Roadmap and breakthroughs for super-critical geothermal power generation

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A team of Japanese geothermal researchers have been investigating a feasibility of commercial geothermal power generation using subduction-origin high temperature resources which is estimated to be super-critical conditions. The potential of the super-critical geothermal resources in Japan can reach to around one TW, and it can cover almost all the baseload electricity demand with drastically reducing emission of CO2. Although there must be a number of scientific and engineering breakthroughs to establish super-critical geothermal power generation, the team has drew a roadmap after identification of key scientific and technological breakthroughs for power generation in 2050. The authors will describe principles and roadmap of the supercritical geothermal power generation in Japan in the presentation.

Keywords: Geothermal energy

Characterization and evaluation of supercritical geothermal resources in Tohoku District , Japan

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Supercritical geothermal resources in Tohoku District , Japan could be characterized by GIS, which includes geological approaches (caldera database Hot spring Data base, hydrothermal alteration Data base, Mine data base, granite data base) and by geophysical approaches (gravity survey, magneto telluric survey, seismic survey)
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 factures zone, dimension of geothermal reservoir.
On the basis of the GIS, potential of supercritical geothermal resources could be characterized into the following four categories. 1. Promising: surface manifestation d shallow high temperature, 2 Probability: high geothermal gradient, 3 Possibility: Aseismic zone which indicates an existence of melt, 4 Potentia : low velocity zone which indicates magma input.

Keywords: supercritical geothermal, seismic activity, volcanic activity

Geochemical characteristics of slab-derived fluid acquired from a study of hot spring waters: our research history and awaiting solutions

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Active empirical researches on the relation between hot spring and deep-generated aqueous fluid accompanied by plate subduction (slab-derived fluid) have been carried out in recent years (e.g., Kazahaya *et al*., 2014; Kusuda *et al*., 2014). We began the pursuit of their relevance by focusing on saline hot springs along the Median Tectonic Line (Amita *et al*., 2004; Ohsawa, 2004). In consequence, we made an educated guess at CO_2-rich Na-Cl type saline spring waters as closely related to a slab-derived fluid and it may be expected regularity between occurrence depth and Li/B or CH_4/CO_2 ratios of slab-derived fluids (Ohsawa et al., 2010; Amita et al., 2014). On the other hand, researches to explore the actual situation of slab-derived fluid using aqueous fluid inclusions in geological samples produced in subduction zones have been promoted (e.g., Nishimura *et al*., 2008; Yoshida *et al*., 2011; Yoshida *et al*., 2015). From studies of aqueous fluid inclusions in mantle xenoliths, slab-derived fluid is estimated to be CO_2-rich Na-Cl type saline waters (Kawamoto *et al*., 2013; Kumagai *et al*., 2014), and from the similarity of the chemical composition of the fluid inclusions and the Arima hot spring water, commentary also began to appear that the Arima-type thermal water is originated from the slab-derived fluid.
After that, when we examined saline hot spring waters and some associated gas in Arima and surrounding areas in southwestern Hyogo Prefecture, we found the discharge of hypersaline hot spring water with similar hydrochemical facies (CO_2-rich Na-Cl type) but different hydrogen and oxygen isotope composition from Arima-type thermal water and also found that He and CO_2 with the hypersaline hot spring water are of crustal origin (Ohsawa *et al*., 2015). This findings show that hypersaline hot spring water of Na-Cl type rich in CO_2 is not always related to slab-derived fluid, and it will be a continued issue to find a definite geochemical indicator in hot spring water which shows clearly that the origin is the slab.

Keywords: hot spring, slab-derived fluid, geochemistry, CO2, Na-Cl, hypersaline

Relation of high-temperature acid hot-springs to volcanoes

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Volcanic-hydrothermal systems can effectively transport heat and mass from deep to shallow environments, providing us a lot of benefits such as resort, thermal energy and mineral resources. Acid hot-springs generally locate in central parts of the systems, and are not still utilized for thermal energy resources. Then, this study investigated geochemical features of acid hot-springs in order to form a basic framework of genesis of acid hot-springs for future development of thermal energy resources.
Acid hot-spring waters exhibit contribution of low-temperature meteoric water to high-temperature magmatic fluids more than 80% based on isotopic compositions, the value which is necessary to form liquid-dominated discharges. Acid hot springs seem to interact fully with rocks, situating at a transitional point in progress from dissolution to neutralization stages. Acid SO4-Cl type waters are classified into HCl-dominated and SO4-dominated waters, probably indicating reduced and oxidized conditions of waters at deep depths, respectively. Geothermometers applied to acid hot-spring waters might suggest acid water reservoirs where mixing between magmatic fluid and meteoric water promote water-rock interaction through dissolution and dissociation of gaseous components.
Referring these lines of consideration, potential resources and tasks to be solved in future for thermal energy exploitation will be discussed.

