

Geological Model and Potential of Supercritical Geothermal Reservoir

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ABSTRACT

Supercritical (“Beyond Brittle” and/or “Superhot”) geothermal reservoir is future target of geothermal energy resources. In order to reveal geological model, the granite–porphyry system provides useful information for creation of fracture clouds in supercritical geothermal reservoirs. An accumulation of geological and geophysical exploration data and hydrothermal experiments were also performed. Supercritical geothermal resources could be evaluated in terms of present volcanic activities, thermal structure, dimension of hydrothermal circulation, properties of fracture system, depth of heat source, depth of brittle fractures zone, dimension of geothermal reservoir. Potential of supercritical geothermal resources could be characterized into the following four categories. 1. Feasibility: surface manifestation and shallow high temperature, 2 Probability: high geothermal gradient, 3 Possibility: Aseismic zone which indicates an existence of melt, 4 Potentiality: low velocity zone which indicates magma input. Base on geophysical data for geothermal reservoirs accumulated on QGIS, we have proposed adequate tectonic model of development of the supercritical geothermal reservoirs. On the basis of hydrothermal experiment such as hydro fracking under supercritical condition, fracture clouds which composed from many tensile fractures within rock specimen can be recognized, and it is possible to maintain relatively high permeability even in supercritical environment.

1. INTRODUCTION

Supercritical state was classified into liquid-like and vapor-like regions in terms of mineral dissolution (Tsuchiya and Hirano, 2007), and it shows great capacity of enthalpy compared with subcritical state. We are conducting supercritical geothermal project, and deep drilling project named as “Japan Beyond Brittle Project”(JBPP) The temperatures of geothermal fields operating in Japan range from 200 to 300°C (average ~250°C), and the depths range from 1000 to 2000 m (average ~1500 m). The project target is over 400°C and estimated depth of such supercritical (and/or superhot) reservoir is deeper than 3000 m. In conventional geothermal reservoirs, the mechanical behavior of the rocks is presumed to be brittle, and convection of the hydrothermal fluid through existing network is the main method of circulation in the reservoir. In order to minimize induced seismicity, a rock mass that is “beyond brittle” is one possible candidate, because the rock mechanics of “beyond brittle” material is one of plastic deformation rather than brittle failure. In that case, the main points for development of supercritical geothermal reservoir is to maintain high permeability of the reservoir even in beyond brittle condition.

Geological models and the properties of supercritical geothermal reservoirs are described with respect to characteristics of supercritical geofluids and mechanical behaviors of reservoir rocks. Mechanical conditions at the elastic-plastic boundaries of granitic rocks, in terms of permeability, indicate potentially exploitable supercritical geothermal resources. Tensile fracturing is possible even in ductile rocks, and some permeability-depth relations proposed for the continental crust show no drastic permeability reduction at the BDT (Brittle-Ductile Transition). The reservoir permeability (more than 10^{-16} m²) could be maintained even under supercritical conditions (Watanabe et al., 2017). The permeable-impermeable boundary of the crust and geothermal reservoirs were affected by water-rock interaction such as dissolution and precipitation of silica minerals. Geochemical processes are a significant influence on the creation of a permeable-impermeable boundary in the crust (Saishu et al., 2014). Possible tectonic settings for supercritical geothermal resources are classified into subduction zones, ridges, rifts, and hot spots. Geological model (particularly Granite-Porphyry system) and its geothermal potential was described. NE Japan is representative of an Island-Arc setting in a subduction system, and it is highly possible that exploitable supercritical geothermal resources.

A granite–porphyry system, associated with hydrothermal activity and mineralization, provides a suitable natural analog for studying a deep-seated geothermal reservoir where stockwork fracture systems are created in the presence of supercritical geothermal fluids. We describe fracture networks and their formation mechanisms using petrological study in order to understand this “Beyond Brittle” supercritical geothermal reservoir (Tsuchiya et al., 2016). A geological model for “Beyond Brittle”, “Supercritical”, and/or “Superhot” geothermal reservoirs in the subduction zone were revealed.

Several kinds of hydrothermal experiments were carried out to reveal water-rock interaction under supercritical conditions. Not only mechanical behaviors but also chemical interactions were affected to permeability and fluid flow in the crust. Experimental approaches can provide useful information for EGS, particularly to enhance permeability even in supercritical environment.

