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Two-stage fluid flow and element transfers in shear zones during collision burial-exhumation cycle: Insights from the Mont Blanc Crystalline Massif (Western Alps)

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ABSTRACT

The Mont-Blanc Massif was intensely deformed during the Alpine orogenesis: in a first stage of prograde underthrusting at c. 30 Ma and in a second stage of uplift and exhumation at 22-11 Ma. Mid-crustal shear zones of 1 mm–50 m size, neighbouring episyenites (quartz-dissolved altered granite) and alpine veins, have localised intense fluid flow, which produced substantial changes in mineralogy and whole-rock geochemistry. Four main metamorphic zones are oriented parallel to the strike of the massif: (i) epidote, (ii) chlorite, (iii) actinolite-muscovite ± biotite and (iv) muscovite ± biotite. In addition, phlogopite-bearing shear zones occur in the chlorite zone, and calcite-bearing shear zones are locally found in the muscovite zone. The initial chemical composition of the granitic protolith is relatively constant at massif scale, which allows investigating compositional changes related to shear zone activity, and subsequent volume change and elements mobility. The variations of whole-rock composition and mineral chemistry in shear zones reflect variations in fluid/rock ratios and fluid's chemistry, which have produced specific mineral reactions. Estimated time-integrated fluid fluxes are of the order of 10^6 m^3/m^2. The mineral assemblages that crystallised upon these fluid-P-T conditions are responsible for specific major and trace element enrichments. The X_{Fe} (Fe/Fe + Mg) pattern of shear zone phyllosilicates and the $\delta^{13}C$ pattern of vein calcite both show a bell-type pattern across the massif with high values on the massif rims and low values in the centre of the massif. These low X_{Fe} and $\delta^{13}C$ values are explained by down temperature up-flow of a Fe-Mg-CO_2-rich and silica-depleted fluid during stage 1, while the massif was underthrusting. These produced phlogopite, chlorite and actinolite precipitation and quartz hydrolysis, resulting in strong volume losses. In contrast, during stage 2 (uplift), substantial volume gains occurred on the massif rims due to the precipitation of quartz, epidote and muscovite from a local fluid hosted in the Helvetic cover. These two fluids advocate for the presence of an upper-crustal scaled fluid convection cell, with up-going fluids through the lower crust and likely down-going fluids in the 15 km upper crust.

1. Introduction

Mid-crustal ductile faults developed in crystalline rocks are zones of intense fluid circulation during orogenesis. Fluid circulation focuses in shear zones as a result of deformation-induced permeability enhancement (e.g., Kerrich, 1986; Cox et al., 1987; O'Hara, 1988; McCaig, 1988; McCaig et al., 1990). Major fluid circulation may result in significant mass and heat transport, which may in turn control the stability of mineral assemblages and the rheology of rocks through fluid-induced softening reactions (e.g., Ferry and Gerdes, 1998; Wibberley and McCaig, 2000). In shear zones, time integrated fluid fluxes estimated from changes in mineralogy, geochemistry and oxygen isotope ratios are of 10^5–10^6 m^3/m^2 (McCaig et al., 1990; Dipple and Ferry, 1992; Streit and Cox, 1998; Cartwright and Buick, 1999), which is significantly higher than time-integrated fluid fluxes estimated in contact and regional metamorphism settings. Such high fluid fluxes localised in narrow zones can result in the formation of ore deposits (e.g., Kerrich and Allison, 1978; Cox et al., 1987, 1991; Roberts, 1987).

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A more complete understanding of fluid-rock reaction processes, including estimates of fluid fluxes and element mobility, as well as precise estimates of pressure, temperature and time of deformation will help determining locus of mineral deposition in shear zone networks during continental collision and will provide data to better constrain elements cycles within the crust (Streit and Cox, 1998; Ferry and Gerdes, 1998).

As granitic bodies have rather homogeneous and almost anhydrous compositions, significant changes in textures and composition occur during deformation and associated fluid circulation, which allows studying the effect of fluid-rock reaction at local and regional scales. Comparison of the compositions of deformed versus undeformed granite helps constraining the fluid chemistry, thus providing useful information on the fluid source. It allows quantifying deformation-induced mineralogical changes and their effect on the whole rock chemistry, volume changes and subsequent time-integrated fluid fluxes.

This paper presents a review of recent data (XRF, ICPMS, mineral LA-ICP-MS analysis, stable isotope analysis and punctual ^{40}Ar/^{39}Ar and U-Pb techniques) from the shear zone network cross-cutting the homogeneous Mont Blanc granite (western Alps), in order to investigate the effects of deformation, metamorphic reactions and fluid flow, on the mobility of elements under greenschist facies conditions during orogenesis. Geological setting and previous works are presented in Section 2. These data are used to derive mineral reactions and to quantify and discuss mass transfer in the MBM shear zones during the Alpine orogenesis.

2. Geological settings and previous work

2.1. Geological context and alpine structures

The Mont Blanc Massif (MBM) is one of the Variscan “External Crystalline Massifs” of the Western Alps (Fig. 1).

