EPITHERMAL AU-AG DEPOSIT TYPES – IMPLICATIONS FOR EXPLORATION….. For the Proexplo Conference Peru May 2005

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ABSTRACT

Explorationists should be aware that differences between epithermal Au-Ag deposit types influence responses in exploration to geochemical and geophysical techniques, as well as the economic value of projects. An understanding of the characteristics of these styles can aid in the prioritisation of the more prospective projects and assist in dealing with pitfalls such as supergene enrichment and irregular Au distribution. Importantly, the exploration implications of deposit style facilitates targeting of higher Au-Ag grade ores.

Traditional subdivisions between high and low sulphidation are further enhanced by analysis of different styles of low sulphidation epithermal Au-Ag. Intrusion-related low sulphidation Au-Ag mineralisation grades temporally and spatially from initial quartz sulphide Au $\pm$ Cu mineralisation to that termed carbonate-base metal Au using SW Pacific examples, and polymetallic Ag-Ag in the Andes. Epithermal terminology is only used for deposits developed at highest crustal levels. The intrusion-related low sulphidation epithermal-quartz Au-Ag deposits, which display links the quartz sulphide Au deposits, are gangue-poor and may host bonanza Au. The low sulphidation epithermal banded chalcedony-ginguro Au-Ag deposits (formerly termed adularia-sericite epithermal Au-Ag) host local bonanza Au-Ag in the ginguro sulphidic layers and may display links to deeper level polymetallic veins, and are common in rift settings. Low sulphidation deposits display varying degrees of flooding by quartz deposited from circulating meteoric-dominated waters and hence the association with dilatant structural settings. High sulphidation Au-Ag deposits develop as a magmatic vapour rich fluid depressurises during the rapid rise to higher crustal levels without interaction with ground waters, and so forms an extremely acidic fluid. The progressive cooling and neutralisation of this acid fluid by wall rock reaction produces the characteristic zoned alteration which is overprinted by sulphides, typically pyrite-enargite and local covellite, with a gangue including alunite and barite.

INTRODUCTION

It is important for exploration geologists to recognise the different types of epithermal Au-Ag mineralisation and the links between them in ore systems. The economic value of a project is influenced by the style of epithermal mineralisation, as some styles display higher Au grades, different Au:Ag ratios and metallurgical characteristics. In the exploration environment there may be considerable variation in pathfinder geochemical signatures and geophysical chargeability and resistivity responses. All these features can be best categorised by geological models built up by analyses of many exploration field examples (Corbett, 2004).

An understanding of epithermal deposit type may facilitate the more rapid identification of economic mineralisation and rejection of unsuitable projects, and also allow the explorationist to better envisage the subsurface anatomy of an exploration project in order to plan drill testing. However, explorationists must remain flexible in the use of geological models for epithermal deposit types and be ready to modify any existing exploration model as new data emerges. The science we use is constantly developing, and so we must always be ready to accommodate geological scenarios which do not fit existing frameworks. Careful preservation of the original factual data is essential in order to facilitate later variations in interpretation.

