Geophysical Research Abstracts
Vol. 19, EGU2017-17515, 2017
EGU General Assembly 2017

Damage localisation and fracture propagation in granite: 4D synchrotron x-ray microtomographic observations from an in-situ triaxial deformation experiment at SOLEIL

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To date, most studies of damage localisation and failure have utilised indirect techniques to visualise the pathway to failure. The advent of synchrotron tomography and x-ray transparent experimental cells provides for the first time the opportunity to image localisation and fracture propagation *in-situ*, in real time with spatial resolutions of a few microns.

We present 4D x-ray microtomographic data collected during a triaxial deformation experiment carried out at the imaging beamline PSICHE at the French Synchrotron SOLEIL. The data document damage localisation and fracture propagation in a microgranite. The sample was deformed at 15 MPa confining pressure and 3x10^{-5} s^{-1} strain rate, in a novel, miniature, x-ray transparent, triaxial deformation apparatus, designed and built at the University of Edinburgh. We used a 2.97 mm diameter x 9.46 mm long cylindrical sample of Ailsa Craig microgranite, heat treated to 600 ˚C to introduce flaws in the form of pervasive crack damage. As the sample was loaded to failure, 21 microtomographic volumes were acquired in intervals of 5-20 MPa (decreasing as failure approached), including one scan at peak differential stress of 200 MPa (1.4 kN end load) and three post-failure scans. The scan at peak stress contained the incipient fault, and the sample failed immediately when loading continued afterwards. During scanning, a constant stress level was maintained. Individual datasets were collected in ∼10 minutes using a white beam with an energy maximum at 66 keV in a spiral configuration. Reconstructions yielded image stacks with a dimension of 1700x1700x4102 voxels with a voxel size of 2.7 μm.

We analysed damage localisation and fracture propagation in the time series data. Fractures were segmented from the image data using a Multiscale Hessian fracture filter [1] and analysed for their orientations, dimensions and spatial distributions and changes in these properties during loading. Local changes in volumetric and shear strains between time steps were quantified using 3D digital image correlation [2]. In combination, these analyses show the extent and evolution of local aseismic deformation and that related to microcracking. Our results provide direct evidence of ongoing deformation processes such as micro-fracture nucleation at pre-existing flaws, in the form of cracks, grain boundaries and pores, and coalescence of en-echelon tensile micro-fractures along a shear fault in response to changes in the local stress field. These direct 4D observations of damage evolution and strain localisation complement the seminal results of Lockner et al. [3], who first imaged the process of fault growth using acoustic emissions locations. Our data provide further insight into the aseismic mechanisms that dissipate 99% of the total accumulated strain energy [4] and the interactions between these mechanisms and the developing microcracks. Our results also provide experimental verification of models for shear fracture formation whereby pre-existing flaws become connected by en-echelon tensile cracks that extend from their edges.

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[2] Hall, S. et al., 2010, *Geotechnique 60*, 315-322.

[3] Lockner, D., et al., 1991, *Nature* 350, 39-42.

[4] Byerlee, J., 1993, *Geology* 21, 303-306.