More is different: On the emergence of collective phenomena in fractured geological media

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Fractures such as joints and faults are widely present in crustal rocks. These discontinuity structures often form complex networks and dominate the bulk behaviour of geological media. Thus, understanding how fracture networks affect multiphysical processes and phenomena in subsurface rock formations is highly relevant to many geoenergy and geoengineering applications. However, the large-scale behaviour of fractured rocks consisting of many fractures cannot be derived by simple applications of the knowledge of single fractures, due to the hierarchy of scales, heterogeneities, and physical mechanisms as well as the possible emergence of qualitatively different macroscopic properties. In other words, macroscopic phenomena in fractured media arise from the many-body effects of numerous interacting fractures, such that the emergent properties at the fracture network scale are much richer and often surprising compared to the behaviour of each individual fracture. So, more is different!

To study this problem, I have developed a novel physics-based discrete fracture network modelling framework to simulate seismo-thermo-hydro-mechanical-chemical processes in fractured rocks. This modelling approach faithfully honours the discontinuous nature of geological media via explicit representations of fracture populations in rock and numerically computes multiphysics processes by solving the governing equations of fundamental mechanics. No \textit{a priori} assumption about the representative elementary volume is needed, rendering this approach as an appropriate tool to study hierarchical crustal rocks that may have no characteristic length scale. Using this modelling paradigm, diverse macroscopic phenomena are spontaneously captured as emergent properties physically arising from the collective behaviour of a large population of existing/growing fractures in rock.

In this presentation, I will illustrate the richness of collective phenomena in fractured media and elucidate the underlying multiscale, multiphysical mechanisms that drive their emergence. I will also show some application examples of using this fractured media simulation framework to address subsurface engineering problems such as underground excavation, injection-induced seismicity, and nuclear waste disposal. The modelling framework established and research findings obtained have important implications for safe and sustainable development of geoenergy and geoengineering.