Synkinematic fluid flow and vein formation by depressurization in magmatic arcs: A case study from Atacama Fault System, northern Chile

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Introduction

Where fluid-transporting fractures in fault zones gradually become sealed with minerals, their damage zone may develop dense networks of mineral-filled fractures, referred to as veins. Several workers (e.g. Ramsay, 1980; Oliver and Bons, 2001) have used structural and geochemical characteristics of veins to understand the kinematics of vein opening and later deformation features of the vein-filling minerals. In synkinematic veins there is potential for constraining the conditions of vein formation as vein filling evolves. However, there are few available studies that relate structural and microstructural observations with thermometric fluid inclusion data to better understand the interplay between crustal deformation and mineral precipitation (e.g. Parry, 1998). Here we present a study of veins spatially associated with an extensional strike-slip duplex belonging to the intra-arc Atacama Fault System in northern Chile. In particular we discuss the origin of the vein-forming fluids, and microstructural conditions of mineral precipitation.

Geological setting and occurrence of veins

The Caleta Coloso Duplex (González, 1996) constitutes a structural arrangement that is representative of the Atacama Fault System along the Coastal Cordillera of northern Chile (Fig. 1a), which develops on Early Jurassic

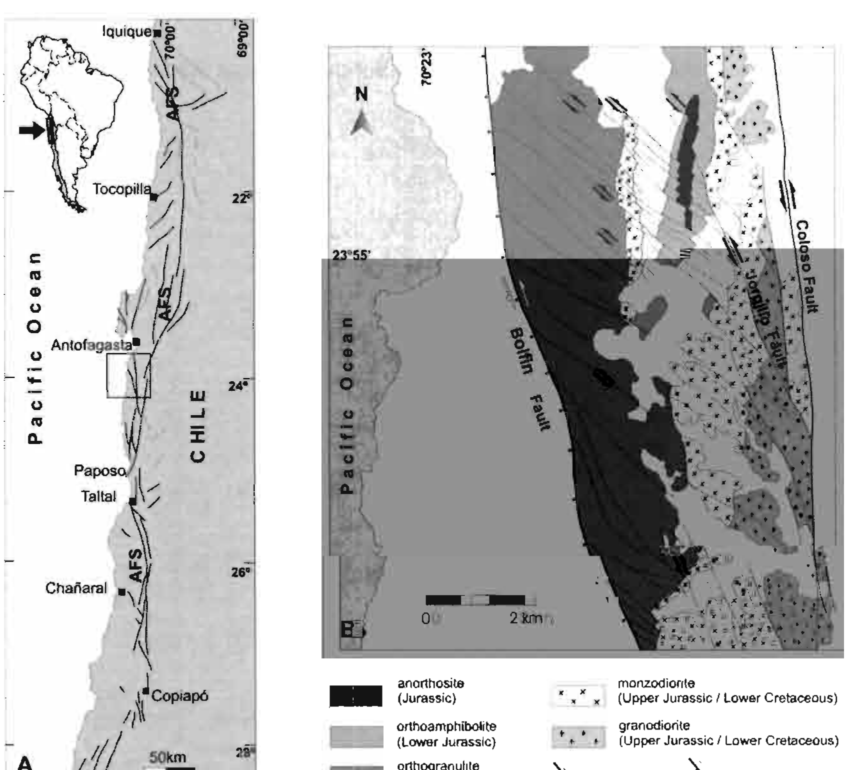

Figure 1: (A) The Atacama Fault System (AFS) in northern Chile. (B) Geological sketch map of the Coastal Cordillera south of Antofagasta showing the distribution of lithological units, three major faults of the AFS (Bolfin fault, Coloso fault and Jorgillo fault), and relates sinistral displacements in Jurassic igneous rocks (modified of Scheuber and González, 1999).

metamorphic rocks of the Bolfin Complex and Late Jurassic-Early Cretaceous plutonic rocks (González and Niemeyer, 2003) (Fig. 1b). The Caleta Coloso strike-slip duplex formed during the waning stages of the Jurassic-Early Cretaceous magmatic arc (at ca. 124 Ma).

The duplex is formed by two, NNW-striking, subvertical master faults: Jorgillo fault and Bolfin fault, that splay off the Coloso Fault, a major structure of the Atacama Fault System. The Jorgillo and Bolfin faults are in turn joined by a set of second-order NW-striking, and third-order EW-striking, imbricate splay faults. Both master and subsidiary faults host spatially and temporally related hydrothermal thin veins (1-25 cm): epidote-chlorite-quartz-calcite-hematite fault-veins and extension veins, which occur within the damage zones of the kilometer to meter-scale faults of the duplex. This suggests a strong link between fluid transport and duplex development.

Microstructure of veins

After a careful examination of oriented thin sections from fault-veins and extension veins by optical microscopy, more detailed information about composition and internal mineral structure was obtained by using the scanning electron microscope (Philips XL30 SEM) equipped with cathodoluminescence (CL) detector

The fault-veins show striated surfaces, mineral fibers and/or crushed material suggesting synkinematic precipitation. The veins are made of euhedral calcite (100-500μm) with slightly deformed twins and internal zoning. The overall vein texture is banded, slip surfaces and hematite fibers are seen at low angle to the vein walls. Also there are quartz-epidote veins exhibiting fractured grains (Fig. 2a).

In the extension veins, subhedral to euhedral epidote crystals lie at a high angle with respect to the vein walls. Chlorite is found as fibrous crystals intergrowth with quartz. Polycrystalline aggregates of quartz and calcite predominate towards the vein center. Some quartz crystals exhibit prismatic terminations with euhedral growth textures (Fig. 2b) which are interpreted to indicate longer-duration growth into open, fluid-filled cracks without high frequency sealing events.

