The role of fluids on strain localization at the base of the seismogenic crust: a case study from the Olkiluoto deep nuclear waste repository, southwestern Finland.

Fluids play a key role in weakening rocks, controlling crustal deformation from fault nucleation to mature strain localization and cumulative slip. Fluid flow coupled with deformation also controls the mobility of elements through rock formations which is extremely relevant to understand mineralization and, as in the present study, integrity of geological resevoirs or repositories.

This study is focused on the detailed investigation of fault zones intersecting the first high-grade nuclear waste repository in the world: the Finnish national deep repository in Olkiluoto (SW Finland). In particular, this thesis investigated how fluid flow triggered the initial embrittlement of the basement and subsequently controlled cycles of frictional and viscous reactivation that are typical at structural levels corresponding to the brittle-ductile transition of the continental crust. The comprehension of the processes of chemical evolution that guide elemental mobility during fault-channelled fluid flow and during crystal-plastic deformation were also addressed.

I investigated a representative fault in the Olkiluoto repository 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 during the late stage of brittle deformation. Raman spectra of graphite associated with the host rock were also acquired to estimate the temperature of last ductile deformation registered by the basement before embrittlement.

Initial, fluid-mediated embrittlement of the Olkiluoto basement occurred at the expense of the rock system that was under overall ductile conditions ($< 530 \pm 50$ °C). Initial embrittlement was

induced by a pulse of hydrothermal fluid (T > 350 °C) at high pressure (> 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 fault reactivations occurred by repeated injections of fluids in overpressure (up to 210 MPa), inducing brittle fracturing mutually overprinted with crystal-plastic deformation. Prolonged reactivation led to continued strain/slip localization forming a narrow fault core.

Later exhumation and cooling of the fault system to fully brittle conditions was aided by reactivations triggered by fluid batches at lower pressure (140-180 MPa) and temperature (≤ 300 °C). Deformation was accommodated at this stage by the interplay of brittle fracturing and low-temperature crystal-plasticity in sulphides. Strain and fluid flow created high diffusivity pathways within the sulphide aggregates enhanced the transport and redistribution of a significant range of heavy elements (e.g. Co, Ni, Cu, Sn, Ag, As, Sb, Pb). The study of the distribution of these elements could be used as a proxy for the mobility of radioactive elements potentially leaking out from the nuclear waste repository through pre-existing faults, which can be reactivated during the lifespan of the facility.

This study shows that fluid overpressure at the brittle-ductile transition, and in general at elevated temperatures plays a key role in the initial embrittlement of the deforming rock and steers subsequent strain localization. Under overall brittle conditions (T < 300 °C), temperature combined with fluid-rock interactions induced by repeating ingress of multiple fluid batches are the key factors steering strain localization and inducing elemental mobility in fluid rich fault systems.