Keywords: acid hot springs, volcanoes, geochemistry

Seismicity Surrounding the Super-critical Fluid Distribution in the Crust: Some Cases in NE Japan

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We have been imaging electrical conductors underneath the volcanic regions in NE Japan using magnetotelluric method. These conductors are compared with seismicity in detail. High seismicity distributes above the crustal conductors beneath Onikobe Caldera, Naruko Caldera, and Sanzugawa Caldera. In these areas, the cutoff depths of the earthquakes almost coincide with the top of the crustal conductor. The high seismicity zones are above the conductors and are in the resistive zones. These links between the fluid and seismicity imply that the fluid distribute in the ductile region and capped by silica cap due to the low solubility around 400 degree C (Saishu et al., 2014, Ogawa et al., 2014). The episodic invasion of fluids into the resistive zones will trigger seismicity by abruptly increasing pore pressures (Sibson, 2007, 2009).
In the case of the Shirasawa Caldera, there was high seismicity after 2011 in the central part of the caldera (Okada, 2014). We have found that this seismicity is located at the western rim of the conductor, which implies that fluids may have invaded laterally.
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Keywords: geofluids, seismicity, resistivity, magnetotellurics

Estimation of the correlation between temperature and resistivity using ANN approach

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Accurate estimation of the underground temperature is essential for the resource evaluation of a geothermal reservoir. However, the quantity of temperature data measured in boreholes is usually limited and therefore the estimation of temperature distribution at depth is often difficult. Here, we have tried to indirectly estimate the underground temperature by geophysical data that depend on temperature, by applying the artificial neural network (ANN) approach.
By using ANN trained by geological and geophysical data, this study aims to estimate underground temperature by resistivity data obtained from magnetotelluric (MT) sounding. MT investigation can estimate resistivity of deep underground easily and reasonably. If we can estimate temperature of deep underground from MT data, for example, we can find a promising geothermal reservoir and decide the location for development of a geothermal power plant.
We chose the Kakkonda geothermal area, Iwate Prefecture, Japan, as a test site of this study. It is because the area is underlain by a high-enthalpy geothermal system, reaching 500℃ at 3700m depth. In addition, many drillings and 2D or 3D resistivity surveys were carried out before.
We educated the ANN by position, depth and temperature data from well logs and resistivity data from MT sounding. After that, we tested various ANN structures to verify output temperature with observed well log temperature. As a result, we obtained good agreement at up to about 2.4 km depth where we have a lot of drilling data and fine resistivity data. However, fitness was not good at deeper part because drilling data were limited and the resistivity structure had low resolution at this depth.

Keywords: Artificial Neural Network, Resistivity, Temperature

Laboratory study of induced seismicity in a brittle-ductile transition regime

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In order to understand the seismic properties induced by artificial effects such as fluid injection in a supercritical geothermal reservoir, I reviewed the current status of laboratory study of induced seismicity in a brittle-ductile transition regime. It is important to evaluate the effects of changes in pore pressure and pore fluid temperature on induced seismicity. Understanding the mechanism of induced seismicity at deep crustal level may be useful to evaluate the possibility of detection of induced seismicity along the development of geothermal energy in the supercritical region.

Keywords: brittle-ductile transition, laboratory rock mechanics, induced seismicity, supercritical geothermal reservoir

Permeability of high-temperature fractured granite under confining stress

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A new and economically attractive type of geothermal resource was recently discovered in the Krafla volcanic system, Iceland, consisting of supercritical water at 450 °C immediately above a 2-km deep magma body. Similar resources may be widespread below conventional geothermal systems. However, in case of such geothermal resources, it is expected that the reservoir rocks are ductile and have low permeabilities. One of possible ways to enhance permeabilities of ductile rocks is hydraulic and/or thermal fracturing. Although creating fractures may be possible, there is concern about the permeability of the fractured rock after recovery of temperature and/or effective confining stress to the initial state, at which plastic deformation of fracture surface may occur. The present study has experimentally explored permeability of thermally fractured granite at temperatures of 350-500 °C under confining stress up to approximately 100 MPa. It has been found that, at each temperature, a change in stress decency of permeability occurs at a specific stress level, beyond which permeability reduction with increasing effective confining stress is much larger, and the permeability reduction is irreversible, due to transition from elastic to plastic deformation of fracture surface.

