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Multi fluid-flow record during episodic mode I opening: A microstructural and SIMS study (Cotiella Thrust Fault, Pyrenees)

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ABSTRACT

Syntectonic veins commonly have been used to assess the composition and source of fluids involved in fault zone activity. Such veins also provide information on the ambient stress conditions during deformation and mineralization. Based on bulk sampling and bulk O- and C-isotope analysis, combined with fluid inclusion microthermometry, many studies have demonstrated that syntectonic veins provide snapshots of fluid composition and stress conditions over the course of fault history. This is widely acknowledged for mode I extension veins that develop in the damage zones of faults. However, an important and unanswered question is the extent to which such veins record a more detailed fault history at the micron scale. In this study, we present new detailed *in-situ* micron-scale $\delta^{18}O$ data, measured using Secondary Ion Mass Spectrometry (SIMS), combined with detailed fluid inclusion microthermometry and Δ_{47} clumped isotope thermometry to document the fluid and temperature conditions during mode I vein growth related to deformation along the Cotiella thrust fault (Pyrenees). All the studied veins show three distinct episodes of vein opening, recording a complex history of varying fluid composition and temperature. Results show that the studied fault portion passed from a hydrological rock-buffered system, in which formation waters were in isotopic equilibrium with the host sediments, to a fluid-buffered system involving meteoric water. However, such information is only achievable at the micron scale using Secondary Ion Mass Spectrometry. This study demonstrates the potential of these new micro-beam techniques for investigating fault behavior in more detail than previously available, particularly with respect to the nature of the fluids involved and the P–T conditions extant during fault activity.

1. Introduction

Fluids are key elements in fault activity, but determining fluid source(s) and their evolution over time can be difficult, despite the fact that fluid conditions almost certainly change during short- and long-term fault ruptures (Boullier and Robert, 1992; Wilkinson and Johnston, 1996; Lacroix et al., 2014). Veins contain a mineralogical record of the fluids that pass through the fault system during fault activity and are common features observed in many geological settings. They are abundant in the crust in the brittle domain under many metamorphic conditions and are often associated with ore deposits (e.g. Diamond, 1990; Goldstein et al., 2005; Yardley and Cleverley, 2015; Fagereng et al., 2018). While vein mineralogy and geochemistry, as well as fluid inclusion compositions, provide valuable information on fluid pressure, temperature, composition and origin during vein growth (e.g. Henderson and McCaig, 1996; Lacroix et al., 2011), vein geometry and mineral textures enable documentation of the stress condition and orientations of the stress field in which they formed (e.g. Lacombe, 2001; Cox, 2010; Bons et al., 2012). One of the most common vein types, mode I veins, requires specific conditions to open: (1) a low differential stress (with $\sigma_1 - \sigma_3 < 4T_0$) and (2) high fluid pressure (where σ_1 and σ_3 are the maximum and minimum stresses, respectively, and T_0 is the tensile strength) (Secor, 1965; Etheridge, 1983). Many studies have suggested that such veins tend to record only a single fluid-flow event in which the fluids are generally derived locally (e.g. Oliver and Bons, 2001; Elburg et al., 2002; Lacroix et al., 2011). Barker et al. (2006) and Cox (2007), however, suggest that mode I veins may record a more complex fluid-flow history that can be unraveled by geochemical investigation at a micron scale. With the recent development of *in-situ* ana-

