PRECIOUS METALS IN HYDROTHERMAL FLUIDS & GENETIC IMPLICATIONS FOR EPITHERMAL DEPOSITS

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ABSTRACT

The concentrations of trace metals in deep hydrothermal solutions (~1 km depth, 200 to >300 °C) from active geothermal systems in the Taupo Volcanic Zone, New Zealand, and Ladolam, Lihir Island, Papua New Guinea range widely: gold (<0.1 to 23 ppb); silver (<3 to 2400 ppb); arsenic (100 to 18,000 ppm); antimony (2 to 1200 ppm); mercury (<1 to 78 ppb). The highest hydrothermal fluxes of gold (~30 to 100 kg/yr) and silver (~5000 to 11,000 kg/yr) occur in the Rotokawa geothermal system (NZ), which, if they remained constant could match the metal inventories of the largest ore deposits in the world in <50,000 years. This relatively short time span is comparable to the amount of time required to account for the known gold resource in ores at Ladolam, which has a slightly lower gold flux (~25 kg/yr). When compared with Ladolam, the absence of strong fluid focusing and efficient metal deposition best explains the lack of precious metal mineralization at Rotokawa.

INTRODUCTION

Modern epithermal environments occur in geothermal systems in arc settings around the Pacific rim, where they are exploited for geothermal energy (Henley and Ellis, 1983). The deep geothermal wells drilled into these systems for energy production provide one of the best opportunities for sampling trace metals in hydrothermal systems. Here we summarize data on the concentrations of gold, silver and related metals in New Zealand systems as well as the Ladolam system in Papua New Guinea, host to one of the world's largest and youngest hydrothermal gold deposits (Simmons and Brown, 2006; Simmons and Brown, 2007; Simmons and Brown, 2008). The results shed light on key processes that discriminate between the formation of a world class deposit versus a sub-economic prospect.

GEOTHERMAL SYSTEMS OF THE TAUPO VOLCANIC ZONE

The Taupo Volcanic Zone (TVZ) is a young (<1.6 Ma) rifted arc that extends ~250 km from Mount Ruapehu to White Island (Fig. 1). It has very high heat flow (4000 to 5000 MW), which derives from convective heat transfer associated with widespread hydrothermal activity (Bibby et al., 1995; Hochstein, 1995). Most of the geothermal systems are concentrated in the central segment of the TVZ (Fig. 1) where felsic magmatism dominates (Wilson et al., 1995). However, the occurrence and distribution of rhyolitic intrusions are poorly known as is their influence on the compositions of hydrothermal fluids. Instead, the compositions of fluids suggest that the magmas intruding beneath the convection cells are andesitic in the eastern part of the central TVZ, but basaltic in the western part (Giggenbach, 1995; Fig. 1).

We sampled the deep hydrothermal solutions from three eastern and three western geothermal systems in the central TVZ (Fig. 1). The geology of the drilled parts of these systems is dominated by a layer-cake sequence (1 to >3 km in thickness) of rhyolitic to andesitic volcanic rocks, which rest unconformably on Mesozoic meta-sedimentary rocks that are locally disrupted by normal faults. The chemical and isotopic compositions of the hydrothermal waters reflect their meteoric origin and deep circulation, the incorporation of magmatic gases, and the subsequent fluid-mineral interactions (Giggenbach, 1995; 1997). All of the solutions are near-neutral pH and reduced. They are close to being in thermodynamic equilibrium with hydrothermal minerals that commonly occur in the deep and altered volcanic country rocks, including albite, adularia, quartz, chlorite, illite, calcite, epidote, and pyrite (Giggenbach, 1997).

The precious metal concentrations in deep solutions span three orders of magnitude (<0.1 to 23 ppb, Au; 2.7 to 2400 ppb Ag) and correlate with H_2S concentration and temperature, which is consistent with experiments on gold and silver solubility (Stefánnson and Seward, 2003; 2004). Gold concentrations are highest at Rotokawa and lowest at Wairakei and Ngatamariki (Fig. 2). Silver concentrations are also highest at Rotokawa, but the lowest values are found at Broadlands-Ohaaki, Kawerau, Wairakei, and Ngatamariki (Fig. 2). The trends indicate that eastern geothermal systems have higher gold concentrations compared to western geothermal systems, but the high dissolved silver concentration at Mokai (250 ppb) indicates that significant precious metal concentrations also occur in hydrothermal solutions from western geothermal systems. The concentrations of dissolved As, Sb and Hg, trace elements only range over about two orders of magnitude, independent of gold or silver concentrations.

