Structural Controls to, and Exploration for, Epithermal Au-Ag Deposits

Introduction

Structural controls to the formation of epithermal Au-Ag deposits within magmatic arc (extending into back arc) environments are apparent as:

- Localisation by major structures,
- Provision of fluid flow paths to enable fluid evolution,
- Dilatant settings of enhanced fluid flow and mineral deposition,
- Sites of mineral deposition by fluid mixing, locally at structural intersections.

Structural controls to epithermal Au-Ag mineralisation must be considered as an interaction with other factors such as mineralisation style, host rock characteristics and mechanisms of precious metal deposition. The path to discovery delineated herein relies on the use of evolving geological models, built up from consideration of many exploration examples (Corbett, 2009), but which should never be treated too rigidly (Lowell, 2012).

Classification of Epithermal Deposits

Epithermal Au-Ag deposits are classified (Corbett and Leach, 1998; Corbett, 2009 and references therein) as formed above the porphyry environment at crustal levels within about 1 km of the surface and subdivided on the basis of ore mineralogy, hydrothermal alteration and fluid flow paths (figure 1).

Figure 1. Conceptual model for the styles of Au-Ag-Cu mineralization developed within magmatic arcs (from Corbett, 2009).
High sulphidation epithermal Au+Ag+Cu deposits are characterised by the reaction with wall rocks of hot acidic fluids to form hydrothermal alteration which is zoned outwards as mineral assemblages dominated by vugly silica, silica-alunite, pyrophyllite-diaspore, and more marginal dickite-kaolin. Au in the SW Pacific, with additional Ag in Latin America, and Cu at deeper crustal levels, are associated with enargite-pyrite-barite-alunite, partly overprinting alteration. Hydrothermal fluid flow is controlled initially by structure then permeable lithologies as well as pheatomagmatic (diatreme) breccia pipes.

Low sulphidation epithermal Au-Ag deposits are characterised by neutral wall rock alteration assemblages dominated by illitic clays, although acidic waters collapsing from near surfical acid sulphate caps deposit kaolin within some ore assemblages (below). Magmatically derived hydrothermal fluids deposit quartz-sulphide Au + Cu veins earliest and commonly (but not always) at deeper crustal levels, and then diverge into two fluid flow trends (figure 1). Typically in extensional settings, such as back arc environments, polymetallic Ag-Au deposits dominate in Latin America (Sierra Madre of Northern Mexico, Peru, Patagonia), and are vertically zoned passing from Au-Cu dominant at depth to higher level Ag with associated sphalerite-galena and sulphosalts and quartz-carbonate gangue. These deposits pass upwards to banded chalcedony-ginguro epithermal Au-Ag ores characterised by bands of chalcedony, deposited from dominantly metroric waters, and ginguro (pyrite-electrum-sulphosalts) derived from the magmatic source. These deposits are well represented throughout the circum Pacific rim magmatic arcs (Hishikari, Japan; Kupol, Siberia; Waili, New Zealand; Vera Nancy-Pajingo, Queensland; Madis US; Ares, Peru; Cerro Moro and Cerro Vanguardia, Patagonia).

Epithermal ores deposited from mainly intrusion-related fluids are recognised in SW Pacific rim magmatic arcs grading from quartz-sulphide Au + Cu to carbonate-base metal Au, and at the highest crustal level, epithermal quartz Au-Ag style mineralisation (Corbett and Leach, 1998; Corbett, 2009; figure 1). Au grades increase in the evolving hydrothermal fluid initially localised within sulphides which vary in time and space towards higher crustal levels, from early pyrite and lesser chalcopyrite at depth, to sphalerite-galena and sulphosalts, and then gangue poor high fineness free Au at highest crustal levels. Dilatant structures are required to bleed ore fluids from the intrusion source rocks at depth to cooler elevated settings where mineral deposition takes place and also to facilitate the mixing of rising ore fluids with oxidising near surfical waters to promote Au deposition.

Carlin (sediment hosted replacement Au) deposits form by the reaction of quartz-sulphide fluids with impure limestone host rocks at elevated crustal settings and are not confined to the western US. The transition between porphyry and epithermal ores is apparent as low sulphidation quartz-sulphide Au + Cu mineralisation within dilatant sheeted vein systems, commonly referred to as wallrock porphyries, locally extending some distance away from the source intrusion, but with typically low metal grades (Cadia, NSW; Maricunga Belt, Chile; Gaby, Ecuador; Whitewash Mo, Queensland).

Major Structures

Major crustal-scale structures which localize magmatic source rocks for low and high sulphidation epithermal Au-Ag deposits are divided (Corbett, 1994; Corbett and Leach, 1998) into 3 classes as:

- Arc parallel structures (Domeyko Fault, Chile; Gilmore Suture, NSW; Kalimantan Suture, Borneo), which commonly developed as terrain boundaries with dominantly reverse senses of movement, often undergo transient changes to strike-slip deformation to localise ore systems in dilatant structural sites. Arc parallel structures may also parallel the structural grain in extensional settings (Carlin, Goldstrike Trends, Nevada; northern Mexico) where they may act as regional feeder structures or host veins, locally within listric faults such as in the Sierra Madre (below).