It is made of paragneisses, orthogneisses and migmatites dated at 453 ± 3 Ma by U-Pb on zircon (migmatitic gneisses; Bussy and von Raumer, 1994) intruded by a late-Variscan calc-alkaline granitic intrusion, the Mont Blanc Granite (Baggio, 1958; Ayrton et al., 1987 and references therein; Bussy, 1990; Bonin et al., 1993). This intrusion is a 35 × 10 km batholith dated at ~300 Ma by the Rb-Sr method (Baggio et al., 1967; Bussy et al., 1989) and at 300 ± 3 Ma by U-Pb on zircon (Bussy and von Raumer, 1994). From the NW margin to the core of the massif, the granite becomes more porphyritic, whereas it is finer-grained near its SE contact (Baggio, 1958; Marro, 1986; Bussy, 1990). Compilation of geochemical data from Marro (1986,1988), Bussy (1990) and Rossi et al. (2005) highlight the rather homogeneous composition of the Mont Blanc granite at the scale of the massif (Table 2). The slight observed composition changes are ascribed to initial magmatic variations and fluid-rock interaction since the granite crystallisation.

The distribution of faults and shear zones within the granite shows a fan-like arrangement, which suggests a “pop-up” structure (Bertini et al., 1985). The massif is bounded by a NW-vergent thrust at its NW (Belliere, 1988; Leloup et al., 2005) and by a SE-vergent thrust at its SE (Antoine et al., 1975; Butler, 1985; Rolland et al., 2007) boundaries. Fluids flowed through a subvertical shear zone network and connected horizontal veins and joints (Figs. 1 and 2; Rossi et al., 2005). The shear zones contain greenschist facies assemblages of muscovite ± chlorite ± epidote ± quartz ± albite that crystallised at 18–36 Ma following the Rb/Sr ages obtained in the granite (Baggio et al., 1967). Biotite dating of slightly deformed granite provided complex ^{40}Ar/^{39}Ar ages, with mixing of Alpine and Variscan end-members, and a mimimum age of ~20 Ma for the Alpine stage (Leloup et al., 2005; Rolland et al., 2007). More recent datings show evidences of two stages in shear zone activity (Fig. 1). Stage 1 occurred at ~30 Ma, as evidenced by dating of *syn*-kinematic allanite at 29 ± 1 Ma (U-Pb method; Cenki-Tok et al., 2014), partial preservation of ~29–32 Ma ages in ^{40}Ar/^{39}Ar spectra of phlogopite (Rolland et al., 2008), and 32–29 Ma Rb-Sr dating in the massif peripheral shear zones (Egli et al., 2015). As stage 1 is contemporaneous with the 29–35 Ma top-to-the-west thrust motion of the Penninic Front (e.g., Simon-Labric et al., 2009), it likely represents underthrusting of the MBM. A second phase of deformation (stage 2) occurred between 22 and 14 Ma, as highlighted by ^{40}Ar/^{39}Ar dating of *syn*-kinematic phengites, biotites and phlogopites (Rolland et al., 2007; 2008). Stage 2 occurred under mid-crustal greenschist facies: pressure of 5.0 ± 0.5 kbar and temperature of 400 ± 25 °C were computed from independent mineral equilibria (Rolland et al., 2003).

Alpine horizontal veins, filled with a quartz + chlorite ± calcite assemblage, developed between shear zones, in the unsheared granite (Fig. 2). They are systematically surrounded by an alteration halo where quartz ± biotite were dissolved resulting in a highly porous granitic rock called episyenite (Rossi et al., 2005). Temperatures of 300–350 °C and pressures of 2.5–3 kbar were estimated from fluid inclusion analysis of vein quartz and chlorite thermometry (Poty, 1969; Poty et al., 1974; Fabre et al., 2002; Rossi et al., 2005; Fig. 3). The veins have been dated at 10–18 Ma using the ^{40}Ar/^{39}Ar, K/Ar and Rb/Sr techniques on adularia and muscovite (Leutwein et al., 1970; Marshall et al., 1998; Rossi and Rolland, 2014) and at 11.1 ± 0.2 Ma by U-Pb on monazite (Grand’Homme et al., 2016). The overlap of the vein opening with the end of stage 2 shear zones, and associated changes in P-T conditions, is consistent with the evolution from ductile to brittle conditions during the MBM uplift.

2.2. The MBM shear zones

Four main mineralogical assemblages can be distinguished in the MBM shear zones (Figs. 4 and 5): (1) epidote-bearing assemblages are mainly found in the north-western part of the massif; (2) chlorite-bearing assemblages are common in the centre of the massif, where phlogopite-rich shear zones are also found in association with a metasomatic front; (3) actinolite-muscovite assemblages occur in the central-east part of the massif, where calcite-bearing shear zones are also locally found (4) muscovite ± biotite ± titanite assemblages are very common in the south-eastern part of the massif. In addition, intense precipitation of Mg-rich biotite and chlorite characterizes some shear zones from the chlorite-rich zone. These shear zones are referred to as “phlogopite-bearing shear zones” in the text. Finally rare calcite-bearing shear zones are found in the SE part of the massif.

Dating of these shear zones (Rolland et al., 2008; Cenki-Tok et al., 2014) indicates that phlogopite-bearing shear zones developed at 30-29 Ma during stage 1 deformation, whereas epidote-, chlorite-, actinote- and muscovite-bearing shear zones developed at 22-14 Ma during stage 2.