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Sound and x-ray vision of a porous rock: micromechanics of shear failure under different loading protocols and implications for managing induced seismicity during subsurface operations

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Progress towards a net zero carbon economy involves subsurface activities, such as geothermal energy production and geological storage of carbon dioxide, hydrogen and radioactive waste, that disturb tectonic stresses in the Earth's crust. Seismicity induced by such stress perturbations is associated with risk from damage due to ground motion, fluid leakage and pollution due to increased permeability, and the potential loss of public confidence. Safe operation of these activities therefore requires effective management to minimise induced seismicity. Failure in brittle, porous materials initiates when structural damage, in the form of smaller-scale fractures, localises along an emergent failure plane or 'fault' in a transition from stable crack growth to dynamic rupture. Due to the extremely rapid nature of this critical transition, the precise micro-mechanisms involved are poorly understood and difficult to capture. However, these mechanisms are crucial drivers for earthquakes, including induced seismicity, and other devastating phenomena.

Here we observe these micro-mechanisms directly by controlling the rate of micro-seismic events to slow down the transition in a unique triaxial deformation apparatus that combines acoustic monitoring with contemporaneous in-situ x-ray imaging of the microstructure. We compare the seismic signatures from this experiment with those from a sister experiment carried out under constant strain rate loading. The results [1, 2] provide the first integrated picture of how damage and associated micro-seismic events emerge and evolve together during localisation and failure and allow us to directly constrain the partition between seismic and aseismic deformation at the micro-scale.

The evolving damage imaged in the 3D x-ray volumes and local strain fields undergoes a breakdown sequence involving several stages: (i) self-organised exploration of candidate shear zones close to peak stress, (ii) spontaneous tensile failure of individual grains due to point loading and pore-emanating fractures within an emergent and localised shear zone, validating many inferences from acoustic emissions monitoring, (iii) formation of a proto-cataclasite due to grain rotation and fragmentation, highlighting both the control of grain size on failure and the relative importance of aseismic mechanisms such as crack rotation in accommodating bulk shear deformation. Dilation and shear strain remain strongly correlated both spatially and temporally throughout sample weakening, confirming the existence of a cohesive zone, but with crack damage distributed throughout the shear zone rather than concentrated solely in a breakdown zone at the propagating front of a discontinuity.

Contrary to common assumption, we find seismic amplitude is not correlated with local imaged strain. The seismic strain partition coefficient is very low overall and locally highly variable. Local strain is therefore predominantly aseismic, explained in part by grain/crack rotation along the emergent shear zone. Reactive loading to maintain a constant micro-seismic event rate increases the seismic b-value, decreases the maximum event magnitude, and reduces the seismic strain partition coefficient compared with loading under a constant strain rate. Adding event rate control to that of maximum recorded magnitude may therefore be more effective than the current 'traffic light'system (based on maximum magnitude alone) for managing the risk of induced seismicity.

Participation

In-Person

References

[1] Cartwright-Taylor et al. (2022), Seismic events miss important kinematically governed grain scale mechanisms during shear failure of porous rock, Nature Communications 13, 6169. https://doi.org/10.1038/s41467-022-33855-z.

[2] Mangriotis et al. (in prep), Micromechanics of failure in a sandstone: loading controls on seismic signatures.

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