

# **GEOLOGICAL MODELS IN EPITHERMAL-PORPHYRY EXPLORATION: TERRY LEACH'S LEGACY**

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## **Summary**

The application by Terry Leach to ore systems, of the understanding of hydrothermal fluids present in Philippine magmatic arc geothermal systems, has led to the development of improved conceptual geological models as a guide to better mineral exploration. Mixing models account for the formation of bonanza Au in low sulphidation epithermal veins, while the application of time to the development of porphyry Cu-Au aids in the understanding of complex overprinting relationships in the evaluation and exploration of prospects of this style. The pH vs temperature chart devised by Terry has been used by many of us to analyse zoned alteration within a variety of styles of hydrothermal systems.

## **Introduction**

In October SMEDG/AIG held the one day Terry Leach Symposium to celebrate the contribution to mineral exploration by the late Terry Leach through his application of petrology to geological models. Terry was able to synthesise his early work on magmatic arc geothermal systems with his consulting work on many exploration projects and mines. This note delineates some of Terry's influences on our geological thinking (Corbett, 2008) and summarises some of papers presented at the Terry Leach Symposium and published in AIG Bulletin 48. Additional background reading including more detailed deposit type descriptions and the basis for the derivation of some concepts described herein, is available on the author's website [www.corbettgeology.com](http://www.corbettgeology.com). Note all these geological models are subject to continual modification as new data comes to hand and so should develop through application rather than be used rigidly.

## **Geological settings for geothermal analogies to mineral exploration**

Pacific rim porphyry-epithermal mineralisation developed in collision-related subduction settings displays two end members of interest here: magmatic arcs and extensional rifts. While most extension is recognised in back arc rifts formed behind magmatic arcs (Taupo Volcanic Zone, New Zealand), intra arc rifts are also common (Bulolo Graben, and Tolukuma, Papua New Guinea).

Linear magmatic arcs are apparent as upstanding dominantly andesitic volcanos, which overlie sites of partial melting developed in relation to subduction of oceanic plates and associated wet sediments, commonly below continental crust. Intrusion sources for mineralisation are emplaced deep within these volcanos and also localised by steep dipping arc-parallel structures, commonly developed as sutures, and also high angle transfer structures, which separate plate or arc segments (Corbett, 1994; Corbett and Leach, 1998). Consequently, some porphyry Au-Cu systems are not overlain by co-genetic volcanic rocks (Grasberg, West Papua; Porgera, Papua New Guinea; Bingham Canyon, USA). By contrast extensional domains such as back arc rifts tend to occur as topographic lows and may be dominated by felsic or bimodal volcanism derived from more distal magmatic sources and are characterised by extensive circulating meteoric-dominated ground waters. Felsic to intermediate flow dome complexes and related ignimbrites occur in the intra arc Bulolo Graben, which hosts the Morobe goldfield in Papua New Guinea.

Early epithermal Au exploration models were derived from research on the New Zealand geothermal systems developed in the Taupo Volcanic Zone extensional environment (Weissberg et al., 1976; Henley and Ellis, 1983). However, since then it has become apparent that only a small portion of the porphyry-epithermal deposit type spectrum (figure 1), the low sulphidation epithermal banded chalcedony-ginguro Au-Ag (formerly described as adularia-sericite or quartz-adularia) veins, might develop in back arc or rift extensional settings (Corbett, 2008). A transitional relationship is apparent in figure 1 as polymetallic Ag-Au veins develop in (mostly Andean) intra arc rifts or magmatic extensional settings and most other Au deposits form within magmatic arcs.

Terry Leach's work (Mitchell and Leach, 1991; Corbett and Leach, 1998) on the Philippine magmatic arc geothermal systems provides useful analogies to a wider range of porphyry Cu-Au-Mo deposits and high sulphidation epithermal and intrusion-related low sulphidation epithermal Au-Ag deposits (figure 1). While these deposits display linkages between deposit types and discernible zonation in time and space, the premise of this argument is that different geological models are appropriate for the analyses of most magmatic arc porphyry-epithermal Au mineralisation, to the back arc rift analogies which only apply to the chalcedony-ginguro veins (Corbett, 2008).