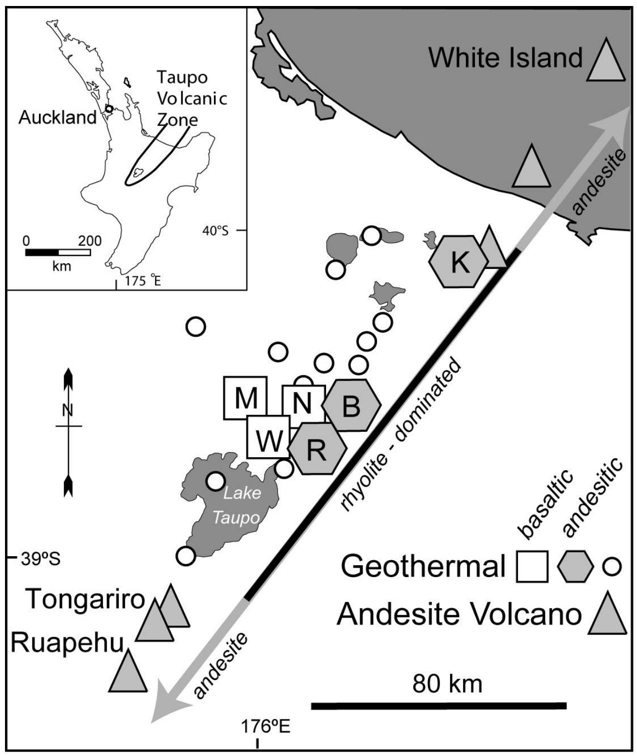

Figure 1. Locations of geothermal systems and andesitic volcanoes in the Taupo Volcanic Zone (TVZ). The eastern geothermal systems have fluid signatures indicating concealed andesitic intrusions (hexagons), and the western geothermal systems with fluid signatures indicating concealed basaltic intrusions (squares) are restricted to the central rhyolite-dominated part of the TVZ. Unsampled geothermal systems (small open circles) are also shown. Abbreviations: B=Broadlands-Ohaaki; K=Kawerau; M=Mokai; N=Ngatamariki; R=Rotokawa; W=Wairakei.

Through speciation calculations, we found that all the deep solutions are undersaturated in gold and, in three systems, undersaturated in silver sulfide (Ag_2S). This indicates that the metal budget, rather than temperature or aqueous H_2S concentration, limits the amount of gold and, to a lesser extent, silver in solution. These results, and the similar stratigraphy of all six geothermal systems, point to a deep local control on the supply of precious metals, exemplified by the sharp differences in fluid compositions and metal concentrations between Rotokawa and Wairakei (Fig. 2), which are only 10 km apart (Fig. 1). Andesitic magmas are a likely source of precious metals in the eastern geothermal systems, and basaltic magma might be responsible for the high silver in Mokai. But the results also indicate that deep country rocks are a potential source of trace metals given the undersaturated state of deep solutions with respect to gold and silver.

