

Structural controls to porphyry cu-au and epithermal Au-Ag deposits

G. J. Corbett

29 Carr St, North Sydney, NSW 2060 cgs@speednet.com.au

Porphyry Cu-Au deposits formed by the emplacement of intrusions in the 1-2 km depth range, and low or high sulphidation epithermal Au-Ag deposits which occur at more elevated crustal settings feature characteristic alteration and mineralisation (Corbett and Leach, 1998, Corbett, 2002 & references therein). Structural control is evident from deposit to ore shoot scale. Critical factors in ore formation include:

- ♥ Pre-, syn-, and post-mineral activation of existing structures locally with varying senses of movement and development of new fracture patterns related to different events,
- ♥ Creation of syn-mineral dilation to facilitate the flow of hydrothermal fluids, containing entrained metals, usually to shallower crustal levels and cooler settings of mineral deposition,
- ♥ Evolution of hydrothermal fluids to form different deposit styles at variable crustal settings,
- ♥ Effective mechanisms of metal precipitation.

Breccias are often an integral part of structural ore control (Corbett and Leach, 1998), but are not discussed in detail in the space available here.

Localisation of ore systems

Major throughgoing structures which may display protracted histories of variable activity provide dilational sites to facilitate rapid emplacement of ore system related intrusions into elevated crustal settings overlying essentially compressional subduction zones (Corbett, 1994; Corbett and Leach 1998). Structures formed at high angles to the magmatic arc include transfer structures (Porgera, Cenrtal Chile), across which the nature (dip, speed, direction) of subduction may vary, and as deep penetrating features may tap mantle derived fluids (Porgera, Lihir). Other structural corridors transect magmatic arcs at less than normal angles, locally continuing for considerable distances, and localise ore systems commonly at intersections with arc parallel structures (Pascua-Lama-Veladero Structure, Lachlan Transverse Zone, Yanacocha).

Laterally continuous, steep-dipping, arc-parallel structures, including terrain boundaries, form as part of the fabric of many magmatic arcs (Gilmore Suture, Falla Oeste/Domeyko Fault, Philippine Fault; Kalimantan Suture, Carlin Trend). Ore systems are localised along these structures at dilational bends (flexures, jogs, splays, horsetails), or intersections of high angle structures where side-stepping jogs may develop. Transitory changes in the nature of convergence, typically from compression to oblique convergence, trigger rapid intrusion emplacement and evolution of ore fluids to higher crustal levels in dilatant sites of arc parallel structures (Corbett and Leach, 1998). Thus, the kinematics of individual ore deposits may not be consistent with the overall regional tectonism (Chuquicamata, Nena).

Dilatant structural styles

While many structures display pre- and post-mineral activation, structural styles which provide dilation to facilitate mineralised hydrothermal fluid flow during tectonism, include:

- ♥ Reactivated elements of the structural grain of a district might dilate to form 'champion veins' (named in older mining literature). These are mostly steep dipping throughgoing linear features, and may display varying strike-slip, normal, or reverse movement, and are characterised by ore shoots as settings of enhanced fluid flow and/or metal precipitation.
- ♥ Movement on elements of the structural grain may form subjacent ore-hosting subsidiary or tension fractures, and sheeted fracture/veins, in which vein width and metal grade may vary in accord with angular relationships to controlling structures.
- ♥ Perturbations in throughgoing structures form dilatant ore environments as side steps, flexures, fault jogs, splays or horsetails, and occur in steep or flat structures, as well as those with normal, strike-slip and reverse senses of movement. These typically represent ore shoots in champion veins, commonly at structural intersections.
- ♥ In steep dipping structures, there is a continuum of ore environments from surficial pull-apart basins, to underlying fissure veins (epithermal), and splays (porphyry) at depth.
- ♥ Flat ore structures include reactivated (compressional) thrusts varying to reverse faults, or (extensional) listric faults, with dramatic examples provided by the collapse of volcanic edifices. Hanging wall or footwall splits may give rise to flat ore shoots.