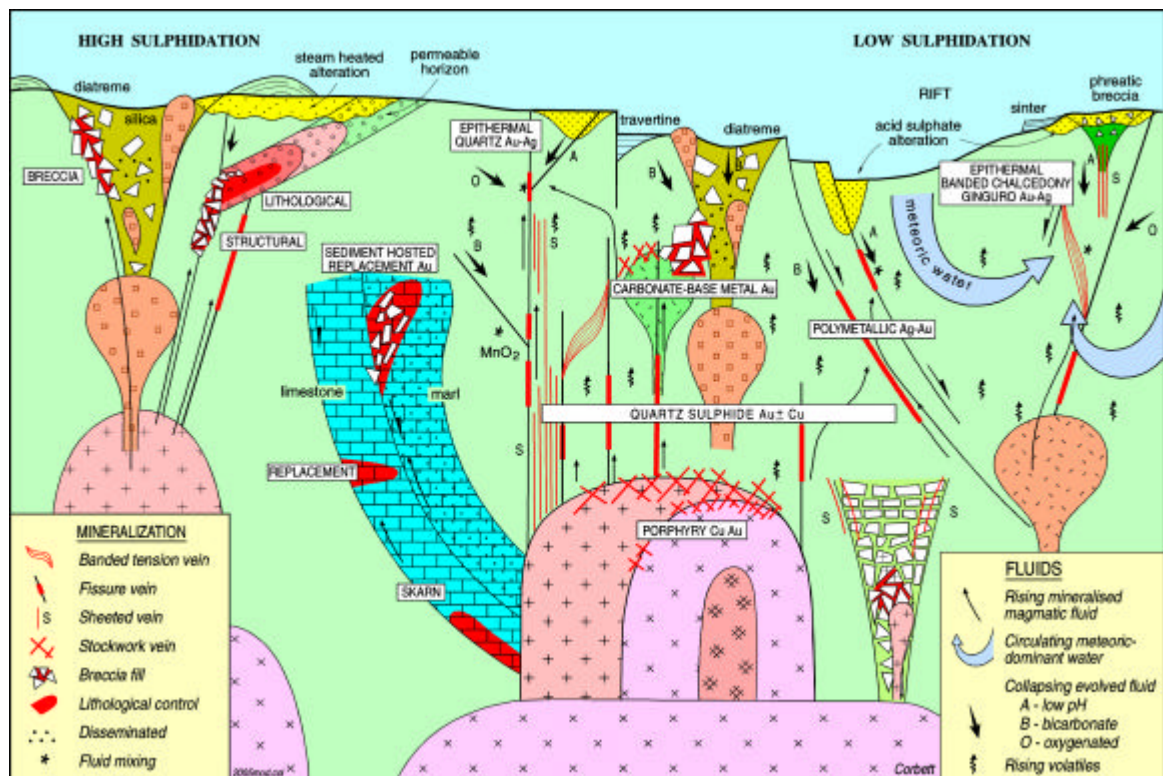


Figure 1. Conceptual model illustrating different styles of magmatic arc porphyry and epithermal Cu-Au-Mo-Ag mineralisation (from Corbett, 2008 and modified from Corbett 2002, 2004).

### Hydrothermal fluid elements

Banded veins develop by the repeated opening of host structures followed by multiple episodes of hydrothermal fluid flow and mineral deposition to form individual bands which make up these veins. Each band might be deposited from a different source of hydrothermal fluid by variable mechanisms of mineral deposition. The original work by

Terry Leach may be expanded upon in an analysis of the various fluids which participate in the development of epithermal-porphyry deposits, with profound implications on mineral exploration of these vein deposits (Corbett, 2008; Leach and Corbett 2008).

