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Fluid mixing as a mechanism for bonanza grade epithermal gold formation

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Footnote

* Corbett and Leach decided to prepare this publication prior to the untimely death of Terry Leach in 2007, and so this text was prepared by Greg Corbett with the assistance of Ray Merchant for the Terry Leach Symposium

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Summary

Although the early geological literature proposed both mixing and boiling as mechanisms for Au deposition, there has been a more recent emphasis upon mainly boiling to account for Au deposition in low sulphidation epithermal deposits. Extensive field studies and analysis of magmatic arc (Philippine) geothermal systems support theoretical considerations in the delineation of other mechanisms of Au deposition in these deposits. While cooling and rapid cooling account for locally elevated Au deposition in quenched fluids (evidenced by very fine grained ores), mixing of rising pregnant hydrothermal fluids with various evolved ground waters provides the most efficient mechanisms of Au deposition and hence elevated Au grades. Different mixing mechanisms account for progressively higher (including bonanza) grade Au mineralisation if ore fluids mix with: deep circulating meteoric waters (evidenced by intergrown sulphide and opal), shallow oxygenated meteoric waters (evidenced by hypogene haematite), grading to bicarbonate waters (evidenced by style of carbonate), and acid sulphate (low pH) waters (evidenced by kaolin), which is associated with highest Au grades. All these mechanisms are easily discernible in hand specimen by the recognition of characteristic mineralogy.

Introduction

Mechanisms are proposed to account for the development of bonanza Au grade epithermal deposits in order to resolve a common discrepancy between published theoretical work and the field observations by experienced exploration geologists. While there is a focus upon low sulphidation epithermal Au-Ag deposits, mixing is also recognised in association with elevated Au in high sulphidation systems (Pierina; Peru; Veladero, Argentina; Leach and Corbett, personal observations), and on the margins of many high sulphidation Au deposits where transitions to lower sulphidation conditions are recognised (Wafi, Papua New Guinea; Leach, 1999). Much of the original science comes from Terry Leach's work on the Philippine Magmatic Arc geothermal systems (Mitchell and Leach, 1991) and the results of this work were initially presented in a series of evolving short courses given for exploration geologists in the 1990's (Corbett and Leach, 1998), and continue to develop by the application to many exploration examples (Corbett, 2007).

Historical Perspective

Much of the early literature on epithermal systems was based on the research done on active geothermal systems in the rift-related examples in New Zealand (Henley and Ellis, 1983). In alteration and mineralization models developed from these studies, fluid boiling and mixing were originally proposed as mechanisms of Au deposition. However, later academic studies focused solely upon fluid boiling as the mechanism to deposit Au (Henley, 1991; Sibson, 1987; Hedenquist et al., 2000; Simmons et al., 2005). Some workers used quantitative models of pressure-temperature conditions and gold solubilities in thermal systems to explain gold deposition by boiling, and cite the results of these calculations as evidence for boiling as the sole means of gold deposition in epithermal systems (Cooke and Simmons, 2000). Meanwhile, empirical petrological work on individual gold deposits published by Leach and others, continued to record observations in mineral textures, associations, and relationships that were more compatible with genetic models based upon fluid mixing as a likely mechanism to account for the geology recognised at those deposits (Emperor, Fiji; Kwak, 1990; Comstock; Vikeri, 1989). Despite these observations, published material on many deposits continued to use boiling models for Au deposition, in keeping with the published research literature even though some authors record difficulties in applying boiling as the sole mechanism of Au deposition.

Boiling of hydrothermal fluids in geothermal systems is reported to initiate the deposition of adularia and a platy form of calcite, commonly later replaced by quartz (Henley, 1991; Hedenquist et al., 2000). It is the presence of these minerals often along with the observed occurrence of gas rich fluid inclusions in gangue minerals, and banded chalcedony, which are taken as evidence for boiling in fossil systems (Henley, 1991). There are problems with the use of these minerals as evidence for Au deposition by boiling. Adularia commonly occurs as wall rock alteration within potassic host rocks whereas minerals deposited by boiling should occur in veins. Redeposition of secondary Kfeldspar should be expected in many hydrothermal systems. Banded veins develop by many individual episodes of mineral deposition. Fluid inclusion studies are often, by necessity, carried out on larger quartz crystals formed in stable conditions of slow cooling, which might not be related to the ore deposition, which generally predominates in quenched fine grained sulphidic bands with no evidence of fluid boiling. Similarly, repeated hydrothermal mineral deposition by rapid cooling might deposit banded chalcedony veins rather than fluid boiling.

