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Incursion of meteoric waters into the ductile regime in an active orogen

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ABSTRACT

Rapid tectonic uplift on the Alpine Fault, New Zealand, elevates topography, regional geothermal gradients, and the depth to the brittle ductile transition, and drives fluid flow that influences deformation and mineralisation within the orogen. Oxygen and hydrogen stable isotopes, fluid inclusion and Fourier Transform Infrared (FT-IR) analyses of quartz from veins which formed at a wide range of depths, temperatures and deformation regimes identify fluid sources and the depth of penetration of meteoric waters. Most veins formed under brittle conditions and with isotope signatures ($\delta^{18}O_{H_2O} = -9.0$ to $+8.7‰_{VSMOW}$ and $\delta D = -73$ to $-45‰_{VSMOW}$) indicative of progressively rock-equilibrated meteoric waters. Two generations of quartz veins that post-date mylonitic foliation but endured further ductile deformation, and hence formation below the brittle to ductile transition zone (>6–8 km depth), preserve included hydrothermal fluids with δD values between −84 and −52‰, indicating formation from meteoric waters. FT-IR analyses of these veins show no evidence of structural hydrogen release, precluding this as a source of low δD values. In contrast, the oxygen isotopic signal of these fluids has almost completely equilibrated with host rocks ($\delta^{18}O_{H_2O} = +2.3$ to $+8.7‰$). These data show that meteoric waters dominate the fluid phase in the rocks, and there is no stable isotopic requirement for the presence of metamorphic fluids during the precipitation of ductilely deformed quartz veins. This requires the penetration during orogenesis of meteoric waters into and possibly below the brittle to ductile transition zone.

1. Introduction

Fluids play a key role in orogenesis through the transport of heat and mass (Bickle and McKenzie, 1987), by changing the rheological behaviour of rocks and localising deformation (Wintsch et al., 1995), and concentrating valuable mineral resources (Weatherley and Henley, 2013). The impact of fluids on mountain building depends on fluid sources, flow paths and temperatures, and extent of fluid–rock interaction at different crustal levels (Yardley, 2009).

Orogenic fluids originate from a variety of sources. During metamorphism fluids are generated by prograde metamorphic devolatilisation reactions and by the release of water during the crystallisation of partial melts (Norris and Henley, 1976; Walther and Orville, 1982; Yardley, 2009, 1997). In some orogenic belts mantle derived fluids (Kennedy and van Soest, 2007) or fluids liberated from igneous intrusions (Burrows et al., 1986; Reynolds and Lister, 1987) play key roles and have been inferred as carriers of gold in Archean shear zones (Groves, 1993). The high relief of collisional mountain belts provides strong driving forces for the deep penetration of meteoric fluids (Barker et al., 2000; Chamberlain et al., 1995; Koons and Craw, 1991) and the brittle upper crust is expected to be saturated with surface-derived waters. However, the relative contributions of different fluid sources remains poorly quantified. In particular, whether meteoric fluids can penetrate beyond the brittle regime into ductilely deforming rocks remains controversial and conceptually challenging (e.g. Connolly and Podladchikov, 2004). Oxygen and hydrogen isotope measurements of minerals and veins from ancient crustal shear zones have been presented as evidence for penetration of meteoric fluids to depths of 5 to 18 km

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(Barker et al., 2000; Clark et al., 2006; Fricke et al., 1992; McCaig et al., 1990; Raimondo et al., 2011). However, low δ^{18}O and δD signatures resulting from near surface alteration prior to burial can be retained in some orogens (Raimondo et al., 2013). Assuming water–rock isotopic equilibrium the high proportion of oxygen in both water and rocks means that "rock dominated" fluid signatures are developed at relatively low water–rock ratios, as expected within or below the brittle to ductile transition zone (BDTZ) where large permeability and porosity and high fluid fluxes are problematic (e.g. Connolly and Podladchikov, 2004 and Fusseis et al., 2009). This means that evolved meteoric fluids have oxygen isotopic signatures that are indistinguishable from metamorphic fluids. Although fractionation equations between hydrous minerals and water are poorly calibrated (Graham et al., 1987), because hydrogen is relatively more abundant in water than in rocks, it provides a more enduring tracer of fluid origins. As such meteoric waters will only attain hydrogen isotopic signatures similar to metamorphic rocks at very low water–rock ratios ($w/r = 0.001$).

To investigate the depth of penetration of meteoric waters we have examined the Southern Alps of New Zealand, an active orogen where uplift rates and depths of formation of hydrothermal veins are well constrained and there is no evidence of syn-orogenic magmatic activity. This study uses oxygen and hydrogen stable isotope analyses of quartz, chlorite and adularia vein minerals to examine fluid flow from near surface to the middle crust. Our study focuses on measurements of δD in fluid inclusions from ductilely deformed veins, providing direct measurements of fluids that formed veins down to the ductile regime.

1.1. *Geological setting*

Oblique convergence of 39.7 ± 0.7 mm/yr (DeMets et al., 2010) between the Pacific and Australian plates through South Island, New Zealand (Fig. 1a) has caused crustal thickening and this, influenced by orographic rainfall and high erosion rates, has built the >3000 m high Southern Alps. Through the South Island the plate boundary is marked by the Alpine Fault which has recorded ~470 km of dextral strike slip motion since the Miocene (Cox and Sutherland, 2007; Sutherland, 1999). Rapid uplift of up to 10 mm/yr (Norris and Cooper, 2007) has exhumed lower crustal rocks in the hangingwall adjacent to the Alpine Fault. Uplift rates decrease towards the south east, where rocks from progressively shallower crustal depths crop out exposing a ~25 km crustal section (Cox and Barrell, 2007). The hangingwall of the Alpine Fault is composed of quartzofeldspathic metasediments and minor metavolcanic units of the Alpine Schists, with the highest metamorphic grade schists (garnet–oligoclase zone amphibolite facies) exhumed adjacent to the Alpine Fault (Cox and Barrell, 2007). These rocks are thrust over Cambrian to Early Ordovician Greenland Group metasediments and Devonian to Carboniferous and Cretaceous intrusives of the Australian Plate (Cox and Barrell, 2007).