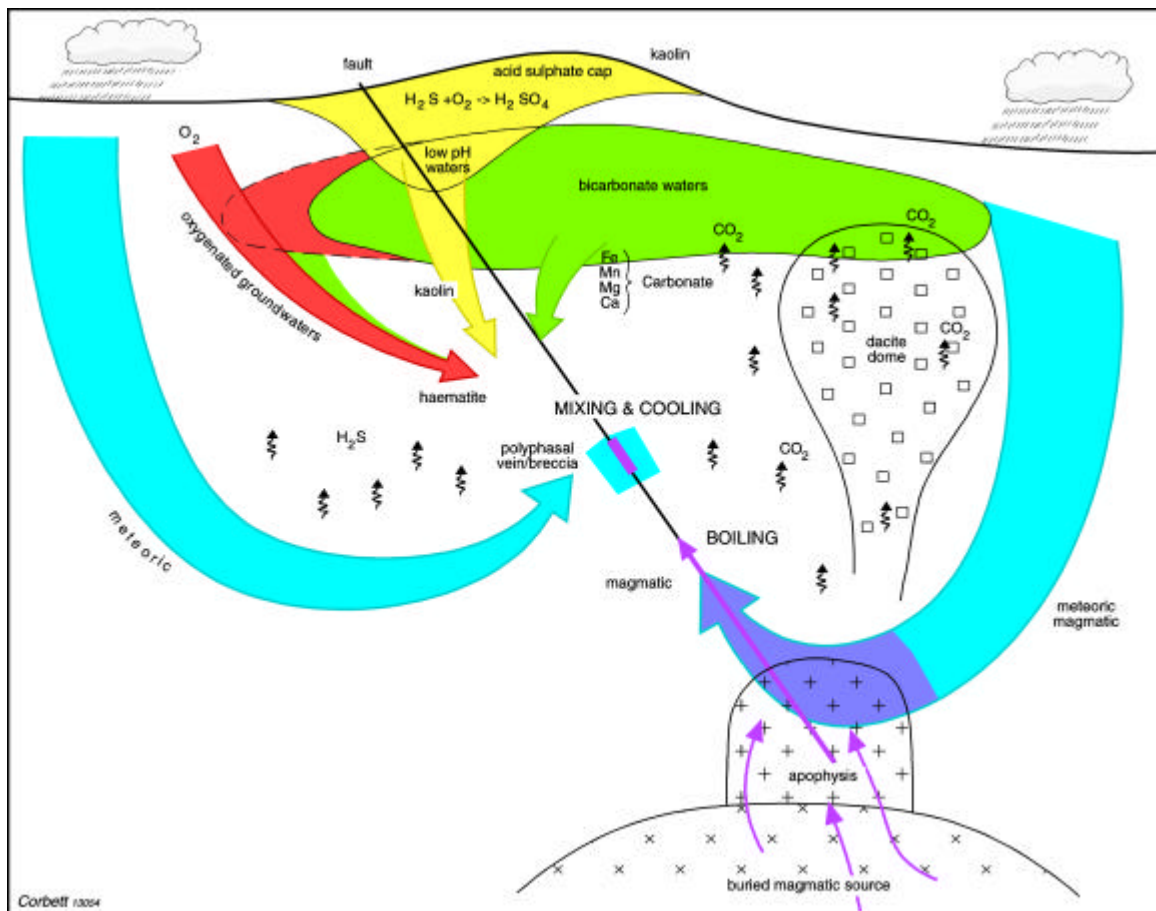


Figure 2. Conceptual model illustrating some of the fluids which may be involved in the development of banded epithermal vein systems.

A typical magmatic arc low sulphidation hydrothermal epithermal system at elevated crustal settings is characterised by interactions of rising and collapsing end member fluids described as:

Cells of circulating hydrothermal fluids driven by a magmatic heat source at depth which rise to participate in vein formation may be considered (Corbett, 2007, 2009) as the three end members (figure 2):

- Hydrothermal fluids emanating from magmatic source rocks at depth are likely to deposit Au-Ag bearing sulphides in addition to quartz with saline fluid inclusions as the dominant gangue mineral. These rise from deepest levels in the hydrothermal system as a result of irregular yet pronounced opening of the host structure, which tapped the magmatic source for metals at considerable depth.
- Some circulating meteoric waters descend to deeper crustal levels and entrain a magmatic component and then rise as a magmatic-meteoric hydrothermal fluid capable of depositing quartz with only moderate salinities along with disseminated sulphides, which contain modest precious metal values.
- Shallow circulating meteoric-dominant waters do not come in contact with the metal-bearing intrusions at depth and so may deposit veins comprising locally

well banded but essentially barren quartz (varying from chalcedony to saccharoidal and comb quartz) along with adularia and locally quartz pseudomorphing platy calcite from boiling fluids. These quartz veins lack sulphides and Au-Ag mineralisation. Fluid flow has been promoted by regular shallow opening of the host structure.

Consequently, it is imperative for explorationists to recognise that many thick epithermal veins may comprise mostly barren quartz deposited from unmineralised meteoric-dominated waters, whereas most mineralisation might be confined to sulphide-rich vein portions derived from a magmatic component to the vein.

Varying mechanisms of Au deposition also influence Au grade in low sulphidation epithermal veins (Corbett, 2008; Leach and Corbett, 2008). While much of the geological literature focuses upon boiling as a mechanism of Au deposition in epithermal deposits, Terry Leach (Corbett and Leach, 1998; Leach and Corbett, 2008) emphasised the importance in precious metal deposition of rapid cooling and mixing between rising ore fluids and locally collapsing ground waters categorised as:

- Low pH acid sulphate waters derived from the oxidation, typically above the water table, of H<sub>2</sub>S rising from boiling and cooling fluids and sulphide-bearing intrusions are generally evidenced by the presence of late kaolin within the ore assemblage, rarely varying to dickite and local alunite. Mixing of these acidic waters with rising ore fluids oxidises the complexes carrying Au as an extremely efficient mechanism of Au deposition and so kaolin is commonly associated with bonanza ores in many low sulphidation vein deposits (Hishikari, Japan; Sleeper, Nevada; Juevos Verde, Patagonia). Collapse of low pH fluids to higher temperature settings may promote local dickite deposition (Sleeper, Nevada).
- Bicarbonate waters, derived from the condensation of CO<sub>2</sub> evolved from boiling hydrothermal fluids and cooling felsic to intermediate intrusions such as dacite flow-dome complexes, are weakly acidic and will also oxidise the thiocomplexes carrying Au in order to promote Au deposition as recognised in the carbonate-base metal group of Au deposits described below (Leach and Corbett, 1994, Corbett and Leach, 1998), such as Porgera, and the Morobe Goldfield in Papua New Guinea; Kelian, Cikotok district in Indonesia; Acupan & Antamok in Philippines; Cowal Australia. This mechanism of Au deposition is evidenced by carbonate, commonly Mn-rich (rhodochrosite, kutnahorite), in the ore assemblage, and Au grade varies with carbonate style (Leach and Corbett, 2008). Au contents decline with acidity of the original bicarbonate waters as indicated by carbonate types grading from Fe to Mn, Mg, and then Ca carbonates are commonly associated with lower Au grades.
- Meteoric groundwaters, which may be oxygenated at shallow crustal levels, also oxidise complexes carrying precious metals and promote precious metal deposition as evidenced by the presence of hypogene haematite within the bonanza ore assemblage (Kupol, Siberia; Fresnillo, Mexico; Gosowong, Indonesia [Sims, 2008]).
- Meteoric ground waters may circulate to deep crustal levels and in Andean low sulphidation epithermal polymetallic Ag-Au veins promote precious and base metal deposition by mixing with rising hot magmatic ore fluids. Here, elevated Au-Ag grades occur where sulphides which typically deposit at high temperatures (black sphalerite, chalcopyrite) are recognised in contact with very low

temperature silica (opal, chalcedony), deposited from the deep circulating meteoric dominated ground waters.

