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Editorial

Geomechanics and Fluid Flow in Geothermal Systems

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1. Motivation and Background

Geothermal systems, including hydrothermal systems [1], enhanced geothermal systems (EGS) [2], and superhot or supercritical systems [3–5], are receiving an increasing interest because they provide carbon-free energy that is necessary to shift the current dependency on fossil fuels and thus significantly reduce CO_2 emissions to the atmosphere [6]. Geothermal energy can potentially provide continuous energy output without daily or seasonal fluctuations—a strong advantage when compared to other renewable sources—and negative emissions if CO_2 is used as the working fluid [7–9]. However, the deployment of geothermal systems is being hindered by insufficient permeability of the reservoir rock [10], excessive induced seismicity during reservoir stimulation [11], and geochemical reactions accelerated by high temperature that lead to corrosion and scaling [12].

To overcome these challenges, interdisciplinary approaches that investigate relevant processes occurring during geothermal energy exploitation are necessary. The focus of this special issue is on geomechanical aspects of geothermal systems, including coupled processes occurring in multiphase systems, experimental characterization of rock and inelastic deformation that may induce seismicity, and geochemistry of geothermal systems. This special issue compiles the most recent advances in geothermal energy and combines the complex interactions between geomechanics, fluid flow, and geochemical reactions.

2. Contents of the Special Issue

2.1. Coupled Geomechanical and Fluid Flow Processes. Suitable sites for exploitation of geothermal resources require high temperatures, large amounts of fluid, and suitable permeability. A. A. Les Landes et al. use a 3D model that includes relevant geological features (e.g., faults) and solves coupled fluid flow and geomechanical equations. The authors study the Upper Rhine Graben—300 km long Cenozoic rifting system in Germany—and obtain a good agreement between the numerically predicted favorable areas for geothermal production and the thermal anomalies measured in the field.

Formations with thermal anomalies do not always present systems with enough permeability to circulate fluids for geothermal production. In such cases, permeability enhancement has to be achieved through stimulation leading to EGS. EGS development requires large fractures in order to provide sufficient areas for heat exchange, and employing proppant to keep the fracture open is unlikely to succeed because of the difficulties involving solid transport over long distances. As an alternative approach, R. Jung et al. investigate the possibility of keeping fractures open due to a self-propping effect. They study a large fracture in the Bunter formation in the Northern German Basin, finding that it would not be advisable to employ proppant for large hydraulic fractures in EGS development for crystalline nor sedimentary rocks, and permeability enhancement is better achieved through the shear-enhanced self-propping effect. The authors have estimated that for a formation temperature of 150°C, a flow rate of 5 l/s, and a pressure difference of 5 MPa, the extracted thermal energy would be around 2 MW from a single wellbore and single fracture configuration—enough to fulfill the heating demands of a medium-sized building complex.

Productivity of EGS is strictly connected to the pressure and temperature difference between the injection and production wells and their evolution throughout the lifetime of the system. The injection-induced thermo-hydro-mechanical couplings often require numerical methods to solve the nonlinear system of equations describing the evolution of the fractured rock. In this line, B. Figueiredo et al. study the effect of such couplings on the productivity of an EGS doublet connected by several fractures. The authors model the fracture permeability changes as a function of the acting effective normal stress and find that thermal effects dominate the pressure response compared to hydro-mechanical couplings. The study provides useful insights for the development of EGS and, in particular, underlines the importance of couplings in numerical predictions.

B. Figueiredo et al. show the importance of considering hydrothermal effects in terms of the fluid equation of state. The role of the fluid behavior is investigated in further detail by A. Parmigiani et al., who perform numerical analyses of phase separation in subsurface flow and its effect in terms of mass and energy transport. The authors employ pore-scale lattice-Boltzmann parallelized simulations to describe the growth and coalescence of droplets under constant hydraulic gradient conditions. This work provides an important piece of evidence of clogging (seen as flow resistance) in geothermal systems caused by phase separation and shows that its main controls are the velocity distribution, the fluid composition, and the pore space geometry.

T. Nohara et al. utilize electron probe microanalysis of granitic rocks to evaluate traces of hydrothermal fluid activity, where the track of supercritical fluid flow was microfracture filling with hornblende and plagioclase. A relationship between the distributions of fractures related to supercritical fluid flow and those of heterogeneous permeability is considered based on the analysis of the cores and existing in situ permeability test data. The authors find that the enhancement of permeability by four orders of magnitude is activated by supercritical fluid flow through granite.

Injection-induced deformation occurring at depth becomes perceivable on the surface. E. Békési et al. use Differential Interferometric Synthetic Aperture Radar (DInSAR) observations to measure ground deformation due to fluid extraction at the Los Humeros Geothermal Field (Puebla, Mexico). The pressure distribution and reservoir compartmentalization are identified to optimize the production of the field. The subsidence in the reservoir is studied and indicates that the geothermal field is controlled by sealing faults separating the reservoir into several blocks. The analytical model relating surface movements with volume changes suggests that the pressure within the reservoir is well supported and that the reservoir is recharging.

2.2. Induced Seismicity. Induced seismicity has become an issue of paramount importance in geothermal systems because the occurrence of perceivable induced earthquakes has led to the cancellation of several geothermal projects (e.g., Basel, Sankt Gallen, and Pohang [13]). In November 2017, 2 months after the stop of injection, the project at Pohang, South Korea, has induced the largest earthquake ($M_W = 5.5$) related to EGS that has occurred to date. R. Westaway and N. M. Burnside propose a potential triggering mechanism of the Pohang earthquake. Their hypothesis is based on fault weakening due to geochemical reactions occurring in the fault that nucleated the earthquake when interacting with the injected surface water. The proposed triggering mechanism requires that the fault was already critically stressed, which was likely the case according to Ellsworth et al. [14].

Continuing with process understanding of induced seismicity, X. Wei et al. aim to gain understanding on injection-induced fault stability changes to avoid risky faults in site selection. They numerically investigate different scenarios and find that low-permeable faults that intersect a small portion of the reservoir thickness are preferable in front of low-permeable faults intersecting most of the reservoir to limit the pressure buildup caused by the flow barrier. The authors conclude that the smaller the portion of low-permeable faults intersecting the reservoir, the smaller the magnitude of induced seismicity.

2.3. Geochemical Reactions. Geochemical reactions in geothermal systems are important because reaction rates increase with temperature. J. Feng et al. study the generation and composition evolution of the geofluids contained in a fractured carbonate reservoir through geochemical numerical modeling. Simulation results show an initial calcite dissolution followed by precipitation once the pore water becomes saturated in calcite. Fracture filling is more pronounced in shallow (colder) fractures and in subhorizontal fractures. These findings can be useful for identifying the most conductive fractures in carbonate rocks.

Because of the low permeability of granitoids, the geothermal water flow is strongly controlled by fault structures. H. Gan et al. study the chemical compounds and elements of both thermal and cold underground waters of the Northwestern Zhangzhou Basin in China to assess the relationship between thermal springs and cold water through cluster analysis and hydrochemical analysis of several hot springs (thermal wells) and cold springs (wells). The reservoir temperature corresponding to the geothermal water is calculated through the geochemical data, and it is found that the underground thermal convection in the Basin is controlled by the main faults at the depth of 3.5-5.5 km.

Conflicts of Interest

The guest editors declare that they have no conflicts of interest or private agreements with companies.

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