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Fault-controlled development of shallow hydrothermal systems: Structural and mineralogical insights from the Southern Andes

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ABSTRACT

Paleofluid-transporting systems can be recognized as meshes of fracture-filled veins in eroded zones of extinct hydrothermal systems. Here we combined meso-microstructural analysis of 107 fractures and mechanical modeling from two exhumed exposures of the faults governing regional tectonics of the Southern Andes: the Liquiñe-Ofqui Fault System (LOFS) and the Andean Transverse Faults (ATF). The ATF specific segment shows two tectonic solutions that can be modeled as Andersonian and non-Andersonian tectonic regimes: (1) shear (mode II/III) failure occurs at differential stresses > 28 MPa and fluid pressures < 40–80% lithostatic in the Andersonian regime; and (2) sporadic hybrid extensional + shear (modes I + II/III) failure occurs at differential stresses < 20 MPa and anomalously high fluid pressures > 85–98% lithostatic in the non-Andersonian regime. Additionally, the LOFS exposure cyclically fails in extension (mode I) or extension + shear (modes I + II/III) in the Andersonian regime, at differential stresses < 28 MPa and fluid pressures > 40–80% lithostatic. In areas of spatial interaction between ATF and LOFS, these conditions might favor: (1) the storage of overpressured fluids in hydrothermal systems associated with the ATF faults, and (2) continuous fluid flow through vertical conduits in the LOFS faults. These observations suggest that such intersections are highly probable places for concentrated hydrothermal activity, which must be taken into consideration for further geothermal exploration.

1. Introduction

The generation and reactivation of geological faults and fracture networks creates and destroys permeability within the Earth's crust (e.g. Faulkner et al., 2010 and references therein). Fault zone permeability influences the spatial distribution and behavior of hydrothermal and geothermal systems at all scales (e.g. Krupp and Seward, 1987; Cole, 1990; Rowland and Simmons, 2012).

From the point of view of its architecture, a brittle fault zone is composed of a core surrounded by a damage zone. The core (simple or multiple) is the volume of rock in which most of the strain is accommodated, whereas the damage zone (symmetrical or asymmetrical) is the volume of rock surrounding the core, in which hydrothermally-filled fractures may occur (e.g. Faulkner et al., 2003; Sibson, 2003).

Fault-driven fluid discharge depends on the macroscopic mode of brittle failure: extension (mode I), shear (mode II/III) and hybrid extension + shear (modes I + II/III) (e.g. Sibson, 1998; Cox, 2010). Extensional (mode I) failure occurs when open fractures are formed orthogonal to the least principal stress σ_3. Shear failure (mode II/III or faulting) takes place when a movement parallel to the fracture boundary occurs. Hybrid extensional + shear (modes I + II/III) failure involves the two previous kinds of failure.

The mode of brittle failure depends on three parameters (Hubbert and Rubey, 1959; Secor, 1965): the pore fluid pressure (P_F), the differential stress (σ_1-σ_3), and the tensile strength (T). The prevailing effective stress field ($\sigma_1' = \sigma_1 - P_F > \sigma_2' = \sigma_2 - P_F > \sigma_3' = \sigma_3 - P_F$) is related to the vertical stress (σ_V) by means of the pore fluid factor (λ), which can be defined as:

$$\lambda = \frac{P_F}{\sigma_V} \quad (1)$$

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Where λ represents the proportion of total fluid pressure into lithostatic pressure. A value λ ∼ 0.4 (40% of lithostatic pressure) is known as hydrostatic, and relates to a fault zone connected to the surface by a water column. This value is obtained by dividing the weight of the water column to the rock column. A value λ ∼ 1 (100% of lithostatic pressure) is known as lithostatic, and represents a fault zone in which the values of fluid pressure equal the overburden pressure (e.g. Sibson, 2004).

The combined effect of pore fluid factors, differential stress and tensile strength on the failure mode can be conveniently represented in a pore fluid factor – differential stress space (Cox, 2010). Failure envelopes in λ – σ space are excellent graphical representations that can be used to illuminate the role of fluid pressure conditions and differential stresses in failure and permeability enhancement. In these graphs, red lines indicate extensional (mode I) failure; green lines, extensional + shear (modes I + II/III) failure; and blue lines, shear (mode II/III) failure (Fig. 1).

The rock will fail in the corresponding failure mode only when pore fluid factors and differential stresses reach the envelope. Below the envelope, the rock is elastically loaded, but will not fail. Pore fluid factors and differential stresses above the envelope are not possible. Cox (2010) provided the theoretical framework necessary to construct λ – σ failure diagrams in an intact rock or cohesion-less fault using three assumptions: (1) one of the principal stresses acts in the vertical direction (following Anderson, 1905), i.e. stresses are said to be *Andersonian*; (2) the medium principal stress σ_2 lies on the fracture plane, and therefore does not influence faulting (following Jaeger and Cook, 1979); and (3) σ_V remains constant and equals the overburden pressure. However, natural fault zones can display extreme geometrical complexity, which makes the first and second assumptions not necessarily true (cf. Hafner, 1951; Yin, 1989; Yin and Ranalli, 1992).