Efficient mechanisms for Au deposition promote the formation of bonanza Au grades within specific portions of banded veins and so contribute towards the development of irregular Au distribution, which characterises epithermal Au deposits. The sulphides with which much of the Au-Ag is associated are commonly not in contact with adularia and quartz pseudomorphing platy carbonate vein portions which are cited as evidence of boiling fluids. While boiling may provide much of the broadly distributed low grade Au in many veins, cooling and mixing reactions account for the development of irregularly distributed bonanza Au grades, locally in small portions of banded veins.

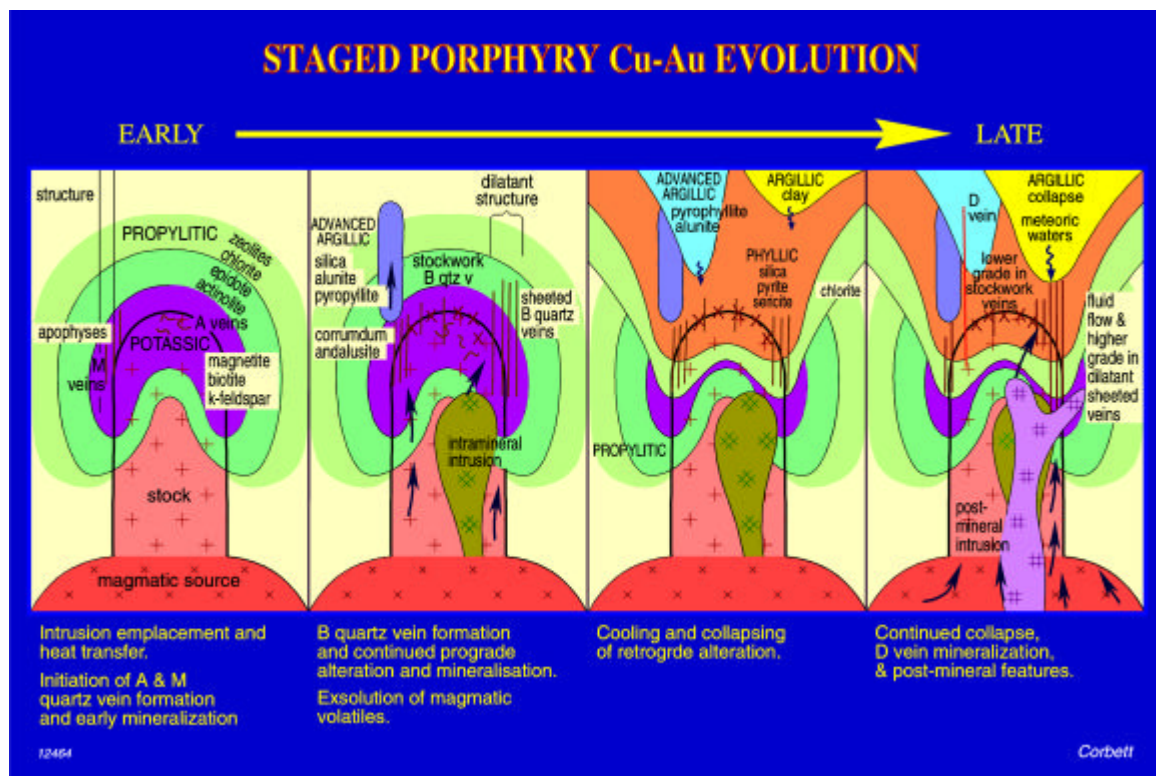


Figure 3. Conceptual model illustrating stages in the evolution of porphyry Cu-Au intrusions, mineralisation, alteration and vein types etc.

### Time in porphyry Cu-Au deposits

Work by Terry Leach on the Philippine geothermal systems (Mitchell and Leach, 1991; Corbett and Leach, 1998) facilitated a better understanding of time in the intrusion-related hydrothermal systems, which can be applied to the study of porphyry Cu-Au mineralisation and alteration. Terry's original work has been expanded upon to provide a current model for staged porphyry development illustrated in figure 3.

- Emplacement of the porphyry intrusion, commonly as an apophysis to a larger underlying magmatic source, results in the development of prograde hydrothermal alteration derived from mainly conductive heat transfer characterised as potassic (magnetite, secondary biotite, Kfeldspar) grading outwards to inner propylitic (actinolite, epidote) and outer propylitic (chlorite, calcite) alteration, formed at progressively cooler conditions with more marginal relationships to the source intrusion. Barren pygmatic and disjointed A style quartz veins developed while the intrusion is cooling may be overprinted by stock work and linear sheeted,

varying to locally wormy A style quartz-sulphide, or M style quartz-magnetite-sulphide veins. These veins and lesser disseminated sulphides represent the main pyrite-chalcopyrite-bornite  $\pm$  Au mineralisation developed during prograde hydrothermal alteration, preferentially concentrated close to the intrusion apophyses, extending into the adjacent wall rocks.

