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The evolution of hydraulic properties during brittle faulting of a sandstone in laboratory experiments: Modelling the developing heterogeneity by multilayer diffusion

Benedikt Ahrens (1,2) and Jörg Renner (1)

(1) Institute for Geology, Mineralogy and Geophysics, Ruhr-Universität Bochum, 44801 Bochum, Germany (benedikt.ahrens@rub.de), (2) Now at: International Geothermal Centre, Bochum University of Applied Sciences, 44801 Bochum, Germany

The structure and the associated hydraulic properties of fault zones are of fundamental importance for many geological processes in the brittle crust, may they be naturally (e.g. groundwater flow) or anthropogenically (e.g. exploitation of geothermal energy reservoirs) induced. Commonly, fault zones constitute a heterogeneity consisting of rocks deformed to various degrees by a range of mechanisms occurring spatially localized and systematically orientated in unfaulted host rock. Fault zones may thus be addressed as anisotropic, heterogeneous lithologies. Previous laboratory experiments focused on determining the bulk or effective hydraulic properties of either experimentally faulted rock samples or samples retrieved from different sections of natural fault zones. Oscillatory hydraulic tests permit to continuously constrain hydraulic properties during deformation, but they rely on analytical solutions of the differential equation for one-dimensional harmonic pressure diffusion through isotropic and homogeneous media and thus do not allow for a separation of hydraulic elements composing a heterogeneous medium. We developed analytical solutions for one-dimensional harmonic diffusion through a stack of up to three layers with different hydraulic properties that can be used for the oscillatory pore-pressure method and the pore-flow method. Our multilayer diffusion model permits to explore the diagnostic potential of oscillation characteristics for evolving fault zones and to spatially resolve their hydraulic properties. The approach was tested on observations for samples of Wilkeson sandstone triaxially compressed at effective confining pressures leading to macroscopic failure modes from dilative brittle faulting to compactive cataclastic flow. The derived hydraulic properties of the developing structural heterogeneities indicate that the localized slip zone dominates transport in fault zones. The network of microcracks surrounding the slip zone, that is, damage zone, constitutes the major contributor to the specific storage capacity and hydraulic diffusivity of the entire fault zone. The results demonstrate that the increased hydraulic diffusivity of damage zones likely compensate the pore-fluid overpressure within the low-diffusivity sections of fluid-bearing fault zones and thereby stabilize in situ faulting.