The optimal windows for earthquake-enhanced gold precipitation in the epithermal environment

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Abstract. Epithermal gold deposits and gold-quartz veins form by a combination of a sustained flux of gold-rich fluids and an efficient precipitation mechanism. Gold precipitation in veins is commonly related to large volumes of hydrothermal fluids that flow along deep, seismically active faults, and recent studies have highlighted the relevance of fluctuating pressures during earthquakes as an efficient mechanism for gold precipitation. Despite these advances, the effects of earthquakes on gold precipitation efficiency and time-integrated contribution are poorly quantified in the epithermal environment. In this study, we combine analytical determinations of fluid inclusions and present-day borehole fluids in geothermal reservoirs with gold and silica solubility calculations and estimations of pressure fluctuations driven by seismic activity. Our results show the optimal conditions for gold precipitation at saturated liquid pressures between 50 and 120 bar, where small adiabatic pressure changes (~50 bar) triggered by transient fault-rupture can drop gold solubility by up to two orders of magnitude. Such pressure perturbations are equivalent to low magnitude earthquakes (Mw<2) which could significantly enhance gold precipitation efficiency.

Keywords: Epithermal, Tolhuaca, seismicity.

1 Introduction

Earthquakes can have a profound impact on metal precipitation, triggering physical and chemical changes in ore fluids that can enhance the whole process (Rowland and Simmons, 2012; Sibson et al., 1988). In epithermal systems, in particular, precipitation of gold and/or silver may occur either as “gentle boiling”, where enthalpy increase produces a small vapor fraction near liquid-saturated conditions, or as “flash vaporization” forced by a transient pressure drop that converts most of the original liquid into a low density vapor phase (Moncada et al., 2012; Simmons et al., 2005; Weatherley and Henley, 2013). There is abundant evidence in the literature documenting that both permeability and gold precipitation are strongly affected by pressure changes triggered by earthquakes (Rowland and Simmons, 2012; Sibson et al., 1988; Weatherley and Henley, 2013). Nevertheless, a general quantitative formulation that describes the optimal conditions for earthquake-enhanced mineralization is still lacking.

Here, we constrain the favorable windows of gold precipitation in the epithermal environment by combining borehole data and analytical determinations of present-day and paleo fluid physicochemical conditions. As endmember case studies, we use available data from i) the gold-poor geothermal system at Tolhuaca in the southern Andes, and ii) gold-rich geothermal systems in New Zealand and Papua New Guinea (i.e., Taupo Volcanic Zone and Lihir Island, respectively). When these data are combined with thermodynamic models of gold and silica solubility, rock mechanics calculations and earthquake frequency distribution analyses, results point to protracted seismic activity as a key factor in building epithermal gold deposits in tectonically active regions.

2 Methods

Temperature data of deep wells after thermal recovery were used to constrain present-day subsurface temperature profiles for endmember cases. In the absence of well-constrained paleofluid data in borehole samples from most of these systems, we used fluid inclusions thermometry data at Tolhuaca (Tol-1 borehole) as representative of long-lived a hydrothermal system undergoing protracted cooling
Furthermore, and long-term pressure-temperature-enthalpy (*P-T-H*) evolution of the hydrothermal fluids in the geothermal/epithermal environment was estimated using heat and fluid transport numerical simulations (Hayba and Ingebritsen, 1997). The modeled heat source of the system is a magma body (~0.5 km^3; at 900°C) that instantly intrudes to a depth of ~3 km beneath a volcanic system.

To quantify the effect of the different *P-T-H* trajectories on dissolved metal species we calculated the solubility of Au for the liquid and the two-phase (liquid and vapor) regions. The GEMS geochemical modeling software (Kulik et al., 2012) was used to compute dissolved Au concentrations with updated thermodynamic data (Stefánsson and Seward, 2004).

Finally, the impact of seismic perturbations on fluid parameters was constrained using a thermo-mechanical piston model (Weatherley and Henley, 2013) that simulates the co-seismic changes in a dilational jog mimicking the "suction pump" mechanism. Results are represented in the *P-H* space, which allows the visualization of vapor fractions in the two-phase region - reduced to a line in the *P-T* space - and an intuitive representation of adiabatic (isoenthalpic) processes.