The study area encompasses the highest uplift region where geothermal gradients are elevated due to rapid uplift and high rates of erosion (Koons, 1989). The depth of the BDTZ is estimated based on geothermal gradients and the base of the seismogenic crust. A geothermal gradient of $62.6 \pm 2.1\,^{\circ}$C/km was measured in a ~150 m borehole adjacent to the Alpine Fault (Sutherland et al., 2012), which is similar to an estimate of ~75 °C/km based on fluid inclusion studies (Craw, 1997). These geothermal gradients indicate that the 300 °C isotherm, which corresponds to the approximate onset of brittle–ductile deformation in quartzofeldspathic rocks (Stockhert et al., 1999), is at ~5 km depth. The true depth may be greater than this estimate as the geothermal gradient may decrease with depth in the crust (Koons, 1987). Regionally few earthquakes occur below 10–12 km depth in the Southern Alps and in the highest uplift region the base of seismogenesis is 3–4 km shallower (Leitner et al., 2001). Taken together, this evidence suggests that the BDTZ is 6–8 km deep in the study area (Fig. 1c).

Highly altered, cataclastic brittle fault rocks crop out directly adjacent to the Alpine Fault, but ~25 to 50 m structurally above these, mylonitic schists showing little near-surface alteration occur for ~1000 m. Both brittle and ductile fault rocks show evidence of fluid–rock exchange and mineral precipitation during deformation. Fluid–rock interaction under ductile conditions is preserved by synkinematic ductilely deformed quartz veins (Toy et al., 2010). Fault rocks deformed in a brittle manner are highly altered and retrogressed to green, clay-rich cataclasite (Warr and Cox, 2001). The presence of ductilely deformed veins, brittle veins, and hydrothermal mineral alteration assemblages suggest that fluids are present in the fault zone from below the BDTZ (>6–8 km) to the surface.

Warm springs emanate from 1 to 20 km south east of the Alpine Fault. Stable isotope signatures of these springs (Barnes et al., 1978; Reyes et al., 2010) and veins (Horton et al., 2003; Jenkin et al., 1994) in the Southern Alps have identified that meteoric waters are the dominant fluid in the upper ~2 km of the crust. At >2 km depth in the brittle crust of the Inboard zone (Fig. 1b) fluid inclusion and stable isotope studies of vein minerals indicate hydrothermal fluids were of relatively low salinity (~2–5 wt.% NaCl equivalent, Craw, 1988), had partially rock-equilibrated meteoric δ^{18}O values ($\delta^{18}O_{H_2O} = -0.7$ to 8.5‰, Horton et al., 2003; Jenkin et al., 1994; Koons et al., 1998), and δD values also indicative of a meteoric origin ($\delta D_{H_2O} = -29$ to −68‰, Jenkin et al., 1994). In samples from the Main Divide zone (Fig. 1b), fluid inclusions are more saline (up to 18 wt.%, Craw, 1988) and oxygen isotope data indicates that waters circulating at more than ~2 km depth (Craw et al., 1987) are in oxygen isotopic equilibrium with host rocks ($\delta^{18}O_{H_2O} > 5$‰, Craw, 1988; Koons et al., 1998). These fluids may therefore be deeply circulating rock-buffered meteoric waters or expelled mid-crustal metamorphic fluids (Craw, 1988; Craw et al., 1987; Horton et al., 2003; Koons et al., 1998; Templeton et al., 1998). δD values of vein generations that formed under ductile conditions have not been measured previously.

1.2. *Sample descriptions*

Vein samples representative of mineral precipitation over a range of conditions into the ductile regime (>6–8 km depth) were taken from the Inboard and Main Divide zones of the Southern Alps (Figs. 1a and b and Table 1). The deepest formed veins display evidence of folding or deformation-induced recrystallisation of vein minerals (Toy et al., 2010). Two types of ductilely deformed veins from the Alpine Fault zone (AFZ) were analysed:

Foliation Parallel and Foliation Boundinage veins: (Types (i) and (iii), Toy et al., 2010). Additionally one sample of a Foliation Parallel vein from Chancellor Dome, ~8 km south east of the Alpine Fault (Wightman et al., 2006), was analysed. Veins are composed of quartz ± calcite ± chlorite, but these minerals may not be in textural equilibrium. Veins cross cut mylonitic foliation (see Fig. 7, Toy et al., 2010) and are further ductilely deformed, as shown by quartz and calcite grain microstructures which are indicative of ductile deformation (see Fig. S1 in the Supplementary Materials). Foliation Parallel veins are 0.5 to 2 cm wide and are more strongly deformed at higher temperatures and record fluid flow at deeper crustal levels than the 0.5 to 4 cm wide Foliation Boudinage veins. All other veins sampled were formed within the brittle crust (at depths of <6 km).

FZ Fissure veins: (Type (iv), Toy et al., 2010). These veins occur only in the Alpine Fault zone. They cross cut the mylonitic foliation and show evidence for limited ductile deformation indicating