The concept that rising depressurised fluids could boil and deposit Au (Sibson, 1987) led to the wide use of 'boiling zone' geological models for the development of flat lying blind ore zones (Lienetz ore zone at Ladolam, Lihir Is., Papua New Guinea; Moyle et al., 1990). The 'boiling zone' model was coined at Lihir in 1985 to account for a flat lying ore zone, with adularia, identified in drilling below essentially barren clay alteration. More detailed petrology (Carmen, 2003) indicated that the adularia is low temperature Kfeldspar which might be expected in such K rich shoshonitic host rocks, and that the flat Lienetz ore zone represents part of a listric fault system which attains higher Au grades and greater widths in steeper dipping portions (Minifie pit; Corbett, unpublished reports 1998-2005). Elsewhere, many epithermal Au-Ag deposits contain flat dipping ore zones which might be accounted for by factors such as host rock competency, permeability, structure, or zones of fluid mixing, with no

relation to fluid boiling (Corbett, 2007). Much of the Au in many epithermal systems is described as intergrown with quartz (Vera Nancy, Bobis, et al., 1995) and may be deposited by boiling, but bonanza Au in epithermal vein deposits of the Vera Nancy (chalcedony-ginguro Au-Ag in Corbett, 2007) style, occurs within fine sulphide bands (Vera Nancy: Ovenden, et al., 2005), which lack evidence of boiling (Corbett and Leach, 1998).

During the late 1980's many explorationists tested the published boiling models by specifically sampling portions of veins in which boiling should have occurred, dominated by adularia or quartz after platy calcite. Commonly it was found that these vein portions were only weakly mineralised, while bonanza Au could often be identified in sulphidic bands, particularly in the dark electrum-rich bands described as ginguro by early Japanese epithermal vein miners (Corbett, 2002).

Boiling is assumed as the mechanism for Au deposition throughout a recent compendium on research related to a distinction between mineralised and barren low sulphidation epithermal quartz veins at Vera Nancy, Queensland (Baker, 2005). These workers (Ovenden, et al., 2005, p. 43, 53 & 60) in suggesting banded chalcedony veins are well mineralised (>10 g/t Au), with highest Au (>100 g/t) within sulphide (herein ginguro) bands, note low Au (<0.1 g/t) in coarser bands (deposited by slow cooling above), and highly variable Au contents in the veins associated with boiling (moss textures and chalcedony). This is because although some Au occurs within quartz, higher grade Au lies mostly in the sulphide bands (Ovenden, et al., 2005; Bobis et al., 1995) and is deposited by rapid cooling not boiling, and possibly fluid mixing. Hence there is no clear correlation between quartz or boiling textures and Au, only a locally accidental one where fine sulphides are present (figure 3, Ovenden et al., 2005). These workers suggest kaolin within the mineralised veins is post-mineral (Ovenden, et al., 2005; Bobis et al., 1995). As discussed below, kaolin, which is often regarded as a late stage associate in many hydrothermal systems, could be an indication of bonanza Au deposition by mixing of ore fluids with low pH waters.

Gold Deposition

In low sulphidation epithermal Au systems, Au is mostly transported in bisulphide complexes (Seaward, 1973), although chloride complexing is also involved in gold transport in the presence of elevated Ag and base metals, such as in the SW Pacific carbonate-base metal deposits Au and Andean polymetallic Ag systems (Corbett and Leach, 1998). The attached figure illustrates the paths taken for various mechanisms of Au deposition for an auriferous geothermal fluid from Broadlands, New Zealand. Gold solubility actually increases during boiling prior to a rapid decline, whereas oxidation by mixing of the pregnant hydrothermal fluid with bicarbonate or acid sulphate low pH waters, promotes a steady decline in gold solubility and immediate gold deposition. Boiling can deposit Au, but we argue other mechanisms might be considered for the development of bonanza Au grades.