- During continued cooling of the porphyry intrusion, magmatic volatiles may exit the cooling magma chamber and as a result of depressurisation and cooling during the rise to higher crustal levels develop acidic fluids which react with wall rocks to develop barren advanced argillic alteration described by Corbett and Leach (1998) as barren shoulders and included within the lithocap model of Sillitoe (1995). Veins described in the geological literature (Gustafson and Hunt, 1975) as B style quartz-sulphide veins overprint earlier veins. These veins contain centrally terminated comb quartz in-filled by later sulphides (mainly pyrite-chalcopyrite). Some workers describe sulphide in-fill as C veins. Depressurisation due to fracturing of the overpressured intrusion carapace promotes quartz deposition and sheeted or linear vein arrays indicate the involvement of structural processes in the failure of the carapace. Dilational sheeted veins may transport mineralised fluids beyond the host intrusion to form wall rock porphyry intrusions (Cadia Hill, Australia). The porphyry intrusion acts as the source for volatiles and metals as well as heat responsible for the development of circulating cells of magmatic-meteoric hydrothermal fluids, which may extend some distance from the source intrusion into the wall rocks where they deposit epithermal veins (below).
- Volatiles (mainly SO<sub>2</sub>, but also CO<sub>2</sub> > HF) venting from cooling intrusions and vein mineralisation condense and acidify, commonly as large bodies of hot acid groundwaters which promote the development of retrograde alteration varying from hot more acidic phyllic (silica, sericite, pyrite, chlorite, carbonate) to variably cooler and less acid argillic alteration (locally but commonly not combined: dickite, kaolinite, illite, pyrite, chlorite). Drawdown as a result of the reversal of the cells of circulating hydrothermal fluids during cooling of the intrusion apophysis prompts collapse of acid waters upon earlier prograde mineral assemblages and the overprinting of retrograde alteration (stage 3 in figure 3). Interaction of the acid fluids with mineralised fluids rising from the major magma source at depth (below the cooling apophysis) promotes enhanced Cu-Au deposition, typically within B style porphyry veins which commonly display halos of phyllic (silica-sericite-pyrite) alteration (Corbett and Leach, 1998).
- The last stage of vein formation typically occurs within the wall rocks outside the source porphyry intrusion as the development of D veins described in the old porphyry Cu literature (Gustafson and Hunt, 1975), and marks the progression from porphyry to both high and low sulphidation epithermal mineralisation described below.

Polyphasal intrusion emplacement may result in repeated Cu-Au mineralisation and so raise the overall metal grades of many porphyry systems (Ridgeway, Australia; Grasberg, West Papua; Oyu Tolgoi, Mongolia). However, many polyphasal intrusion scenarios culminate in the emplacement of barren late to post-mineral intrusions, which may stope out mineralisation and lower the overall Cu-Au tenure of the deposit (Bajo del la Alumbrera). Elsewhere, diatreme breccia eruptions associated with the emplacement of deeper level intrusions may also stope out Cu-Au mineralisation (El Teniente, Chile; Dizon, Philippines).

In order to identify settings of possible increase and decrease in metal grade, it is important for explorationists to be able recognise features indicative of polyphasal intrusion activity such as: xenoliths, cross cutting dykes, overprinting stock work veins and changes in hydrothermal alteration. Similarly, the complex overprinting alteration and mineralisation relationships which characterise most porphyry systems are best understood using the time-based framework illustrated in figure 3.

### **Porphyry-epithermal transition**

High sulphidation epithermal Au-Cu deposits occur in settings where volatiles rise rapidly from a magma source at depth without interaction with wall rocks or ground waters, and become depressurised to progressively develop as hot acid hydrothermal fluids, which at epithermal levels react with wall rocks (Corbett and Leach, 1998 & Corbett, 2004; and references therein). The progressive cooling and neutralisation of the hot acid hydrothermal fluids by wall rock reaction produces zoned hydrothermal advanced argillic alteration which characterises high sulphation ore deposits, although most Cu-Au mineralisation (typically associated with pyrite-enargite-barite-alunite) commonly post-dates alteration. Root zones of high sulphidation systems may contain D veins characterised by quartz, enargite, pyrite, barite and alunite as a porphyry-epithermal transition. Note the terminology high sulphidation epithermal relates to the sulphidation state of enargite within the characteristic ore mineral, or its low temperature polymorph luzonite, whereas the term advanced argillic alteration is used to describe the associated wall rock alteration (Corbett and Leach, 1998 and references therein).

