The mineral products of boiling in the Golden Cross epithermal deposit

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Abstract

The Golden Cross low sulfidation epithermal deposit shows a number of features that are directly or indirectly related to boiling hydrothermal fluids. Occurrences of lattice calcite and their quartz pseudomorph equivalents in veins, and occurrences of adularia in veins and in the surrounding altered rocks in the vicinity of ore, are direct evidence of deposition in the presence of boiling hydrothermal fluids. Loss of carbon dioxide causes calcite deposition (platy variety) near the level of first boiling, while adularia deposits due to the attendant pH increase and cooling.

Indirect evidence of boiling includes crustiform-colloform quartz banding, late massive calcite veins, and clay-carbonate alteration in the shallow and peripheral parts of the ore zone. The colloform quartz banding strongly resembles the banding in amorphous silica deposits found in geothermal surface pipes. This implies that fluids ascending the Empire vein structure were saturated in amorphous silica. If so, then they must have undergone phase separation, which initiated at considerable depth (e.g. ≥1000 m) and very hot temperatures (e.g. ≥300°C).

On the basis of stable isotope data, late massive calcite veins appear to have deposited from CO_2-rich steam-heated waters. Calcite deposited along heating paths as these waters descended into the upflow zone during late stage collapse of the hydrothermal plume. In active systems, such steam heated waters form by deep boiling. The high CO_2 contents of these waters promote hydrolytic alteration and the formation of clay-carbonate alteration.

Reaction path modelling using CHILLER and a deep, Broadlands-Ohaaki water as an analogue, shows that minerals deposit at discrete sites along boiling flow paths. Calcite and adularia deposit near the site of first boiling followed by gold and then by amorphous silica. For deep boiling starting at 300°C, these minerals deposit over a path length that exceeds 1000 m. The distribution of banded quartz and gold at Golden Cross are consistent with such a boiling model. However, the elevation of first boiling must have fluctuated over 500 m to account for the coincidence of lattice quartz (pseudomorphs of platy calcite) and crustiform-colloform banded silica in veins.

Introduction

Boiling and mixing are the two most commonly ascribed processes leading to the formation of low-sulfidation epithermal gold-silver deposits (Henley and Ellis, 1983; Heald et al., 1987; Cooke and Simmons, 2000). Despite overwhelming evidence in support of boiling, some workers advocate mixing or cooling as the principal means of precious metal deposition (e.g. Vikre, 1989; Sander and Einaudi, 1990; Corbett and Leach, 1998). The distinction between boiling and mixing is relevant to explorers in so far as the process controls the sites of gold and silver deposition (over vertical or horizontal distances >100 m; e.g. Hayba, 1997). This paper builds on earlier studies (de Ronde and Blattner, 1988; Simpson, C. et al., 1995; Simpson, M. et al., 1995; Simmons et al., 2000) in presenting the mineralogical evidence that boiling hydrothermal fluids formed the Golden Cross Au-Ag deposit. In doing so, we rely heavily on our work on the Broadlands-Ohaaki geothermal system which contains an analogous modern epithermal ore-forming environment (Simmons and Browne, 2000). The main aims are to highlight the mineralogical evidence of boiling, describe their distribution and occurrence with respect to ore, and to discuss their relevance in exploration.

Golden Cross deposit

The Golden Cross low-sulfidation epithermal Au-Ag deposit is one of forty-seven known epithermal vein deposits in the Hauraki Goldfield (Figure 1; Brathwaite et al., 1989). From 1895 to 1998, approximately 750,000 oz of gold were produced. The host rocks are made up of andesitic to dacitic lavas, pyroclastic deposits and epiclastic sedimentary deposits (Caddey et al, 1995; Brathwaite and Christie, 1996). The

