BRITTLE DEFORMATION AND FLUID TRANSPORT IN MAGMATIC ARCS: A CASE STUDY FROM THE ATACAMA FAULT ZONE

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INTRODUCTION

Several workers (e.g. Etheridge, 1983; Sibson, 1996; 2000) have set theoretical constraints on the dynamic interaction between fluid transport and faulting, especially for mesothermal ore deposits associated with reverse faulting (e.g. Sibson, 1988; Cox, 1999) and epithermal veins associated with strike-slip faulting (Sibson, 1987). However, to date there is little published field evidence that accounts for the operation of those processes in real examples (e.g. Bonson et al. 1997; Foxford et al. 2000). Furthermore, although the theoretical constraints on the dynamic interaction between fluid transport and deformation seem clear, few studies concentrate on the consequences of active deformation on the time-space physical and chemical evolution of hydrothermal fluids transported and emplaced in fracture networks (e.g. Coombs et al. 1993).

Fracture meshes, hydrothermal fluid circulation and mineral deposition in strike-slip environments

Sibson (1987, 1990, 1996) emphasizes the close relationship between the earthquake cycle and hydrothermal fluid migration and subsequent mineral precipitation in strike-slip settings. During a slip event on one master strike-slip fault, pre-existing and/or newly created vertical fractures that face the instantaneous extension direction will be sites of a sudden, significant decrease in fluid pressure. This local depressurization drives fluids into the extension fractures; a geologically instantaneous process lasting until internal fluid pressures re-establish equilibrium with the environmental hydrostatic pressures typical of upper crustal levels (< 4 km) (Figure 1a). This sort of dynamic interaction between brittle deformation and fluid flow is known as the suction pump mechanism. Under certain conditions, this mechanism can result in the precipitation of hydrothermal minerals triggered by boiling, mixing with cold meteoric waters and/or hydration reactions (e.g. Drummond and Ohmoto, 1985; Sibson, 1987, 1990; Coombs, 1993). According to Sibson (1990, 1996), the theoretical geometry of interconnected fault-veins networks at dilational jogs in strike-slip settings consists of vertical strike-slip barren master faults and subvertical extensional fault-vein networks with different geometries (Figure 1b). In particular, our experience shows that other subsidiary fractures, similar to those reported in Riedel type models, also host mineralized veins.

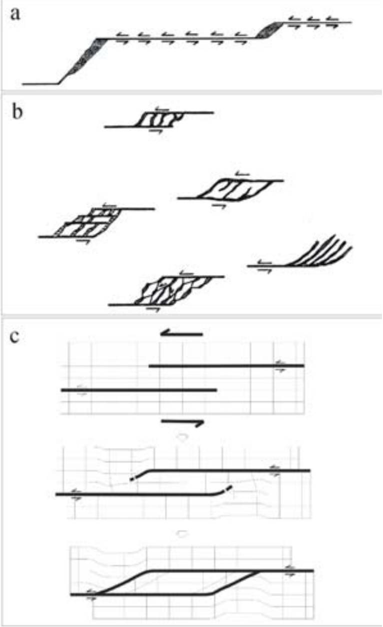

Figure 1. (a) Dilational jog linking two overstepping sinistral strike-slip fault zones. Rupture propagation is from right to left. Sudden drop in fluid pressure inside the jog during rapid slip transfer between master faults induces fluid flow towards the jog. This process may trigger mineral precipitation in response to boiling and/or by mixing with meteoric waters (e.g. Sibson, 1987). Internal geometry and kinematics of fault-vein networks forming at dilational jogs (b) is very similar to that resulting from the structural development of extensional strike-slip duplexes (c)
(Modified from Sibson, 1990; Woodcock and Fisher, 1986).