In low sulphidation epithermal Au-Ag vein deposits, Au deposition is promoted (Corbett, 2007) by:

- Cooling of auriferous hydrothermal fluids,
- Cooling and dilution by mixing of auriferous hydrothermal fluids with deep circulating meteoric-dominant waters,

- Boiling of auriferous hydrothermal fluids,
- Mixing of auriferous hydrothermal fluids with oxygenated ground waters,
- Mixing of auriferous hydrothermal fluids with bicarbonate waters,
- Mixing of auriferous hydrothermal fluids with low pH acid sulphate waters.

More efficient mechanisms of Au deposition result in the development of elevated gold grades.

Cooling

Cooling in hydrothermal systems generally arises by either conduction or mixing. Rising hydrothermal fluids derived from deeper crustal levels, commonly with a substantial magmatic component, cool at shallow depths in contact with lower temperature wall rocks. This is conductive cooling albeit from a fluid driven by convective processes. Grain size, composition, and mineralogy of the mineralization provide indications of the cooling history of mineral deposition.

The quartz-sulphide Au \pm Cu style low sulphidation epithermal mineralisation (Leach and Corbett, 1995; Corbett and Leach, 1998) is characterised by Au which occurs at grain boundaries within relatively coarse grained pyrite and chalcopyrite. This is an example of deposition by slow cooling of a hydrothermal fluid at relatively deep epithermal, or near porphyry crustal levels. Slow cooling accounts for Au deposition within coarse grained sulphides but provides only relatively low Au grades, as it is not a strongly dynamic process. However metallurgical characteristics are generally very good.

Rapid cooling is recognised in some Au (Lihir, Kerimenge, Papua New Guinea) and Ag (Corani, Peru) deposits, where native gold or Ag minerals are often included in fine grained sulphides and may be difficult to beneficiate. Terry Leach studied Au at Lihir encapsulated within arsenean pyrite (Corbett et al., 2001). Elsewhere, rapid cooling deposits fine silica-sulphide, termed 'silica gris' in South America, where it may cap blind polymetallic Ag-Au mineralisation (Arcata, Peru) as part of an early event in the polymetallic paragenetic sequence (Corbett, 2007). Rapid unroofing of hydrothermal systems by sector collapse (Lihir, Papua New Guinea), or tectonic erosion (Corani, Peru), is recognised as an important contributor to the development of quenched hydrothermal fluids and precipitation of elevated precious metal grades within fine grained ores. Rapid cooling of hydrothermal fluids is a more efficient mechanism of Au deposition and so can account for the development of elevated Au grades, but metallurgical characteristics may be poor. Arsenean pyrite is a common associate with rapidly quenched mineralization and the iron sulphide mineralogy reflects depths and temperatures of formation dominated by marcasite-pyrite.

Mixing with deep circulating meteoric-dominant waters

In many Andean low sulphidation epithermal polymetallic Ag-Au deposits, higher precious metal grades occur in breccias and to a lesser extent banded veins in which sulphides (dark Fe-rich sphalerite and chalcopyrite) typically formed at high temperature from rising magmatic-dominated fluids, are in contact with opaline silica typical of very low temperatures of deposition. Here, it is interpreted that rising magmatic-dominated hydrothermal fluids have been rapidly cooled, and diluted by mixing with meteoric-dominated ground waters, which will be non-oxygenated where circulated to deep crustal levels. At Fresnillo, Mexico, veins locally contain the mix of

high temperature sulphides and low temperature silica described above (Corbett, pers. observation, 2005; Simmons et al., 1988). Detailed work by Vikre (1989) on the Comstock lode demonstrated bonanza Au precipitation resulted from the mixing of mineralised rising mineralised magmatic fluids with collapsing cooler ground waters. Similarly, at the Buckskin mountain sinter system, Vikre (2007) attributes the deposition of silica, Hg-Se-S-Cl complexes and precious metals to the mixing of rising pregnant fluids with meteoric waters. Kwak (1990) provides an extensive explanation for his deviation from standard boiling models to cite mixing with meteoric waters to explain the substantial temperature drop responsible for Au deposition at the Emperor gold mine, Fiji.

Mixing with shallow oxygenated ground waters

The mixing of auriferous hydrothermal fluids with shallow level oxygenated meteoric-dominant hydrothermal fluids has the effect of destabilising the bisulphide complexes which transport Au, and so results in Au deposition (figure 1). The presence of hypogene haematite in such ore provides evidence of this mechanism of Au deposition. Often this event is followed by sulphide deposition once the oxygen has been consumed. It is important to ensure, by careful inspection of drill core, that haematite is hypogene and not supergene. The position below the base of oxidation and presence of sulphides overprinting haematite are good indications of hypogene haematite.