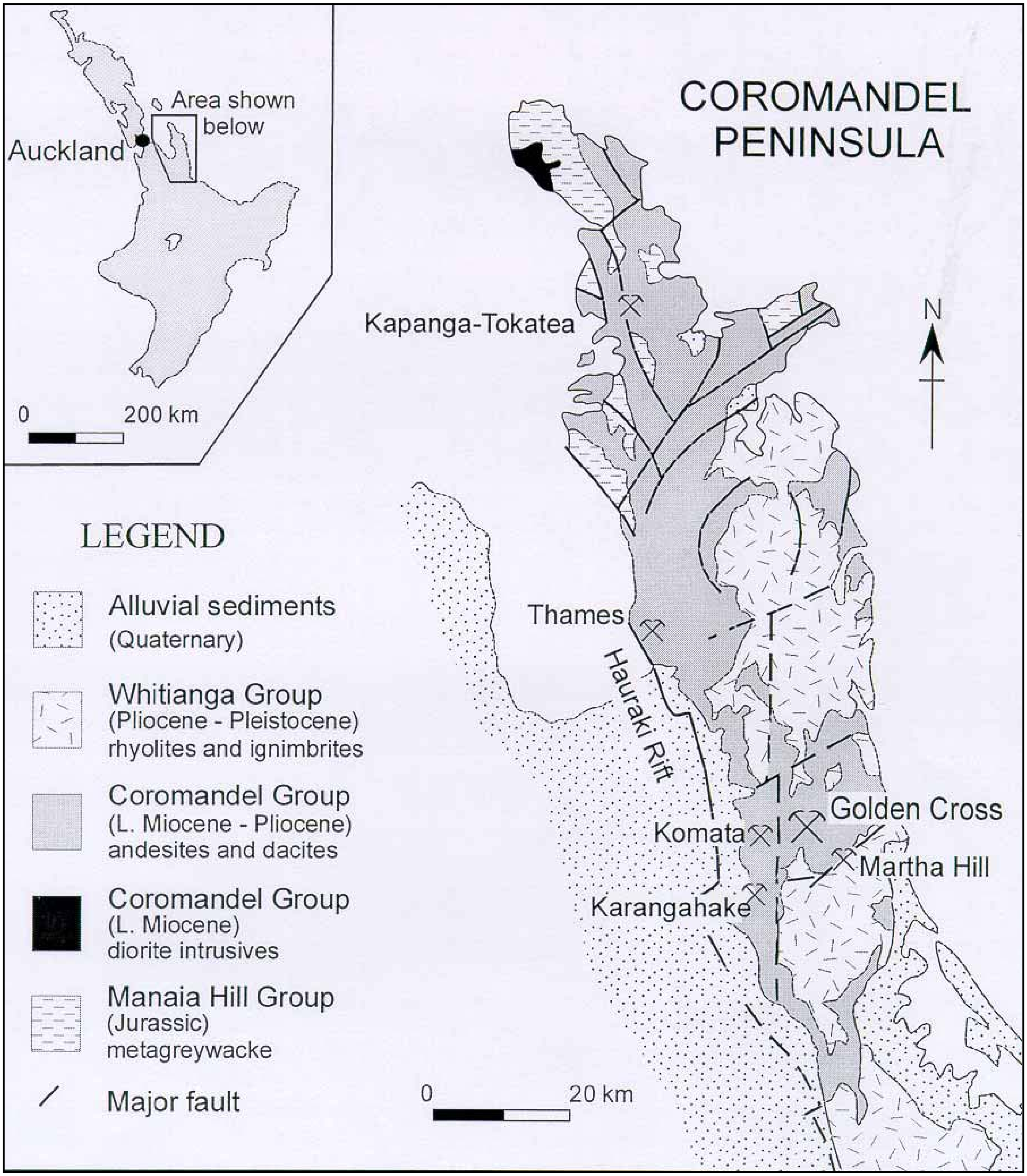

Figure 1. Location of the Golden Cross epithermal deposit (after Skinner, 1986).

Empire and Western Boundary faults are the most prominent faults in the mine zone (Figures 2 and 3). Precious metals occur in quartz-sulfide-bearing veins associated with the Empire zone and the hanging wall stockwork. The Empire zone is an upward-branching network of crosscutting veins, which contains ore for approximately 600 m along strike. Poorly mineralized segments extend at least another several hundred meters north. The Empire vein is the main, steeply dipping vein that dominates the Empire zone (Figure 3), and it appears to disappear or at least substantially narrow beneath the ore zone (Keall et al., 1993; Caddey et al., 1995). The Golden Cross 1 Reef mined early in this century is the southern extension of the Empire vein.

Ore from the Empire zone was mined by underground methods at an average grade of 6 to 7 g Au/tonne. In the hanging wall,

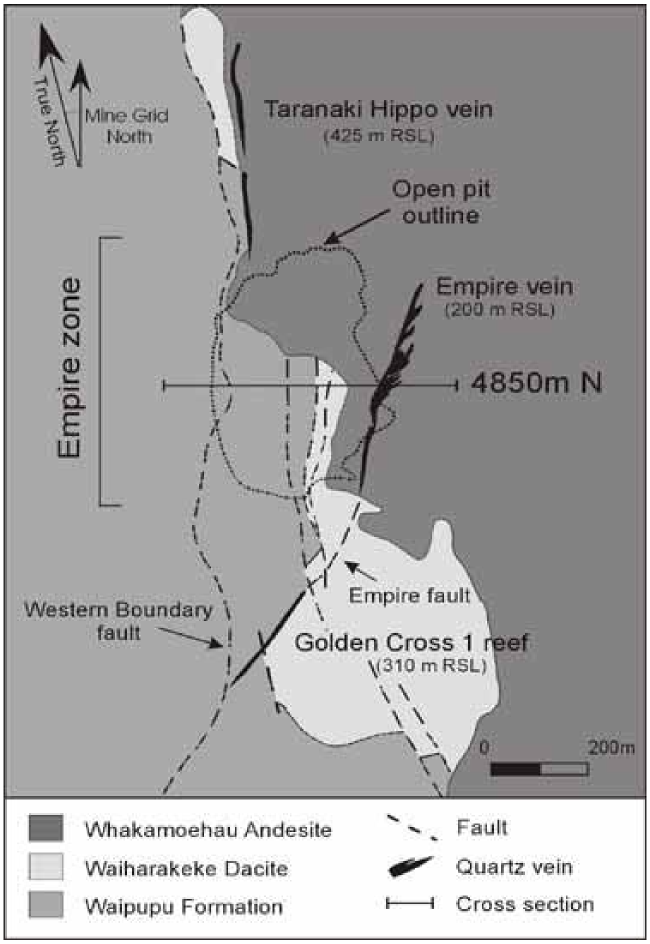

Figure 2. Geological map in the vicinity of the Golden Cross epithermal deposit.