2. GEOLOGICAL BACKGROUND

Porphyry copper deposits represent natural “Beyond Brittle” analogs where fluids from molten material (magma) infiltrate a ductile rock mass at ~600°C, and where lithostatic pressures cause fractures in the rock mass, creating a stockwork fracture system (Batkishig et al., 2014; Ingebritsen, 2012; Rusk and Reed, 2002). In these porphyry deposits we are able to observe several kinds of fractures represented by millimeter- to centimeter-scale quartz veins (Okamoto et al., 2010), where quartz filled and plugged the fractures; apparently the quartz was precipitated during adiabatic decompression and cooling as the fluids traversed from lithostatic to hydrostatic pressure regimes.

Figure 1 shows schematic geological models of magma-hydrothermal regimes for processing in supercritical geothermal reservoirs associated with volcanic activities. Deep magma chamber supplies ascending magma which is active magma chamber and direct heat source for supercritical and conventional geothermal reservoirs. Before eruption, the supercritical resources can exist within granite-porphphy system under cap rock. After eruption, the cap rock is broken and breaching. An active magma can be upwelling through the cap rock and then shallow magma chamber and hydrothermal systems are enhanced within caldera underneath active volcano. Hydrothermal activities are also enhanced, for instance, epithermal gold deposit will be formed in and around the caldera. Fournier (1999) had already mentioned general model of transition from magmatic to in a subvolcanic environment, where brittle to plastic transition occurs at 370°C to 400°C. Several important points to preserve supercritical fluid which provided from magma chamber are as follows: a) permeable and/or fractured rock mass were formed on the top of granite and porphyry system, b) volatile and supercritical geofluids were released from active magma and chilled magma, c) impermeable and self-sealed layer were formed around 370°C-400°C. We accumulated geological and geophysical data such as location and size of caldera, hot spring, hydrothermal alteration, geothermal gradient, earthquake and gravity on QGIS. Based on exploration data, we can recognize “Surface Anomaly” (eruption and degassing), “Shallow Anomaly” (magma ascent), “Deep Anomaly” (deep magma input), and “Tectonic Anomaly” (deep fluid input). Then regional potential areas can be classified into four kinds of geothermal resources such as Feasibility, Probability, Potentiality and Possibility with four axes of High Temperature, Magma input, Active volcano and High geothermal gradient. Fig. 1 shows geological models of magma-hydrothermal processes before and after eruptions. The geological model are corresponded to geophysical models such as earthquake waves (V_p, V_s and V_p/V_s) and MT. For instance, Low V_p and V_s zones associated with large V_p/V_s were recorded in geophysical model before eruption around 4 to 8 km in depth, we could estimate existence of active magma chamber in geological model. If relatively high V_p and V_s with small V_p/V_s layers above zone of V_p and V_s zones with large V_p/V_s was recognized around 3 to 5 km in depth, it is possible to consider there was potential candidate of supercritical geothermal reservoir. After eruption, active zones should be upwelling compared with situation before eruption, and then low V_p and V_s with large V_p/V_s zone was to be conventional geothermal reservoir underneath active volcano within the caldera.