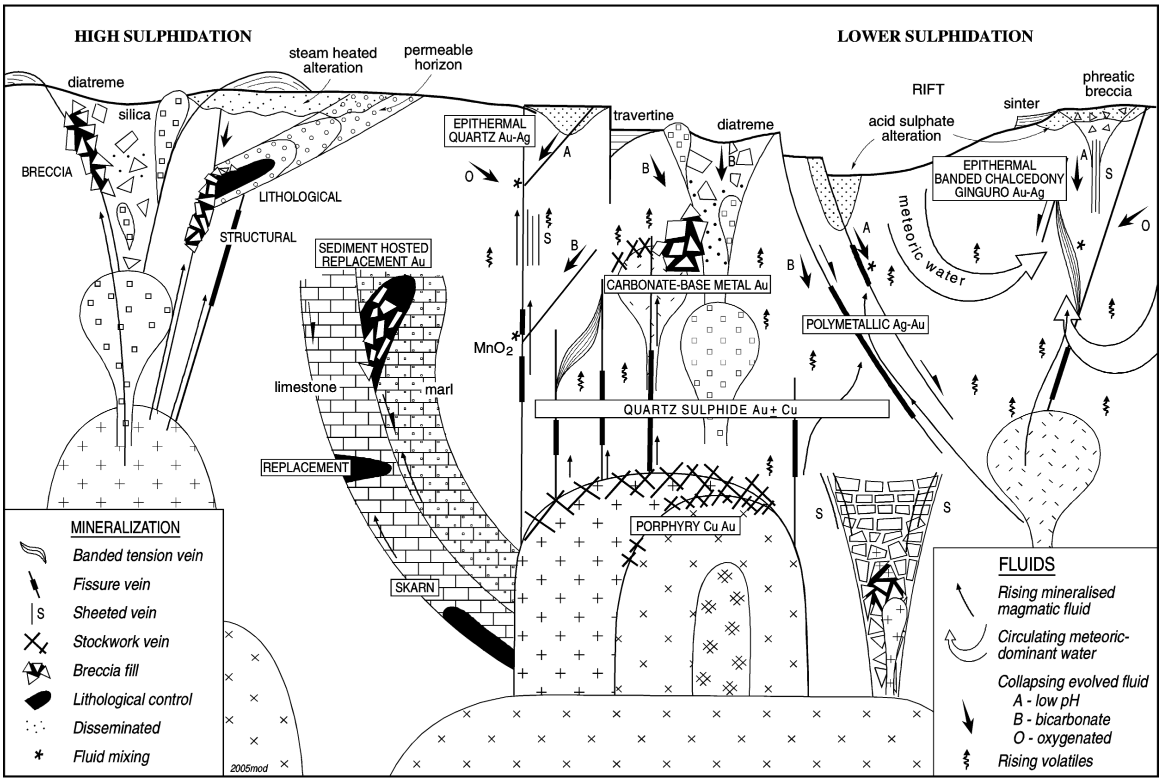

Figure 1. Conceptual model illustrating styles of magmatic arc Au-Ag-Cu mineralisation.

EPITHERMAL TERMINOLOGY

Schemes for the classification of epithermal Au-Ag deposit styles began with the initial recognition of the development of epithermal mineralisation at shallower crustal levels than mesothermal and porphyry deposits (Lindgren 1922, 1933), and progressively incorporated different deposit styles using the acid sulphate and adularia-sericite terminology (Hayba et al., 1985; Heald et al., 1987), which later became the high and low sulphidation classifications (Hedenquist 1987; White and Hedenquist, 1990). This classification relied upon the sulphidation state of sulphur within characteristic mineral assemblages such as enargite for high sulphidation, and pyrite, galena, sphalerite for low sulphidation, and not the overall sulphide content, as well as recognition of associated alteration types. Using mainly Southwest Pacific rim deposit examples, low sulphidation Au $\pm$ Ag $\pm$ Cu deposits have for some years divided into an intrusion-related sulphide-rich group, grading from early to late and generally deeper to shallower crustal levels as: quartz-sulphide Au $\pm$ Cu, carbonate-base metal Au, (including the Andean polymetallic Au-Ag veins), and epithermal quartz Au-Ag, the latter distinguished from the low sulphidation sulphide-poor banded epithermal quartz vein deposits (Leach and Corbett, 1993, 1994, 1995; Corbett and Leach 1998; Corbett, 2002a). More recently, Sillitoe and Hedenquist (2003) cite a similar sulphide distinction documented from Nevada by John (2001) in attributing part of the carbonate-base metal Au – polymetallic Au-Ag portion of the intrusion-related low sulphidation group of deposits to the intermediate sulphidation epithermal Au class, as categorised by Einaudi et al. (2003). The intermediate sulphidation terminology is applicable to the rare settings where hydrothermal fluids evolve from high to low sulphidation, commonly with tennantite-bearing mineral assemblages (Wafi, Papua New Guinea; Leach, 1999: Viento-Cuarzo, El Indio district). However, the existing terminology is preferred for the continuum of low sulphidation deposit types identified in numerous examples as passing through early low sulphidation quartz-sulphide Au, to carbonate-base metal Au – polymetallic Ag-Ag and later epithermal quartz Au-Ag mineralisation, generally with overprinting ore mineralogies (Corbett and Leach, 1998 and references therein). Although these workers (Sillitoe and Hedenquist, 2003; Einaudi, 2003) distinguish between deposits containing Zn-rich sphalerite as intermediate sulphidation and Zn-poor sphalerite as low sulphidation (cut off as 20 mole percent FeS), sphalerite composition varies progressively with temperature (described below; Corbett and Leach, 1998) favouring the existing simpler low sulphidation terminology for the carbonate-base metal Au – polymetallic Ag-Au deposits.

Epithermal Au deposits extend from shallow crustal levels (<1 km) to near porphyry levels where the low sulphidation quartz-sulphide Au ± Cu deposits are transitional to D veins described in the porphyry Cu literature (Gustafson and Hunt, 1975), and so approach mesothermal levels of formation in the original definition of the term (Lindgren, 1922). The term epithermal is therefore herein only included in the names of deposits formed at shallow crustal levels (epithermal quartz Au-Ag and epithermal banded chalcedony-ginguro Au-Ag), and not the quartz-sulphide Au ± Cu and carbonate-base metal Au – polymetallic Ag-Ag styles. Low sulphidation epithermal Au-Ag deposits are classified as two end members. The epithermal quartz Au-Ag deposits were defined (Leach and Corbett, 1995; Corbett and Leach, 1998) as the epithermal end member of the intrusion-related series, using mainly southwest Pacific rim examples, and so commonly overprinting quartz-sulphide Au or carbonate-base metal Au mineralisation within magmatic arcs. The epithermal banded chalcedony-ginguro Au-Ag veins (formerly termed epithermal adularia-sericite Au-Ag veins; Corbett and Leach, 1998), predominate as fissure veins formed in dilational structural settings, often in rift environments without obvious associated intrusions, and locally pass downwards to Andean polymetallic Ag-Au veins. The new terminology is more accurately descriptive rather than historical.