A sub-horizontal zone of haematite occurs above and extending down into the blind polymetallic Ag veins at Fresnillo, Mexico (Corbett, pers. observation, 2005). Here rising mineralised hydrothermal fluids have mixed with oxygenated ground waters at a particular level in the hydrothermal system, often influenced by host rock permeability, as a mechanism of Au deposition. Similarly, many other high crustal level epithermal deposits with interpreted strong magmatic components host high grade Au in the presence of hypogene haematite (Porgera, Papua New Guinea; Corbett et al., 1994; Palmarejo, Mexico and Kencana at Gosowong, Indonesia: Corbett, unpubl. reports).

Mixing with bicarbonate waters

Early studies in active geothermal systems (Henley and Ellis, 1983) identified broad zones of fluid chemistry (and associated rock alteration) consistent with the presence of bicarbonate dominant waters. These are thought to be the product of the condensation of CO₂, derived from deeper boiling of geothermal fluids and/or the degassing of cooling high level intrusions. The blanket-like zones of bicarbonate waters, which usually lie below the water table, may locally vent to the surface and form travertine deposits (sinters) and are better developed in magmatic arc systems dominated by intermediate volcanic rocks. Empirical observations suggest bicarbonate waters are well developed in regions characterised by the presence of dacite domes and phreatomagmatic breccias, and so contribute towards the development of the intrusion-related low sulphidation epithermal carbonate base-metal Au deposits (Leach and Corbett, 1994; Corbett and Leach, 1998).

If rising auriferous hydrothermal fluids, commonly with a magmatic component, come in contact with blankets of weakly acidic bicarbonate waters, the bisulphide complexes carrying Au become destabilised and so deposit Au. This mixing reaction to deposit Au and locally base metal sulphides as well as carbonate, is an essential

component of the carbonate-base metal Au deposit model (Leach and Corbett, 1994, 1995; Corbett and Leach, 1998). These deposits include some of the most prolific gold producers in the SW Pacific (Porgera, Mt Kare, Morobe goldfield, Woodlark & Misima, in Papua New Guinea; Kelian, Cikotok & Mt Muro in Indonesia; Antamok, Acupan & Victoria in the Philippines; Cowal, Australia), and this same model is also employed in the genesis of the Andean polymetallic Ag-Au deposits (Palmarejo & Fresnillo in Mexico; Corani, Arcata & Caylloma in Peru; Cerro Moro, San Jose [Huevos Verde] & Martha in Argentine Patagonia; El Penon & Cerro Bayo in Chile).

Intrusion-related low sulphidation epithermal Au deposits without associated dacite domes and/or phreatomagmatic breccias commonly lack bicarbonate blankets and so do not exhibit carbonate-base metal style Au mineralisation. Rather, they are dominated by only the quartz-sulphide Au \pm Cu and later epithermal quartz Au-Ag styles of intrusion-related low sulphidation epithermal Au-Ag mineralisation (Emperor, Fiji; Lihir, Papua New Guinea; Corbett and Leach, 1998; Corbett et al., 2001).

The chemistry of the carbonate associated with the ore reflects the pH of the original bicarbonate waters and influences Au grades. The more acidic bicarbonate waters are more effective in the destabilisation of bisulphide complexes, to provide higher Au grades with siderite. However, the bicarbonate waters are generally not this acidic. Typically, the bicarbonate waters dissolve manganese cations from volcanic wall rocks, leading to the deposition of manganese carbonates and so there is a common association between rhodochrosite and Au mineralisation in many carbonate-base metal Au deposits. Progressive neutralisation of the acidic bicarbonate waters by wall rock interaction, is often reflected in declining Au grades as the carbonate chemistry moves from manganese to magnesian, and then calcic dominant mixed carbonates (progressively kutnahorite, ankerite, dolomite, Mg calcite and calcite; Corbett and Leach, 1998). Little Au is associated with calcite (deposited from near neutral waters) as there is no significant oxidation of the ore fluid to promote Au deposition.