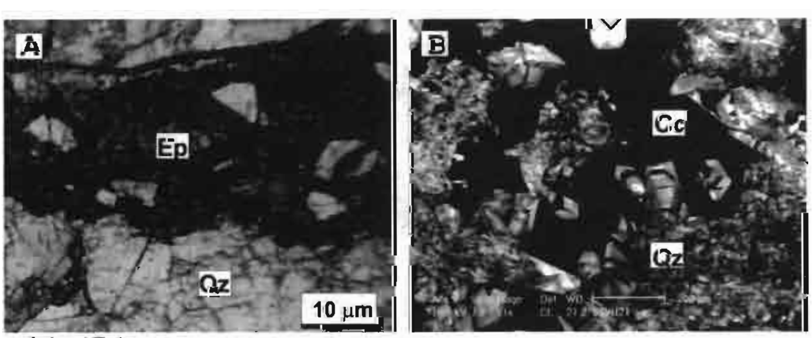

Figure 2: (**A**) Photomicrography of epidote (Ep) and quartz (qz) fault-vein thin section characterized by cataclastic texture. (**B**) CL image of extension vein shows euhedral zoning growth in quartz crystal intergrowth with calcite (Cc).

P-T-X condition and isotopic composition

One hundred eighty four primary fluid inclusions in quartz and calcite were measured by microthermometry using a Linkam THMS 600 heating-freezing stage. Phase changes were used to determine homogenization (Th) and salinities estimated from ice melting temperatures and regression equation Bodnar (1993). Fluid pressures have been calculated using the computer program LOONER 32 (Bakker, 1999) on basis of Th and salinities, and equation of Bodnar y Vityk (1994).

The studied fluid inclusions do not exceed 25μm, are round, oval and frequently resemble the shapes of negative crystals. Liquid-rich inclusions are found co-existing with vapor-rich inclusions which is a good evidence for entrapment of inclusions during boiling of the fluid (Roedder, 1984). Microthermometry studies document homogenization temperatures ranging from about 100 to 250°C, in which temperatures for boiling fluids represent the trapping temperature of the fluid. Salinities of inclusions are in the rangeof 4 to 23 wt% NaCl equivalent. Hence, the fluid pressure for boiling fluids can be well-established and range from 0.4 to 7.4 MPa. These are extremely low values considering the geologic setting of the veins suggesting depths of at least 3 km (Herrera *et al.*, submitted) for both hydrostatic and lithostatic conditions (Fig. 3).

Oxygen and carbon isotope compositions were measured in 6 quartz-calcite veins respectively, $\delta^{18}O_{SMOW}$ ranging from +14.1 to +10.8‰, and $\delta^{13}C_{PDB}$ from -1.4 to -4.2‰. Assuming oxygen isotope equilibrium exchange between solution and crystallizing calcite and quartz, the isotopic composition of fluid ($\delta^{18}O_{fluid}$) was calculated for range of homogenization temperatures and range from -3.4 to +6,9‰. They suggest that the fluids from calcite and quartz crystallized could not be solely meteoric (low $\delta^{18}O$ values), but likely have more complex origin, like a mixture with magmatic water.

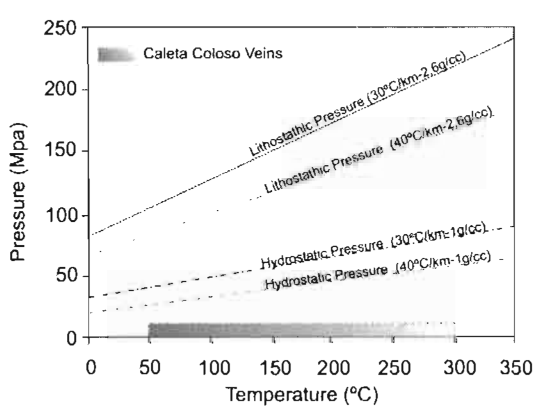

Figure 3: Estimated pressure for Caleta Coloso veins in function of temperature and salinities. Also shown are lithostatic and hydrostatic pressure gradients (Rothstein y Manning, 2003) evidencing decompression of vein fluids.

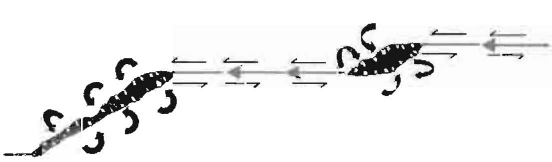

Figure 4: Schematic representation of rupture propagation. Sudden drop in fluid pressure inside the dilational jog during rapid slip transfer between master faults induces fluid flow towards the jog. (Modified from Sibson *et al.*, 1975)

Discussion and Conclusions

The fluid pressures supported by Caleta Coloso Duplex geological setting and fluid inclusion show a relatively sharp transition from lithostatic (or lithostatic gradient) to below hydrostatic pressure gradient (0.4 to 7.4 MPa). The process depicted in Fig.3 is similar to mechanisms for fluid circulation envisaged by Scholz *et al.* (1973) and Sibson *et al.* (1975): suction pump mechanism which local depressurization drives fluids into the extension fractures (Fig. 4).

Optical microscopy and scanning electron microscope-cathodoluminiscence analysis of quartz and calcite veins of the Caleta Coloso Duplex indicate that veins have undergone crystal growth into a fluid-filled space,