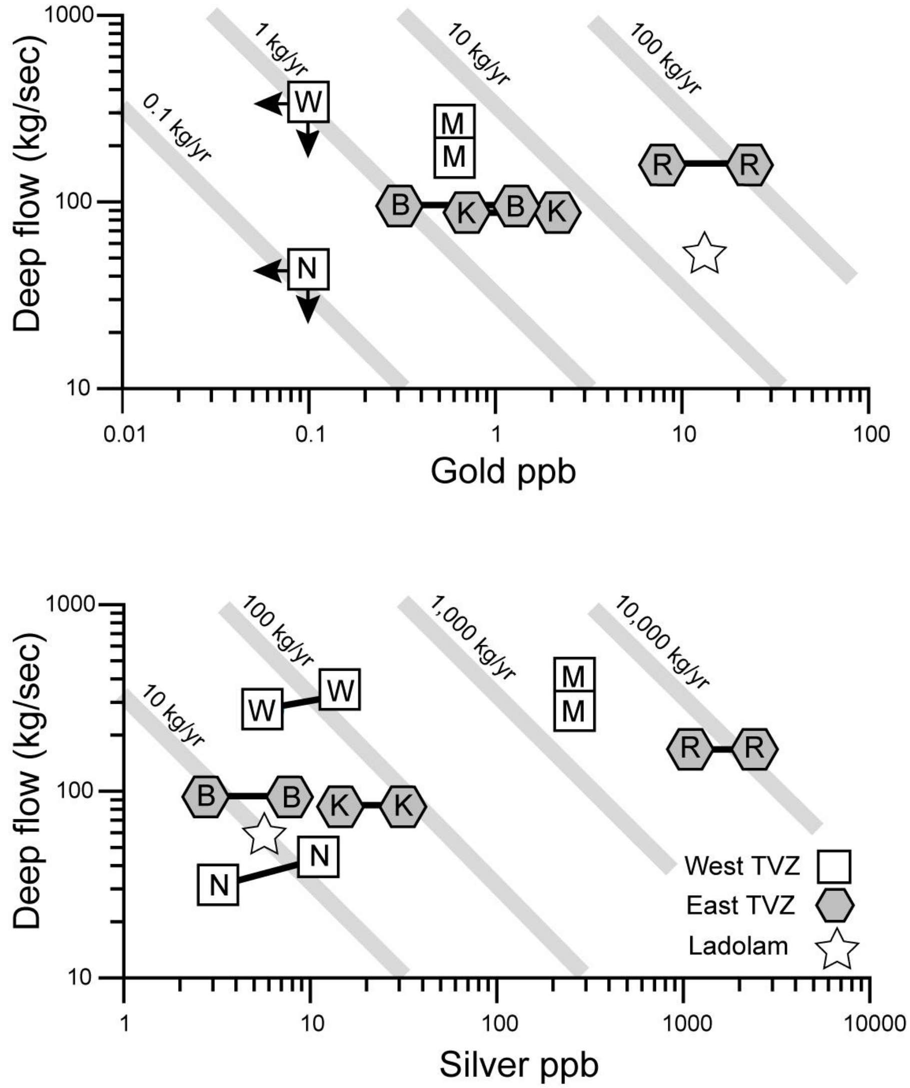

Figure 2. Gold and silver concentrations of deep thermal waters versus deep up-flow rates, showing the metal flux rates in kilogram/year (Simmons and Brown, 2007; 2008). Abbreviations same as Figure 1

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HYDROTHERMAL SYSTEM AT LADOLAM, LIHIR ISLAND, PNG

The Ladolam gold deposit occupies the center of the extinct Luise volcano on Lihir Island (Fig. 3), where tabular ore zones cover ~2 km^2 and extend from the surface to 400 m below sea level. These ore zones lie in the middle of a breached crater that formed in response to sector collapse of the volcanic edifice ~400,000 years ago (Moyle et al., 1990; Sillitoe, 1994; Carman, 2003). The explosive depressurization of the magmatic-hydrothermal system produced a diatreme breccia complex and highly permeable rocks, which host the ore. Mineralogical, fluid inclusion, and stable isotope studies (Carman, 2003) show that the gold was deposited in two stages between 150° and 250° C, from solutions of magmatic origin when they mixed with other fluids or boiled. The magmatic gold-bearing solutions were near-neutral to slightly alkaline pH and contained 5 to 10 wt % equiv. NaCl.

A number of shallow to deep geothermal wells were drilled to understand the hydrology of the system and to remove hot water from the mine site. The deepest wells terminate at >1 km below sea level in K-silicate altered rocks with hydrothermal fluids at >275° C. This fluid is saline, oxidized and made up of predominantly magmatic water, and its composition closely resembles the composition of the fluid responsible for ore formation (Simmons and Brown, 2006). The deep hydrothermal brines contain ~15 ppb Au (Fig. 2), and calculations suggest that this brine is between ~20 and 100% of gold saturation. If the deep brine is indeed under-saturated, then the gold budget, rather than the H_2S budget, of the system limits the gold concentration of the solution, as is the case for the above described geothermal systems in New Zealand.