closely spaced narrow (<1 to 20 cm width) veins form a stockwork zone that was mined by open pit methods (Figure 3), and ore from here had an average grade of 2 to 3 g Au/tonne. The ore for both zones is confined to a vertical extent of approximately 300 m (Figure 3). Very fine-grained quartz dominates the Au-Ag-bearing vein mineral assemblage, with lesser and varying amounts of adularia, pyrite, rare kaolinite and rare calcite. Crustiform textures and areas of complex vein brecciation are common. Gold and silver occur as electrum, acanthite, polybasite and pyrargerite, and these are associated with minor base metal sulfides (Simpson, C. et al., 1995). Late barren calcite veins which attain maximum widths of 10 m, are most abundant in the southern part of the mineralized zone and crosscut precious metal-bearing quartz veins (Figure 3).

Hydrothermal alteration patterns and fluid inclusion data show that the deposit formed around 180 to 220^{o}C at <500 m depth where boiling upflow conditions existed within a geothermal system (de Ronde and Blattner, 1988; Simpson, C. et al., 1995; Simpson, M. et al., 1995).

In the next two sections we review the mineralogical evidence of boiling at the Broadlands-Ohaaki geothermal system and compare these occurrences with those at Golden Cross.

Mineral indicators of boiling at Broadlands-Ohaaki

The Broadlands-Ohaaki geothermal system is one of the well-studied geothermal systems in the Taupo Volcanic Zone (e.g. Browne and Ellis, 1970; Hedenquist, 1990; Simmons and Browne, 2000). There are over 50 wells, most of which are vertical, ranging from 400 to ~2600 m depth. The compositions of fluids sampled from wells have been used to map out the chemical structure of the system (Hedenquist, 1990). Minerals and textures that indicate boiling, described below, deposit from two water types, deeply derived chloride water and shallow formed CO_2-rich steam-heated water.

Deep water that ascends the upflow zone is termed chloride water because chloride is the dominant aqueous solute in liquid discharged at the surface (~0.2 wt % NaCl), though pre-boiled water can contain ten times or more dissolved carbon dioxide (~2-3 wt % CO_2). At >500 m depth, quartz, adularia, albite, illite, calcite, chlorite and pyrite are the alteration minerals in volcanic host rocks produced by these waters (Browne and Ellis, 1970; Simmons and Browne, 2000).

Chloride waters enter geothermal wells via deep (>500 m) feed points at temperatures of $\geq 250^{o}$C. As the liquid ascends, it flashes (losing steam and dissolved gases) and cools, depositing calcite, precious metals and sulfides, and amorphous silica as shown in Figure 4. Loss of CO_2 causes calcite, with a characteristic platy habit to precipitate near the level of first boiling (Browne, 1978; Tulloch, 1982; Simmons and Christenson, 1994). These deposits grow from the pipe wall and have a restricted vertical interval of 100 to 300 m (Tulloch, 1982). As flashing progresses, loss of H_2S and H_2 leads to electrum and chalcopyrite precipitation in surface pipes, attaining concentrations of up to 5 wt. % Au and 17 wt. % Ag (Brown, 1986). Although favoured by cooling, slow reaction kinetics prevents quartz deposition from chloride water in the well, and the build up of aqueous silica in the residual liquid leads to amorphous silica deposition downstream of the separator (Fournier, 1985; Christenson and Hayba, 1995; Brown, 1999). These deposits commonly display crustiform-colloform banding (Christenson and Hayba, 1995; Simmons and Browne, 2000). Some of the precipitates remain in the flow stream (i.e. they do not stick to the pipes) and they ultimately settle out in the weirbox where chloride water flashes and discharges to atmospheric pressure. These unconsolidated materials comprise amorphous silica, sulfides and rock clasts and contain up to 100 ppm Au and up to 1000 ppm Ag. While it is absent from geothermal wells, adularia is commonly found in veins with quartz and platy calcite and in the enclosing host rocks of geothermal reservoirs (Browne, 1978). Adularia deposits due to gas loss, pH increase and cooling and has long been known to be strong evidence of boiling and good permeability in reservoir production zones (Browne, 1970; Browne and Ellis, 1970).