- Arc normal transfer structures may extend through magmatic arcs into the underlying basement to tap mantle derived melts as sources of Au mineralization, or focus overprinting magmatism and locally delineate changes in the dip or rate of subduction in adjacent plates (Porgera, Wafi and Grasberg Transfer structures, New Guinea; Lachlan Transfer Zone, NSW).

- Conjugate fractures are recognized as controls to magma emplacement in some orthogonal magmatic arcs (Andes, North Sulawesi and Banda arc), commonly at the intersections with arc-parallel terrain boundaries. Strike-slip movement on these fracture systems during orthogonal compression or transient episodes of relaxation aids the creation of dilatant structural sites for ore formation.

Hydrothermal Fluid Evolution

Epithermal deposits develop by ore fluid evolution during structurally controlled flow.

High sulphidation epithermal ore fluids display characteristic evolution and vertical separation between the magmatic source and epithermal environment of ore deposition. The structural control therefore represents an essential element to facilitate the flow of rapidly rising volatile (SO2) rich magmatic fluids which become depressurised and exsolve SO2, which then oxidises (to H2SO4) to form hot acidic fluids. At epithermal levels these fluids are progressively cooled and neutralised by reaction with wall rocks to provide the characteristic hydrothermal alteration described above. Sulphide mineralisation is deposited by the liquid-rich phase of the ore fluid, mostly later. This fluid evolution provides a lower limit to high sulphidation deposits which are therefore rootless.
Low sulphidation vein systems commonly comprise banded veins in which different bands are deposited within a host structure from variable fluid sources (Corbett, 2008). Dilatant structures may host shallow circulating cells of meteoric-dominated waters which deposit barren gangue minerals such as chalcedony, carbonate and adularia. Some deeper circulating fluids entrain a magmatic component and deposit quartz with disseminated sulphides and low grade Au. Structures may occasionally tap deep magmatic ore fluids to deposit most precious metals in thin sulphide bands. Of interest to explorationists, some recent discoveries feature surficial barren quartz underlain by mineralised sulphide-bearing veins (Huevos Verde and Cerro Moro, Argentine Patagonia), as only some elements of veins host mineralisation.

Controls to Epithermal Ores

Many epithermal Au deposits host most ore within ore shoots (clavos in Spanish), developed as wider and higher precious metal grade vein portions, most easily discernible on gram x plots (Corbett, 2007). Epithermal vein systems (mostly low sulphidation) are controlled by the interaction of:

- Competent host rocks fracture to aid vein formation. Volcanic sequences of interlayered competent (andesite) and incompetent (tuffs) provide stacked flat plunging ore shoots. This may be accentuated as moderately dipping faults preferentially host veins where they refract to steeper angles in bands of competent host rock (figure 2). There are a number of exploration examples of discovery of epithermal veins within competent host rocks obscured by overlying incompetent tuffs.

- Permeable host rocks control mostly high sulphidation epithermal fluid flow with ore shoots at the intersection with feeder structures, although host permeability is less commonly recognised in low sulphidation ores (Lihir Papua New Guinea; Round Mountain, Nevada).

- The style of epithermal mineralisation described above influences Au grade, distribution of Ag and Cu and metallurgical characteristics, as the structural environment influences fluid evolution. Ores may occur as veins, breccia matrix or disseminations.

- Field studies using models derived from analyses of magmatic arc (as different to back-arc) geothermal systems (Corbett and Leach, 1998; Leach and Corbett, 2008) demonstrate bonanza Au grades mostly result from the mixing of rising ore fluids with collapsing near surficial waters or rapid cooling of rising ore fluids. Boiling deposits barren gangue minerals (adularia, quartz pseudomorphing platy calcite) and mostly low grade Au-Ag. Mixing environments are strongly structurally controlled, typically at structural intersections (below).

- Structures also influence to form of ore shoots developed at dilatant structural settings of enhanced fluid flow.

Structural Control to Epithermal Ores

Structural environments provide the dominant control to the form (typically plunge) of ore shoots developed as regions of elevated fluid flow under different conditions (figure 2) as:

- Orthogonal extension (Sierra Madre northern Mexico, southern Peru, Argentine Patagonia; Gosowong, Indonesia; Hidden Valley, PNG) generally occurs on listric faults which host epithermal veins within flat plunging ore shoots confined to the steeper dipping fault portions. Refraction of dipping faults through competent host rocks will provide steep dipping portions as vein hosts (El Penon, Chile; Palmarejo Mexico; Kupol, Siberia). Variations of just a few degrees dip control changes from ore shoots to waste. At Lihir, Papua New Guinea, similar to Mt St Helens, USA, sector collapse of a volcanic edifice has occurred on listric faults which then host ore shoots in steeper portions (Minifie Zone at Lihir). Caldera collapse provided flat ore shoots within reactivated bedding planes of adjacent lavas at Emperor Gold Mine, Fiji.

