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# 4D in-situ x-ray microtomography reveals that material heterogeneity influences microfracture network evolution in deforming rocks

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Catastrophic failure of rocks and engineering materials is a critically important phenomenon over a wide range of scales. It occurs when structural damage, consisting of fractures and faults, concentrates within localised zones. Failure eventually occurs along these zones, often suddenly and with devastating consequences. A great deal about how fractures nucleate, grow and coalesce is known from monitoring and locating acoustic waves emitted during fracture, combined with microstructural and field observations of damaged rocks. However, the precise mechanisms involved in localisation remain elusive. How do cracks, pores and grain boundaries interact locally under stress to cause failure at a specific place, orientation and time? Why can we detect precursors to failure only in some cases?

Heterogeneity is a strong control on failure forecasting; more heterogeneous materials exhibit precursors to failure, while more homogeneous materials do not (Vasseur et al., 2015). Here, we investigate the micro-mechanisms behind this observation: the influence of heterogeneity on the geometry and spatial distribution of evolving microfractures during rock deformation. Synchrotron microtomography makes this possible, allowing us to observe directly and in-situ the deforming microstructure at micron-scale resolution. We deformed two Ailsa Craig microgranite samples, known to be isotropic and almost entirely crack free. To control for heterogeneity, one sample was heat-treated to induce an isotropic crack network prior to deformation, increasing its microstructural heterogeneity, while one sample was left untreated. We test the hypothesis that the deformation-induced microcrack network in these two samples will evolve differently and that the heat-treated sample will show clear precursors to failure in this evolution, while the untreated sample will not.

We present the 4D deformation-induced microfracture evolution from tomographic volumes acquired in-situ during these two triaxial deformation experiments, conducted using our x-ray transparent apparatus at SOLEIL synchrotron. Spatially, the microfracture network evolves differently in each case. Fractures in both samples accumulate along localised zones as en-echelon tensile microfractures that subsequently coalesce, and become overall more elongate along strike and flatter down-dip as failure approaches. The heat-treated sample shows localisation along an initial but arrested shear zone followed by localisation along a second shear zone that propagates to failure. The untreated sample shows spalling; localised axial zones developing in a radial pattern, followed by sudden failure along an unrelated shear zone. Both samples exhibit power-laws in their microcrack volume and inter-crack distance distributions, and symmetry-breaking in the mean radius of gyration. Inter-crack length fractal dimension gives an earlier indication of spatial clustering than visual inspection and a precursory double minimum is seen in the microcrack volume scaling exponent. All these parameters clearly indicate the onset of localisation along the failure plane in the heat-treated sample, but not the untreated sample. Interestingly, a precursory double minimum in the microcrack volume scaling exponent is seen very close to failure in the untreated sample.

Thus, heterogeneity does influence microfracture network evolution, with precursors to failure detected reliably in all analysed parameters for the heterogeneous (heat-treated) sample, whereas clear precursors are generally not detected in the homogeneous (untreated) sample, except in one parameter.