Shallow-formed CO_2-rich steam-heated waters contain up to 1-2 wt % CO_2 (but nil chloride) and are the principal diluent of the chloride water, occupying the margins of the upflow zone (Hedenquist and Stewart, 1985; Hedenquist, 1990). This

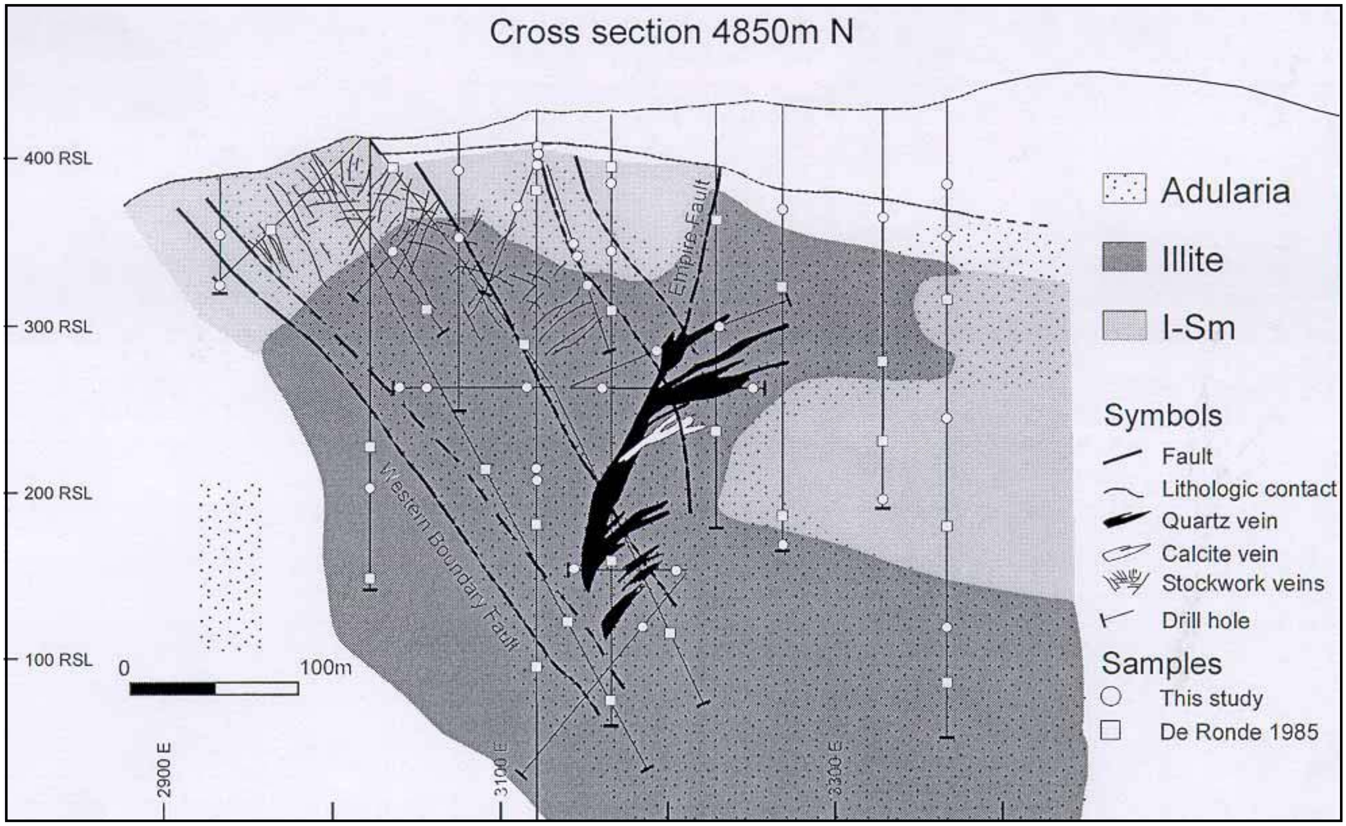

Figure 3. Cross section (4850 N) through the Empire and stockwork ore zones showing the relationship between veins, illite, illite-smectite and adularia occurrences.

fluid owes its origins to condensation of steam and absorption of carbon dioxide (separated from the deeply boiling chloride water) into cool, shallow ground waters. Apart from the absence of chloride, the composition of this water type is distinguished by its relatively low δ^{18}O composition, which is about 1.5 to 2.5 ‰ lower than chloride water (Hedenquist and Stewart, 1985). Illite, smectite, calcite and siderite are the main alteration products due to the weakly acidic nature of the steam-heated water, and they occur in the shallow and peripheral parts of the system. As the CO_2-rich water is saturated in calcite, any slight heating causes calcite deposition due to its reverse solubility (Simmons and Christenson, 1994).

Mineralogical indicators of boiling at Golden Cross

The minerals and textures that indicate boiling at Golden Cross are described below.

Lattice textures

Aggregates of platy calcite forming lattice textures and their quartz pseudomorph equivalents are characteristic features of low sulfidation epithermal veins (e.g. Hedenquist et al., 1996; Cooke and Simmons, 2000). At Golden Cross, quartz lattice textures are common and largely restricted to subvertical quartz veins (<1 cm to 20 cm in width) within the stockwork zone (420 to 320 m elevation). They are typically localised along the vein contacts and extend continuously over distances of ~10 m or more. Individual platy crystals range from < 1 cm to ~5 cm across and are substantially larger than crystals depositing in geothermal wells. By contrast to the stockwork zone, lattice textures were noticeably rare in the ore-bearing quartz veins of the Empire zone, though platy calcite occurs in the late massive calcite veins (Figure 3) discussed below.

