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Fluid systems above basement shear zones during inversion of pre-orogenic sedimentary basins (External Crystalline Massifs, Western Alps)

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ABSTRACT

In the inner part of the External Alps, inherited Liassic basins were buried and inverted during the Oligo-Miocene collisional phase of the Alpine orogeny. In northern Oisans, during crustal shortening, the basement was locally sheared while the cover was disharmonically folded above the main basement shear zones that did not propagate into the cover. In this contribution, we analyze the witnesses of paleo-fluid circulations associated with these crustal deformations, focusing particularly on Bourg d'Oisans and Mizoën basins (external Western Alps). On the basis of structural and microstructural observations coupled to geochemical analyses (cathodoluminescence, O and C stable isotopes, trace elements) of vein versus host-rock minerals, we show that in the cover, fluids mainly circulated over short distances (closed-system). However, trace element data also show that percolation of small amounts of basement-derived fluids occurred over several tens of meters in cover rocks right above basement shear zones. Indeed, the three successive vein sets recognized in the field display enrichments in basement-derived Ni, Co, and Cr, which indicate that fluid transfer from the basement was efficient since the beginning of basin inversion, therefore confirming the synchronous deformation of cover and basement. Fluid temperatures and pressures are estimated (microthermometry coupled to $\delta^{18}O$ of vein minerals) to about 250–400 °C and 2–5 kbar for veins that most likely formed at or close to metamorphic peak conditions. These results coupled to literature data are finally integrated into a model of fluid circulation evolution through progressive deformation of the whole external Western Alps.

1. Introduction

In convergent settings (subduction or collision), large amounts of fluids are released in rocks by successive metamorphic dehydration reactions occurring during burial (e.g., Walther and Orville, 1982). The occurrence of fluids in rocks, in particular water, has crucial effects not only on the scale of mass transfer processes and fluid–rock interactions (e.g., John et al., 2012; Penniston-Dorland et al., 2010), but also on the deformation mechanisms and rock rheology (e.g., Bos and Spiers, 2000, 2002; Gueydan et al., 2004; and references therein). Moreover, there is a strong link between mass transfer and deformation mechanisms (Stünitz, 1998). Indeed, the scale of fluid circulation and mass transfer through rocks is mainly controlled by the size and connectivity of the deformation structures, and their evolution through time (Fisher et al., 1995). The permeability of high-pressure rocks being low and fluid pressure close to lithostatic (Etheridge, 1983), most rocks may behave as almost closed-systems, experiencing only small-scale (mm–dm) diffusive mass transfer through the pervasive fluid produced locally by dehydration reactions (Cartwright and Buick, 2000; Fisher et al., 1995; Garofalo, 2012; Spandler et al., 2011; Verlaguet et al., 2011). In these rocks, fluid flow may be channelized in highly deformed zones (shear zones, faults), which form localized preferential pathways for large-scale (m–km) advective mass transfer; open-system fluid–rock interactions are restricted to mm–m scale halos in the surrounding rocks (Abart et al., 2002; Badertscher et al., 2002; Burkhard et al., 1992; John et al., 2012; Li et al., 2013; McCaig et al., 1995, 2000a,b).

However, it is still unclear how open systems develop in previously closed-system rocks and what are the transitional stages. Yet these stages are keys for understanding the fluid system evolution and constraining the (early) rheological evolution of the continental crust when it is subducted or underthrusted. It is therefore a major issue to characterize the fluid system(s) at that time, i.e., the fluid source, the

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circulation timescale and pathways, the intensity of fluid–rock interactions along pathways, as well as the evolution of the fluid system with progressive deformation, especially during the early stages.

Such a study has been performed in the External Crystalline Massifs (ECM) of the external Western Alps. During the Alpine collision phase, this proximal part of the European passive margin was buried to mid-crustal depth below the internal Alpine units at Oligo-Miocene times (Bellahsen et al., 2012; Rolland et al., 2008; Simon-Labric et al., 2009). The ECM experienced mainly thick-skinned deformation during collision: shortening was accommodated by hundred meter-wide shear zones in the basement, while the overlying sedimentary cover was disharmonically folded (Bellahsen et al., 2012; Bellanger et al., 2014; Boutoux et al., 2014). In the northern ECM, i.e., the Mont-Blanc and Aar–Gothard massifs (Fig. 1), the fluid system in the sedimentary cover nappes remained closed to external fluid infiltration, even in highly cleaved metasediments (e.g., Kirschner et al., 1995, 1999; Marquer and Burkhard, 1992). However, the major cover thrusts or mylonites and associated veins record the infiltration of important amounts of basement-derived fluids (Burkhard and Kerrich, 1988; Kirschner et al., 1995, 1999; Marquer and Burkhard, 1992). Indeed, the major basement shear zones propagated as thrusts into the cover, resulting in local opening of the fluid system: ascendant fluids were then channelized within the thrust zones and flowed through both basement and cover (Marquer and Burkhard, 1992; Rolland et al., 2003). Further North, in the Glarus thrust, a localized fluid flow occurred at the basal contact of the sedimentary nappes, as attested by a clear isotopic front due to northward metamorphic fluid flow (Badertscher et al., 2002).