LOW SULPHIDATION EPITHERMAL AU

As ore fluids responsible for the development of the intrusion-related series of sulphide-rich low sulphidation Au-Ag deposits migrate from intrusion source rocks at depth to higher crustal levels, often entrained within circulating cells of meteoric-dominated waters, they progressively deposit mineralisation classed as: quartz-sulphide Au ± Cu, overprinted by carbonate-base metal Au, (including the Andean polymetallic Au-Ag veins), and then later epithermal Au-Ag deposits. Numerous exploration examples display similar paragenetic sequences (Corbett and Leach, 1998).

Quartz-sulphide Au ± Cu

Quartz-sulphide Au + Cu deposits contain iron sulphides with a quartz-rich and local barite gangue. Sulphide contents vary from as little as 1% (Chatree, Thailand) to > 50% in lodes (Hamata, Papua New Guinea). They demonstrate pronounced mineral zonation with varying crustal levels of formation. At deepest crustal levels these deposits may contain pyrite, pyrrhotite and chalcopyrite, with lesser specular haematite and magnetite, in a comb or druzy quartz gangue. Slow cooling fluids deposit Au with coarse grained sulphides which generally display good metallurgy, especially where weathered. At elevated crustal settings the pyrite may pass to marcasite and arsenean pyrite, in combination with opal to chalcedony as the silica component. Many high level deposits are therefore characterised by an arsenean pyrite bearing Au-As-Ag anomalous grey silica, commonly termed 'silica gris' in Andean deposits, which may display poor metallurgy if Au is encapsulated in the sulphide lattice. Gold is of a high fineness (Corbett and Leach, 1998).

Quartz-sulphide Au $\pm$ Cu deposits at deeper crustal levels tend to exploit pre-existing structures and commonly display a close relationship to porphyry Cu-Au intrusions, locally representing the porphyry-epithermal transition, commonly described as D veins in 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 distances from source porphyry Cu-Au intrusions to form wall rock porphyry Au deposits. The sheeted veins in some Maricunga Belt, Chile and Cadia, Australia porphyry Au deposits, are typical of quartz-sulphide Au $\pm$ Cu mineralisation.

Quartz-sulphide deposits are well documented in the Southwest Pacific as steep dipping lodes within pre-mineral structures (Mineral Hill and Adelong, Australia; Bilimoia [Irumafimpa], Papua New Guinea; Jaing Cha Ling, China; Rawas, Indonesia), or stockwork and sheeted veins (Nolans, Australia; deeper parts of Porgera, Papua New Guinea and Kelian, Indonesia). Flat dipping structures formed by collapse of volcanic edifices host ore at Emperor Gold Mine, Fiji, and the giant Ladolam deposit Lihir Is, Papua New Guinea. At both these deposits fine variably arsenean pyrite deposited as the ore fluid has rapidly cooled by contact with the wall rocks may display difficult metallurgy. The early low Au grade poor metallurgy sulphide breccias at Sleeper, Nevada are of this style.

Much quartz-sulphide Au $\pm$ Cu mineralisation occurs as small scale veins, reminiscent of D veins marginal to intrusions, commonly in association with magmatic hydrothermal breccias (San Cristobal, Chile; Kidston, Australia), and are frequently worked by small scale miners throughout Latin America. Many weathered bulk low grade ore are amenable to treatment as heap leach operations (Sleeper, San Cristobal). Quartz-sulphide mineralisation occurs as an early stage of polymetallic Ag-Au veins commonly rising to higher levels in quartz-filled structures as ‘silica gris’.

<u>Exploration Implications</u>

Gold is readily liberated from oxidised coarse grained quartz-sulphide Au $\pm$ Cu ores and so very low metal grades may be worked as bulk low grade heap leach operations (San Cristobal, Sleeper). However, explorationists should be aware that quartz-sulphide Au deposits are notorious for surficial supergene Au enrichment, particularly in steeply dipping structures as sites of chemical and mechanical concentration and so surficial elevated assay results should be treated with caution. Supergene settings are evidenced by box works after pyrite, or Au anomalous jarosite at the surface, base of oxidation and collapsing down structures.

