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Permeability evolution of normal faults with clay smear: insights from structural observations in water saturated sandbox models and numerical simulations

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Fault processes are complex phenomena that defy reliable prediction. Clay smear in particular is difficult to predict for sub-surface flow applications and would benefit from an improved understanding of controlling processes. In this study, we present a series of water-saturated sandbox experiments producing large clay smear surfaces up to $\sim$500 cm^2. In these experiments, we couple across-fault flow measurements with structural analysis of post-mortem excavated clay smear surfaces. To develop a tool for evaluating the evolving fault structure during formation, we compare measured flow data to simplified numerical flow simulations. Results show diagnostic relationships between the observed fault structures and measured cross-fault flow.

In experiments with one or two clay layers and a cumulative thickness of 10 mm and 100 mm displacement, we observe that normally consolidated clay, in a structural domain of graben faulting, initially yields in hybrid brittle/ductile failure. Characteristic for this type of failure is an early breaching of the clay layer by brittle fracturing causing increased cross-fault flow. However, the type of failure varies laterally and shear failure occurs as well. We observed that holes preferably form beneath extensional parts of the footwall cutoff. These can be identified in map-view as the fault curves towards the hanging wall. During the evolution of the fault, this is typically followed by fault back-stepping, formation of clay smears and reworking of clay fragments in the fault. These processes lead to slower increases of cross-fault flux. Holes that formed during the early breaching of the clay layer mostly remain open during the evolution of a fault, although there is some evidence for occasional resealing of holes.

Fault zones are segmented by fault lenses, breached relays and clay smears in which sand and clay mix by deformation. Experiments with two clay layers show that holes rarely form at the same position on the fault planes. This produces a layered sand-clay fault rock with greater tortuosity and therefore lower overall permeability than in one-layer experiments. We compare our results with observations of faults in nature and discuss progress towards models with sufficient detail and understanding to allow prediction of flow across evolving faults, first in laboratory models and then in the subsurface.