Low sulphidation epithermal deposits are characterised by variable entrainment of metals within circulating cells of meteoric-dominant, becoming meteoric-magmatic waters, and so feature near neutral ore fluids and hydrothermal alteration of the wall rocks. Deposit types are clearly zoned moving away from the source porphyry intrusion at depth within the wall rocks (Corbett and Leach, 1998; Corbett, 2002, 2004, 2008) from deep to shallow levels as:

- Wall rock porphyry deposits typically comprise sheeted arrays of B style quartz-chalcopyrite veins (Cadia Hill, Australia; Maricunga Belt, Chile; Gaby, Ecuador).
- Quartz-sulphide Au  $\pm$  Cu mineralisation is characterised by veins comprising comb quartz in-filled by auriferous pyrite (Nolan's, Adelong, Australia; Bilimoia, Papua New Guinea; Round Mountain, Sleeper, Nevada; Emperor, Fiji). Deeper level deposits may contain chalcopyrite (Mineral Hill, Australia), specular haematite (Hamata, Papua New Guinea) or pyrrhotite (Porgera, Papua New Guinea; Kelian, Indonesia) although varying to lower temperature marcasite-opal assemblages at elevated crustal settings (Rawas, Indonesia; Chatree, Thailand). Rapid cooling or sulphidation reactions may result in the deposition of fine arsenian auriferous pyrite of questionable metallurgy (Kerimenge, Lihir, Papua New Guinea). Reaction of these mineralised hydrothermal fluids at elevated crustal settings with impure limestone rocks (marls) may give rise to Carlin style (sediment hosted replacement) Au deposits. Many deeper level quartz-sulphide deposits are Cu-bearing and most are Bi-anomalous (Mineral Hill, Australia; Bilimoia, Papua New Guinea).
- Carbonate-base metal Au mineralisation contains early quartz-sulphide Au overprinted by sphalerite>galena with lesser chalcopyrite and tennantite-tetrahedrite, and late stage carbonate (Porgera, Morobe Goldfield in Papua New Guinea; Mt Muro, Kelian, Cikotok district in Indonesia; Acupan & Antamok in Philippines; Cowal Australia). These deposits may evolve to contain overprints of

low temperature epithermal quartz Au-Ag mineralisation (Porgera, Mt Kare; Papua New Guinea). Au is associated with the sulphide content and metal deposition is promoted by mixing reactions of ore fluids with bicarbonate waters derived from the cooling intrusion (Leach and Corbett, 2008).

- Polymetallic Ag-Au deposits comprise quartz-sulphide-carbonate banded fissure vein equivalents of the quartz-sulphide and carbonate-base metal Au deposits which are best developed in Central and South America, where they have been mined since Inca times as important Ag ores. Quartz and pyrite of the quartz-sulphide Au  $\pm$  Cu mineralisation occur early in the paragenetic sequence, as for carbonate-base metal Au, and polymetallic Ag-Au veins evolve to later stage higher crustal level epithermal equivalents characterised by high Ag contents (typically within argentite or freibergite [Ag tetrahedrite]) in association with white low temperature sphalerite. Polymetallic Ag-Au veins may pass upwards to low sulphidation epithermal banded chalcedony-ginguro Au-Ag veins in diatlonal structural settings where circulating meteoric waters deposit banded chalcedony and possible adularia.
- Two end epithermal members developed at highest crustal levels comprise:
  - Epithermal quartz Au-Ag mineralisation which contains high fineness Au with little gangue and overprints quartz-sulphide Au  $\pm$  Cu and carbonate-base metal Au mineralisation (Porgera Zone VII, Mt Kare, Edie Ck in Papua New Guinea; Emperor, Tavatu in Fiji; Sleeper, Round Mountain, Nevada). These deposits are preferentially developed within magmatic arcs (figure 1).
  - Chalcedony-ginguro Au-Ag banded epithermal veins (formerly termed adularia-sericite or quartz-adularia) represent the low sulphidation epithermal veins most commonly described from around the Pacific rim in the geological literature. They are characterised by low fineness Au contained within the black sulphidic ginguro portion of banded veins which also contain chalcedony, quartz pseudomorphing platy calcite and adularia gangue (Pajingo-Vera Nancy, Australia; Waihi, New Zealand, Hishikari, Japan; Midas, US). The term ginguro is derived from the 19<sup>th</sup> century miners who recognised the elevated Au-Ag grades in these bands comprising fine pyrite, electrum Ag sulphosalts and Au.

### **Zoned alteration and the pH vs temperature chart**

Porphyry-epithermal ore systems are characterised by wall rock alteration grouped in the geological literature according to characteristic mineral assemblages. These minerals form under specific pH and temperature conditions and so the pH vs temperature chart (figure 4) by Terry Leach (Corbett and Leach, 1998) is a valuable tool for explorationists as a guide in the analysis of zoned alteration. For instance, the well documented zonation of wall rock clay alteration in low and high sulphidation epithermal deposits may be used to vector to the core portions of zoned alteration where mineralisation might occur with low sulphidation epithermal quartz veins or the vughy silica core of zoned advanced argillic alteration within high sulphidation epithermal Au deposits. Ever improving technology, from original powder XRD to PIMA, to ASD and now CSIRO Hylogger, aid in the development of sophisticated data bases for the analysis of alteration patterns (Camuti, 2008). It is possible to use the pH vs temperature chart to analyse the flow paths of hydrothermal fluids, which contribute to the development of hydrothermal alteration.

