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Effects of Rock Mechanical Behaviors and Silica Precipitations on the Permeability Development in High-Temperature Granitic Rock Bodies: Numerical Studies

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ABSTRACT

Recent laboratory experiments suggest that, at very high-temperature conditions, the permeability of a granitic rock can significantly be affected by rock mechanical behaviors and geochemical reactions, namely the brittle-ductile transition, the elastic-plastic transition, and silica precipitations. A better understanding of spatial and temporal permeability development in high-temperature granitic rocks is desired for the exploration of supercritical geothermal resources in the continental crust. In this study, we numerically investigated effects of those mechanisms on the permeability development in the high-temperature granitic rock bodies. The simulations were conducted with the multiphase flow simulator HYDROTHERM which we extended to include the new stress-dependent permeability models and silica reactive transport modeling. Current results indicate that the mechanical behaviors may play a dominant role in the permeability development and subsequently control the formation of supercritical geothermal resources in granitic rocks.

1. INTRODUCTION

Permeability in high-temperature rock bodies is of great interest in understanding and exploring supercritical geothermal resources (Scott et al. 2015, Reinsch et al. 2017, Watanabe et al. 2017). Based on numerical studies, Scott et al. (2015) suggest that the extent and temperature of the supercritical resources may largely depend on geological conditions as temperature dependency on permeability varies with rock types, namely granitic rocks or basaltic rocks. The study assumed permeability decreases drastically at the brittle-ductile transition (BDT) as suggested in Fournier (1991) and Hayba & Ingebritsen (1997). Muraoka et al. (1998) also discussed that the BDT might control the boundary between the shallower convective zone and the deeper conduction zone observed at a depth of around 3 km in Kakkonda WD-1a wellbore, Japan.

Recent laboratory studies provide further insights into the permeability of the granitic crust at very high-temperature conditions above the critical temperature of water. Watanabe et al. (2017) showed that the permeability behavior of fractured granite is characterized by a transition from a weakly stress-dependent and reversible behavior (elastic) to a strongly stress-dependent and irreversible behavior (plastic) at a specific effective stress. The transition stress is mainly determined by temperature. Based on these findings, the authors suggested that potentially exploitable supercritical geothermal resources may exist at temperatures from 375^{o}C to approximately 460^{o}C at depths of approximately 2-6 km. Saishu et al. (2014) argued that silica precipitation might play an important role in the formation of the permeable-impermeable boundary at PT conditions near the critical point of water. Fournier (1991) showed that quartz solubility drastically changes near the critical point and it could result in the formation of a silica sealing layer at high-temperature environments. Saishu et al. (2014, 2015) showed that such drastic changes of the solubility can easily lead to supersaturated solutions and invoke rapid precipitation of silica via nucleation. Effects of those mechanisms on spatial and temporal developments of crustal permeability at high-temperature environments have not been investigated yet.

In this study, we conduct numerical experiments to investigate effects of the rock elastic-plastic transition (EPT) and the silica precipitation on the permeability development near a heat source in granitic rocks. For this purpose, we extended the non-isothermal multiphase flow simulator HYDROTHERM (Kipp et al., 2008). The extension includes the new permeability model based on the EPT behavior, silica reactive transport calculations, and permeability changes due to quartz dissolution and overgrowth precipitation. The precipitation process via nucleation has not been considered yet. Current results imply that the mechanical behavior may play a dominant role in the early development of permeability structure near a heat source and subsequently control the formation of supercritical geothermal resources in granitic rocks.

2. SIMULATOR

Here we provide a brief description of the extensions we made in HYDROTHERM. HYDROTHERM is a multiphase groundwater flow simulator which can also handle phase transition and support the temperature range of 0 to 1200 ^{o}C (Kipp et al., 2008). Further details of the simulator can be found in extensive literature (e.g. Kipp et al. 2008, Weis et al. 2014). To understand the dynamics of water-quartz interactions and its impact on permeability development, we extended HYDROTHERM to enable simulating reactive silica transport including quartz dissolution and precipitation. For the kinetic reaction of water-quartz interaction, we use Manning (1994) for the quartz solubility, and Rimstidt & Barnes (1980) for the dissolution rate constant.