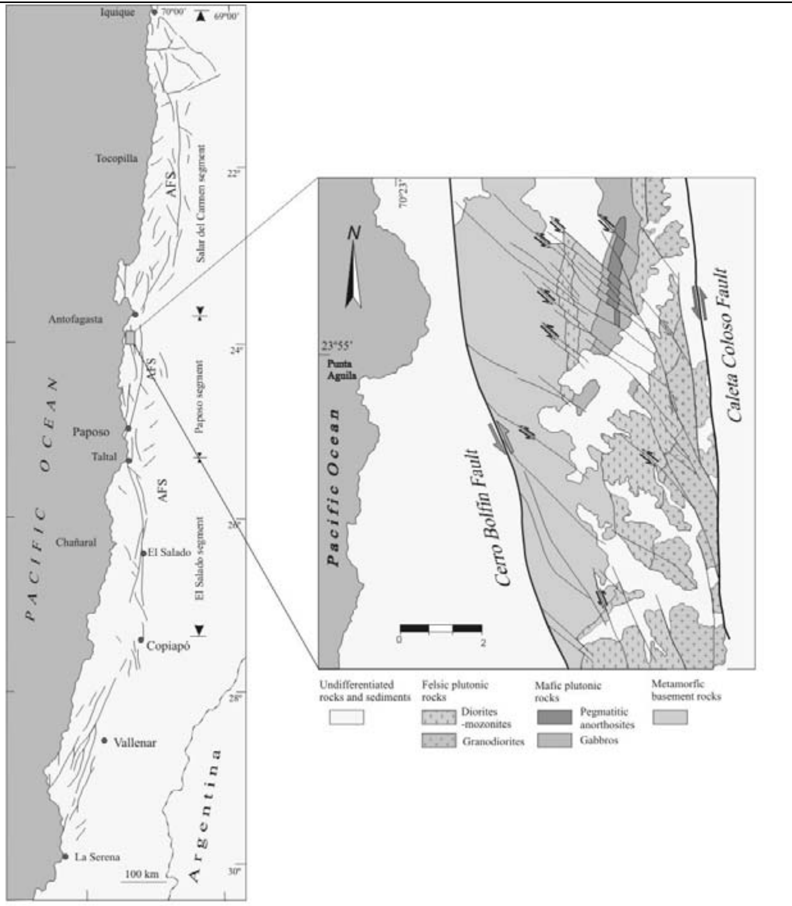

Figure 2. Regional scale geometry of the Atacama Fault System (AFS) in the Coastal Cordillera of northern Chile. Inset shows the Caleta Coloso Duplex formed by NW striking faults linking the ~NS-striking Bolfin and Caleta Coloso faults (modified of Brown et al. 1993; Scheuber and González, 1999).

If one compares the geometry and kinematics of extensional strike-slip duplexes described by Woodcock and Fisher (1986) and the structural mesh concept suggested by Sibson (1996) for fluid flow in strike-slip settings, there are remarkable similarities that demand further attention (Figure 1a,b, c). For instance, a requirement for the suction pump mechanism to operate in strike-slip settings is that slip occurs in one of two flanking strike-slip overstepping master fault (Figure 1a). Potential slip transfer from one master fault to the other is accomplished via propagation of extensional and/or hybrid fractures from one master fault to the other at a dilational jog. This propagation may result in a physical linkage between the two overstepping master faults in an analogous way to that proposed by Woodcock and Fisher (1987); to form strike-slip duplexes (Figure 1b,c). According to these authors, extensional duplexes may form from progressive propagation of Riedel-type shears from the tip of both overstepping master faults (Figure 1c). Consequently, we propose that extensional strike-slip duplexes play a twofold role of accommodating strike-slip displacement and serve as channelways for the migration of hydrothermal fluids in the upper crust.

In this contribution we focus on the processes related to the formation of a mid-Cretaceous strike-slip duplex belonging to the intra-arc Atacama Fault System in northern Chile. This structure, the Caleta Coloso Duplex, meets many of the requirements needed to address the problem of deformation and fluid migration. Master and subsidiary faults that form the duplex are filled with hydrothermal mineral associations constituting fault-veins, oblique extension veins and extension veins. Fault and veins show spectacularly well-preserved internal structures such as mineral fibers, striated planes, banding, etc, that allow to reconstruct the deformation-mineralization history at both the local and regional scale.

