Record by quartz veins of earthquakes and slow slip events

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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 prism in Alaska) and tectonic nappes in collisional orogens (Flysch à Helminthoides in the Alps, the southern domain 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 with 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 with 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 and electron microprobe mapping, the variations in CL colors appear correlated with the trace element content of quartz, the short-lived CL-blue being associated with the substitution of Si\textsuperscript{4+} by Al\textsuperscript{3+}+Li\textsuperscript{+}/H\textsuperscript{+}.

Due to their ubiquitous presence in various settings, the variations in CL colors in the lower T range reflect a common, general process. We interpret these cyclic growth structures as a reflection of deformation/fracturing events, which triggered transient changes in (1) the fluid pressure through fluid flow and (2) the chemistry of the fluid due to enhanced reactivity of the fractured material. 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 a lower pace after fluid pressure and composition evolved to equilibrium conditions, leading to the formation of CL-brown quartz with few 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 and composition, similar to vein quartz at $T < \sim 300 \, ^\circ \text{C}$. 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 is a useful tool to track variations in fluid conditions. In particular, at seismogenic depths (i.e. near 250$^\circ$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$^\circ$C), the variations in fluid pressure conditions are smaller.