We implemented several new permeability models in the simulator. The first one is the elastic-plastic transition (EPT) permeability model based on Watanabe et al. (2017). The laboratory experiments show weak-reversible and strong-irreversible permeability changes of fractured granite depending on the effective stress and the deformation behavior (i.e. elastic or plastic). The deformation behavior is determined by the effective stress and temperature. For the sake of simplicity, we assume that the total stress is invariant, i.e. the effective stress varies only due to pore pressure changes. Furthermore, we assume that permeability changes by the elastic deformation is negligible compared to the plastic deformation effect. Another permeability model is the quartz dissolution-precipitation permeability model. To consider the permeability changes due to the quartz dissolution and precipitation, we first solve the silica reactive transport equation and calculate the porosity changes from the volume removal or creation of the mineral. Finally, the empirical porosity-permeability relationship of fractured granite reported in Watanabe et al. (2017) is used to obtain the new permeability.

3. NUMERICAL EXPERIMENT SETUP

We carried out numerical experiments to investigate effects of the mechanical and geochemical behaviors on the permeability development near a heat source in the granitic crust. The experiment is conducted in a 2D vertical space including 20 km horizontal length and 5 km depth. The heat source is located at a depth of 5km (right below the domain bottom) with a horizontal length of 4 km and has a fixed temperature of 1000 ^{o}C. As shown in Figure 1, the simulation considers only a horizontally half-space of the entire domain because the problem is symmetric. We set initial permeability of 5E-16 m^2 as a base case. Porosity is set to 1%. The volumetric fraction of quartz is set to 20 %. Other granite properties are given from literature.

The initial temperature distribution is given with the geothermal gradient of 30 ^{o}C/km. Initial pore pressure follows hydrostatic. We assume water and quartz are initially in equilibrium. As boundary conditions, pressure and temperature at the ground surface are fixed to the atmospheric pressure and 15 ^{o}C. No flux conditions are applied to other boundaries except for some part of the bottom boundary where the diffusional heat exchange with the heat source occurs. A numerical mesh is prepared with uniform gridding of 50 m cell length. Time step lengths are automatically adapted in HYDROTHERM.

We also replaced the linear solver module with Lis (Library of Iterative Solvers for linear systems) (Nishida, 2010) which supports various kinds of preconditioning and solution algorithms and works as multi-thread computations.

4. RESULTS

4.1. Simulations with the Elastic-Plastic-Transition Permeability Model

Simulation results after 100 kyears with the elastic-plastic-transition permeability model are shown in Figure 2. Rocks in the vicinity of the heat source were rapidly heated and their temperature easily exceeded the elastic-plastic transition temperature. This resulted in the formation of very low permeable zones near the heat source. A convective system evolved above the low permeable zone and stabilized after around 60k years under the conditions of this study.

As it can be seen from a vertical profile at x=200m in Figure 3, the permeable-low permeable boundary was formed at around 3.5km depth. The depth also corresponds to the elastic-plastic boundary. Additional simulations with different initial permeability revealed that the boundary depth varies with initial crustal permeability (see Figure 3). Higher permeability tends to deepen the boundary depth probably because it leads to faster convective process, i.e. a stronger cooling effect. We also found that the permeable-low permeable boundary also corresponds to the convection-conduction boundary in these cases.