♥ Magmatic, phreatomagmatic and phreatic breccias, create permeability for rapid fluid flow in open space breccia matrix and fractured wall rocks.

Telescoping, normally regarded as collapse of later higher-level upon earlier deeper alteration and mineralisation, represents a compaction of the hydrothermal system, commonly by removal of overlying rock, by factors such as volcanic sector collapse, or rapid arc uplift including thrust-related tectonic erosion. By contrast, dilatant structural settings may telescope mineralisation outwards from source rocks at depth, to form sheeted vein related porphyry Cu-Au systems extending into wall rocks, or laterally and vertically to form epithermal Au-Ag deposits.

Porphyry systems

Porphyritic textures in porphyry Cu-Au deposits are indicative of rapid and no doubt forceful emplacement often evidenced by repeated and overprinting intrusion events in an apophysis to larger buried magmatic source rocks. While some disseminated mineralisation is recognised, most ore occurs in association with fracture/quartz veins, variably described as stockwork veins (random and overprinting) or sheeted veins (parallel and locally reactivated). In many porphyries (St Thomas II, Didipio) emplaced in strike-slip terrains sheeted fracture veins parallel the orientation of dilatant splays (including horsetails, long recognised by prospectors). Other sheeted fractures mimic deep crustal structures which are formed at high angles to the magmatic arcs and localise the intrusion system (Cadia). Dilatant sheeted, and also stockwork fractures provide a mechanism for the evolution of ore fluids from the magmatic source at depth to higher crustal levels where mineral deposition occurs at cooler levels. Many extend into the adjacent host rocks and so account for the formation of wall rock porphyry systems. Mineralised flat-dipping sheeted veins may also mimic thrust faults (Hinoba-an, Ortiga).

Thus, there are links between structures which localise magmatic intrusions, focus repeated porphyry emplacement (Grasberg, Ridgeway), and facilitate the concentration of mineralised ore fluids from buried magmatic source rocks to cooler, higher crustal level sites of metal deposition, within the porphyry, wall rocks, and peripheral epithermal environments. During exploration, it is imperative to correctly determine the orientation of stockwork and sheeted veins so as to optimise drilling direction, commonly incorporating angle diamond drill holes in any program.

Low Sulphidation Epithermal gold \pm silver \pm copper

Low sulphidation epithermal gold-silver (LSE) deposits are categorised as the Arc LSE deposit group, commonly related to intrusions within magmatic arcs, while Rift LSE deposits comprise banded adularia-sericite epithermal Au-Ag veins which occur in intra arc rifts or back arc environments (Corbett, 2002).

The hydrothermal fluids, which form the Arc LSE group of deposits, host metals entrained within circulating waters that exploit dilatant fractures. These fluids evolve while migrating to higher crustal levels where varying ore styles relate to depth, relationship to intrusions, and mechanism of metal deposition aided by mixing with groundwaters (Corbett and Leach, 1998).

The quartz-sulphide gold + copper deposits commonly form at deeper levels close to 'source' intrusions, some transitional to wall rock porphyries and D veins near to porphyry Cu-Mo-Au intrusions. Those formed close to the intrusion source rocks may exploit pre-existing structures, while dilatant structures facilitate vein formation considerable distances from intrusion source rocks (Mineral Hill, Adelong), and to shallow levels (Rawas). At the Ladolam gold deposit Lihir Is., spoon shaped listric faults formed by sideways collapse of the volcanic edifice which removed about 1 km from above an active porphyry, juxtapose lower temperature epithermal pyritic ores upon the porphyry Au and anhydrite breccia ores. Structures formed at mesothermal crustal levels may be exhumed and reactivated to host ore (crenulation cleavage at Bilimoia, or mylonite at Hamata, laminated quartz at Reefon and Penjom). Fractured quartzite overlying a porphyry Cu hosts ore at La Arena, while at Nolans flat fractures in a carapace to a batholithic intrusion have been reactivated. Better grades and vein widths which facilitate economic mining occur in ore shoots at flexures in throughgoing structures (Jaing Cha Ling, San Cristobal).