With the objective of proposing a temporal-spatial conceptual model of a fault-controlled shallow hydrothermal system, we studied two extinct paleofluid-transporting hydrothermal systems, now exposed as mineral-filled networks. These examples represent the major fault systems controlling the tectonics of the Southern Andes: the Liquiñe-Ofqui Fault System and the Andean Transverse Faults (Fig. 2). For the purposes of this work, the active Andean margin is an exceptional natural laboratory for studying the interactions between fault systems, fluid flow and tectonic state of stress mainly for 2 reasons: (1) hydrothermal systems occur in close spatial relationship with active volcanism and major seismically-active fault systems, and (2) excellent exposures can be found.

Here, fluid redistribution accompanying faulting was studied using classical structural methods (field and analytical), and models of failure conditions. Field and analytical methods were used to determine the dominant modes of failure (from textural analysis) and temperature conditions (from mineral assemblages). Models of failure conditions in λ – σ space were constructed in Andersonian and non-Andersonian cases. For the non-Andersonian cases, we developed a new methodology based on the work of Cox (2010). Then, we propose the final conceptual models relating the dominant modes of failure with specific hydromechanical λ – σ conditions from mechanical calculations.

This work is a contribution to a better understanding of the still poorly documented development of fault-controlled hydrothermal systems in an Andean-type environment, which can lead to the improvement of efficient strategies for geothermal exploration in one of the largest, unexploited geothermal regions in the world.

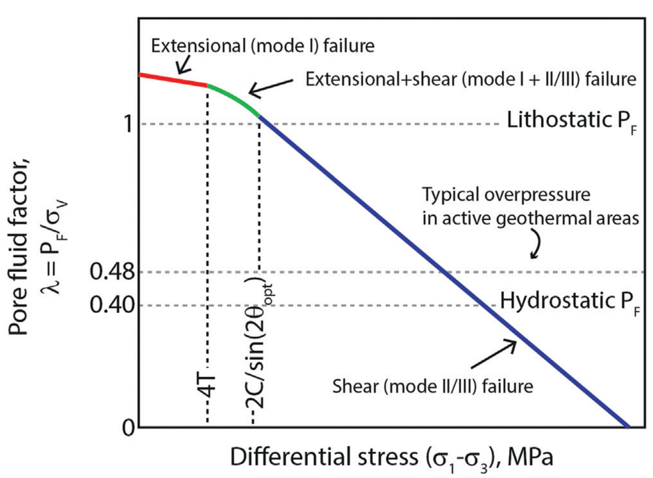

Fig. 1. Generic failure mode diagram in the λ - σ space, for a given depth and tensile strength (T) (modified from Cox, 2010). The red line indicates failure in extension (mode I); the green line, failure in extension + shear (modes I + II/III); the blue line, failure in shear (mode II/III). The rock will only fail when the pore fluid pressures and the differential stresses reach the envelope. Lithostatic and hydrostatic pore fluid factors are depicted along with typical overpressures in active geothermal areas (Rowland and Simmons, 2012). C = cohesion = 2T (Sibson, 2000), θ_{OPT} = maximum shear angle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

2. Geological setting

The arc-parallel Liquiñe-Ofqui Fault System and the Andean Transverse Faults constitute the main structural features in the Southern Volcanic Zone of the Andes (33–46°S) (Lavenu and Cembrano, 1999; Rosenau et al., 2006; Sánchez et al., 2013). At least from ca. 25 Ma, these structural features have been controlled by the subduction of the Nazca and Antarctic plates beneath the South American continental plate (Somoza and Ghidella, 2005) (Fig. 2a).

2.1. Liquiñe-Ofqui Fault System (LOFS)

The LOFS is an active ca. 1200 km long Cenozoic intra-arc, strike-slip fault system. Master faults strike NS to NNE, whereas splay faults strike NE and ENE, forming strike-slip duplexes with dextral and dextral-normal movement mostly developed in the last 6 Ma (e.g. Arancibia et al., 1999; Lavenu and Cembrano, 1999; Cembrano et al., 1996; Folguera et al., 2002). The LOFS displays a kinematics compatible with strain partitioning due to the decomposition of the convergence vector: (i) NS to NNE-striking master faults accommodate the margin-parallel component, and are favorably oriented for dextral shear; and (ii) the NE to ENE subsidiary faults, in turn, are favorably oriented for dextral-transtensional to purely extensional failure (Arancibia et al., 1999; Lavenu and Cembrano, 1999; Reuther et al., 2003; Rosenau et al., 2006; Cembrano and Lara, 2009). In particular, the northernmost tip of the LOFS has been described as an active, east-branching "horse-tail" fan, with faults that strike NE, progressively becoming EW towards the east (Fig. 2a). Present-day activity of this fault system is evidenced in shallow seismic activity (< 25 km) (e.g. Lange et al., 2008).

2.2. Andean Tranverse Faults (ATF)

The ATF refer to crustal faults and morphotectonic lineaments striking oblique to the Andean orogen. These include a group of NW to WNW-striking faults identified throughout the Andes, either in the fore-arc, intra-arc and/or back-arc regions (Salfity, 1985; Cembrano and Lara, 2009; Rivera and Yáñez, 2009; amongst others). The ATF are apparently older than the LOFS, and are at least present between 25°30′–41°00′S (e.g. Taylor et al., 1998; Rivera and Cembrano, 2000; Moreno et al., 2011; Aron et al., 2010). This group of faults is probably related to the tectonic segmentation of the Andes, emplacement of NW-striking intrusive bodies, Paleozoic-Mesozoic volcanic and volcano-tectonic processes, and genesis of one or several NW to WNW-trending basins oblique to the actual