The role of fluids on strain localization at seismogenic depth: a case study from brittle-ductile faults from Olkiluoto Island, SW Finland

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Fluids play a key role in weakening rocks, controlling crustal deformation from early fracture development to mature strain localization, fault nucleation and propagation through cumulative slip. In particular, at the brittle-ductile transition zone crustal deformation and fluid flow are mutually interconnected by repeating cycles of transient frictional and viscous deformation. Uncertainties remain, however, on the details of the micromechanical and chemical influence of fluids in facilitating strain localization processes.

N-S to NW-SE sub-vertical brittle-ductile faults cut across the Paleoproterozoic migmatitic basement of southwestern Finland on the island of Olkiluoto, where the Finnish authorities plan the construction of a deep repository for high-grade nuclear waste. The faults are characterized by a brittle–ductile to fully brittle deformation style resulting from transient fluid pressurization. We investigated a representative fault by combining field and microstructural observations with fluid inclusion and mineral chemistry analysis on synkinematic and authigenic minerals in order to reconstruct the temporal variations of pressure, temperature, composition and salinity of the synkinematic fluids that controlled strain localization. Combined laser ablation inductively coupled plasma time-of-flight mass spectrometry (LA-ICP-TOFMS) and electron back-scattered diffraction analysis (EBSD) were also applied on authigenic sulphides to gain insights into their role upon strain accommodation and deformation-induced elemental transport and distribution at the microscopic scale.

Initial embrittlement of the Olkiluoto basement occurred under a first event of fluid overpressure conditions (> 210 MPa) with formation of a diffuse network of joints and/or hybrid–shear fractures in a volume that corresponds to the fault damage zone. Subsequent deformation was caused by repeated hydrofracturing induced by fluid pressure up to 210 MPa. Brittle ruptures affected a system that was otherwise under overall ductile conditions, as demonstrated by mutually overprinting veining, cataclasite and plastic deformation.

Later exhumation and cooling of the fault system to fully brittle conditions was aided by reactivation triggered by a distinct fluid ingress at lower pressure (140-180 MPa) and temperature
(≤ 300° C). Deformation was accommodated at that stage by the interplay of brittle fracturing and low-temperature crystal-plastic in sulphides. Strain and fluid flow created high diffusivity pathways within the pyrite crystal lattices contributing to- and enhancing the net transport of a significant range of heavy elements (e.g. Co, Ni, Cu, Sn, Ag, As, Sb, Pb). These data indicate that the studied fault zone acted as a chemically open system and fault valve.