THE CALETA COLOSO DUPLEX

The Caleta Coloso Duplex is part of the Atacama fault system (AFS) in the Central Andes (Figure 2). It is flanked by the Caleta Coloso Fault and the Bolfin Fault, two important regional-scale brittle structures of the AFS. The geometry, kinematics and timing of deformation of the AFS are very well known at the regional-scale (e.g. Brown et al. 1993; Grocott et al. 1994; Taylor et al. 1998; Scheuber and Gonzalez, 1999). Although the kinematics and timing of deformation vary along-strike, most authors agree that intra-arc transtensional to transpressional sinistral displacement was active during arc construction at least from 190 to 110 Ma along most of the present-day Coastal Cordillera from Antofagasta to Vallenar. Absolute age determinations of ductile deformation document coeval sinistral and dip-slip normal displacement at around 145 Ma and sinistral displacement around 125 Ma in the Paposo segment where the duplex is located (Scheuber et al. 1995; Scheuber and Gonzalez, 1999). Published data and our own field observations indicate that the Caleta Coloso strike-slip duplex formed during the last stages of activity of the AFS, shortly after 125 Ma, the age of mylonites near Cerro Paranal, 100 km farther to the south (Scheuber and Andriessen, 1990). Fission tracks in apatite from rocks crosscut by the duplex document that the rocks passed through the ~100° C geotherm at ca. 118 Ma (Scheuber and Andriessen, 1990), constraining the age of the duplex formation between 125 and 118 Ma . This time span is widely accepted to be the age of cooling and waning stages of arc magmatism in the Coastal Cordillera.

The Caleta Coloso duplex constitutes a structural arrangement that is representative of the AFS along the Coastal Cordillera between Paposo and Antofagasta. The first duplex-like structure of the area was described by Herve (1987), who identified some northwest striking faults with sinistral separation linking major north-south striking faults. All faults affect volcanic and plutonic rocks of the Coastal Cordillera magmatic arc. Preliminary structural investigations carried out in the faults of the Caleta Coloso Duplex show that bulk deformation was accommodated in a complex way. The subvertical Caleta Coloso fault strikes NNW and is marked by an hectometric-wide zone of striated faults, fault gouge, foliated cataclasites and foliated breccia that locally overprint and early mylonitic fabric. The matrix of the cataclastic rocks is filled with chlorite an epidote. Kinematic indicators document sinistral and sinistral-oblique normal displacement. The Cerro Bolfin fault strikes NNW, has a curved shape, and consists of a meter-wide zone of fault gouge. Last movement on the fault seems to be normal dip slip. Multiple sets of subsidiary northwest striking faults splay off the Caleta Coloso fault joining it with the Bolfin fault as a duplex structure. The northwest structures dip steeply to the southwest and consist of sinistral meter-wide fault-fracture zones and epidote-chlorite veins whose overall branched geometry and synthetic kinematics resembles consecutive sets of Riedel shears as seen in analog experiments (e.g. Naylor et al. 1986). Individual veins, up to 10 cm thick, are commonly banded and show isolated inclusions of altered wallrock fragments. The dioritic wallrock shows alteration haloes of albite and sericite. Under the microscope, the bands consist of coarse-grained and fine-grained isotropic aggregates of euhedral and anhedral epidote respectively. Preliminary SEM analysis of veins indicates that narrow zones of ultracataclasite cut the epidote bands, which are made of least two types of epidote according to its iron content.

CONCLUSION

We propose that the fault-fracture network forming the Caleta Coloso duplex in the Atacama fault system is one remarkable example of a regional scale geological structure resulting from the dynamic interaction between brittle deformation and hydrothermal fluid migration and mineral precipitation in the upper crust Northwest striking chlorite-epidote-bearing veins and fault veins likely formed in response to sudden pressure drops at dilational sites during multiple slip events along the flanking Caleta Coloso and Bolfin faults. Our observation that the master and subsidiary faults contain a range of rocks from mylonites to cataclasites and fault gouge strongly suggests the extensional strike-slip duplex developed during progressive cooling in a magmatic arc dominated by margin-parallel sinistral deformation. As the arc cooled down, deformation became brittle, allowing the suction pump mechanism, well known for epithermal systems, to operate during major slip events of the master faults. In this tectonic setting, veins are expected to occur at the oblique-slip/extensional sites represented by linking faults of the duplex, as is observed in the present study. Regional-scale cooling of arc rocks may have resulted from regional exhumation accompanying a mid-Cretaceous sinistral transpressional event and/or from the well-documented migration of the magmatic foci towards the east during mid-Cretaceous time.

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