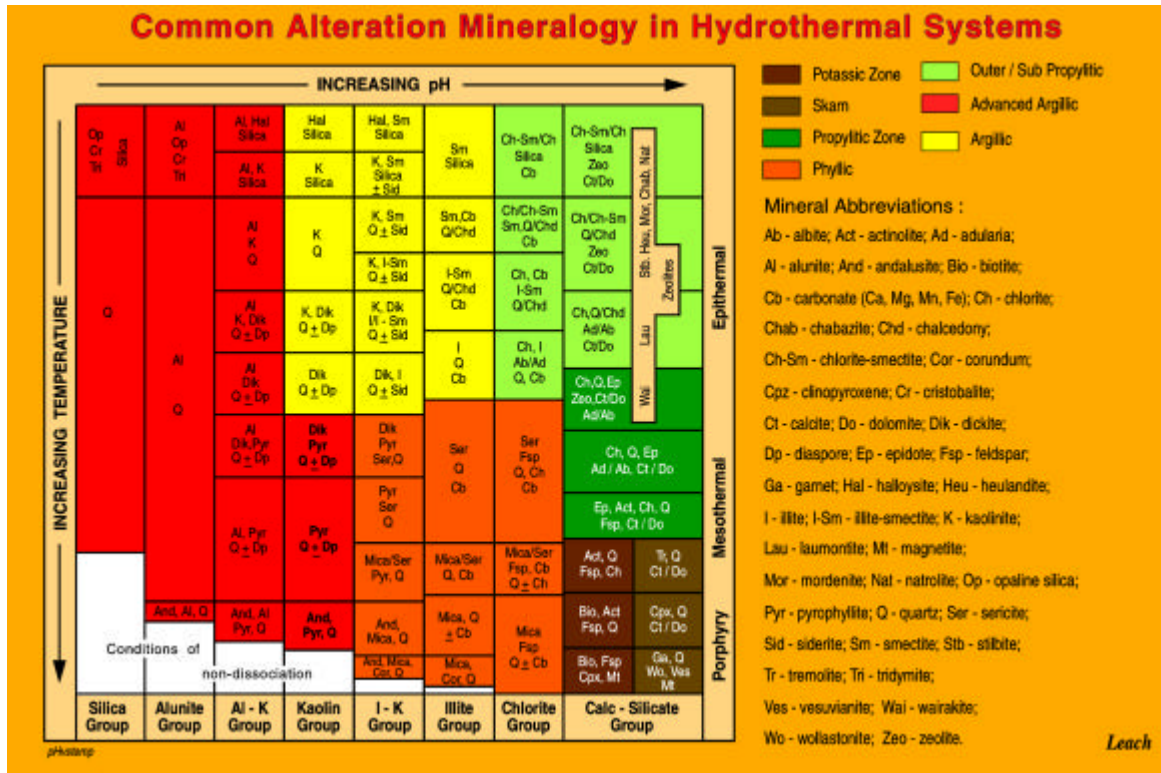


Figure 4. Chart of the pH vs temperature conditions for the formation of many hydrothermal alteration minerals and standard alteration types.

**Lithocaps** are regarded by most explorationists as zones of acid (advanced argillic) alteration which comprise minerals such as silica, alunite, pyrophyllite, diaspore, dickite, with locally abundant pyrite. In most instances lithocaps are considered to develop overlying or adjacent to porphyry intrusions. However, acid alteration mineral assemblages develop in many settings (Corbett, 2008) with highly variable relationships to intrusion source rocks such as:

- Acid sulphide caps to low sulphidation epithermal Au-Ag vein deposits,
- As part of the zoned hydrothermal alteration which characterises high sulphidation epithermal Au deposits which may collapse upon deeper level pre-existing mineral assemblages,
- Within zoned alteration described as barren shoulders (Corbett and Leach, 1998) formed by the reaction of magmatic volatiles with wall rocks which may display structural or lithological permeability controls to fluid flow and contain high temperature minerals such as andalusite or corundum,
- Portions of phyllic alteration involving strongly acidic condensate hydrothermal fluids, commonly form pyrophyllite ± alunite alteration as a core to more extensive silica-sericite-pyrite alteration overlying porphyry intrusions,
- Magmatic solfataras resulting from the reaction with wall rocks of venting magmatic volatiles,
- Supergene weathering promoted by the development of strongly acidic ground waters, commonly developed from the oxidation of pyrite during weathering.

The correct recognition in the field of the nature of acid hydrothermal alteration, which is loosely included within the lithocap alteration style by some workers, and an understanding of its relationship to Au-Cu mineralisation, remains one of the continuing challenges for explorationists.

