



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



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ABSTRACT

Epithermal gold (Au) deposits result from the combination of a sustained flux of metal-rich fluids and an efficient precipitation mechanism. Earthquakes may trigger gold precipitation by rapid loss of fluid pressure but their efficiency and time-integrated contribution to gold endowment are poorly constrained. In order to quantify the feedbacks between earthquake-driven fracturing and gold precipitation in the shallow crust, we studied the gold-rich fluids in the active Tolhuaca geothermal system, located in the highly seismic Southern Andes of Chile. We combined temperature measurements in the deep wells with fluid inclusion data, geochemical analyses of borehole fluids and numerical simulations of coupled heat and fluid flow to reconstruct the physical and chemical evolution of the hydrothermal reservoir. The effect of seismic perturbations on fluid parameters was constrained using a thermo-mechanical piston model that simulates the suction pump mechanism occurring in dilational jogs. Furthermore, we evaluated the impact of fluid parameters on gold precipitation by calculating the solubility of gold in pressure (P)–enthalpy (H) space. The reconstructed fluid conditions at Tolhuaca indicate that single-phase convective fluids feeding the hydrothermal reservoir reach the two-phase boundary with a high gold budget ($\sim 1\text{--}5$ ppb) at saturated liquid pressures between 20 and 100 bar ($210\text{ }^\circ\text{C} < T_{\text{sat}} < 310\text{ }^\circ\text{C}$). We show that if hydrothermal fluids reach this optimal threshold for gold precipitation at a temperature near $250\text{ }^\circ\text{C}$, small adiabatic pressure drops (~ 10 bar) triggered by transient fault-rupture can produce precipitation of 95% of the dissolved gold. Our results at the active Tolhuaca geothermal system indicate that subtle, externally-forced perturbations – equivalent to low magnitude earthquakes ($M_w < 2$) of a hydrothermal reservoir under optimal conditions – may significantly enhance gold precipitation rates in the shallow crust and lead to overall increases in metal endowment over time.

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1. Introduction

The interplay between seismic activity, fluid flow and mineral precipitation exerts a first-order control on the strength and permeability of the crust, and plays a critical role in promoting the development of hydrothermal systems and the formation of giant ore deposits

(Richards, 2013; Sibson, 1987). External forcing such as earthquakes can have a profound impact on metal solubility, triggering physical and chemical changes in ore fluids that can enhance the precipitation process by phase separation (Rowland and Simmons, 2012; Sibson et al., 1988). This is particularly relevant in shallow crustal settings where porphyry copper and epithermal gold deposits form as a result of phase separation or boiling of a single-phase fluid. In the epithermal environment, in particular, precipitation of gold and/or silver may occur in association with gentle boiling, where fluid enthalpy is sufficiently high to produce a small vapor fraction upon ascent, or with 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;

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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). Furthermore, studies have inferred that flash vaporization of gold-rich fluids in dilational jogs during an earthquake can result in the rapid co-deposition of silica to form gold-enriched quartz veins (Moncada et al., 2012; Sibson, 1987; Weatherley and Henley, 2013). However, these concepts have never been tested for the effect of externally-triggered pressure variations on gold solubility in the epithermal environment. Therefore, the relative contribution of seismic activity on gold precipitation rates – and thus, on the overall metal endowment of epithermal gold deposits – remains largely unknown.

In this study, we integrate geochemical data of gold-bearing borehole fluids with temperature profiles in an active, high-enthalpy geothermal system at Tolhuaca, in the seismically active Chilean Southern Andes. By combining these data with thermodynamic calculations of gold solubility and simulations on pressure drops driven by earthquakes, we constrain the optimal depth window for seismically enhanced gold precipitation. Our analysis points to favorable conditions for highly efficient gold extraction from hydrothermal fluids by flash vaporization in the epithermal environment. We further quantify the magnitude of these externally triggered perturbations, and explore the role of frequent, low-magnitude seismic activity as a relevant factor in building epithermal gold deposits in tectonically active regions.

2. Geological setting

The Andean Cordillera of Central-Southern Chile, where hydrothermal systems occur in close spatial relationship with active volcanism as well as major seismically-active fault systems, provides an excellent natural laboratory to study the interplay between earthquakes, fluid flow and metal precipitation (Fig. 1). In this region it has been shown that the nature and evolution of volcanic and hydrothermal systems is controlled by the NNE-striking, 1200 km long Liquiñe–Ofqui Fault System (LOFS) and the NW-striking Arc–Oblique Fault System (ALFS) (Cembrano and Lara, 2009; Sánchez et al., 2013; Tardani et al., 2016; Perez-Flores et al., 2016). Within this setting, the active Tolhuaca geothermal field in the northern termination of the LOFS hosts a high enthalpy system that has been drilled to ~3 km depth, but is not yet affected by geothermal production or re-injection (Melosh et al., 2012; Sánchez et al., 2016).