Fine grained As-rich ores (Sleeper, Lihir), formed by fluid quenching display poor metallurgy, and high As contents in these ores may prove to be an environmental liability. However, this mineralisation which occurs as ‘silica gris’ may be used as a vector to buried polymetallic Ag-Au ores in Andean settings where extreme topographic variations allow access to much deeper levels in outcropping veins.

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 kaolin (low pH waters), or more commonly manganese oxide (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 (Sleeper, Emperor, Ladolam).

Carbonate-base metal Au – Polymetallic Ag-Au

While carbonate-base metal Au deposits are some of the most prolific epithermal Au producers in the southwest Pacific rim (Porgera; Kelian; Antamok, Phillipines), polymetallic Ag-Au vein systems have provided much of the world's Ag since the Spanish colonial era, particularly in Peru and Mexico.

Carbonate-base metal Au deposits are characterised by 1-10% sulphides, commonly as pyrite > sphalerite > galena with a gangue of carbonate and variable quartz and display pronounced zonation (Corbett and Leach, 1998), and commonly overprint lower Au grade quartz-sulphide mineralisation. At deeper levels the transition to quartz-sulphide style may be reflected by minor pyrrhotite (Porgera, Kelian). A 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, formed 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.

Many carbonate-base metal Au deposits contain early quartz-sulphide mineralisation while others evolve to host bonanza Au grade epithermal mineralisation. Settings vary from fissure veins (Acupan & Antamok, Philippines; Cikotok and Pongkor, Indonesia), which may become quartz-rich (Misima, Papua New Guinea), to fracture/breccia networks adjacent to intrusions (Porgera), brecciated intrusion margins (Bulawan, Philippines) or controlled by structures (Hidden Valley, Papua New Guinea; Lake Cowal, Australia). At higher crustal levels fracture mineralisation occurs in competent host rocks adjacent to diatreme breccias (Kelian) varying to fracture (Cripple Creek, USA) and breccia matrix fill at deeper portions of diatreme breccia pipes (Montana Tunnels, USA; Mt Leyshon, Australia; Rosa Montana, Romania). In older more deeply eroded terranes such as the Ordovician Lachlan Fold Belt of eastern Australia, quartz-sulphide 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 sulphide and so commonly display higher precious metal grades.

Polymetallic Ag-Au veins are distinguished from carbonate-base metal deposits by the generally fissure vein character with local high sulphide contents and elevated Ag contents in Andean magmatic arcs, with variable to abundant quartz. Host rock competency provides a strong influence upon vein character and it is common in volcanic sequences for some units such as lava flows to contain well mineralised veins, while interlayered incompetent lapilli tuffs will be unmineralised. Most deposits occur as fissure veins within extensional settings characterised by listric style faults. Ore shoots which host wider and higher precious metal grade vein portions occur in flexures formed as variations in the vein strike and steeper vein portions. These latter ore shoots and others developed by fluid mixing at intersections of hanging wall splays with normal faults, may be blind at the surface. As with carbonate-base metal Au deposits, polymetallic Ag vein deposits are commonly associated with felsic domes and locally extensive illite-chlorite-pyrite wall rock alteration.

Polymetallic Ag veins contain early low precious metal grade quartz-sulphide mineralisation and display similar zonation to carbonate-base metal deposits, although rhodonite locally occurs in addition to the normal rhodochrosite. Deeper veins may contain pyrite, pyrrhotite, chalcopyrite and dark sphalerite, while higher level veins may contain early arsenean pyrite as 'silica gris', pale sphalerite, and chalcedonic to opaline silica, with minor stibnite. The mineralisation style and mechanism of metal deposition contribute towards elevated (local bonanza) Ag grades common in association with Ag-rich tetrahedrite (freigbergite), and argentite and other Ag minerals at elevated crustal settings. As some higher level polymetallic veins become flooded by banded silica in dilatant structural settings, this latter material may take on the appearance ginguro bands, and so provide a transition low sulphidation epithermal banded chalcedony-ginguro Au-Ag veins. Elevated Ag-Au grades may result from rapid cooling of ore fluids as an efficient mechanism of precious metal deposition, commonly at elevated crustal settings as evidenced by the presence of opal. The mixing of rising ore fluids with collapsing low pH condensate waters, which also account for development of surficial acid sulphate (cristobalite, kaolinite, alunite) caps, also represents an efficient mechanism of Au deposition, evidenced by hypogene kaolin within the bonanza Au-Ag ore mineral assemblage (Arcata, Peru; Palmarejo, Mexico).

