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Fluid pressure variations recorded by quartz vein geochemistry

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Veins that form contemporaneously with deformation are the best recorders of the fluids circulating in the depths of orogenic and subduction zones. We have analyzed syn-kinematic quartz veins from accretionary prisms (Shimanto Belt in Japan, Kodiak accretionary Complex in Alaska) and tectonic nappes in collisional orogens (Flysch à Helminthoïdes in the Alps, southern nappes of the variscan Montagne Noire), which formed at temperature conditions between 250 and 350°C, i.e. spanning the downdip limit of large subduction earthquakes and the generation of slow slip events. In all geological domains, veins hosted in rocks that have experienced the lower temperature conditions (~250-300°C) show quartz grains with crystallographic facets and growth rims. Cathodoluminescence (CL) imaging of these growth rims shows two different colors, a short-lived blue color and a brown one, attesting to cyclic variations in precipitation conditions. In contrast, veins hosted in rocks that have experienced the higher temperature conditions (~350°C), show a homogeneous, CL-brown colored quartz, except for some very restricted domains of crack-seal structures of CL-blue quartz found in Japan, Kodiak and Montagne Noire.

Based on laser ablation analysis and electron microprobe mapping, variations in CL colors appear correlated with the trace element content of quartz. The highly luminescent quartz contains high concentrations of aluminum (Al) and lithium (Li), up to 3000 and 400 ppm, respectively. Variations in Al and Li correlate well, so that Li appears as the main charge□compensating cation for SiàAl substitution.

Due to their ubiquitous presence in various settings, the variations in CL colors in the lower temperature range reflect a common, general process. We interpret these cyclic growth structures as a result of deformation/fracturing events, which triggered transient changes in fluid pressure. The CL-blue growth rims delineate zones where quartz growth was rapid and crystals incorporated a large proportion of Al and Li. Crystal growth continued at lower pace after fluid pressure evolved to equilibrium conditions, leading to the formation of CL-brown quartz with fewer substitutions of tetrahedral Si. The variations in fluid pressure fluctuated at values close to lithostatic conditions, as indicated by growth in cavities that remained open.

The crack-seal microstructures have been interpreted as the result of slow-slip events near the base of the seismogenic zone (Fisher and Brantley, 2014; Ujiie et al., 2018). Our observations on quartz composition suggest that the quartz in crack-seal microstructures records episodic variation in fluid pressure, similar to vein quartz at T<~300 °C. In contrast to the cooler and shallower domain, the variations are significantly smaller, as recorded by the very limited extent of the CL-blue domains, and most if not all of the quartz growth occurred under constant physico-chemical conditions, including a near lithostatic fluid pressure.

We conclude that quartz trace element content might be a useful tool to track variations in fluid conditions. In particular, at seismogenic depths (i.e. near 250°C), fluid pressure varies significantly around a lithostatic value. In contrast, deeper, near the base of the seismogenic zone where slow slip events occur (i.e. near 350°C), the variations in fluid pressure are smaller.