Adularia

Adularia is widespread and common within the Empire and stock work zones (Figure 3). It occurs in quartz precious metal veins and veinlets as microscopic crystals (Simpson, C. et al., 1995). Adularia also occurs as an alteration product of the volcanic host rocks. It is most abundant in the vicinity of veins, comprising up to about 15% of the rock and diminishes laterally away from the ore zones (Simpson, M. et al., 1995). These occurrences are very similar to those in Broadlands-Ohaaki.

Crustiform-colloform banded quartz

Crustiform colloform quartz textures dominate the ore-bearing parts of quartz veins in the Empire vein zone. Their occurrences are described in detail (Simpson, C. et al., 1995; Simpson, C., 1996). Individual laminations are on the order of 0.5 to 5.0 mm thick and are composed of cryptocrystalline to microcrystalline grains of quartz. In places, their grain size variations resemble fining upward sequences in sedimentary rocks (Simpson, C. et al., 1995), and along with

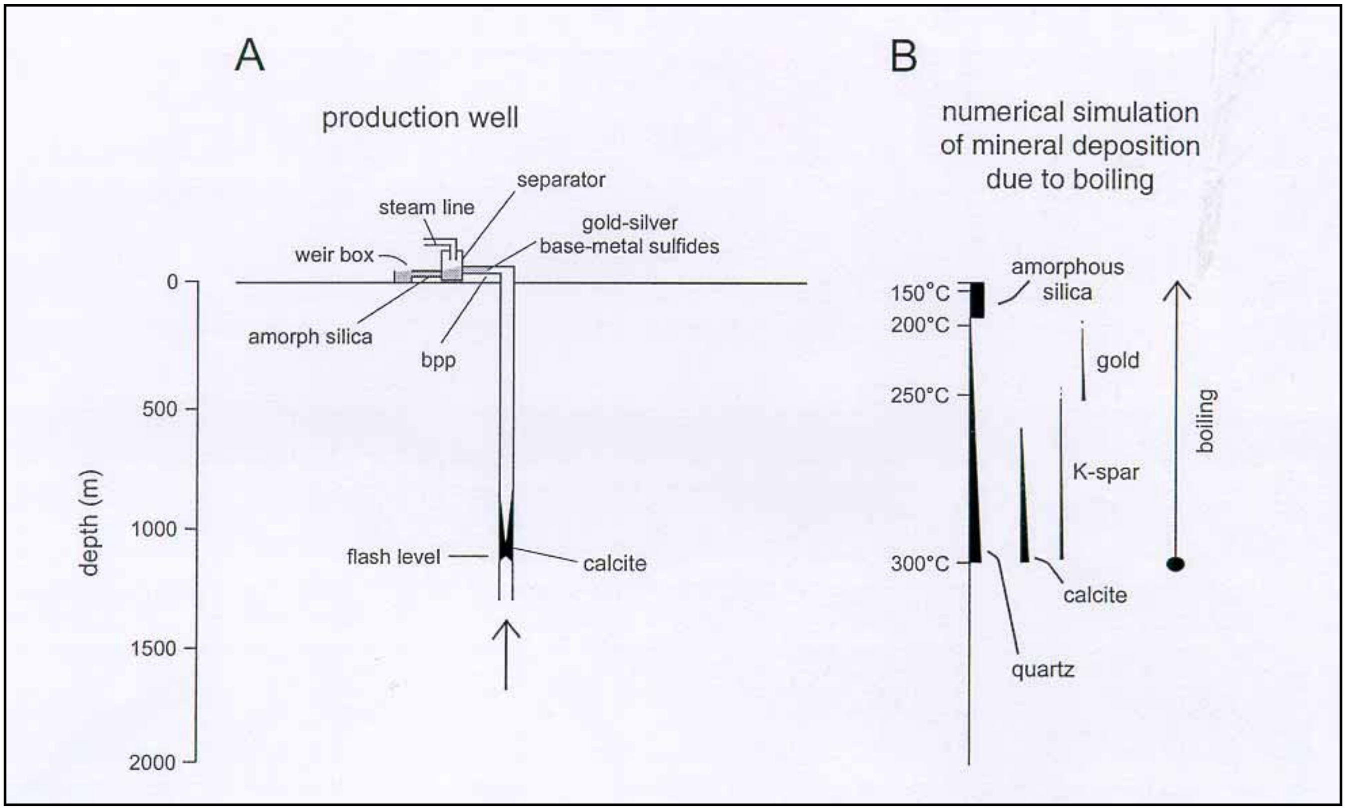

Figure 4. Mineral products of boiling in geothermal systems. (A) Schematic diagram showing the locations of calcite, gold-silver and amorphous silica deposits due to flashing in a geothermal well at Broadlands-Ohaaki. (B) Mineral products of flashing calculated for a deep Broadlands-Ohaaki chloride water rising along an adiabatic flow path using CHILLER, assuming a hydrostatic pressure gradient. The graphic is a compilation of two different calculations (from Simmons and Browne, 2000). In one calculation, quartz is allowed to precipitate and it is the main silica phase; in the other calculation, quartz precipitation is suppressed so that amorphous silica saturation is reached. In other words, only one SiO_2 polymorph deposits in each calculation. These two different calculations have negligible affect on the deposition sites of the other phases shown.