It is important to recognise that in this mixing phenomenon the rising magmatic fluid carries Au-Ag mineralisation and the bicarbonate waters are barren. In many exploration examples, low to moderate gold grades occur in specimens or drill intercepts where fluid cooling has promoted the deposition of only sulphides, but no carbonate in the absence of fluid mixing, whereas elevated Au grades occur with intergrown sulphides and carbonate derived from fluid mixing. Similarly, carbonate deposited from bicarbonate waters, which have not come in contact with sulphides, is generally barren.

Of interest to explorationists is that the Mn carbonates associated with mineralisation are often discernible by the presence of MnO in weathered exposures, Au-Ag grades in carbonate-sulphide mixes can be correlated with carbonate type, as described above, and zonation patterns in carbonate type reflect neutralisation trends (Corbett and Leach, 1998; Corbett, 2007).

Mixing with low pH acid sulphate waters

Acid sulphate caps commonly develop at, or near the surface within low sulphidation epithermal hydrothermal systems by the reaction of warm acidic ground waters with the wall rocks, typically above the water table. These acidic (low pH) waters have

been generated by the reaction (oxidation) of bisulphide volatiles with near surface oxygenated meteoric water creating sulphuric acid solutions. The bisulphide commonly comprises rising H_2S volatiles exsolved from cooling sulphides within veins, and disseminated within intrusions and wall rock alteration halos at depth. The interaction of acid sulphate waters with wall rocks creates amorphous silica, sulphates, oxides, and acid stable clays, and so in the field acid sulphate caps are readily recognised by explorationists as bleached areas of poor vegetation with amorphous silica, alunite, kaolin and local sulphur.

The mixing of rising auriferous hydrothermal fluids with low pH waters (associated with acid sulphate caps) is a most effective mechanism for the oxidation and destabilisation of the gold bearing bisulphide complexes, and so results in the development of elevated Au grades. Evidence from some geothermal systems (Leach, pers. observation) suggests low pH waters may collapse from near surficial levels to very deep portions of hydrothermal systems, as supported by ore deposit studies (Corbett, pers. observation). The mixing reaction produces kaolin typically deposited late in the paragenetic sequence of the ore minerals, which may pass to the more crystalline higher temperature dickite at deeper levels (Sleeper, Nevada, G. Ferlock, pers. commun.; Vera Nancy, K. Camuti, pers. commun.), and locally alunite. Explorationists should distinguish hypogene kaolin and alunite from supergene kaolin-alunite which results from the reaction with wall rocks of acidic ground waters generated during sulphide weathering. Hypogene kaolin is locally inter grown with sulphides, typically pyrite, while supergene forms are typically inter grown with iron oxides. Similarly, many workers assume kaolin which is generally deposited late in the paragenetic sequence, often replacing adularia, is post-mineral, however in banded veins deposited from polyphasal hydrothermal events, the low pH waters may be available to mix with later Au-bearing fluids. Kwak (1990) cites the presence of barite and adularia altered to illite, in suggesting a low pH (acid sulphate) character for meteoric waters which mixed with ore fluids to promote bonanza Au deposition at the Emperor gold mine, Fiji.

As arguably the most efficient mechanism of Au deposition, the mixing of ore fluids with low pH waters produces the highest Au grades in epithermal Au systems (Hishikari, Japan; Sleeper, Nevada). Repetition of high grade ore deposition, typically by reactivation of the host dilatant structures (Corbett and Leach, 1998) and other factors such as host rock competency and style of mineralisation (Corbett, 2007) also contribute towards the development bonanza Au grades. Ore shoots characterised by elevated Au grades may develop at structural intersection such as where ore fluids rising up a normal fault may mix with low pH fluids collapsing down a hanging wall splay (figure 2; Corbett, 2007). An analogous situation occurs at the Palinpinon geothermal field, Philippines (figure 2.12, Corbett and Leach, 1998) where acid sulphate waters collapsing down a fault zone mixed with pregnant fluids rising up a geothermal drill hole, which became blocked with scale containing base metal sulphides and electrum (Leach, unpubl data; pers. commun. to Corbett, 2001). Similarly, the Buchanan (1981) epithermal model may be reinterpreted from existing boiling, to a demonstration of fluid mixing at a structural intersection with acid waters collapsing down the hanging wall structure.

It is important for explorationists to note that mixing zones tend to have sharply defined lower limits to the better Au grades governed by the depth to which low pH

waters have collapsed. One author herein (GC) has seen exploration properties in which bonanza Au quickly declines as kaolin terminates with increasing depth.

