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Constraints on structural evolution from correlations between hydraulic properties and P-wave velocities during brittle faulting of rocks

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One of the key challenges in geophysics concerns the derivation of structure and state of rocks and rock formations from constraints on the spatial distribution of their physical properties, as gained from laboratory experiments, borehole logging, and surveys at the surface covering scales from centimeters to kilometers. The use of information from the propagation of elastic waves constitutes the most common approach to derive the structure and state of rocks, if direct information on in-situ properties is limited (e.g., through boreholes) or inaccessible. Furthermore, the determination of hydraulic rock properties serves the dual purpose of constraining structure and providing the basis for predictions of the behavior of a system of interest during continued fluid injection or production, as associated with, e.g., exploitation of hydrocarbon reservoirs, operation of subsurface liquid-waste repositories, or geothermal energy provision. In-situ, wave observations potentially provide better coverage of rock volumes (in space and time) than hydraulic investigations and thus constraints on correlations between elastic and hydraulic properties bear the potential to improve subsurface characterization.

In our laboratory study, we continuously monitored hydraulic properties and elastic wave velocities of porous Wilkeson sandstone samples during conventional triaxial deformation. Confining pressures applied in the tests cover the range from below to above the critical pressure for crack closure to control the state of pre-existing cracks. Hydraulic properties were determined using the oscillatory pore-pressure method owing to its benefits regarding continuous and highly resolved monitoring of permeability and specific storage capacity during deformation and even imminent localized failure.

The magnitude of the deformation-associated variations in the monitored physical properties strongly depends on initial microstructure and degree of hydrostatically induced crack closure. Except during the development of a localized fault at the lowest imposed effective confining pressure, we found permeability and hydraulic diffusivity to increase during progressing brittle deformation associated with dilation. Thus, in-situ faulting of fluid-bearing rocks should in general exhibit self-stabilization. Contrary, diffusivity decreases during ongoing inelastic compaction by non-localized cataclastic flow at the highest explored effective pressure.

Hydraulic properties exhibit systematic correlations with inelastic radial strain, a rather expected result for permeability, but stress ratio and mean stress seem to control hydraulic properties before inelastic deformation begins. For permeability, radial strain, a likely surrogate for characteristics of cracks aligned with the flow direction, constitutes a reference unifying results up to about peak stress from experiments performed at different effective pressures. Such a relation with radial strain appears to hold even more uniformly for P-wave velocity throughout almost all of the deformation stages. The observed correlation between hydraulic diffusivity and P-wave velocity in the direction of fluid flow suggests that monitoring changes in elastic wave velocities bears the potential to constrain changes in conditions for transient fluid flow.