cross-bedding-like textures, suggest physical accumulation of fine silica particles (colloids?), analogous to silica deposits in the weirbox described at Broadlands-Ohaaki (Figure 4a). The colloform nature of many silica bands is texturally similar to bands of amorphous silica found in the surface pipes of geothermal wells. On this basis, we infer that this silica initially deposited as amorphous silica and later crystallized to quartz, as is described for silica sinters (Herdianita et al., 1999). Assuming this inference is correct, steam loss and boiling must occur in order for solutions to become supersaturated in amorphous silica (Henley, 1983; Fournier, 1985; Simmons and Browne, 2000).

Late massive calcite veins

Massive calcite fills late veins that are a prominent feature of the Empire vein zone. Coarse calcite comprises over 95% of these veins, with minor amounts of quartz and trace amounts of clay and pyrite. As described above, calcite occurring along vein contacts locally has a platy texture indicating boiling conditions. More relevant here are the $d^{18}O$ calcite compositions, which suggest that the waters from which the calcite precipitated were steam-heated in origin (Simmons et al., 2000). The occurrence of carbonate minerals in clay altered host rock also supports the shallow development of CO_2-rich steam-heated waters. We believe that during late stage collapse of the hydrothermal system, the CO_2-rich steam-heated waters descended into the Empire vein zone and heated, thereby selectively depositing calcite due to its inverse solubility (Simmons et al., 2000). The presence of platy textures in these veins simply indicates that the descending waters boiled.

Discussion

The deposits of platy calcite and adularia described in this paper are taken as direct evidence of boiling due to the influence of gas loss and cooling on their solubilities. Similarly, crustiform-colloform banded silica could be considered direct evidence of boiling if it retained its amorphous structure, however the conversion to quartz reduces the strength of the argument so that the textural evidence is at best permissive. Late massive calcite veins and clay-carbonate alteration are also indirect evidence of boiling, in so far as they are genetically linked to a steam-heated water which in turn resulted from boiling (i.e. the minerals are one step removed from the process of boiling). The strength of their evidence lies in analogy with occurrences of clays and carbonates at Broadlands-Ohaaki (see Simmons et al., 2000; Simmons and Browne, 2000).

Considered as a group, the presence of all of these mineralogical indicators at Golden Cross supports the interpretation that boiling was important in ore formation (e.g. de Ronde and Blattner, 1988), substantiated by the fact that boiling also favours gold deposition (Brown, 1986; Seward, 1989). Even so, the evidence from Broadlands-Ohaaki suggests that boiling causes minerals to deposit over long path lengths (>500 m), much greater than the vertical distance of the ore zone at Golden Cross.

To better understand the spatial relationships of mineral formation, we have simulated their deposition due to boiling of the deep chloride water at Broadlands-Ohaaki using the reaction path software CHILLER (Reed and Spycher, 1985; Spycher and Reed, 1989; Simmons and Browne, 2000). The results are schematically shown in Figure 4b.

Of all the precipitates that form from the CHILLER calculation, quartz or amorphous silica, calcite and adularia are the most important in order of abundance. As mentioned above, quartz does not normally precipitate in geothermal wells due to slow reaction rates associated with quenching and instead amorphous silica precipitates at <200°C at shallow levels along the reaction path. Thus, in order for amorphous silica to deposit at temperatures of around 200°C or greater as inferred for the Empire vein zone, the temperature of first boiling would have to be >300°C, implying very deep boiling, extending to depths of 1000 m below the ore zone. Under such conditions, silica deposits would be restricted to the upper few hundred meters of the vein structure as represented by the Empire and stockwork zones, explaining the sharp reduction in quartz vein widths beneath the ore horizon.

Calcite deposits near the level of first boiling as observed in geothermal wells. The presence of quartz pseudomorphs of platy calcite in the stockwork ore zone thus potentially mark a very shallow paleo-boiling level in the vicinity of stockwork veins. This boiling level is substantially shallower than that suggested above for the Empire vein zone.

Adularia deposits over a relatively long vertical range though it is most abundant near the level of first boiling. Like quartz, its formation is partially kinetically controlled explaining its absence from geothermal wells (Simmons and Browne, 2000). Nonetheless, its deposition is favoured by the effects of boiling and so it is common in veins filled with platy calcite and as an alteration mineral in nearby host rocks (Browne and Ellis, 1970).

Gold precipitates (along with silver and chalcopyrite) over a depth interval that lies between calcite and amorphous silica, again consistent with its occurrence in a geothermal well. Figure 4b shows that the vertical interval of gold deposition is restricted and on the order of 100-200 m, similar to ore intervals in a number of low sulfidation epithermal deposits (Buchanan, 1981; Cooke and Simmons, 2000).