Acid sulphate caps are therefore highly prospective sites for further investigation, not only as they represent the uppermost generally poorly mineralised portions of vertically zoned low sulphidation epithermal Au deposits, but that these deposits may feature more elevated Au resulting from the mixing of collapsing low pH waters with rising ore fluids.

Conclusion

Analysis of numerous exploration examples of fossil geothermal systems, coupled with the application of models derived from earlier studies of magmatic arc geothermal systems (Mitchell and Leach, 1991; Corbett and Leach, 1998), demonstrates there are a variety of mechanisms for Au deposition in epithermal systems. Diverse mechanisms destabilise complexes carrying Au in hydrothermal fluids with varying efficiency and so account for different Au grades. Detailed observations of ore and gangue mineralogy often indicate that several mechanisms of Au deposition have been active at individual Au deposits, and contribute towards formation of variable Au grades. Based upon empirical analyses of many exploration and mining examples, cooling and mixing the mechanisms of Au deposition might be ranked in order of efficiency, and hence associated with rising Au grade, as: cooling, rapid cooling, mixing with deep circulating ground waters, mixing with oxygenated ground waters, mixing with bicarbonate waters, and mixing with low pH acid sulphate waters. Explorationists should consider a wider variety of mechanisms for Au deposition than the boiling models often promoted in the research and academic literature, and previously applied to exploration scenarios. There is also potential to reconsider many exploration prospects previously evaluated using boiling models. Use of mixing models may provide vectors towards blind ore systems, such as high grade Au below barren acid sulphate caps. However, explorationists should also be mindful that mixing zones associated with kaolin locally display sharp lower limits of the elevated Au grades, governed by the extent of collapse of low pH waters. Potential remains for further academic work to contribute towards the continued development of these geological models which aid mineral exploration.

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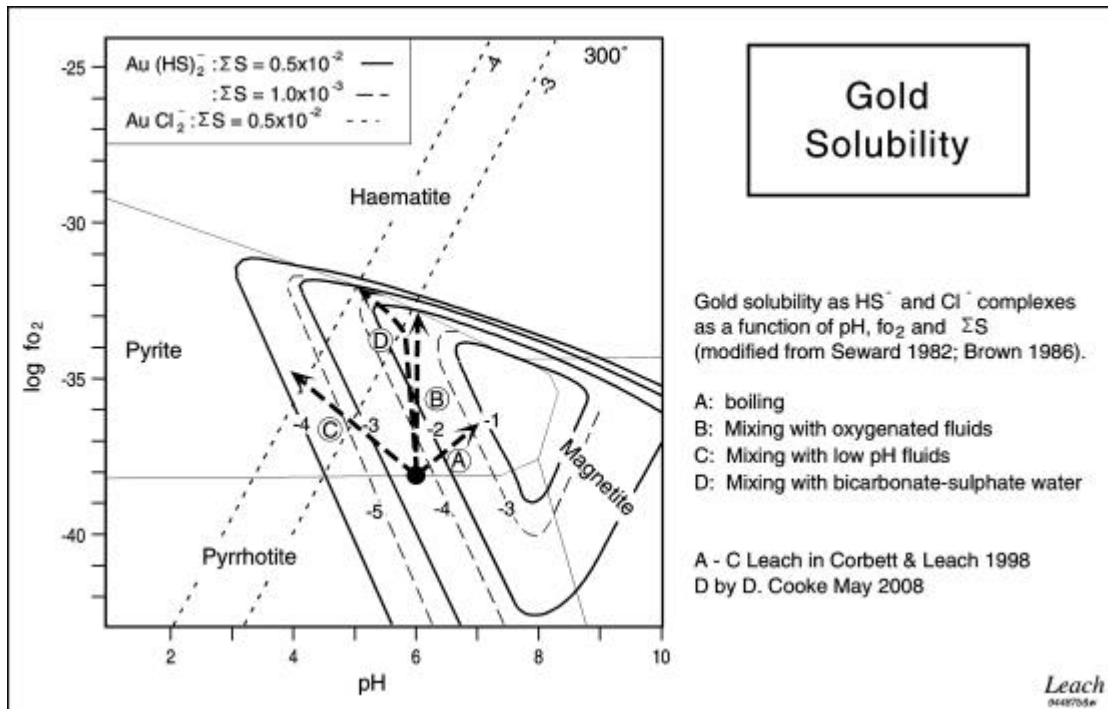


Figure 1. Flow paths of a Broadlands geothermal fluid in which Au deposition results from either boiling or mixing with ground waters. Note that for the boiling (A) Au solubility initially decreases and before a sudden decrease and mineral deposition, while this effect is less pronounced in path B, yet path C is progressively down hill with ready Au deposition. Dave Cooke kindly calculated and provided fluid flow path D. The rest of this figure is from Corbett and Leach, 1998.

