deposits are Au-rich in the SW Pacific rim, in Latin America these deposits become Ag-bearing and locally Ag-dominant. Examples in Eastern Australia include Peak Hill, Gidginbung and Dobroyd in NSW and Mt Mackenzie in Queensland, and while some important examples occur in the SW Pacific rim (Lepanto, Martabe, Indonesia; Nena & Wafi, Papua New Guinea; Mt Kasi, Fiji), the home of high sulphidation Au deposits is in the high Andes (Yanacocha, La Arena, Pierina, Peru; Pascua-Lama, El Indio, La Coipa, Chile; Veladero, Argentina). As apparent in the mining of Gidginbung and Peak Hill, and exploration at Wafi, Papua New Guinea (Erceg et al., 1991), these deposits are commonly worked only in the oxide zone as sulphide ores display refractory metallurgy.

Steam heated blankets from the reaction of evolved acid ground waters above the palaeo water table and are preserved as caps to poorly eroded high sulphidation epithermal Au deposits, typically in the arid high Andes. These laterally continuous zones comprise cristobalite, kaolin, a characteristic powdery alunite and local sulphur, and although anomalous in Hg contain no Au and locally very weakly anomalous Ag. There is commonly a silica-rich base formed at the palaeo water table. The oxidising acid waters which react with wall rocks to form steam heated alteration locally collapse into the ore environment and through hypogene oxidation may participate in the deposition of elevated Au grades (Pierina, Peru; locally at Veladero, Argentina).

CONTROLS TO HIGH SULPHIDATION Au

The model for the origin of high sulphidation epithermal Au deposits is dependent upon evolution of the hydrothermal fluid during rapid migration from an intrusion source at depth to an elevated crustal setting. Consequently, there is a strong association between major structures and high sulphidation epithermal Au deposits although the actual mineralisation may occur in smaller scale subsidiary fracture systems (Corbett, 2012).

The nature of mineralised fluid flow, within wall rocks which provides the overall form of high sulphidation epithermal Au deposits, is controlled by:

- Permeable lithologies such as fiamme tuffs (Pierina, Peru; Quimsacocha, Ecuador), basement conglomerate (Wafi, Papua New Guinea) or sandstone (La Arena, Peru), although ore shoots occur at intersections with feeder structures with permeable lithologies (La Coipa, Chile; Nena, Papua New Guinea; Sipan, Peru; Gidginbung, Australia).
- Structures as dominantly dilatant fracture-veins, (El Indio, La Coipa, Chile; Peak Hill, Australia) or intersections of structures with breccia pipes (Lepanto, Philippines) or permeable lithologies (Nena, Papua New Guinea).
- Breccias, as phreatomagmatic (diatreme) breccia pipes (Pascua-Lama, Chile-Argentina; Veladero, Argentina; Yanacocha, La Virgin, Peru; Lepanto, Philippines; Miwah, Indonesia) although the diatreme pipe may locally predate the high sulphidation system (Wafi, Papua New Guinea). Elsewhere, brecciated dome margins also provide permeability (Mt Kasi, Fiji; Yanacocha, Peru).
- In many cases earlier lithological control to hydrothermal alteration might overprinted by a later structural control to mineralisation within veins and breccias (Peak Hill, Australia; Pascua-Lama, Chile-Argentina).

Refractory metallurgy of high sulphidation epithermal Au ore has restricted the mining of many deposits to oxide ores, terminating downward intersection with sulphide ore (Gidginbung, Peak Hill, Australia; Sipan Peru). The high As content of the enargite-bearing sulphide can be a metallurgical issue. However, some lower temperature, higher crustal level examples evolve in time and space to display improved metallurgy and higher Au grades (below).
DOES INTERMEDIATE SULPHIDATION EXIST?

The Mt Carlton deposit in Queensland displays advanced argillic alteration with initial enargite-pyrite with low grade Au mineralisation overprinted by low-Fe yellow sphalerite and Ag sulphosalts with associated high Ag grade mineralisation, as an example of the transition from high to lower sulphidation mineralisation. Sufficient cooling and neutralised by reaction with wall rocks or ground waters, of a high sulphidation fluid, particularly at an elevated crustal setting, may facilitate a change from a high to lower sulphidation style hydrothermal fluid. A rare intermediate sulphidation mineralisation might be characterised by the presence of tennantite in these circumstances. At the El Indio mine, Chile, the bonanza Au grade direct shipping ore is interpreted by many workers as a later low sulphidation overprint on high sulphidation, also apparent in the Viento vein portion from the south to northern change in mineralogy as; low temperature high sulphidation enargite-luzonite-pyrite, to carbonate-base metal Au with galena, sphalerite and rhodochrosite, and then epithermal quartz Au ± Ag style quartz with free Au, at the north limit of drilling (Corbett and Leach unpubl reports; Heberlein, 2008). Similarly, later quartz-sulphide-carbonate-Au veins overprint earlier advanced argillic alteration related to high sulphidation Au mineralisation at Wafi, Papua New Guinea. Although not common, some high sulphidation deposits evolve to host locally higher Au grades and improved metallurgy.