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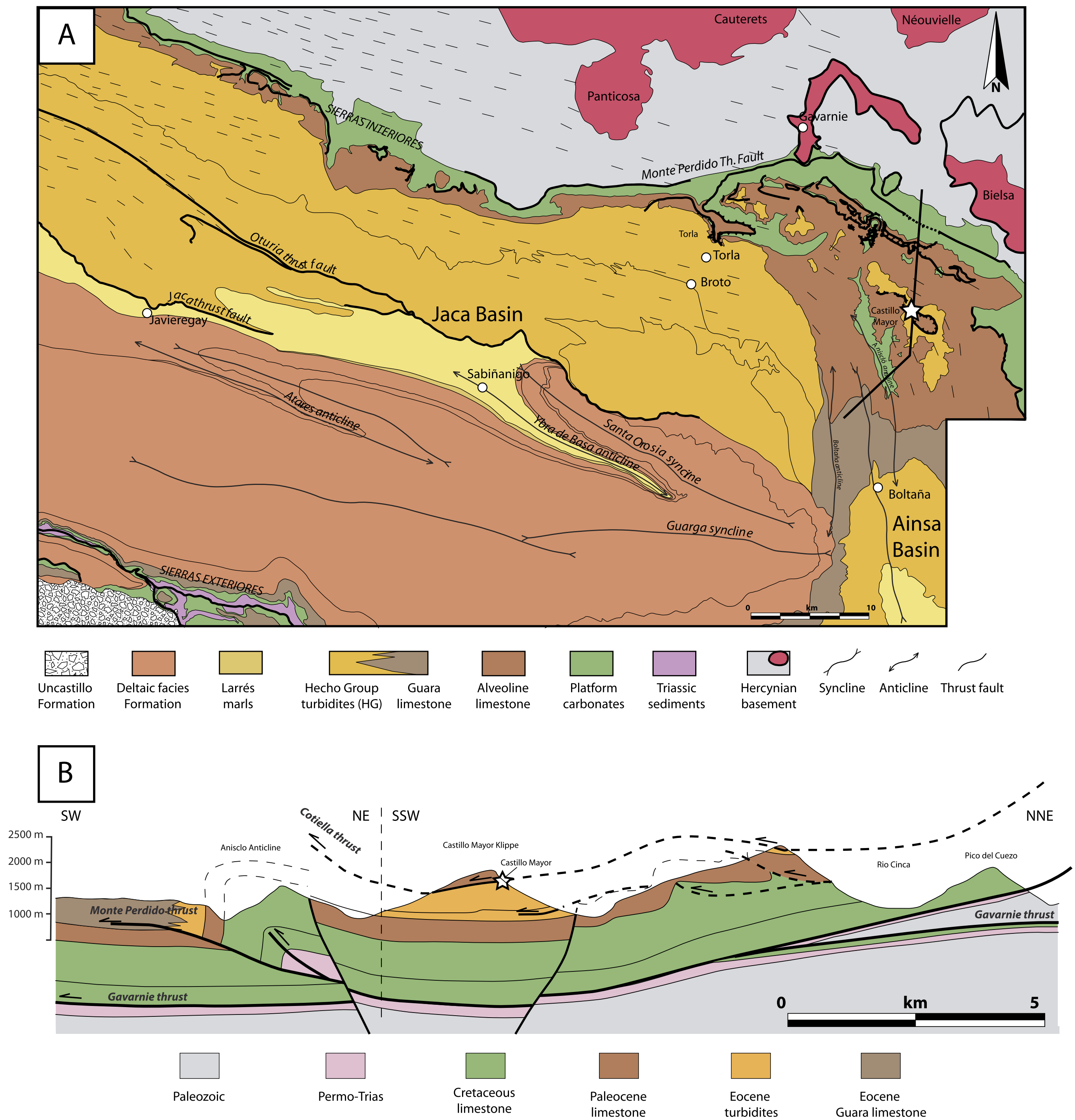

Fig. 1. Detailed geological map (A) and cross section (B) of the study area. Geological map was compiled from geological maps published by IGME (Instituto Geológico y Minero de España) and BRGM (Bureau des recherches géologiques et minières). White star: Castilló Mayor outcrop studied here. Modified from Lacroix et al. (2014). Black line in A; cross section in B.

lytical techniques, e.g. Secondary Ion Mass Spectrometer (SIMS), the fluid–rock interaction can be documented at fine spatial scale, resolving more of the detail of the fluid history during vein formation (e.g. Peterson and Mavrogenes, 2014).

Here we present a detailed stable isotope investigation of the Cotiella thrust fault (Pyrenees) in which we combine *in-situ* micron-scale oxygen isotope analysis with fluid inclusion and Δ_{47} clumped isotope thermometry on specific calcite vein fillings in order to document multi fluid-flow during fault activity. We show that variations in calcite oxygen isotope composition and fluid temperature document the change in the fluid sources and fault burial levels during vein growth. Finally, the implications of these data for the nature of the paleohydrological system that existed during fault activity are discussed.

2. Geological setting and fault zone structures

The study area is located in the Jaca–Ainsa fold-and-thrust belt of the South-Pyrenean Zone, a south-vergent thrust-fold system that overthrusts the Ebro foreland basin along the South-Pyrenean