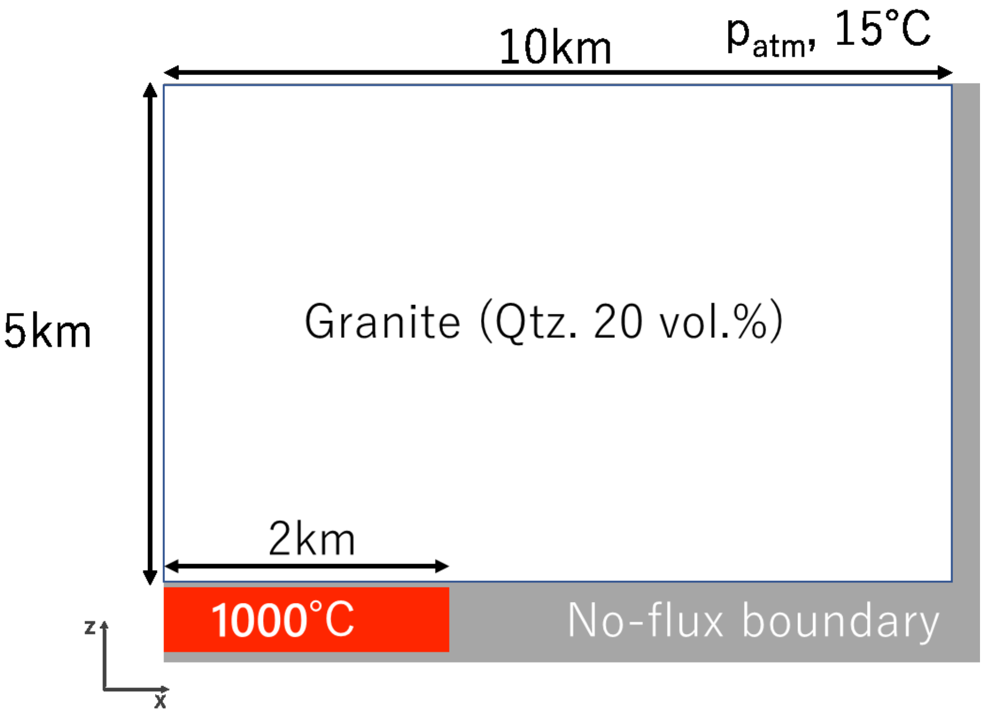

Figure 1: 2D vertical model used in the numerical experiments. Please note that the model shows only a half-space of the entire domain considered in this study. The initial temperature distribution is given with the geothermal gradient of 30 oC/km. Initial pore pressure follows hydrostatic. Silica is initially in equilibrium. Pressure and temperature at the ground surface are fixed to the atmospheric pressure and 15 ^{o}C. No flux conditions are applied to other boundaries except for some part of the bottom boundary where the diffusional heat exchange with the heat source takes places.