Was the fluid evolution similar in the southern ECM (i.e., North Oisans), which underwent less burial and shortening? In the north-eastern part of the northern Oisans massif (Fig. 1), the cover is locally detached from its basement, which is consequently not involved in crustal shortening (i.e., local thin-skinned tectonic style; Bellahsen et al., 2012). There, cover rocks behaved as a closed-system during the whole deformation process; fluid circulations were restricted to the sedimentary unit scale (Henry et al., 1996). On the contrary, the north-western part of the Oisans massif is characterized by thick-skinned deformation (Bellahsen et al., 2012). However, basement shear zones did not propagate into the cover. Each of these structures having accommodated an amount of shortening of only a few hundred meters they are most likely key features on which one can study the early fluid circulations and probably the transition from closed to open fluid system.

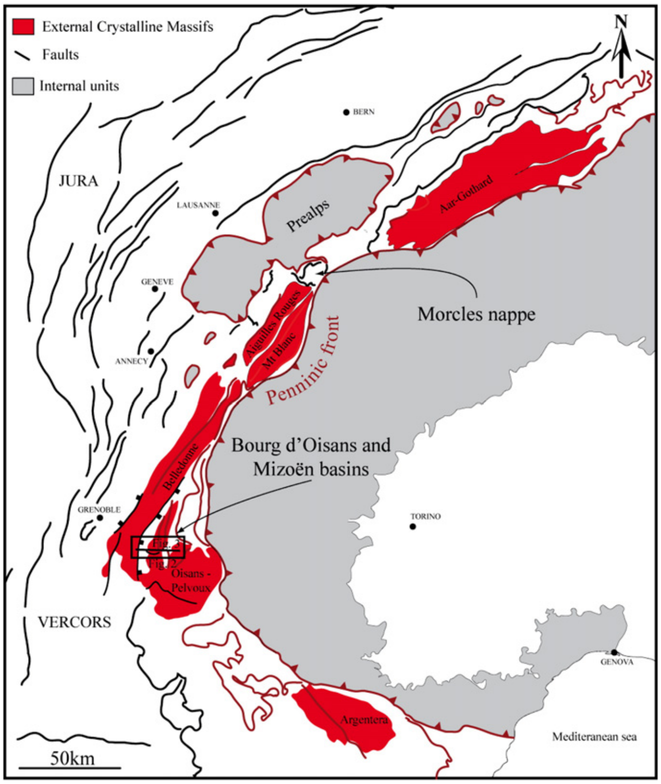

Fig. 1. Schematic structural map of the Western Alps showing the location of the studied area.

The questions we address in this contribution are the following: what is the scale of the fluid system and its evolution with progressive deformation? As the basement shear bands did not propagate into the cover, how is the deep fluid circulation (if any) accommodated at the basement–cover interface? Can the fluid system give information about the relative timing of basement and cover shortening during the margin inversion? In order to answer these questions, we combine the structural and microstructural analysis of basement shear zones and the overlying metasedimentary cover in the northern Oisans massif with geochemical and microthermometric investigation of the successive vein filling material and host-rocks.

2. Geological setting

2.1. The External Alps

The external zone of the Western Alps arc consists of fold-and-thrust belts (Vercors, Chartreuse, Bauges, Bornes, Aravis, Haut Griffre) and External Crystalline Massifs (ECM, Argentera, Oisans, Grandes Rousses, Belledonne, Mont Blanc, Aiguilles Rouges, Aar, Gothard; Fig. 1). It corresponds to the proximal part of the European margin, thinned during Liassic to Dogger times, with the formation of tilted blocks (Lemoine et al., 1989) limited by normal faults oriented N–S to NE–SW in the ECM (Figs. 1, 2).

During the collisional phase of the Alpine orogeny, the ECM were buried down to mid-crustal depth below the internal (Penninic) units. The ECM burial was deeper in the North (400 °C, 5 kbar in the Mont Blanc massif; Rolland et al., 2003; Rossi et al., 2005; 450 °C, 6 kbar in the Aar massif; Challandes et al., 2008) than in the South (270–360 °C and 2–5 kbar in the Oisans massif; Bellanger, 2013; Crouzet et al., 2001; Jullien and Goffé, 1993; Poty et al., 1974).

During collision, basement shortening was accommodated by West-verging reverse shear zones (e.g., Bellahsen et al., 2012; Bellanger et al., 2014; Leloup et al., 2005; Rolland et al., 2008) or anastomosed steep shear zones (e.g., Marquer et al., 2006; Rolland et al., 2008; Oliot et al., 2010, 2014). In the northern Oisans area, the cover was mainly disharmonically folded over basement West-verging shear zones, without significant décollement between the basement and its sedimentary cover (Fig. 3). The main difference between the northern and the southern ECM is that, in the North (Mont Blanc, Aar), basement shear zones propagated into the cover, while in the South (Oisans) shear zones were restricted to the basement and did not propagate into the cover. Moreover, basement shear zones and the associated significant crustal shortening are mainly observed in inverted pre-orogenic Liassic basins (Bellahsen et al., 2012). On the contrary, where the crust was not pre-structured by Liassic extensional basins (e.g., La Grave area in the north-eastern Oisans; Figs. 2, 3), there is less field evidence of significant crustal East–West shortening in the basement, and the cover is detached from the basement, i.e., the shortening style is locally thin-skinned. A striking point in all the basins is the absence of any significant reactivation of the inherited normal faults (Bellahsen et al., 2012; Tricart and Lemoine, 1986).

2.2. Bourg d'Oisans and Mizoën basins

The Bourg d'Oisans and Mizoën basins are pre-orogenic Liassic–Dogger N–S extensional basins bounded by East-dipping normal faults,