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Fluid inclusion hardening: Nanoscale evidence from naturally deformed pyrite

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The interaction of trace elements, fluids and crystal defects plays a vital role in a crystalline material's response to an applied stress. For example, dislocations can be arrested by the strain field of immobile defects (i.e., particles or precipitates) or by the accumulation of mobile solutes in their cores, which can lead to strain hardening. The rheology of minerals is also strongly influenced by interactions with fluids, which are typically known to facilitate ductile deformation in geomaterials (i.e., hydrolytic weakening, dissolution creep). Investigation of these nanometer scale processes however, requires a correlative approach combining high-spatial resolution analytical techniques. In recent years, increasing developments in microscopy and microanalysis have allowed for the compositional measurements and spatial imaging of materials at the near-atomic scale. Herein, we have combined electron backscatter diffraction (EBSD) mapping, electron channeling contrast imaging (ECCI), scanning transmission electron microscopy (STEM) and atom probe tomography (APT) on a naturally deformed polycrystalline pyrite aggregate from the Abitibi Subprovince in Canada to investigate the role of fluid inclusions on mineral rheology. The combined EBSD and ECCI data reveal minor crystal misorientation and low-angle grain boundary development in the vicinity and at the tip of microfractures indicating a dominantly brittle regime with minor strain accommodation via crystal-plasticity where dislocations are mostly emitted by the propagating fracture. These interpretations are consistent with the peak temperature conditions of the sample estimated at $302 \pm 27^\circ\text{C}$, which falls within the lower range of the brittle to crystal-plastic behaviour of pyrite (260–450°C). Nanoscale structural and chemical data reveal nanoscale fluid inclusions enriched in As, O, Na and K that are linked by As-enriched dislocations. Based on these results, we propose a model of fluid hardening whereby dislocations get pinned at fluid inclusions during crystal-plastic deformation, initiating pipe diffusion of trace elements from the fluid inclusions into dislocations that leads to their stabilization and local hardening. Although additional experiments are required on other mineral phases, our initial efforts advance the understanding of the interplay between nanostructures and impurities and its impact on the rheology of geomaterials during relatively low temperature deformation.