Carbonate-base metal gold deposits develop as intrusion-derived ore fluids migrate within favourable structures to elevated settings where mineral deposition is promoted by mixing with bicarbonate groundwaters. These are the most prolific SW Pacific gold producers and display metal and gangue zonation (Corbett and Leach, 1998). Some occur as fracture/veins intimately associated with high level intrusions interpreted to be derived from deeper magmatic source rocks for the ore fluids (Porgera, Kelian, Bulawan). Others form as tension style (Acupan) or champion (Rio de Medio) veins. In some instances the evolution of fluids from intrusion source rocks at depth to higher level cooler conditions of mineral deposition is promoted by phreatomagmatic breccias which contain ore within: breccia matrix at deeper levels (e.g., Montana Tunnels, Mt Leyshon), intrabreccia fracture veins (Acupan, Gold Ridge, Cripple Creek), or the adjacent

fractured host rocks at higher elevations (Wau, Kerimenge, Kelian). At Kelian a long lived fault jog formed a pull-apart basin which hosts pre-mineral sedimentation, and later andesitic and felsic magmatism with associated diatreme and ore breccias. This negative flower structure progresses downwards to control mineralised sheeted quartz-sulphide and carbonate-base metal veins.

The epithermal quartz gold-silver ores which form at the highest crustal level of Arc LSE deposits commonly display strongly dilatant characters consistent with considerable transport of intrusion related fluids. Best vein widths and metal grades occur in ore shoots formed at fault jogs (Porgera Zone VII, Viento at El Indio), and splays (including footwall and hanging wall splits), or at intersections of groundwater-bearing cross-faults with dilatant fractures (Thames).

Sediment hosted replacement gold (Carlin) deposits comprise As, Hg, Sb anomalous pyritic replacement of reactive carbonate rocks, localised on major structural trends (Post Fault), and display controls varying from structure at depth (Meikle) to lithology at higher levels (Goldstrike), commonly within the one deposit (Mesel, Mercur).

Adularia-sericite epithermal gold-silver veins, which constitute Rift LSE ores (Corbett, 2002), predominate within intra arc rifts (Tolukuma, El Peñón), or back arc environments (Taupo Volcanic Zone, Cerro Vanguardia), associated with bimodal volcanism. These deposits require repeated reactivation of strongly dilatant structures to entrain circulating groundwaters, draw metals from (felsic) magmas at depth, and so form the characteristic banded veins with marginal floating clast breccias. Champion veins form in dilated throughgoing, commonly pre-mineral, faults (Vera Nancy, Tolukuma), and display greater vein widths and higher metal grades in ore shoots, which may be regularly spaced along the throughgoing fault (Vera Nancy), at marginal splays indicative of components of strike (Tolukuma), or normal fault development (Golden Cross). Tension veins may host entire ore systems formed as subsidiary fractures to more regional structures (Waihi, Cracow; Galadriel-Julia vein at Esquel, Sillitoe et al., 2002), best developed in settings of transient strike slip faulting. Exhumed reactivated flat ductile faults may also host ore (Chatree). Phreatic or eruption breccias overlie many major structures as settings of venting fluids and are exploited by dilatant ore hosting sheeted veins (McLaughlin, Yamada, Twin Hills). Competent host rocks that readily fracture permit ore formation. Many deposits occur in intrusive domes (Sado, Sleeper), and rock competency contrasts may provide upward vein terminations forming bonanza ore shoots (Hishikari) or stockworks (Karangahake).