While in many instances carbonate-base metal Au deposits occur in the same terranes as high sulphidation deposits (Rio de Medio at El Indio, Chile; Victoria at Lepanto, Philippines), it is also possible, but only rarely noted, for the fluids responsible for the formation of high sulphidation Au-Ag deposits to undergo progressive cooling and neutralisation by rock reaction to evolve through intermediate to lower sulphidation mineralisation (below).

Exploration Implications

The size of fissure veins which host polymetallic Ag-Au mineralisation and precious metal grades are influenced by rock competency, the presence of dilational structures to focus fluid flow, the mechanism of mineral deposition, and style of epithermal mineralisation. Elevated epithermal portions of polymetallic Ag-Au veins display bonanza Ag-Au grades where they pass to an epithermal character characterised by argentite with opal, locally with a ginguro appearance, while deep level veins tend to be more poorly mineralised. In elevated vein portions mixing with collapsing low pH condensate waters may enhance precious metal values, as evidence by the presence of hypogene kaolin.

Although carbonate-base metal Au deposits are important Au producers in the western Pacific rim, explorationists should be aware that these deposits may display considerable internal mineralogical variation resulting in highly irregular precious metal grades and variable metallurgical characteristics (Kelian, Porgera). While both carbonate base metal and polymetallic deposit styles are associated with felsic domes, phreatomagmatic (diatreme) breccias are a common component of carbonate base metal systems such that breccia pipes may be barren at surface but host Au mineralisation in the fractures adjacent country rocks at that level, or within the breccia matrix at depth.

Explorationists may prefer to prospect carbonate base-metal and polymetallic Au-Ag veins formed at higher crustal levels, as evidenced by pale sphalerite or opal, which provide potential to evolve to epithermal Au-Ag mineralisation which may host bonanza Au-Ag grades. The mixing of collapsing low Ph waters from acid sulphate caps, as evidenced by kaolin in the ore assemblage, provides an efficient mechanism of Au-Ag deposition for bonanza ore formation. Ore shoots formed in dilatant structural settings (flexures, hanging wall splays) host higher Au-Ag grades and wider veins and so represent favourable exploration targets. The characteristic Mn wad formed by weathering of Mn carbonates provides a ready indication of this mineralisation style where it overprints lower Ag grade quartz-sulphide deposits.

Low sulphidation 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 sulphidation Au deposits and so typically overprint quartz-sulphide Au $\pm$ Cu (Ladolam, Emperor, Sleeper), or carbonate-base metal Au (Porgera Zone VII; Mt Kare, Papua New Guinea) deposits and may also occur marginal to porphyry Cu-Au deposits (Thames, New Zealand). Bonanza quartz veins at Selene, Peru are also of the epithermal quartz Au-Ag style. Although not common, it is possible for fluids responsible for the development of high sulphidation mineralisation to evolve to lower sulphidation as recognised recognised at the Wafi, Papua New Guinea (Leach, 1999) and Viento veins, El Indio district. Some workers have speculated that the bonanza Au at El Indio is of a lower sulphidation style which overprints the high sulphidation Cu-rich mineralisation. The strongest association appears to be overprinting quartz-sulphide style mineralisation where bonanza mineralisation was mined from overprinting quartz-Au veins (Sleeper, Emperor, Lihir, Bilimoia; Chatree, Thailand).

Epithermal quartz Au-Ag mineralisation is characterised by the presence of free Au with minor gangue, typically quartz and minor clay. Sulphide contents are commonly <1% typically as minor pyrite/marcasite although tellurides are well developed in some projects. Gold is commonly of a high fineness and Ag minerals are rare. The vanadium mica, roscoelite, occurs at Porgera, Mt Kare and Emperor, tellurides at Emperor and tellurobismuthinite at Bilimoia. Most display a strong structural control as they form at great distances from the magma source, and bonanza Au deposition is considered (Corbett and Leach, 1998) to result from the rapid cooling of the ore fluid, locally by mixing with oxygenated or low pH ground waters. Consequently, some deposits (Sleeper) formed by the mixing of mineralised fluids with collapsing low pH acid waters feature abundant kaolin with the quartz-Au veins. The banded quartz at Sleeper supports a polyphasal activation of the dilatant structural setting so that multiple mineralising events contribute towards the spectacular bonanza Au grades. High grade ores may occur in ore shoots developed at sites of preferential fluid mixing, such as the blind Porgera, Zone VII mineralisation.

Recent work (Corbett, 2004) at Porgera suggests that thrust erosion initiated renewed felsic magmatism and the epithermal quartz-roscoelite-Au event, which produced substantial bonanza Au from Zone VII, overprints much deeper quartz-sulphide and carbonate-base metal mineralisation in which the dark sphalerite and pyrrhotite are indicative of formation at elevated temperatures and hence deep crustal levels.