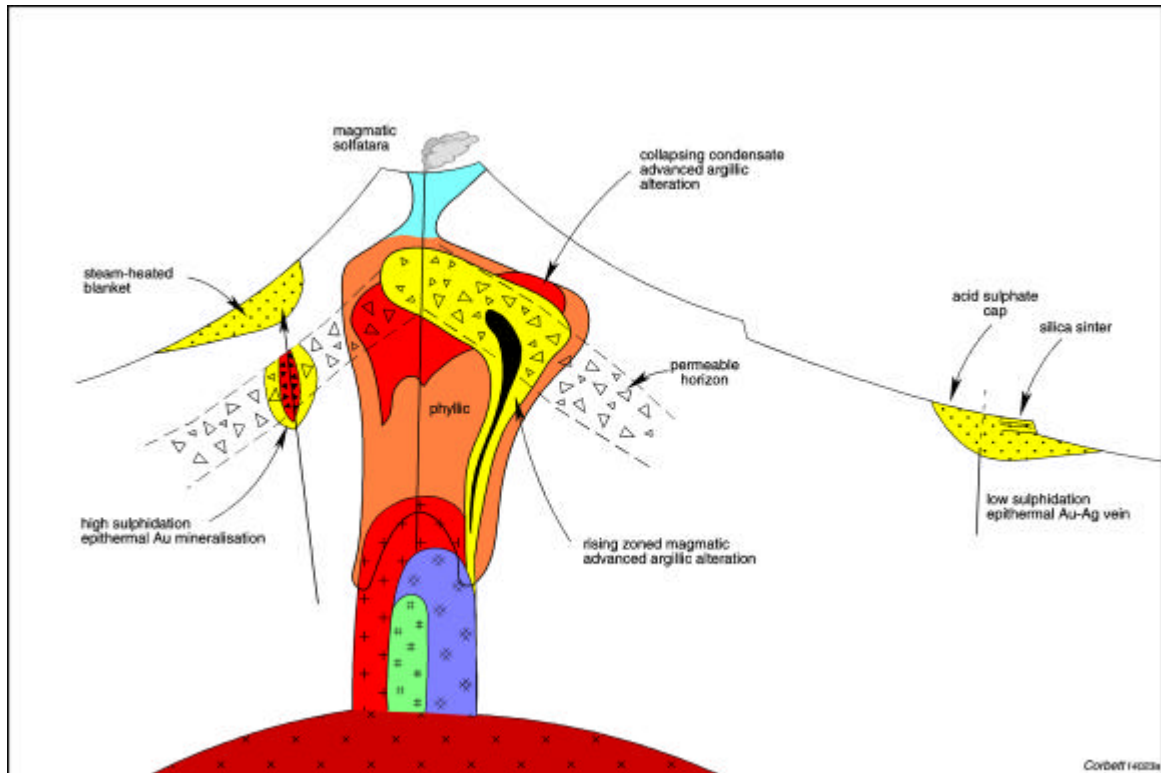


Figure 5. Common settings for the development of acidic alteration.

## Conclusions

Terry Leach's recognition of the differences between magmatic arc and rift geothermal environments when applied to ore systems and the synthesis with his geothermal studies and many exploration case studies has led to the development of improved geological models used in mineral exploration. Whereas many geological models focus upon boiling as a mechanism of Au deposition in low sulphidation epithermal deposits, Terry presented mixing models to account for the development of bonanza Au in low sulphidation epithermal Au deposits.

Analyses of magmatic arc geothermal systems has allowed a better understanding of time in porphyry Cu-Au deposits so that the complex patterns of overprinting alteration and mineralisation in these systems can be better understood.

The temperature vs pH figure by Terry Leach is used throughout the mineral exploration industry to categorise and analyse zoned alteration systems and to plot fluid flow paths. Geological models, which consider the setting of mineralisation within zoned alteration patterns, may aid in the design of drill targets during exploration.

Terry's original view of fluids in porphyry-epithermal ore systems can be developed further to now consider different types of circulating hydrothermal fluids, which contribute towards the development of banded veins as well as collapsing evolved ground waters which contribute towards Au deposition.

## References cited

Camuti, K., Clay minerals in alteration systems: Terry Leach Symposium, Australian Institute of Geoscientists, Bulletin 48, p. 13-18.

- Corbett, G.J., 2002, Epithermal Gold for Explorationists: AIG News No 67, 8p.
- Corbett, G.J., 2004, Epithermal and porphyry gold – Geological models in Pacrim Congress 2004, Adelaide, The Australasian Institute of Mining and Metallurgy, p. 15-23.
- 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](http://www.smedg.org.au)
- Corbett, G.J., 2008, Influence of magmatic arc geothermal systems on porphyry-epithermal Au-Cu-Ag exploration models: Terry Leach Symposium, Australian Institute of Geoscientists, Bulletin 48, p. 25-43.
- Corbett, G.J., and Leach, T.M., 1998, Southwest Pacific gold-copper systems: Structure, alteration and mineralization: Special Publication 6, Society of Economic Geologists, 238 p.
- Gustafson, L.B., and Hunt, J.P., 1975, The porphyry copper deposit at El Salvador, Chile: *Economic Geology*, v. 70, p. 857- 912.
- Henley, R.W., and Ellis, A.J., 1983, Geothermal systems ancient and modern: a geothermal review: *Earth Sciences Review*, v. 19, p. 1-50.
- Mitchell, A.H.G., and Leach, T.M., 1991, Epithermal gold in the Philippines; island arc metallogenesis, geothermal systems and geology: London, Academic Press, 457 p.
- Leach, T.M. and Corbett, G.J., 2008, Fluid mixing as a mechanism for bonanza grade epithermal gold formation: Terry leach Symposium, Australian Institute of Geoscientists, Bulletin 48, p. 83-92.
- Sims, D, 2008, The Gosowong Goldfield; 5 M oz and still growing!: Terry Leach Symposium, Australian Institute of Geoscientists, Bulletin 48, p. 97-106.
- Weissberg, B.G., Brown, P.R.L., and Seward, T.M., 1979, Ore metals in active geothermal systems, *in* Barnes, H.L., ed., *Geochemistry of hydrothermal ore deposits*, 2nd edition: New York, John Wiley & Sons, p. 738-780.