3 Results and discussion

3.1 Pressure-temperature-enthalpy evolution

The general agreement between fluid inclusions data and present-day temperature measurements suggest a continuity of "gentle boiling" conditions (Fig. 1). The liquid saturated conditions are reached at geothermal reservoir depths

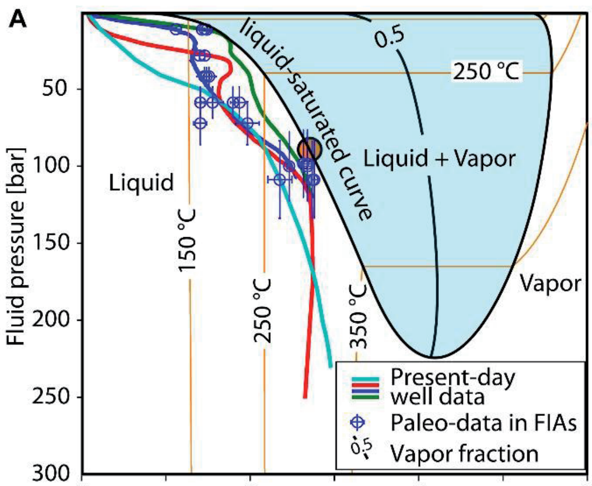

Figure 1. Microthermometric data and present-day conditions in pressure-enthalpy (P-H) space. Blue open circles show the average homogenization temperatures of fluid inclusions with 1-sigma standard deviation. Depth was converted to pressure assuming a hydrostatic gradient, and vertical error bars indicate the difference between hydrostatic and boiling pressure gradient. The colored curves show the temperature profiles obtained in four boreholes at Tolhuaca. The orange circle shows the metastable reservoir conditions.

Numerical simulations of the *P-T-H* evolution support such observations (Fig. 2). Results indicate that a shallow (<4 km) magmatic intrusion, increases enthalpy and decreases fluid-pressure as a result of a transition from the hydrostatic pressure gradient to a liquid-saturated "gentle boiling" environment at the reservoir. Such critical condition at the two-phase boundary are sustained until the waning and cooling of the hydrothermal system, as previous studies have shown (Hayba and Ingebritsen, 1997; Weis et al., 2012).

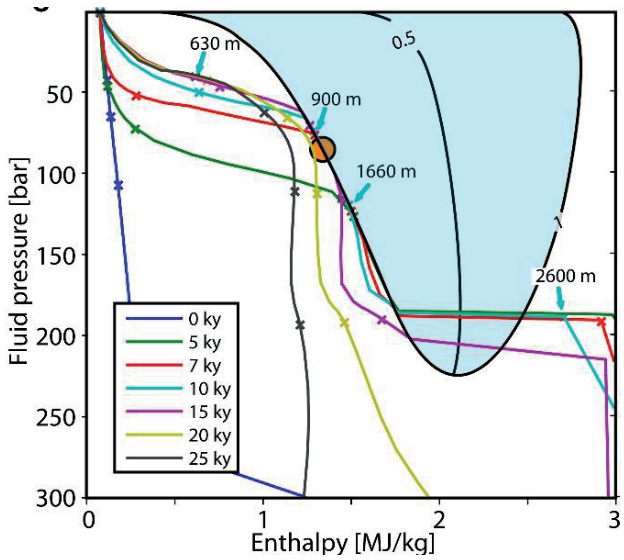

Figure 2. Simulated, time-dependent pressure-enthalpy fluid trajectories at Tolhuaca, calibrated with present-day data.

3.2 Optimal conditions for gold precipitation

Calculated Au solubility isopleths show high solubility conditions for metal transport in the epithermal/geothermal environment, comprised between ~210 to 370°C (P_{sat} eq. 20 to 220 bar) in the liquid-phase region as widely recognized in previous studies (Williams-Jones et al., 2009). More interestingly, our results indicate that subtle adiabatic pressure drops of, e.g., ~50 bar, from liquid-saturated conditions (where saturated liquid pressure (P_{sat})<100 bar,and T_{sat} eq.<310°C) cause a sharp solubility decrease. If the adiabatic pressure drops occur at higher pressures (P>P_{sat}~100 bar), the solubility decrease is moderate. Therefore, we recognize an optimal window for efficient metal precipitation (210°C<T_{sat}<310°C) that can be triggered by adiabatic pressure decreases, coincident with the documented ore precipitation conditions in epithermal Au deposits (Simmons et al., 2005). Such optimal environment for ore transport and precipitation naturally develops through a combination of sustained heat and high permeability conditions.

4. Implications for the formation of gold deposits

Under the estimated reservoir conditions used in this study (T_{sat}~300°C, P_{sat}~85 bar), our calculations indicate that a pressure drop of more than 55 bar, equivalent to a seismic event of Mw=1, would generate a vapor fraction of 0.25 and at least a 2 log-units decrease in Au solubility. The association of Au precipitation to small magnitude earthquakes, i.e., small slips, is consistent with the observation that low-displacement, second-order fractures predominate as high grade ore-veins in geothermal systems and epithermal Au deposits (Simmons et al., 2005). This supports the idea invoked in petrographic and mineralogical studies of ore textures and fluid inclusions assemblages that flash vaporization is more efficient than gentle boiling for ore precipitation (Moncada et al., 2012). Thus, our results stress the potential relevance of frequent small magnitude earthquakes (Mw<2) on metal precipitation by triggering transient flash vaporization.

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