In summary, the minerals which deposit due to boiling simulated by CHILLER are similar to those found in boiling environments in active geothermal systems and the Golden Cross epithermal veins; however, some of their spatial occurrences differ. Most obvious is the occurrence of lattice textures in quartz veins of the stockwork zone at elevations that overlie crustiform-colloform banded quartz veins of the Empire zone. To accommodate these occurrences within the model described above (Figure 4b), requires a shift in the level of first boiling of at least several hundred meters. Such a shift may simply represent two distinct boiling hydrothermal events as suggested from interpretation of vein structures (Keall et al., 1993; Caddey et al., 1995; Mauk et al., 1998). Within a single vein-forming event, boiling level fluctuations are also possible as interpreted from the common occurrence of lattice textures, crustiform colloform silica banding and gold over a few centimeters distance. Such telescoping of boiling indicators has been related to a downward propagating boiling front and vertical expansion of two-phase flashing in a flowing water column during period of high vertical permeability and fluid flux (Simmons and Browne, 1998; Simmons and Browne, 2000). On the basis of the CHILLER simulation, we infer that the level of first boiling was at least a few hundred meters below the ore zones for most of the period of gold deposition.

For comparison, calculations of the effects of mixing between chloride and CO_2-rich steam-heated waters, using CHILLER, produced deposits of quartz, calcite, illite and pyrite, but no gold or silver (Simmons and Browne, 2000). While we expect mixing to take place, especially on the margins of upflow zones, it does not appear effective in ore genesis.

Relevance to mineral exploration

The boiling genetic model accounts for mineralisation and many of the mineralogical attributes of the Golden Cross deposit. Clay-carbonate alteration and calcite veins are evidence for CO_2-rich steam-heated waters at shallow level within a boiling epithermal environment. Unfortunately, these indicators can be laterally extensive over distances exceeding 100 m, and mask the positions of subjacent veins and drilling targets. This alteration and co-existing calcite veins also tend to be barren of gold and silver. Nevertheless, they provide clues of underlying prospective ground. At a finer scale, the presence of lattice textures, adularia and crustiform-colloform banding in quartz veins are strong indicators of boiling, and they commonly occur in the proximity of gold-silver ore. If quartz veins containing these textures lack gold and silver, then the metal transporting capacity of hydrothermal solutions may have been too low to produce ore grades, despite the existence of conditions favourable for metal deposition.

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References

Brathwaite, R. L., Christie, A. B., and Skinner, D. N. B. 1989. The Hauraki Goldfield–regional setting, mineralisation and recent exploration. in Mineral Deposits of New Zealand, Kear D. ed., Australian Institute of Mining and Metallurgy Monograph 13, p. 45-56.

Brathwaite, R. L. and Christie, A. B., 1996, Geology of the Waihi area, scale 1:50,000, Institute of Geological and Nuclear Sciences Geological Map 21, Lower Hutt, New Zealand, 1 sheet + 64 p.

Brown, K. L. 1986. Gold deposition from geothermal discharges in New Zealand. Economic Geology v 81: 979-983.

Browne, K. L. 1999. Silica scaling and geothermal development. Advances in Geochemical Methods for Geothermal Applications, Workshop Sponsored by Idaho National Engineering and Environmental Laboratory and The Geothermal Resources Council.

Browne, P. R. L. 1970. Hydrothermal alteration as an aid in investigating geothermal fields. Geothermics v 2 (part 1): 564-570.

Browne, P. R. L., 1978. Hydrothermal alteration in active geothermal fields. Annual Reviews Earth Planetary Sciences v 6: 229-250.

Browne, P. R. L. and Ellis, A. J. 1970. The Ohaki-Broadlands geothermal area, New Zealand: mineralogy and related geochemistry. American Journal of Science v 269: 97-131.

Buchanan, L. J. 1981. Precious metal deposits associated with volcanic environments in the southwest. Arizona Geological Society Digest v 14: 237-262.

Caddey, S.W., McOnie, A.W. and Rutherford, P. G. 1995. Volcanic stratigraphy, structure and controls on mineralization, Golden Cross Mine, New Zealand. Pacrim Congress '95, Australasian Institute of Mining and Metallurgy, p. 93-98.

Christenson, B. W. and Hayba, D. O. 1995. Hydrothermal eruptions in ore forming reservoirs: analogues and models. Pacrim Congress '95, Australasian Institute of Mining and Metallurgy, p. 119-124.

Cooke, D. R. and Simmons, S. F. 2000. Characteristics and genesis of epithermal gold deposits. Reviews in Economic Geology, in press.

Corbett, G.J., and Leach, T.M. 1998. Southwest Pacific Rim gold-copper systems: structure, alteration and mineralisation. Society of Economic Geologists, Special Publication No. 6, 237 p.

de Ronde, C. E. J. and Blattner, P. 1988. Hydrothermal alteration, stable isotopes, and fluid inclusions of the Golden Cross epithermal gold-silver deposit, Waihi, New Zealand. Economic Geology, v 83; 895-917.