The recent term “intermediate sulphidation” (Einaudi et al., 2003), defined as containing Fe-poor sphalerite, tennantite-tetrahedrite and lacking pyrrhotite (Sillitoe and Hedenquist, 2003), works well for the local transition from high to low sulphidation. However, this terminology has also been extended (Sillitoe and Hedenquist, 2003) to include the entire suite of sulphide-bearing low sulphidation epithermal deposits originally classified as low sulphidation carbonate-base metal Au (Leach and Corbett, 1994) and the Ag-rich variant, polymetallic Ag-Au deposits. The Fe-poor (yellow) sphalerite definition should restrict these deposits to low temperature which is not always the case. For example, Sillitoe and Hedenquist (2003) attribute Kelian, Indonesia, to the intermediate sulphidation class, although it contains black (high temperature) Fe-rich sphalerite and pyrrhotite, and so more correctly fits the carbonate-base metal Au style where is placed by Corbett and Leach (1998). The similarity of hydrothermal wall rock alteration in both intermediate and low sulphidation, and pronounced contrast with alteration associated with high sulphidation epithermal Au deposits, is consistent with the inclusion of the carbonate-base metal Au and intermediate sulphidation as sulphide-rich sub-type of low sulphidation, deposited from a magmatic fluid which evolves to low sulphidation where mixed with substantial meteoric waters (above). There is no distinctly different intermediate sulphidation hydrothermal fluid of the same calibre as the difference between high and low sulphidation. Consequently, the original (low sulphidation) carbonate-base metal Au terminology (Leach and Corbett 1994, Corbett and Leach, 1998) is preferred to the recent intermediate sulphidation as the former more correctly accounts for wide temperature range and the paragenetic sequence from quartz-sulphide Au ± Cu to carbonate-base metal Au and on to epithermal quartz Au ± Ag (above).

EXPLORATION IMPLICATIONS

Epithermal Au deposits display well documented controls to mineralisation which may contribute towards the development of ore shoots, characterised by higher Au grades and wider ore zones, with profound exploration implications as:

- Volcanic successions which host epithermal mineralisation should be properly understood. Low sulphidation epithermal Au-Ag veins which develop in competent hosts may be obscured by incompetent commonly clay altered overlying (permeable) rocks. By contrast, high sulphidation epithermal Au mineralisation preferentially develops in permeable host rocks. Growth faults may be identified from this understanding of volcanic successions as important hosts to mineralisation (Palmarejo, Mexico; Waihi, New Zealand; Kupol, Eastern Russia).
- Models for low sulphidation epithermal Au mineralisation should take greater consideration of Au deposition by cooling for the bulk of mineralisation and fluid mixing for the formation of
bonanza Au grades. While MnO provides evidence of carbonate-base metal style Au (including polymetallic Ag-Au) mineralisation in weathered surface exposures, highest Au grades result from the mixing of rising ore fluids with acid waters, evidenced the presence of kaolin in the ore assemblage. Consequently, barren acid sulphate caps represent prime exploration targets.

- Drill testing of epithermal Au deposits should understand the orientation of ore shoots, driven in low sulphidation deposits by the interaction of structure and lithology, particularly as listric faults provide flat plunging ore shoots, while oblique convergence results in the formation of steep plunging ore shoots. Similarly, ore shoots in high sulphidation epithermal deposits are commonly localised at the intersections of feeder structures and permeable lithologies or breccias.

- An understanding of the wide variety of high and low sulphidation epithermal Au mineralisation styles, including the evolution from high to low sulphidation, provides a critical basic first pass exploration tool as the different ore styles display variations in:
  - Zoned hydrothermal alteration, manifest in clay studies and geophysical magnetic, chargeability and resistivity responses,
  - Au grades varying from bulk low grade open pittable to bonanza Au grade underground operations which should be evaluated differently,
  - Metallurgical response in order to allow for the exploration implications of difficult metallurgy of the sediment hosted replacement Au or quenched quartz-sulphide styles, versus bonanza grade free Au elsewhere.

One of the challenges in epithermal exploration remains to correctly access the different styles of advanced argillic alteration classed (Corbett, 2008) as: acid sulphate caps to low sulphidation epithermal, steam heated blankets overlying high sulphidation epithermal Au, zoned advanced argillic alteration within high sulphidation Au and porphyry-related advanced argillic alteration which varies from structurally controlled barren shoulders at depth (Corbett and Leach, 1998) to broader scale lithocaps within higher crustal level permeable host rocks (Sillitoe, 1995). Each displays profoundly different relationships to mineralisation and can be used as vectors to varying styles of porphyry and epithermal mineralisation.

CONCLUSIONS

Epithermal Au deposits formed in the upper portion of the crust display ultimate intrusion sources for precious metals although with different fluid flow paths and various interplay of magmatic and meteoric waters. Exploration would be enhanced by the understanding of the controls to mineralisation, including the different styles of mineralisation, just as the estimation of ore shoot geometries will aid the planning of drilling programs. The original carbonate-base metal Au terminology is preferred for the sulphide-rich low sulphidation epithermal ores, to the more recent intermediate sulphidation epithermal class, as it better accounts for the type of ore fluid, variations in temperature of formation, and paragenetic sequence.

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REFERENCES CITED
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