High Sulphidation epithermal gold \pm copper \pm silver deposits

High sulphidation epithermal gold (HSE) deposits develop in response to volatile-rich magmatic derived fluids which rapidly migrate from deeper to higher crustal levels and evolve without significant interaction with the host rocks or dilution by groundwaters (Corbett and Leach, 1998; Corbett, 2002). Depressurising fluids exsolve volatiles (dominantly SO_2) which in turn oxidise to become hot, strongly acidic ($\text{pH} \leq 2$) solutions which by reaction with the host rocks create the zoned alteration and later sulphide deposition, Au-Ag-rich at high levels passing to Cu at depth.

Efficient plumbing promotes rapid ascent of intrusion-derived fluids which evolve without host rock interaction, and then at epithermal levels, structural, breccia and lithological permeability facilitate ore forming rock reaction (Sillitoe, 1995; Corbett, 2002). Here, fluid flow occurs in dilatant portions of throughgoing faults (El Indio, Peak Hill), subsidiary fractures (Mt Kasi), permeable volcanic lithologies (Pierina, La Coipa), and phreatomagmatic breccias within diatreme felsic flow dome complexes (Yanacocha), where fluid flow may occur within the breccia matrix (Pascua-Lama, Veladero) or in the adjacent fractured host rocks (Lepanto, Wafi). HSE deposits are derived from intrusion source rocks localised by regional throughgoing structural corridors (Nena, Pascua-Lama, Veladero, Wafi), which through movement provide dilatant fractures which host higher metal grades and vein widths (Mt Kasi, El Indio, Peak Hill), locally at the intersection with permeable lithologies (Nena, Gidginbung), or at margins of breccia pipes (Lepanto, La Virgin) or domes (Mt Kasi). As HSE deposits typically display low metal grades and difficult sulphide metallurgy, high grade ore shoots may be critical to deposit economics (El Indio, Mt Kasi). The same structural conditions are commonly evident from the regional scale of intrusion emplacement, to individual HSE deposit, and ore shoot formation.

Conclusion

In magmatic arcs major throughgoing structures display pre-, syn-, and post-mineral reactivation as changes in the nature of convergence may promote differing senses of movement (i.e. reverse to strike-slip) which act as triggers for intrusion emplacement (porphyry Cu-Au mineralisation) and evolution of rapidly rising hydrothermal fluids (HSE), locally with metals entrained in circulating groundwaters (LSE). Fluid flow is facilitated by dilatant portions of the major structures, subjacent subsidiary fractures, breccia pipes (Arc LSE and HSE), or interaction with permeable host rocks (Arc LSE replacement and some HSE). Thus, there is a mappable and commonly predictable continuum between the major ore localising structures and ore hosting fracture systems, in a variety of distinguishable ore types. These relationships can be used to explore for ore and must be taken into account when evaluating (drill testing) vein systems.

Acknowledgements

Co-workers too numerous to name assisted through discussion and access to projects.

References

- Corbett, G.J., 1994, Regional structural control of selected Cu/Au occurrences in Papua New Guinea, in Rogerson, R., ed., *Geology, exploration and mining conference*, June 1994, Lae, Papua New Guinea, Proceedings: Parkville, The Australasian Institute of Mining and Metallurgy, p. 57-70.
- Corbett, G.J. 2002, *Epithermal Gold for Explorationists: AIG Presidents Lecture*, online
- Corbett, G.J., & Leach, T.M., 1998, Southwest Pacific gold-copper systems: Structure, alteration and mineralization: Special Publ. 6, Society of Economic Geologists, 238 p.
- Sillitoe, R.H. 1999, Styles of High-Sulfidation Gold, Silver and Copper Mineralization in Porphyry and Epithermal Environments in Pacrim '99 Proceedings, Bali, Indonesia; The Australasian Institute of Mining and Metallurgy, Melbourne, p.29-45.
- Sillitoe, R.H., Cooper, C., Sale, M.J., Soechting, W., Echavarria, D., & Gallardo, J.L., 2002, Discovery and geology of the Esquel Low Sulphidation Epithermal gold deposit, Patagonia, Argentina: Society of Economic Geologists Special Publication 9, p. 227-240.