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Emergent permeability in dehydrating rocks is controlled by the stress state and orientation

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Fluid-rock interaction relies on the fluid's ability to migrate through rocks, utilising permeable pore space. While we understand permeability in rocks that interact with fluids to evolve dynamically, e.g. in dehydration or carbonation reactions, we have very little quantitative information on these dynamics, as direct measurements of permeability in reacting rocks are inherently difficult.

Here, we present a series of permeability measurements that capture the evolving fluid transport properties of dehydrating gypsum samples. To derive these measurements, we used an X-ray transparent deformation rig to document gypsum dehydration in 4-dimensional µCT datasets and then modelled the permeability evolution for a segmented sub-volume numerically. In doing so, we were able to characterise the grain-scale porosity and permeability evolution of a dehydration reaction for the first time. We present analyses from two experimental time-series run at a fixed confining pressure, temperature and pore fluid pressure (Pc = 20 MPa; T = ~125 C; Pf = 5 MPa) but contrasting stress states: one with the largest principal stress (Δσ = 16.1 MPa) parallel to the sample cylinder axis and another the largest principal stress (Δσ = 11.3 MPa) being radial. In both cases, as pore space formed due to the negative change in the solid molar volume during the reaction, permeability evolved and increased congruently with porosity in time until ultimately reaching average values of 3.14E-13 m² and 4.55E-13 m², respectively. A clear spatial heterogeneity of fluid flow develops at the grain-scale along with the fabrics in the samples. Importantly, the calculated permeability tensors are anisotropic from the onset, but develop over different spatiotemporal trajectories and have different preferred orientations in the two experimental geometries: If the anisotropy is expressed as 1-(min_eigenvalue/max_eigenvalue) of the permeability tensor (where isotropy = 0), then the experiment with the largest principal stress applied radially has a final anisotropy of 0.45, with fluid flow efficiently focussed into a vertical lineation. In the case with an axial largest principal stress, the final anisotropy of permeability is 0.30 with fluid flow being channelled along a foliation that developed orthogonally to σ1.

Our results suggest that the spatial and temporal developments of permeability during a dehydration reaction are controlled by the orientation and relative magnitudes of the principal stresses of a tectonic environment, and that these two parameters exert a strong control on the efficiency of drainage and thus reaction progress. This has consequences for our understanding of fluid movements in thrust tectonics and subduction zones, but also in applications such as the in-situ carbonation of ultramafic rocks.