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The role of porosity at the brittle-ductile transition: from laboratory experiments to lithospheric scale models

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Targeting deep unconventional geothermal reservoirs at or nearby the brittle-to-ductile boundary has become recently the subject of several experimental and modelling studies. In this context, understanding the non-linear dynamics controlling the brittle-to-ductile transition at depth under different tectonothermal conditions and their modifications by operational activities is crucial not only to assess the strength and long-term behaviour of the lithosphere, but also to characterize emplacement conditions and the evolution in space and time of geothermal resources. Published results from laboratory studies, have clarified how porosity evolution in time and space exerts a critical control on the different deformation modes (from diffusive to localization), dynamically buffering the transition from one mode to the other. However, few numerical models have succeeded to account for such porosity feedbacks on the deformation of porous rocks.
In this study, we present a new modelling framework together with its implementation in the numerical simulator LYNX (Lithosphere dYnamic Numerical toolboX) which relies on implicit multiphysics coupling of the physics describing the deformation modes as they occur in the rigid portion of lithosphere plates including thermal, mechanical and hydraulic feedback processes. In particular we address, as based on a new theoretical understanding of the role that porosity and its evolution through time within porous rock compartments, the long-term dynamic responses of geological systems to external forcing of diverse nature (from natural, tectonic driven to anthropogenic ones). The LYNX simulator in its core compartments relies on the Multiphysics Object-Oriented Simulation Environment (MOOSE), which provides a powerful and flexible platform to solve for multiphysics problems implicitly and in a tightly coupled manner on unstructured meshes, thus providing an efficient computational base to tackle the non-linear, multiphysics problem at hands.
In a first part, we present a thermodynamically consistent physical framework describing deformation of porous rocks accounting for coupled thermal, hydraulic and damage visco-plastic rheology together with key aspects of its numerical implementation. In a second part, we present two applications to illustrate the robustness and novelty of the physical framework. In particular, we address (1) how the modelling framework consistently integrate observations at the laboratory scale as derived on tri-axial experiments. These experiments nicely illustrate the influence of porosity and pressure on the transition between brittle and ductile deformation modes and therefore provide useful to text both the theoretical and numerical framework. (2) Insights into how permeable structures can be generated and evolve in time and space under varying external forces, and under which poro-thermo-mechanical conditions such structures can be maintained over human up to geological time scales.