Exploration Implications
The free milling nature of bonanza Au has led to the ready identification of many epithermal quartz Au-Ag deposits by panning (Porgera; Edie Creek, Papua New Guinea), but may also promote the presence of artisan miners (Mt Kare, Kelian). The improved metallurgy and higher precious metal grades within epithermal quartz Au-Ag

mineralisation have enhanced the economics of otherwise lower Au grade or metallurgically difficult quartz-sulphide Au and carbonate-base metal Au deposits (Sleeper, Porgera, Emperor). As Au grades within narrow gangue-poor fracture/veins are extremely irregular, 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. A geologist should mark where core should be sawn and sampled to ensure best possible assay 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), and preferential metal deposition (at cross structures [Thames] & hanging wall splays [Porgera Zone VII], and many of these settings may be blind at the surface.

Epithermal banded chalcedony-ginguro Au-Ag mineralisation

The low sulphidation epithermal banded chalcedony-ginguro Au-Ag deposits have formerly been termed adularia-sericite banded epithermal Au-Ag quartz veins (Corbett and Leach, 1998). The more descriptive term is now used in response to comments from explorationists that adularia is not always present and illite wall rock alteration is more common than sericite, which dominates at deeper crustal levels. These deposits are the most extensively documented low sulphidation Au-Ag deposits, particularly using the parallels with the New Zealand geothermal systems. While many occur in back arc environments (Drummond Basin, Australia; Taupo Volcanic Zone, New Zealand; Argentine Patagonia; Japan; western US), or some are noted within intra-arc rifts (Tolukuma, Papua New Guinea), other individual deposits occur within magmatic arcs (El Peñon, 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 (Thormodsdalur vein). All these environments display characteristic of bimodal volcanism, evident as the association of Au-Ag mineralisation with felsic magmatism, although hosted rock sequences which contain andesitic or basaltic volcanism.

The low sulphidation epithermal banded chalcedony-ginguro Au-Ag veins typically comprise fine interlayers of chalcedony varying to opal, with lesser adularia, quartz pseudomorphing platy calcite, and black sulphidic ginguro bands which may contain electrum, Ag sulphosalts and Au and were named by the nineteenth century Japanese miners. Sulphide contents which are generally less than 1% electrum, silver sulphosalts pyrite/marcasite, minor chalcopyrite, and rare sphalerite, galena etc. Comparisons with geothermal systems aid existing interpretations that meteoric dominant waters rise rapidly up dilatant fracture systems hosted within competent rock packages and boil to deposit much of the vein mineralogy such as adularia, quartz pseudomorphing platy calcite and possibly chalcedony. However, these mineral assemblages tend not to contain Au-Ag mineralisation, which dominates in the ginguro bands and to a lesser extent chalcedony. Some workers (Corbett and Leach, 1998) therefore invoke rapid cooling, locally aided by mixing of the ore fluid with varying ground waters, as a mechanism for deposition of bonanza Au-Ag mineralisation. Fluid mixing is evidenced by the presence within the ore assemblage of kaolin for low pH acid sulphate waters, hypogene haematite and jarosite for oxygenated waters and Mn oxide for bicarbonate waters.

The two end members of the low sulphidation epithermal class are distinguished on the basis of mineralogy (table 1), although they do tend to dominate in different geological settings.

Characteristic	Epithermal quartz Au-Ag	Epithermal banded chalcedony-ginguro Au-Ag
Visible Au	Abundant	Present
Ore mineralogy	Free Au local Te and Bi	Electrum, silver salts and Ag-bearing sulphides
Au fineness	High	Low
Ag:Au ratio	High	Low
Gangue	Minor as quartz and some clay	High as banded chalcedony with local quartz pseudomorphing calcite and adularia
Setting	Magmatic arc	Common in rift settings
Associated mineralisation	Common overprinting quartz-sulphide Au	May pass downwards to polymetallic Ag-Au

Table 1. Comparison of the two end members of low sulphidation epithermal Au-Ag mineralisation.

The low sulphidation epithermal banded chalcedony-ginguro Au-Ag veins display pronounced vertical zonation. At surficial levels phreatic or eruption breccias act as fluid up flow sites for adjacent laminated silica sinter deposits (McLaughlin USA; Champagne Pool and Puhipuhi in New Zealand; Toka Tindung, Indonesia; Twin Hills, Australia), although some sinters lack associated feeder breccia bodies (Manchuria, Patagonia). Although anomalous in toxic elements (Hg, As, Sb, W), many silica sinter deposits are barren with respect to Au. Metal deposition is recognised at sites of mixing of rising neutral waters and collapsing acid waters close to fluid up flow centres (Champagne Pool). Feeder structures for phreatic breccias are often exploited by dilatant sheeted veins which may extend as mineralised veins into the deeper portions of breccia pipes (McLaughlin; Twin Hills;), 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 within competent host rocks (Ares; Pajingo and Vera Nancy, Australia; Tolukuma; Hishikari and Sado in Japan; Waihi, New Zealand; Asacha; Kamchatka, 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 sulphate 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 precious metal deposition (Corbett and Leach, 1998).