- Transpressional environments characterised by strike-slip structures host steep plunging ore shoots formed in dilatant structural settings such as fault jogs containing tension vein links between two structures, flexures as bends in throughgoing structures, splays or horsetails (in older literature). Normal (growth) faults which participate in pull-apart basin formation host tension veins at depth and splays at deepest levels, within vertically stacked negative flower structures (Corbett and Leach, 1998). Two transpressional end members are apparent as flexures within throughgoing (champion) veins with intervening poorly mineralised vein portions (Vera Nancy, Queensland), or tension vein arrays constrained between barren strike-slip structures (Waihi, New Zealand). Caution is urged as mineralized tension veins formed at high angles to the structural grain of the district (controlling structures), prospected as the elongation of soil geochemical anomalies, may then be sub-parallel to the drilling direction and provide erratic results. Geological mapping and not grids should localize drill holes and veins at low angles will suggest the structural model required further work.

- Orthogonal compression is an uncommon ore setting despite the overall compressional nature of magmatic arcs. Flat plunging ore shoots develop in the flatter dipping portions of moderate dipping reverse faults (Kencana, Gosowong, Indonesia; Hamata, Morobe Goldfield, Papua New Guinea) and may be blind at the surface (Kencana). Curiously, each of these two examples is oriented normal to outcropping mineralized veins within listric faults (Gosowong vein and Hidden Valley ore systems above).

- Plunging ore shoots (El Inido, Chile) develop by the interaction of strike-slip and mostly normal fault movement, although a reverse component is possible.
Repeated activation of the kinematic controls to vein formation promotes the development of banded veins with polyphasic events of Au–Ag deposition and associated elevated precious metal grades.

**Fluid Mixing and Ore Shoots**

Low sulphidation epithermal vein systems may host bonanza Au grades derived from the mixing of rising pregnant ore fluids with collapsing oxidizing near surficial waters. Here, ore shoots of variable plunge are localized at the intersection of the separate structures which transport the different fluids and so commonly display rod-like forms. The rising hydrothermal fluids set up circulating hydrothermal cells which promote the collapse of the near surficial waters down cross structures. Low pH waters collapsing from near surficial acid sulphate caps to settings of low sulphidation vein formation provide the best mixing environments, evidenced by hypogene kaolin in the sulphide ore assemblage. While an interesting prospecting model, ore shoots may bottom at the limit of the downward collapse of the low pH waters. Gold is also deposited by the mixing of rising ore fluids with oxidizing ground waters evidenced by hypogene haematite in the ore assemblage, or mixing with bicarbonate waters recognized in carbonate-base metal Au deposits (Corbett and Leach, 1998; Leach and Corbett, 2008). Incompetent acid sulphate caps inhibit vein formation and so may obscure blind bonanza grade ore systems (Guadalupe at Palmarejo, Mexico).

**Conclusions**

Mineral exploration benefits from an understanding of the controls to epithermal mineralization as:

- Major structures localise ore systems and locally display components of movement which control dilational settings of ore formation. Epithermal fluids evolve during fluid flow within structures to provide viable ore systems. The composite fluid types responsible for banded low sulphidation vein formation may provide barren veins at the surface which are mineralised at depth, and different portions of veins may display dramatically different precious metal grades.

- High sulphidation epithermal Au deposits are characterized by a two stage (early volatile and later liquid) fluid developed by evolution during the rise from a deep magmatic source to higher crustal level epithermal sites of mineral deposition. Many high sulphidation epithermal Au systems host ore shoots at the intersection of feeder structures and permeable host rocks, typically altered to vughy silica, and display distinct bottoms.

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**Figure 2.** Epithermal vein ore shoots in different structural settings including the development of bonanza Au at a site of fluid mixing (modified from Corbett, 2007).
• Incompetent and commonly clay altered tuffs may obscure veins within underlying competent andesite or felsic sills (Arcata, Peru; El Penon, Chile). Acid sulphate caps may obscure bonanza Au-Ag grades developed by fluid mixing (Guadalupe at Palmarejo, Mexico). Rod-like linear ore shoots develop as a result of Au deposition by fluid mixing at structural intersections (COSE, Argentine Patagonia, Kupol, Siberia).

• Kinematic environments control the form of ore shoots which host most mineralization in many vein systems. Steep plunging flexures in strike-slip structures may be identified by magnetite destruction in andesite terrains, or using integrated resistivity and chargeability data in more permeable rock types. Only steep dipping portions of listric faults host ore as flat plunging ore shoots, while similar plunging ore shoots in moderately dipping reverse faults are commonly blind at the surface. Interaction of extensional and strike-slip controls are common and may provide plunging ore shoots.

References Cited

Corbett, G.J., 2007, Controls to low sulphidation epithermal Au-Ag: Talk presented at a meeting of the Sydney Mineral Exploration Discussion Group (SMEDG) with powerpoint and text on SMEDG website www.smedg.org.au


