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Multiphysics of transient deformation processes leading to macroscopic instabilities in geomaterials

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Material instabilities are critical phenomena which can occur in geomaterials at high stress and temperature conditions. They generally result in the degradation of the microstructure organisation, ultimately leading to material failure. These phenomena are relevant to a large variety of geoscientific and geotechnical applications including earthquake physics, fault mechanics, successful targeting of unconventional georesources and mitigation of induced seismicity. Quantifying and predicting the onset of material degradation upon instability remains a major challenge due to our lack of understanding of the physics controlling the behaviour of porous rocks subject to high temperature and pressure conditions.

In the laboratory, rocks gradually transition from a time-independent brittle behaviour to a transient semi-brittle, semi-ductile behaviour upon an increase in pressure and/or temperature. Furthermore, even when subject to constant subcritical stress conditions rocks have been observed to macroscopically fail due to growth of subcritical processes such as stress corrosion. Brittle creep is a phenomenon observed on a variety of rock types (volcanic and sedimentary) and shows a high sensitivity to temperature and stress conditions. In the field, such subcritical transient processes are difficult to detect and can jeopardise the safety of geothermal projects. Transient failure mechanisms in the reservoir have set back geotechnical projects through induced seismicity occurring days or even weeks after stimulation shut in as observed at the Basel geothermal site in Switzerland or at the Pohang geothermal project in South Korea. These observations demonstrate how conventional techniques fail at describing the physics responsible for fault reactivation, which is controlled by dynamic processes resulting from transient multiphysics coupling.

In this contribution, we detail the theory and procedure to develop a constitutive model for rate-dependent damage poro-elasto-plastic material behaviour suitable for porous rocks. To allow for a generic framework for assessing geomaterials instabilities, this model incorporates the potential for microstructure degradation and a path- and rate-dependence. To that purpose, we rely on thermodynamic principles to derive in the frame of the hyperplasticity theory a coupled hydro-mechanical rate-dependent plasticity and damage rheology. We present numerical examples of this new constitutive model at the laboratory scale using experimental data on brittle creep in

sandstones and discuss the implications upon upscaling at the reservoir and lithosphere scale.