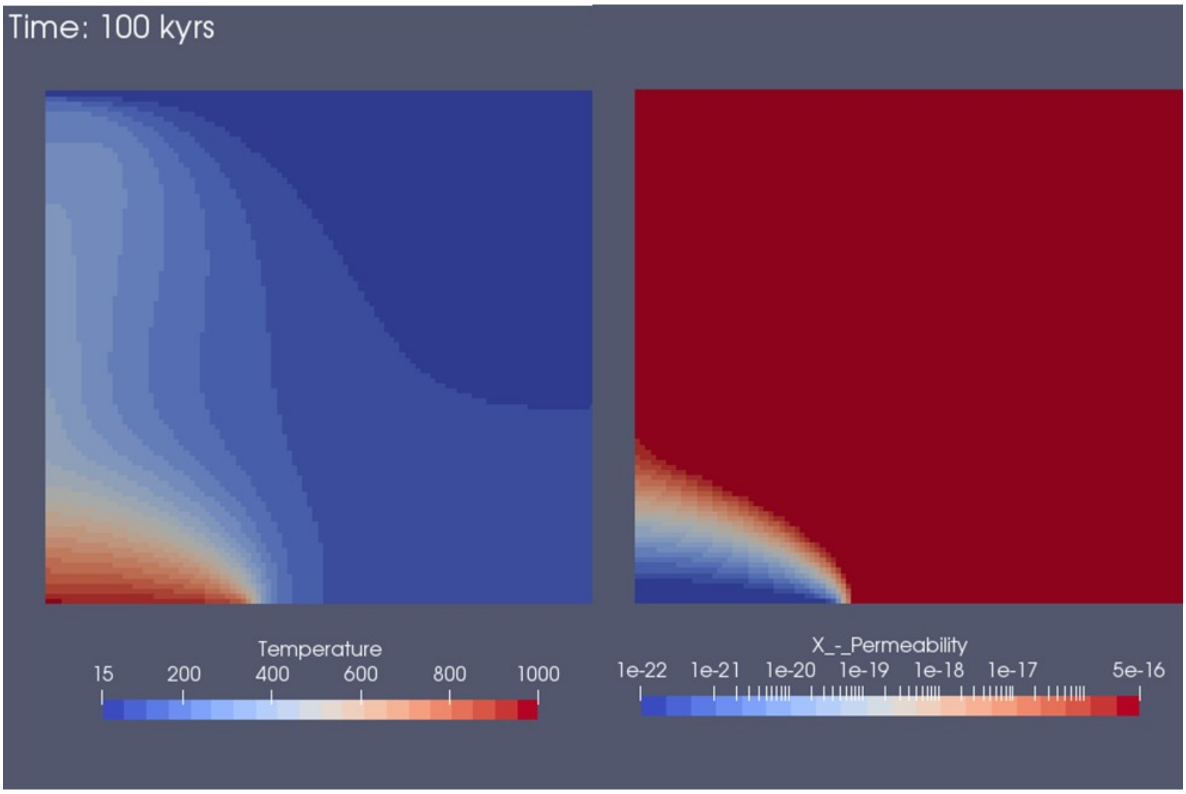

Figure 2: Simulation results after 100 kyears using the elastic-plastic-transition permeability model. The left figure shows temperature distribution and the right figure shows permeability distribution.

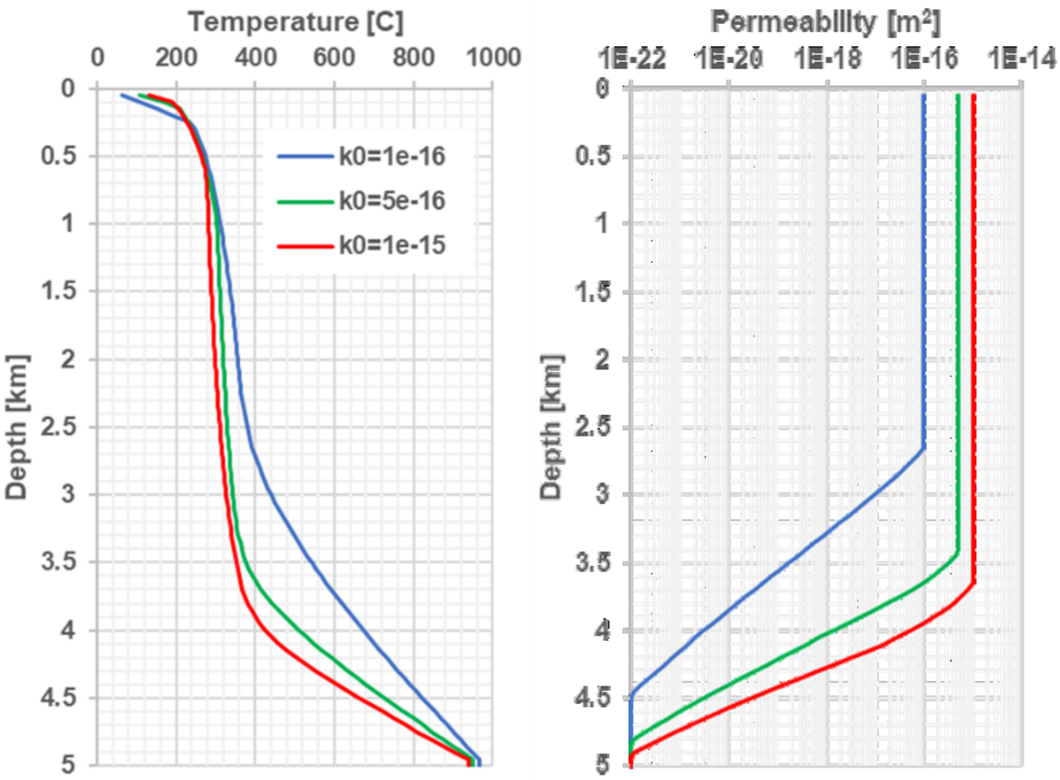

Figure 3: Vertical profiles of temperature and permeability after 10k years at x=200m (200m away from the left boundary). Results with different initial permeability values are plotted.