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 Au-Ag grades, occurs in ore shoots developed as preferential sites of mineralised fluid flow within flexures in otherwise poorly mineralised throughgoing structures (Vera Nancy; Simms, 2000), fault jogs between structures, or splays (Corbett, 2002b). Structures dominated by strike-slip fault movement host steeply plunging ore shoots (Vera Nancy), while those within listric faults will display flat plunges (Sierra Madre, Mexico). Rock competency influences the manner in which host rocks fracture during vein formation and barren less competent sequences may cap ore. At Hishikari, the brittle Shimanto Group shale (phyllite), which hosts vertical quartz veins, is overlain by incompetent volcanic breccias which have undergone clay alteration and do not fracture well. As many veins terminate upward at the lithological contact preferred mineral deposition here has lead to the development of a flat dipping ore shoot comprising bonanza Au grades. At Karangahake, the andesite-hosted mineralised fissure veins become a less well mineralised stockwork in overlying incompetent rhyolite. The Chon Aike ignimbrite hosts veins at Cerro Vanguardia and elsewhere in Argentine Patagonia. Other veins are limited to the competent margins of felsic domes at Ares and Asacha. 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 portions of the vein systems.

Exploration Implications

Epithermal banded chalcedony-ginguro Au-Ag 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), 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 Vanguadia). Resistive geophysical techniques (including CSAMT) have targeted quartz veins for drill testing (Hishikari) and identified vein extensions within covered throughgoing structures (Vera Nancy). Equipment such as XRD, PIMA and ASD provide detailed analyses 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 may be blind at surface. Geological settings include steeper portions of listric fault control, or changes in host rock (Hishikari), and the intersection of hanging wall splits with main the fault (Asacha, Tolukuma). Often unmineralised eruption breccias and acid sulphate alteration may cap mineralised vein systems and so vector towards mineralisation.

Careful geological mapping is essential in order to plan drill testing at best possible directions and distribution with respect to ore shoot distribution (Corbett, 2002b; Corbett and Leach, 1998). The angle of veins to the core axis should be monitored to ensure optimum drill direction is maintained. As bonanza ores comprising ginguro sulphidic 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.

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 noted in SW Pacific magmatic arcs (Mesel, Indonesia; Bau, Malaysia), and remain as important exploration targets worldwide, especially in new emerging provinces such as China and Mongolia. These deposits develop from the interaction of an ore fluid typical of quartz-sulphide 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 arsenean 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.

<u>Exploration Implications</u>
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 is not 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.

HIGH SULPHIDATION Au - Ag – Cu DEPOSITS
High sulphidation epithermal Au deposits result from the interaction with host rocks of magmatically-derived ore fluids, which have developed to attain a characteristic very acidic character. In simple terms, a volatile-rich fluid (dominantly SO_2, but also containing CO_2, H_2S, HCl) exits a deeply buried magmatic source and becomes depressurised during the rapid migration to epithermal crustal levels, causing the volatiles to come out of solution and oxidise (as O_2 and H_2O 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 and so the fluid has evolved during rapid ascent from a near neutral in the porphyry environment, to strongly acidic (pH 2) at epithermal levels. Here host rock reaction results in the development of the characteristic high sulphidation alteration zonation and mineralisation.

High sulphidation deposits commonly develop without the repeated activation of dilational structures, which in low sulphidation systems drive hydrothermal cells of meteoric-dominated waters to facilitate banded quartz vein formation. Rather, the development of high sulphidation 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 sulphidation fluid travels more rapidly than the liquid-rich portion, and reacts with the host rocks to produce the characteristic alteration zonation (Corbett and Leach, 1998). At the core of the alteration zone the host rocks undergo intense leaching by the extremely acidic fluid (pH 2) to produce a rock composed almost entirely of silica, termed residual silica, as silica is the remnant component after leaching, or vughy silica, indicative of the characteristic open space texture. As the hot acidic fluid is progressively cooled and neutralised by rock reaction the zoned alteration grades outwards through alteration assemblages indicative of less acidic conditions 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 (e.g., dickite at deeper levels passes to kaolin in higher level cooler settings).

Mineralisation commonly post-dates alteration and is deposited from a liquid-dominated fluid component which utilises the same plumbing system as supplied the volatile portion of the ore fluid, and so generally enters the siliceous centre of the alteration zonation. Mineralisation occurs as sulphides comprising dominantly pyrite, enargite (including the low temperature polymorph luzonite) and local covellite, along with gangue minerals; alunite, often as coarse crystalline material, barite and late stage sulphur. Most sulphides are deposited in open space including vughs and breccia matrix in the silica core, locally extending into the adjacent silica-alunite portion of the zoned alteration. High sulphidation deposits display a zonation from Cu-rich at deeper levels, grading to Au-rich at higher crustal levels where Hg and Te are locally recognised. While Andean deposits may contain appreciable Ag, those in the southwest Pacific contain virtually no Ag.