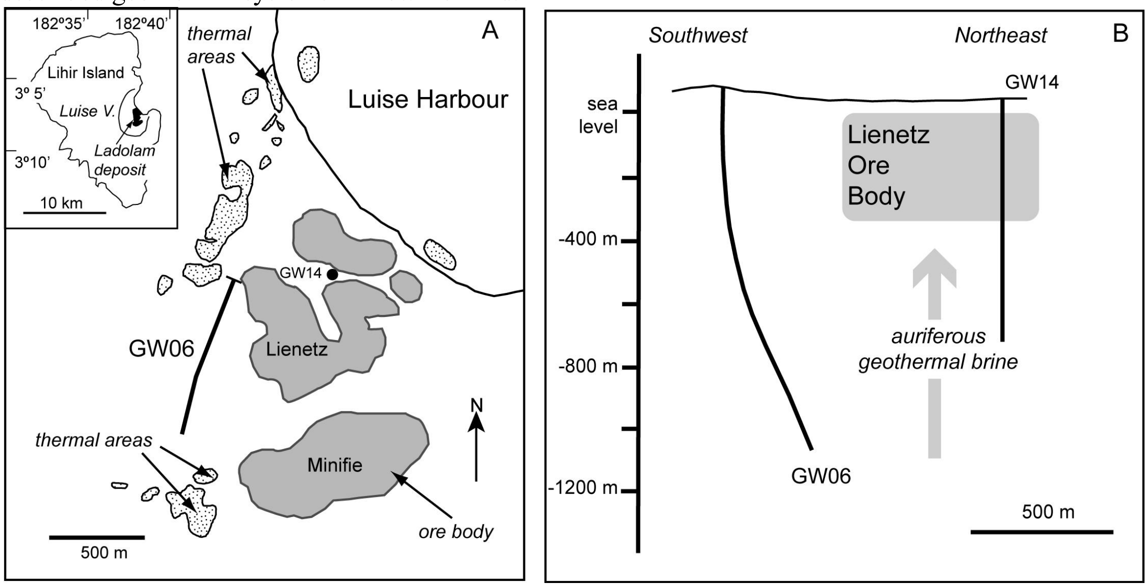

Figure 3. (A) Location of the Ladolam gold deposit, orebodies (Minifie and Lienetz), geothermal wells, and thermal areas of surface discharge on Lihir Island; and (B) schematic southwest-northeast cross section showing the relation between sampled geothermal wells and the Lienetz orebody. Map and cross-section from Simmons and Brown (2006, 2008).

METAL FLUXES AND IMPLICATIONS

Metal fluxes were calculated for individual systems (Fig. 2) by combining the precious metal concentrations for deep hydrothermal solutions with their rates of thermal fluid up-flow. Rotokawa has the highest gold flux of ~30 to 100 kg/yr and the highest silver flux of ~5000 to 11,000 kg/yr. Ladolam ranks second in gold flux (~25 kg/yr), whereas Mokai ranks second in silver flux (~1500 to 2100 kg/yr). The remaining systems have gold fluxes of <1 to 10 kg/yr and silver fluxes of 10 to 100 kg/yr. These metal flux estimates are huge considering the largest magmatic-hydrothermal ore deposits in volcano-plutonic arcs contain ~1000 to 2000 tonnes Au and as much as 100,000 tonnes Ag (e.g., Sillitoe, 2000; Simmons et al., 2005). The metal fluxes for Rotokawa, alone, produce such ore deposit inventories in <20,000-55,000 years for gold and <10,000-20,000 years for silver, and the metal flux for Mokai produces a silver inventory of 100,000 tonnes in 45,000-75,000 years, although orebodies have yet to be found in either system. By comparison, the metal flux at Ladolam accounts for all the reported gold ore in ~55,000 years.

The results indicate that there is a wide variation in the concentrations of precious metals in deep hydrothermal solutions and that magmas are viable sources of high concentrations of gold and silver in hydrothermal solutions, even in ones dominantly formed from meteoric water, but they are not the sole source of precious metals. The results also indicate that metal-saturated solutions are not essential to ore formation. The apparent absence of naturally-formed precious metal orebodies in the TVZ geothermal systems, despite spectacular gold-silver scale deposits in wells (Brown, 1986; Simmons and Browne, 2000), emphasizes the importance of fluid focussing and efficient metal precipitation as ore-forming processes that clearly had to have operated at Ladolam.

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