4.2. Simulations with the Quartz Reaction Permeability Model

Figure 4 shows simulation results after 100 kyears with the quartz dissolution-precipitation permeability model. It should be noted that the mechanical behavior was not considered in this setup. Compared to the previous cases, a convective system evolved in a more complex way at the begging of the simulation but stabilized earlier (around 30k years). Once the convective system got stabilized, a silica sealing layer (permeability ≤ 1E-17 m^2) started forming along the solubility ridge. As shown in Figure 5, the thickness of the sealing layer after 200 k years became almost 400 m and will increase further with time. The convection-conduction boundary is also found in this simulation at a depth of the sealing layer. Interestingly, even after the boundary was formed, the conduction zone still kept the initial permeability, whereas the conduction zone formed in the previous cases has low permeablility. The result indicates that the convection-conduction boundary should be low permeable but it does not necessarily mean that a conduction zone below the boundary is always low permeable.

Figure 6 shows how the initial permeability affects the formation time of a silica sealing layer via surface overgrowth precipitation. As one can expect, a higher permeability leads to a shorter formation time of the sealing layer. The formation time is 40 kyears with the initial permeability of 5E-16 m^2. It decreases to ca 30 kyears with the permeability of 1E-15 m^2. The result indicates that, at usual crustal conditions, it takes at least several thousand years for the formation of a silica sealing layer if the precipitation is mainly via surface overgrowth. Since the rock mechanical response is much faster than the silica overgrowth-precipitation, it implies that the mechanical behaviors might play a dominant role in the development of permeability structure near a heat source and subsequently control the development of supercritical geothermal resources. The effect of the silica overgrowth precipitation could continue for a long-term but have a limited impact on the location and extent of the resource.

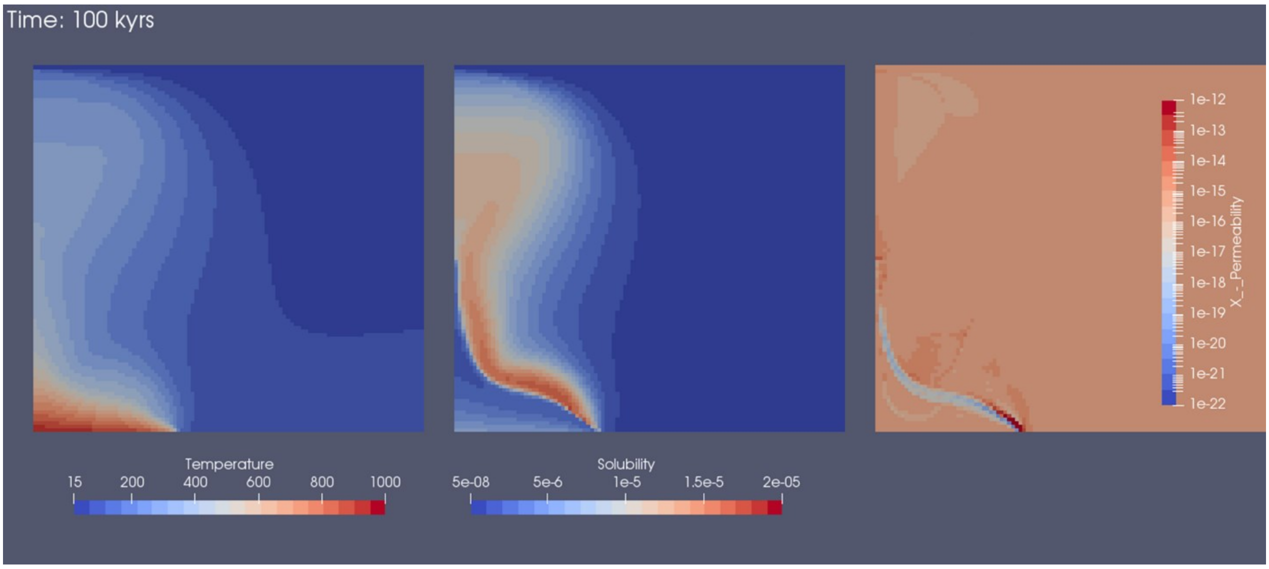

Figure 4: Simulation results after 100 kyears with consideration of permeability changes due to quartz dissolution and precipitation. The left figure shows temperature distribution, the middle figure shows quartz solubility distribution, and the right figure shows permeability distribution.