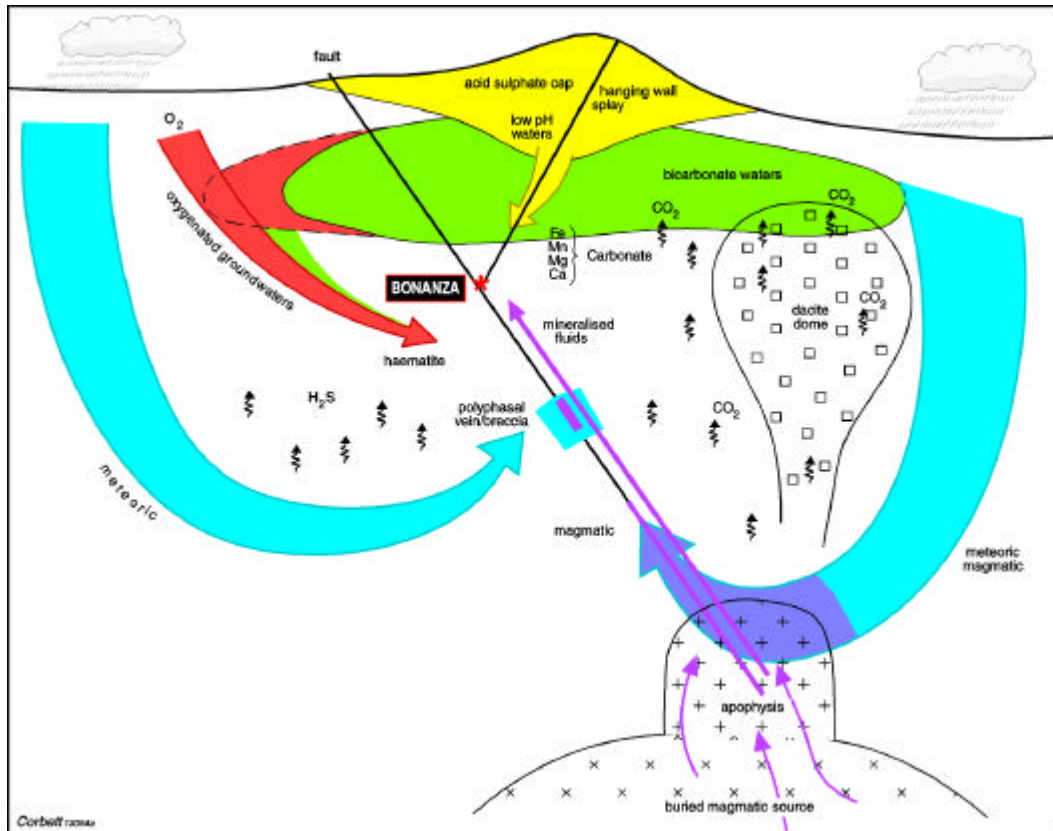


Figure 2. The various circulating waters which deposit hydrothermal minerals to form quartz veins include: shallow circulating meteoric waters which might deposit only barren quartz with adularia or quartz after platy calcite, composite meteoric-magmatic waters which have entrained metals to deposit lower grade Au mineralisation as disseminated sulphides within quartz veins, and magmatic dominated hydrothermal fluids which deposit the well mineralised sulphide dominant vein portions. The ground waters which contribute towards mixing reactions include: shallow oxygenated meteoric waters, blankets of bicarbonate waters related to CO_2 exsolved from a cooling dacite dome, and low pH waters derived by the oxidation of H_2S volatiles above the water table where reaction with wall rocks resulted in the development of an acid sulphate cap. Note the bonanza Au developed where low pH waters have mixed with rising auriferous magmatic dominated hydrothermal fluids at the intersection of a hanging wall splay and normal fault. (Adapted from Corbett, 2007).