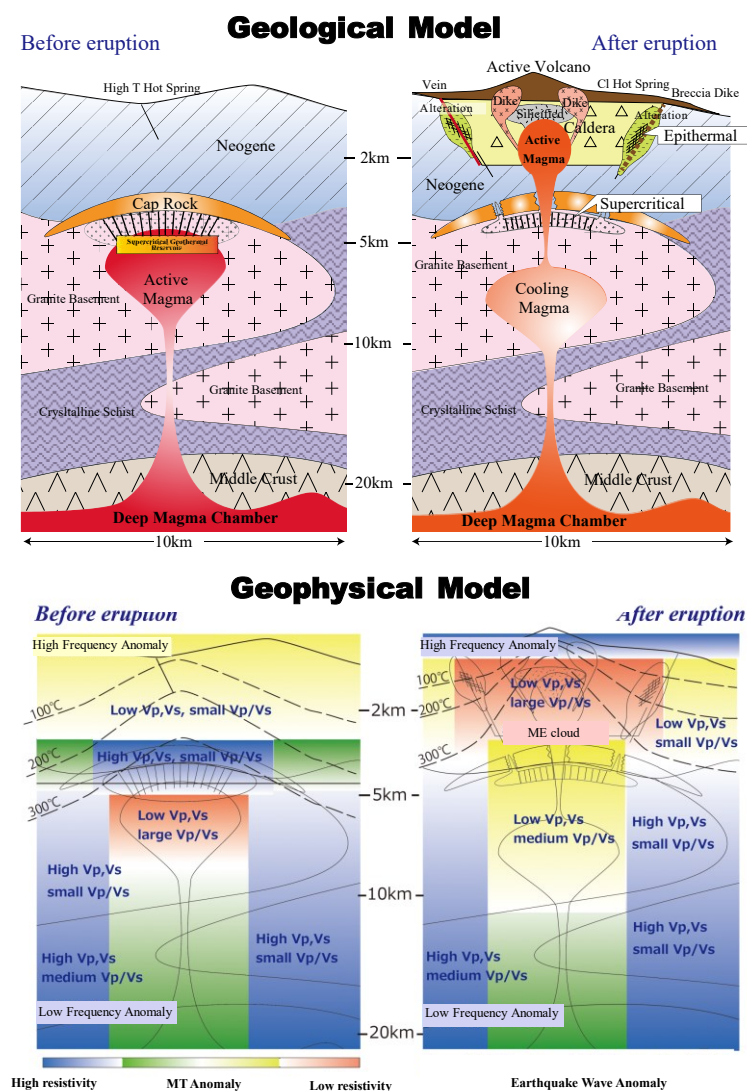


Figure 1: Geological and geophysical models of magma-hydrothermal processes for supercritical geothermal reservoir before and after volcanic eruptions.

Geophysical model describes present subterranean conditions by using acoustic waves and resistivities, and geological model demonstrates an interpretation of geophysical properties on the basis of additional geological information such as petrological

processes of active volcanos. An ideal and schematic framework of time and depth of porphyry copper deposit, epithermal deposit, volcanic eruption and supercritical geothermal resources in Fig. 2. Porphyry copper deposit was formed relatively deeper part (~5 km) and volcanic eruption was clearly surface phenomenon. Geothermal activity is expanding from surface to certain depth. Duration of those magma-hydrothermal activities show wide variation. Magmatism and mineralization were intermittently in case of porphyry copper deposit and total duration was considered to be around 1 Mys (Rusk and Reed, 2002), in constant, surface volcanic eruption was relatively short term event compared with other subterranean magma-hydrothermal activities. Geothermal activity was considered to be between 10 kys and 100 kys. Supercritical geothermal reservoir was forms around 2 to 5 km and its duration maybe between event of porphyry copper deposit and surface volcanic eruption. Cap rock of the supercritical geothermal reservoir is self-sealing layer due to silica precipitation, and also permeability of the middle crust was controlled by deposition of silica under super-sub critical conditions (Saishu et al., 2014). Epithermal deposit such as gold mineralization and operating geothermal reservoir were formed shallower than ~2 km.