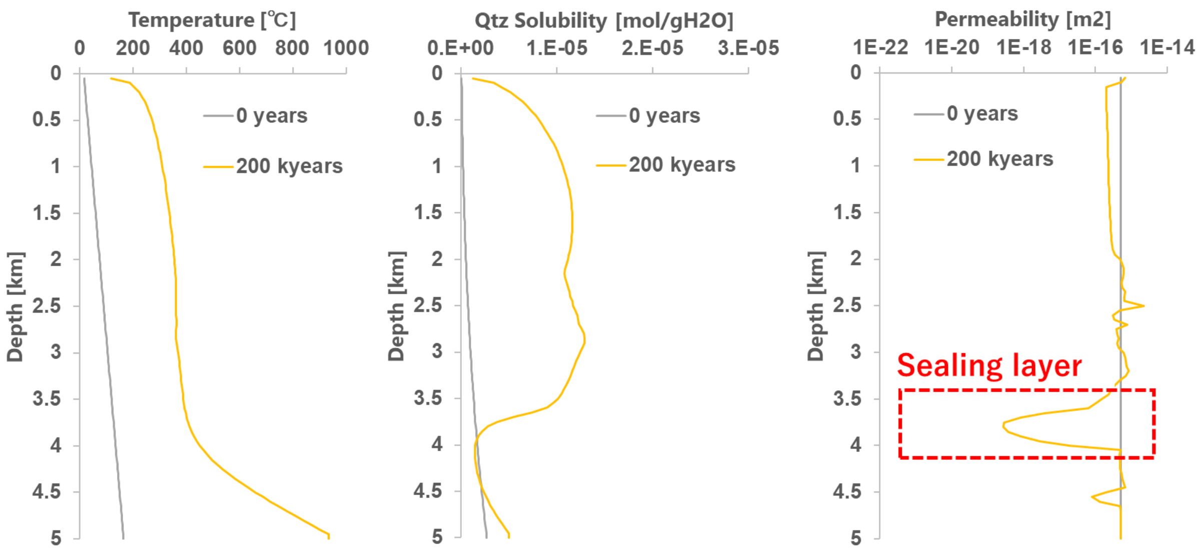

Figure 5: Vertical profiles of temperature, quartz solubility, and permeability after 20k years at x=200m (200m away from the left boundary).

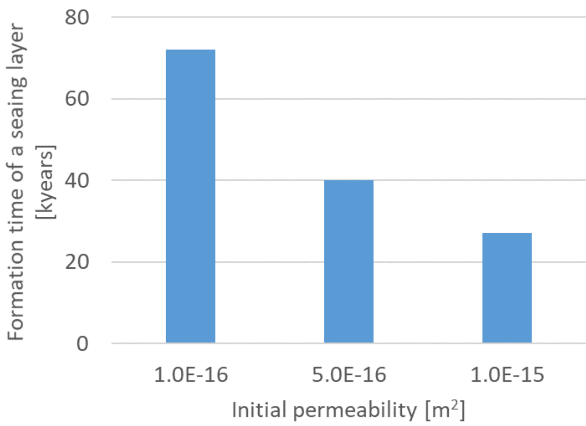

Figure 6: Formation times of a silica sealing layer (k≤1E-17 m²) with different initial permeability. Note that we consider quartz precipitation via surface overgrowth.

5. CONCLUSION

In this work, we extended HYDROTHERM and numerically investigated effects of the rock elastic-plastic-transition behavior and quartz dissolution-precipitation on permeability development near a heat source in the granitic crust. Current results indicate that the mechanical behaviors may play a dominant role in the permeability development and subsequently controlling the formation of the supercritical geothermal resources in granitic rocks.

Some of the important future works will be

- Including silica precipitation via nucleation
- Consideration of dynamic stress redistribution coupled with other processes, i.e. fully THMC simulation
- Integrated modeling of fracture initiation/propagations and plastic deformation

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