

EGU21-15655

<https://doi.org/10.5194/egusphere-egu21-15655>

EGU General Assembly 2021

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Periodic Fluid-mediated Weakening and Cementation Drives Cyclic Reorganisation of Shallow Basaltic Fault Zones

Bob Bamberg, Richard Walker, and Marc Reichow

School of Geography, Geology and the Environment, University of Leicester, LE1 7RH, Leicester, United Kingdom
(bb224@le.ac.uk)

Faults constitute the major source for mechanical and permeability heterogeneity in basaltic sequences, yet their architecture, and mechanical and physical properties remain poorly understood. These are however critical as basaltic reservoirs are becoming increasingly important for geothermal applications and CO₂ storage. Here we present a detailed microstructural- to outcrop-scale characterisation of mature (decametre-hectometre displacement) fault zones in layered basalts, in the Faroe Islands. Outcrop scale structures and fault rock distribution within the fault zone were mapped in the field to build 3D virtual outcrop models, with detailed characterisation of fault rock microstructure and petrology obtained from optical and SE-microscopy.

The fault zones exhibit evidence for cyclic activity controlled by fault internal fluid pressure variation. Deformation mechanisms in the core alternate between shear-compaction, evidenced by foliated cataclasite and gouge development, and dilatation through fluid overpressure, leading to hydrofracture and vein formation. Generally, a decametre-wide damage zone of Riedel faults is centrally transected by the fault core. The fault core is organised around a principal slip surface (PSS) hosted in a decimetre-wide principal slip zone (PSZ). The PSS and PSZ are dominantly composed of (ultra-) cataclasites, while the remaining core comprises anastomosing cataclastic bands bounding lenticular zones of various brecciated fault rocks. Further, PSS-proximal zones show significant late-stage dilatation by hydrothermal breccias or tabular veins with up to decimetre apertures, filled with early syntaxial to blocky zeolite and/or late coarse (≤ 1 cm) blocky calcite. The structures in the fault core are mutually overprinting, evidencing pulsed fault activity and PSS migration. The native plagioclase-pyroxene assemblage of the host rock is almost completely altered to zeolites and red-brown smectites in the fault core and along surrounding damage of mature faults, while lower displacement faults preserve the host rock mineralogy even in gouge. We infer that fluid flow along initial damage promotes alteration and the associated chemical weakening localises strain into a narrow PSZ. Here, fault activity is governed by alternating deformation styles – shear-compaction and dilatation – suggesting changes in deformation mechanism linked to transient permeability decrease within the PSZ, followed by fluid overpressure and hydrofracture. Overall rock mechanical properties are thus governed by the combined effects of permanent chemical weakening and transient fluid-mediated mechanical weakening, alternating with cementation and healing, and will be explored by direct shear

deformation experiments in the future.