High sulphidation fluid flow is influenced by permeability controls classed as structural, lithological and breccia (Corbett and Leach, 1998). While many deposits are localised either on major throughgoing structures (Meikle, Post along the Post Fault, Nevada; Gidginbung, Australia, on the Gilmore Suture; Wafi, Papua New Guinea on a transfer structure; Mt Kasi, Fiji), or on dilational fractures between throughgiong faults (El Indio occurs within a sigmoidal loop; Nena in Papua New Guinea and Lepanto each lie on splay fautls), the contacts of these structures with permeable lithologies (Sipan, Peru; El Guanaco, Chile; Nena and Gidginbung), or breccia pipes (below), provide suitable settings for development of alteration and mineralisation. Other deposits are wholly controlled within permeable lithologies in volcanic sequences (Pierina, Peru; La Coipa, Chile). Many high sulphidation deposits are associated with phreatomagmatic breccias (Wafi; Pascua, Chile; Veladero, Argentina; La Virgin, Peru; Lepanto), which no doubt facilitate the rapid rise of ore fluids from porphyry to epithermal levels, and so some high sulphidation deposits also occur within felsic domes (Mt Kasi), or dome/breccia complexes (Yanacocha, Peru; Veladero). Felsic domes are an important link to magmatic source rocks at depth, and therefore commonly associated with high sulphidation Au deposits. Some deeper level systems collapse upon porphyry Cu-Au deposits (Monywa, Myanmar; Tampakan, Philippines).

Higher Au-Ag grades are noted in settings of improved precious metal deposition such as settings where oxidising acid sulphate waters collapse back into a deposit to produce hypogene oxidation (Pireina), or where higher sulphidation fluids evolve to lower sulphidation mineralogies. Many districts contain both high and low sulphidation Au deposits (Lepanto, Nena) as separate ore systems. Although not common, high sulphidation fluids may become progressively cooled and neutralised to locally pass to lower sulphidation mineralogies. This is well documented in two districts at Wafi, (Leach, 1999), and El Indio (Jannas et al., 1999), where ore mineralogies pass both spatially and temporally from high sulphidation pyrite-enargite to overprinted by tennantite-tetrahedrite typical intermediate sulphidation then galena-sphalerite-pyrite-marcasite, typical of low sulphidation. Free milling Au, often at bonanza grades, deposited in the later stage lower sulphidation ores, contrasts with the early stage metallurgically difficult enargite ore. While pyrite may predate enargite in many high sulphidation deposits (El Indio, Jannas et al., 1999), in some high sulphidation deposits a trend towards later stage pyrite and hypogene haematite may also be indicative of a transition from higher to lower sulphidation.

Exploration Implications

The characteristic zoned hydrothermal alteration is one of the most important features of high sulphidation deposits, in which most mineralisation is confined to the central siliceous core. The strong conductivity contrast between this resistive siliceous core and marginal clay alteration contributes towards the definition of the anatomy of these alteration systems by resistivity studies (CSAMT or IP). The hard siliceous core commonly occurs as prominent topographic features, or is easily recognised in float. The alteration is magnetite destructive and strongly pyritic contributing towards the identification on aeromagnetic and chargeability-based geophysical studies. As the nature of the zoned alteration has been clearly defined from numerous case studies over many years, detailed spectural clay analyses (using XRD, PIMA or ASD) may provide vectors towards the central mineralised portion of high sulphidation alteration zones.

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 commonly oxidised ores are conducive to extraction as heap leach operations (Sipan, Yanancocha). Acid mine waters produced by weathering of the pyritic clay alteration, and the high As content of sulphide ores, as well as common Hg by-products, may all provide environmental concerns.

CONCLUSION

An understanding of the different styles of epithermal Au-Ag mineralisation may assist explorationists 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. Early estimation of the style of epithermal mineralisation provides a framework for continuing exploration. For instance, quartz-sulphide Au deposits often undergo surficial supergene enrichment and so surface assay data must be treated with caution. Upper levels of carbonate-base metal Au – polymetallic Ag-Au deposits are prospective for higher precious metal grade epithermal end members. In low sulphidation gold deposits clean banded chalcedony veins, interpreted as deposited from shallow circulating meteoric-dominated waters, lack any ginguro component and so are essentially unmineralised. The alteration zonation in high sulphidation Au deposits varies according to crustal level, relationship to fluid up flow and style of host rocks.

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

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