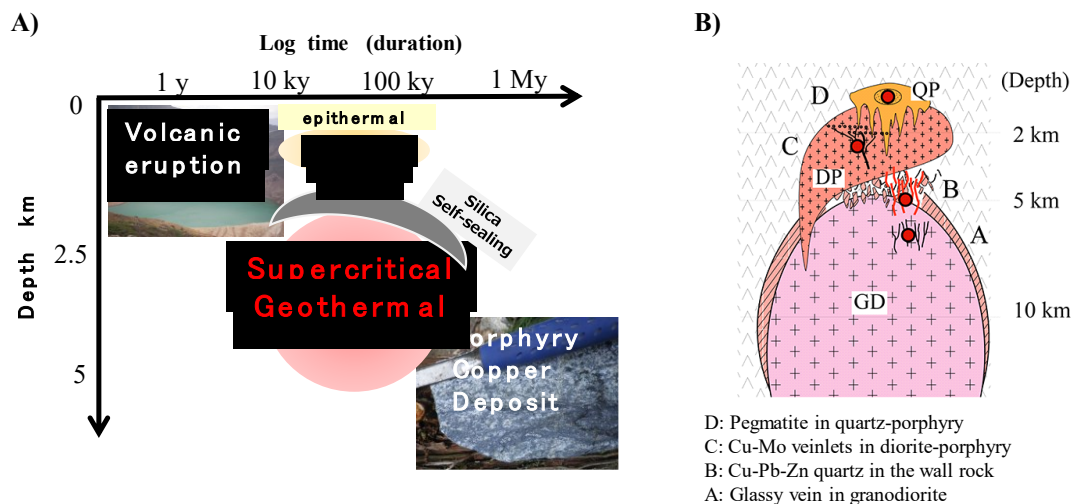


Figure 2: A): Schematic illustration of time and depth frame work of supercritical geothermal resources and magma-hydrothermal activities. B): Granite-porphyry system and supercritical geothermal reservoir (see Tsuchiya et al., 2016)

2. SUPERCRITICAL GEOTHERMAL RESOURCES

In Northeast Japan, Tohoku District, there are many calderas which were formed in Pliocene and Pleistocene, and we have active volcanoes along the volcanic front located on the back born of Tohoku District. Those areas show highly potential of supercritical geothermal resources (Amanda et al., 2019). We accumulated geological and geophysical data such as location and size of caldera, hot spring, hydrothermal alteration, geothermal gradient, earthquake and gravity on QGIS. Base on exploration data, we can recognize “Surface Anomaly” (eruption and degassing), “Shallow Anomaly” (magma ascent), “Deep Anomaly” (deep magma input), and “Tectonic Anomaly” (deep fluid input). Then regional potential areas can be classified into four kinds of geothermal resources such as Feasibility, Probability, Potentiality and Possibility with four axes of High Temperature, Magma input, Active volcano and High geothermal gradient. Feasibility area is the most promising area for supercritical resources, however, those areas are almost covered by national parks and sometimes local Onsen (Hot spring) owners have negative opinion to development of geothermal resources.

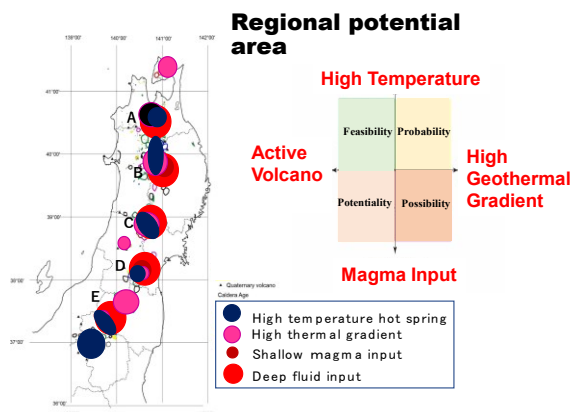


Figure 3: Regional potential areas for supercritical geothermal resources.

3. HYDROTHERMAL EXPERIMENTS

Hydrothermal experiments were very important to understand mechanical and chemical behaviors beyond brittle condition. Our research group are conducting the following hydrothermal experiments using specific experimental apparatus which were designed by ourselves.

- Dissolution and precipitation of rocks and minerals under supercritical condition (Saishu et al., 2012, 2014)
- Decompression of fluid for flash vaporization of fluid through fracture (Takagi et al., 2017)
- Hydro Fracking under supercritical condition (Watanabe et al., 2017a, 2017b, 2019)
- Flashing and mineral deposition (Amagai et al., 2019)
- Fluid flow experiments and numerical simulation through rock fracture (Ishibashi et al., 2012, 2013, 2015)
- Flow through experiment for monitoring changes of permeability due to water - rock interaction (Okamoto et al., 2017)

Particularly hydro fracking experiments by using tri-axial pressing machine reveal remarkable results. An experimental system newly developed by ourselves was used for permeability measurement. The novelty of this system is the use of a special tri-axial cell, which uses a high-viscosity plastic melt as a confining fluid and a thin plastic film as a sleeve. The plastic melt is composed of PEEK (polyether ether ketone), which has a melting point of 343 °C and a decomposition temperature greater than 538 °C (Fig. 4). It is possible to perform hydrothermal fracturing and then take measurements of permeability in supercritical conditions under differential pressure conditions. Details were shown in Watanabe et al. (2017a and 2019) The figure shows a photo of a granite specimen after hydro fracking under supercritical conditions. Hydro fracking can usually create a sheared fracture under in brittle material condition, however, “Fracture Cloud” behavior which means indicates that permeability is strongly enhanced (Fig. 4). The fracture style is completely different in sub- and supercritical conditions: single and sheared fracturing occurs in subcritical condition, and a fracture cloud occurs in supercritical condition.