Geological mapping, drillcore logging studies and kinematic analysis of fault-slip data have revealed that the Tolhuaca geothermal system is characterized by a structural and mineralogical compartmentalization in a transtensional stress regime (Sanchez-Alfaro et al., 2016). Based on core logging, mineralogical observations and fluid inclusion data, four stages (S1–S4) of progressive hydrothermal alteration have been recognized (Sanchez-Alfaro et al., 2016). An early heating event (S1) was followed by the formation of a clay-rich cap in the upper zone (<670 m) and the development of a propylitic alteration assemblage at greater depth (S2). Boiling, flashing and brecciation occurred later (S3), followed by a final phase of fluid mixing and boiling (S4). The ubiquitous co-precipitation of silica phases (amorphous silica, chalcedony and quartz) and the formation of hydrothermal breccias at the end of S1 are indicative of widespread boiling and flashing conditions (Sanchez-Alfaro et al., 2016). Calcite with lattice-bladed texture, quartz with plumose texture and the coexistence of silica phases with variable degrees of crystallinity formed in stage S3, are indicative of boiling and flashing episodes which are likely triggered by transient pressure drops during the hydrothermal evolution at Tolhuaca (Sanchez-Alfaro et al., 2016). Transient pressure changes triggered by seismicity are likely produced at the tip of faults and in linkage zones, such as dilational jogs (Curewitz and Karson, 1997; Sibson, 1987; Weatherley and Henley,

2013). At Tolhuaca, structural logging of the Tol-1 core indicates the presence of dilational jogs infilled with calcite and quartz (Fig. 1 D&E; Sanchez-Alfaro et al., 2016). In the vicinities of Tolhuaca volcano, detailed structural studies of fault systems revealed that dilatational jogs are formed at linking zones between NNE- and NE-striking faults. Syntaxial bladed-like calcite crystals of about 1 cm in size fill these dilatational jogs which indicate transient pressure drop likely related to fault activity in the LOFS (Perez-Flores et al., 2016). Therefore, the Tolhuaca geothermal system is a good analogue to evaluate the impacts of internal and external triggers on fluid evolution and mineralization in a hydrothermal reservoir.

3. Methods

Considering the role of phase separation in the precipitation of precious minerals in the epithermal environment, we use pressure–enthalpy (P – H) space to represent the thermodynamic conditions of the system. The P – H space allows the visualization of vapor fractions in the two-phase region, reduced to a line in pressure–enthalpy space, and an intuitive representation of adiabatic (isoenthalpic) processes. This is justified because transient co-seismic thermodynamic changes are likely to be adiabatic in nature (Henley and Hughes, 2000).

In order to represent temperature logs of deep wells and homogenization temperatures of fluid inclusion data in P – H space, enthalpy was calculated as a function of temperature assuming liquid phase conditions and depth was converted to pressure assuming a hydrostatic gradient, as indicated by the temperature and pressure data from deep wells (Sánchez et al., 2016).

3.1. Gold solubility calculations in pressure–enthalpy space

The GEMS geochemical modeling software (Kulik et al., 2012) was used to compute dissolved gold concentration in hydrothermal fluids under epithermal conditions. As the gold solubility calculation is highly dependent on fluid chemistry (especially on sulfur content, salinity and pH), an accurate reconstruction of the chemical conditions of the deep reservoir is fundamental. Reservoir fluid samples are commonly collected at the wellhead after fluid ascent in the well has triggered depressurization boiling and separation between vapor and liquid. To reconstruct fluid chemistry at pre-sampling conditions the methodology developed by Scott et al. (2014) was used. Such methodology corrects the effect of the separation and segregation of liquid and vapor phases driven by adhesion of the liquid phase onto mineral surfaces in the porous aquifer rock upon rapid depressurization and boiling. The reconstruction was performed using the WATCH geochemical modeling software (Arnórsson et al., 1982), assuming a unique segregation step and using temperature measurements to constrain reservoir temperature. The reconstructed chemistry was obtained for major elements included in the thermodynamic database of WATCH, which are: SiO₂, B, Na, K, Ca, Mg, Al, Fe, CO₂, H₂S, SO₄, Cl and F. Volatiles such as CO₂ and H₂S are significantly affected by phase segregation whereas the non-volatile components such as Na, Cl and Si are only mildly affected.

For gold solubility calculations, feldspar-buffered acid-base conditions were assumed, i.e., excess Kfeldspar + albite + muscovite + quartz (Heinrich, 2005). The GEMS code uses the PSI/Nagra database (Hummel et al., 2002) as the core thermodynamic data source, which is complemented with SUPCRT92 (Johnson et al., 1992) for aqueous species and minerals. We updated the gold thermodynamic data for Au(Cl)_n, Au(OH)_n and Au(HS)_n species ($n = 1, 2$) with self-consistent experimental results (Stefánsson and Seward, 2004, 2003a, 2003b). Direct calculation of gold solubility with GEMS is restricted to the stability field of aqueous liquid, hereby computed within an equidistant temperature–pressure grid ($\Delta T = 5$ °C; $\Delta P = 10$ bar), ranging from 10 to 300 bar and 50–375 °C.

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