Fournier, R. O. 1985. The behavior of silica in hydrothermal solutions. Geology and Geochemistry of Epithermal Systems (eds. B. R. Berger and P. M. Bethke), Reviews in Economic Geology v 2: 45-59.

Hayba, D. O. 1997. Environment of ore deposition in the Creede mining district, San Juan mountains, Colorado: Part V. Epithermal mineralization from mixing in the OH vein. Economic Geology v 92: 29-44.

Heald, P., Hayba, D. O. and Foley. N. K. 1987. Comparative anatomy of volcanic-hosted epithermal deposits: acid-sulfate and adularia-sericite types. Economic Geology v 82: 1-26.

Hedenquist, J. W. 1990. The thermal and geochemical structure of the Broadlands-Ohaaki geothermal system. Geothermics, v. 19: 151-185.

Hedenquist, J. W. and Stewart, M.K. 1985. Natural CO_2-rich steam-heated waters at Broadlands, New Zealand: their chemistry, distribution and corrosive nature. Geothermal Resources Council Annual Meeting, Transactions v 9: 245-250.

Henley, R. W. 1983. pH and silica scaling control in geothermal field development. Geothermics v 12: 307-321.

Henley, R.W., and Ellis, A.J. 1983. Geothermal systems, ancient and modern. Earth and Planetary Science Reviews v 19: 1-50.

Herdianita, N.R., Browne, P.R.L., Rodgers, K.A., and Campbell, K.A. 2000. Mineralogical and textural changes accompanying ageing of silica sinter. Mineralium Deposita v 35: 48-62.

Keall, P. C., Cook, W. C., Matthews, S. J., and Purvis, A. H., 1993, The geology of the Golden Cross orebody: Complex veining and evolving mining responses: Proceedings 27th Annual Conference, NZ Branch, Australian Institute of Mining and Metallurgy, p 143-160.

Mauk, J. L. Begbie, M. J. and Spörli, K. B. 1998. Structural setting of the Empire vein system of the Golden Cross deposit, New Zealand. in Proceedings of the 31st Australasian Institute of Mining and Metallurgy annual conference 24-34.

Reed, M. H., and Spycher, N. F. 1985. Boiling, cooling, and oxidation in epithermal systems: A numerical modelling approach. Reviews in Economic Geology v 2: 249-272.

Sander, M.V., and Einaudi, M. 1990. Epithermal deposition of gold during transition from propylitic to potassic alteration at Round Mountain. Economic Geology v 85: 285-311.

Seward, T. M. 1989. The hydrothermal chemistry of gold and its implications for ore formation: boiling and conductive cooling as examples. Economic Geology Mon. 6, p. 398-404.

Simmons, S. F.and Christenson, B. W. 1994. Origins of calcite in a boiling geothermal system: American Journal of Science, v 294: 361-400.

Simmons, S. F., and Browne, P. R. L. 1998. Lattice textures in vein deposits and geothermal systems in New Zealand: Clues to understanding boiling processes in epithermal environments. 14th Australian Geological Convention, Geological Society of Australia, Abstracts No 49, p. 406.

Simmons, S. F. and Browne, P. R. L. 2000. Hydrothermal minerals and precious metals in the Broadlands-Ohaaki geothermal system. Implications for understanding low-sulfidation epithermal environments: Economic Geology v 95: 971-999.

Simmons, S. F., Arehart, G., Simpson, M. P. and Mauk, J. L. 2000. Origin of Massive Calcite Veins in the Golden Cross, Low-Sulfidation Epithermal Au-Ag Deposit, New Zealand. Economic Geology v 95: 99-112.

Simpson, C.R.J., Mauk, J. L., and Arehart, G. B. 1995. The formation of banded epithermal quartz veins at the Golden Cross mine, Waihi, New Zealand. Pacrim Congress '95, Australasian Institute of Mining and Metallurgy, p. 455-450.

Simpson, C.R.J. 1996. The formation of banded epithermal quartz veins at the Golden Cross mine, Waihi, New Zealand. unpub. MSc Thesis, University of Auckland, pp 100.

Simpson, M. P., Simmons, S. F., Mauk, J. and McOnie, A.,1995. The distribution of hydrothermal minerals at the Golden Cross epithermal Au-Ag deposit, Waihi, New Zealand. Pacrim Congress 1995, Australasian Institute of Mining and Metallurgy, p. 551-556.

Skinner, D.N.B. 1986. Neogene volcanism of the Hauraki volcanic region. in Smith, IEM (ed). Late Cenozoic Volcanism in New Zealand: Royal Society of New Zealand Bulletin v 23: 20-47.

Spycher, N. F. and Reed, M. H. 1989. Evolution of a Broadlands-type epithermal ore fluid along alternative P-T paths: Implications for the transport and deposition of base, precious and volatile metals. Economic Geology v 84: 328-359.

Tulloch, A. J. 1982. Mineralogical observations on carbonate scaling in geothermal wells at Kawerau and Broadlands. Proceedings 4th New Zealand Geothermal Workshop, p. 131-134.

Vikre, P.G. 1989. Fluid-mineral relations in the Comstock Lode. Economic Geology v 84: 1574-1613.

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