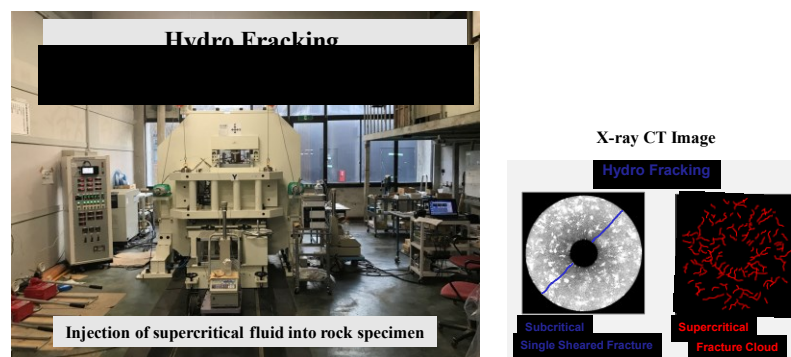


Figure 4: Hydrothermal fracturing under supercritical condition: Experimental apparatus and X-ray CT images after fracking

The mechanical and hydrological behaviors are different under supercritical condition compared with a subcritical state. Water-Rock Interaction also shows unique characteristics under supercritical conditions (Okamoto et al., 2017; Saishu et al., 2012, 2014). Permeable and impermeable condition of the crust, particularly in geothermal field with high geothermal gradient, was strongly controlled by dissolution and precipitation behaviors of silica.

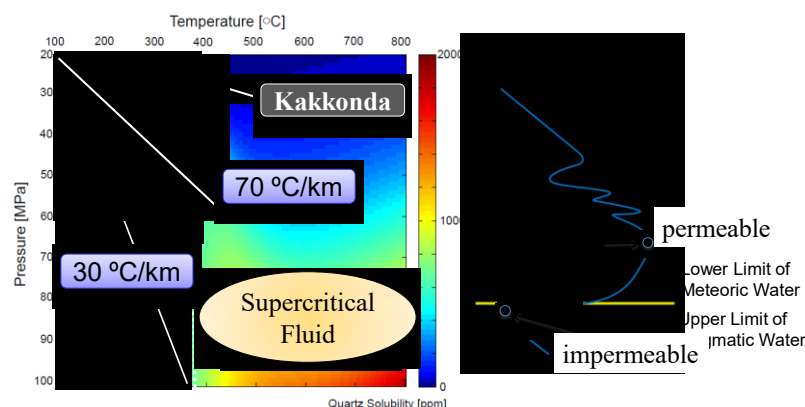


Figure 5: Quartz solubility on pressure and temperature diagram (left) and solubility curve of quartz in the Kakkonda geothermal field, Japan (right).

JBBP is a challenging project to touch at the cutting-edge of a real “Geothermal Frontier” in subduction zone as an energy system. After hydro fracking under supercritical condition with differential pressure condition can create fracture cloud which means many microcracks can be formed in granitic specimen instead of single sheared fracture. In case of subcritical condition, sheared fracture is dominant by hydro fracking under differential pressure regimes, however, many micro tensile fractures were formed in supercritical condition, and permeability can be enhanced due to fracture cloud.

4. CONCLUSION

Our research group is conducting fundamental and engineering studies of “Supercritical Geothermal Development”. Fracture networks and their formation mechanisms would be studied by using petrological and experimental works in order to understand the geological model of a supercritical geothermal reservoir. The granite–porphyry system provides useful information for understanding supercritical geothermal reservoirs and EGS technology as novel energy system in subduction zone. Supercritical and/or Superhot geothermal resources are future target of stable renewable energy resources, and it is also provides academic knowledge of deep structure of volcano and mechanisms of earthquakes.

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