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Dynamic flow localization in porous rocks under combined pressure and shear loading

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Flow localization occurs in deforming porous fluid saturated rocks. It exhibits itself as veins, pockmarks on the ocean floor or gas chimneys visible on seismic images from several chalk fields of the Central North Sea and from the Utsira formation at Sleipner in the Norwegian North Sea, which is one of the best documented CO_2 storage sites.

Porosity waves were repeatedly shown to be a viable mechanism of flow self-localization that does not require the pre-existence of a connected fracture network. Porosity waves result from an instability of the Darcy flow that occurs in porous rocks with time-dependent viscous or viscoelastoplastic rheology. Local fluid overpressure generated by fluid injection or chemical reactions aided by buoyancy force drives upward fluid migration. Viscous deformation delays pressure diffusion thus maintaining local overpressure for considerable periods of time. Development of an under-pressured region just below the over-pressured domain leads to separation of the fluid-filled high-porosity blob from the source and the background flow. The instability organizes the flow into separate vertical channels. Pressure distribution, shape and scaling of these channels are highly sensitive to the rheology of the porous rock.

In this contribution, based on a micromechanical approach, we consider the complex rheology of brittle, ductile and transitional regimes of deformation of porous rocks in the presence of combined pressure and shear loading. Accurate description of transitional brittle-ductile deformation is a challenging task due to a large number of microscopic processes involved. We use elastoplastic and viscoplastic analytical solutions for the non-hydrostatic deformation of a singular cavity in the representative volume element in order to deduce expected behavior of the porous rock. The model provides micro-mechanisms for various failure modes (localized and homogeneous) and dilatancy onset. In particular, the model predicts that dilatancy (decompaction) might occur under compressive effective mean stress if shear stresses are present. We study propagation of porosity waves in rocks with such rheology and show that overpressures on the order of 70% of the lithostatic stress can be sufficient to generate channeled flow. Thus, porosity waves can be competitive mechanism to fracture generation in explaining flow localization, especially, in the ductile or brittle-ductile environment.