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Imaging crack and pore anisotropy in deformed rocks: Quantifying the crack fabric tensor

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Cracks and pores in crustal rocks are often fluid-saturated and subjected to stresses arising from both the overburden and regional tectonics. These stresses produce changes both in the shape and volume of the rock, and in the shape and volume of the voids i.e. the cracks and pores. Patterns of parallel fluid-filled cracks around major earthquake prone faults are more compliant to applied stresses compared to randomly oriented cracks and hence could produce a short-term (i.e. undrained) fluid pressure change along the fault equal to the fault normal stress, allowing the fault to slip in an earthquake [1]. Therefore, developing methodologies to quantify the orientation of pores and cracks and their mutual arrangement in deformed rocks is of primary importance to understand large active fault behaviour during earthquake cycles.

X-ray micro-CT analyses, using both intact and laboratory deformed samples, provide high-resolution (micrometre) volumetric scans from which we quantify pore and crack fabrics. Image processing provides adaptive methods to extract information from such datasets. In particular, we combine Hessian matrix filtering [2] and anisotropic wavelet analysis [3] to extract three-dimensional arrays of pores and cracks with different aspect ratios (i.e. pores and cracks) at different scales of analysis.

Observed changes in pore and crack fabrics between the intact and deformed samples allow us to characterise the multi-scale microstructural variations in anisotropy that form due to the applied stresses. In turn, the information gathered at the micro scale can be used to improve our understanding of the fundamental relationship between the theory of anisotropic poroelasticity and the measurable properties of fluid-saturated fault zones.

References:
[1] Wong, T.F., 2017. J. Geophys. Res; [2] Voorn M. et al., 2013. CaGeo; [3] Rizzo R. et al., 2018. J. Geophys. Res.

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Coulomb Failure Stress and triggered seismicity: The consequences of fault zone damage

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Predictive models for the stress triggering of earthquakes have been built on the concept of Coulomb Failure Stress (CFS). CFS is the change in proximity of a given ‘target’ fault to the Mohr-Coulomb shear failure criterion due to changes in stress induced by slip on a neighbouring ‘source’ fault. Stress triggering models, often based on Okada’s elastic dislocation solution for a fault in an isotropic elastic half-space, form the basis of many seismic hazard assessments, e.g. the Coulomb software package from the USGS.

A common assumption in CFS models of stress triggering is that of constant apparent friction. Apparent friction is a term used to combine frictional strength and effective stress contributions to the localised stress changes at the target fault. Beeler et al. (2000) and Cocco & Rice (2002) have both explored the underlying mechanics of apparent friction, and considered isotropic and anisotropic poroelastic effects in fault zones. We know that fault zones are inherently anisotropic in their physical properties, in part due to arrays of sub-parallel cracks and fractures in their damage zones (Faulkner et al., 2006; Mitchell & Faulkner, 2009). We can model the mechanical influence of these crack patterns using anisotropic poroelasticity (Sayers & Kachanov, 1995; Wong, 2017). For short-term effects, we can consider the target faults responding as ‘undrained’ poroelastic materials (constant fluid mass, varying pore fluid pressure), and for longer-term deformation we can use the ‘drained’ case (constant pore fluid pressure, varying fluid mass). We have built a new open source software tool called CFSape (Coulomb Failure Stress anisotropic poroelasticity), using MATLAB. The tool includes a GUI to collect source and target fault parameters, select among alternative poroelastic boundary conditions, and specify the required outputs.

Calculations using CFSape show that the possible consequences of ignoring anisotropic poroelasticity at the target faults are highly significant. Faults which appear stable (locked) under either of the typical assumptions of constant apparent friction or isotropic poroelasticity are predicted to fail when anisotropic poroelasticity is incorporated. The converse is also true: apparently ‘risky’ faults are predicted to be stable. The model predictions confirm the theoretical finding of Cocco & Rice (2002) that in the extreme case of perfectly fault-parallel cracks at the target fault, an assumption of constant apparent friction is generally valid. However, this begs the critical question: what is the correct or best value of the Skempton coefficient (isotropic case), or the Skempton tensor (anisotropic case), for these models? We urgently require more and better experimental data on the anisotropic poroelastic response of rocks, measured under likely crustal conditions of true triaxial stress. We need data for both the Skempton (undrained) and Biot (drained) tensors to apply better constraints for short- and long-term seismic hazard assessments due to stress triggering of earthquakes.

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Seismic envelopes at laboratory sample scale from rock physics measurements

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Fracture- and fluid-induced heterogeneities in rocks generate scattering sources that attenuate direct-wave seismic energy. This scattered energy is recorded later in seismograms and is measurable as coda envelopes, which hold information about fracture networks and fluid content in the rock. Seismic coda analysis has the potential to provide useful information about fracture systems and fluid-flow process, while coda imaging is currently a state-of-art technique in highly heterogeneous media.

These techniques have already been applied at field scale (10^1-10^3 m) to characterize lithospheric and volcanic settings; however, the connection between smaller scale rock physics (10^{-3}-10^{-1} m) and seismic scattering parameters is still unclear. In this study, we developed computational tools that use rock physics observations to model seismic envelopes at core plug scale (mm-cm) in the laboratory. We use field-dependent qualitative measurements of seismic heterogeneity, like fracturing, porosity and saturation, as inputs for constructing synthetic coda envelopes. The computational framework applied is radiative transfer theory (RTT), which allows us to compute envelopes that are comparable with experimental data.

The synthetic envelopes are computed using stochastic parameters and follow a Born approximation. We use as input an analysis of the statistical distribution of fractures previously estimated in a sandstone core plug, deformed with a confining pressure of 35 MPa and pore fluid pressure of 10 MPa. The results can be up-scaled to model seismic attenuation observations at field scale; the outcomes provide a novel and useful approach for quantifying fractures network and saturation directly from seismic coda analysis.