Keywords: Permeability, Fracture, Geothermal

Depth distributions of magma chambers under old calderas revealed by melt inclusions, and their relation with geofluid activities: Examples from Shirasawa caldera, NE Japan

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Arc magma is one of the main sources of the aqueous fluids to the crust, and their distributions and volatile contents are important for understanding the dynamics of arc crust. Especially after 2011 Tohoku-oki earthquake, numerous earthquake swarms were observed under old calderas. Shirasawa caldera (7–8 Ma), is one of such old calderas, and is located ~15 km east from the present volcanic front. Under Shirasawa caldera, presence of geofluid and its activities are suggested by the seismic reflectors, low seismic anomaly, and earthquake swarms. In order to understand the petrological components of such fluid-rich area under old calderas, the depth distribution of the magmatic chamber, the volatile contents of the melt, and their fractionation processes were revealed through the analysis of melt inclusions. In this talk we will discuss the relations between the depth distributions of old magmatic chambers and geophysical observations, and show that the remnants of magmatic chamber act as fluid reserviors.

Keywords: Geofluid, Old caldera, Melt inclusion

Occurrence of rock fracture under the rapid decompression condition of hot water

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In our previous water-rock interaction experiments under the various hydrothermal conditions using granite or artificial quartz samples, clear cracks or fractures in the samples were observed under the specific hydrothermal condition. This phenomenon was derived by heat stress of cooling by evaporation of water. And, this cooling effect is caused by latent/sensible heat of water. So, it is possible to generate heat stress by rapid decompression of high pressure hot water around the rock samples. Understanding of details and application of this fracturing mechanism may be useful for technological development of geothermal reservoir usage or clarification of vein formation mechanism in the Earth crust. We tried to rapid decompression experiment using granite sample. Experimental sample has a borehole, and rapid decompression is started in borehole bottom. Experimental conditions are from 500 C - 30 MPa to 600 C - 45 MPa. After the experiments, we confirmed the fracturing around the borehole by X-ray CT. In addition, we observed porosity and p-wave velocity of experimental samples. As a result, Fracture and porosity were increased with temperature rising. Maximum porosity was 3.3 %. P-wave velocity was decreased with temperature rising. And, some sample's has a very low P-wave velocity that it is below water's P-wave velocity 1.5 km/s. These results indicate that it is possible to make fracture in rocks under the hydrothermal conditions with rapid decompression.

Keywords: rapid decompression fracturing, Water-Rock Interaction, granite, Hydrothermally Derived Fracture

Molecular Dynamics Simulations of NaCl-H_2O fluid: Prediction of Electrical Conductivity of Salt Water in the Crust

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Presence of water reduces the strength of rock fracture and the frictional strength of faults, and the distribution of water in the crust, therefore, should be revealed for understanding the mechanism of earthquake occurrences. Water in the crust is considered to be salt water dissolving various ions. The electrical conductivity of such salt water shows six orders magnitude higher than that of common rocks at ambient conditions. In this context, electrical conductivity measurements have been performed for determining the distribution of salt water in the crust. Available conductivity data of NaCl-H_2O fluid, however, was limited to low pressure (<0.4 GPa) [1,2]; thus, it was difficult to discuss whether the presence of salt water can explain observed highly conductive zones in the crust.
In this study, we performed classical molecular dynamics (MD) simulations for predicting the electrical conductivity, density, and molecular behavior of NaCl-H_2O fluid at elevated temperatures and pressures in the crust. Our H_2O interaction model used for the MD simulations has succeeded in reproducing the density and permittivity of H_2O at temperatures and pressures over the critical point [3]. This H_2O model has been applied for reproducing and predicting the density and isothermal compressibility of NaCl-H_2O fluid [4]. Finally, we have derived the electrical conductivity of NaCl-H_2O fluid in the *pT* conditions of the crust [5].
In this talk, we discuss the behavior of NaCl-H_2O fluid in the crust as a function of temperature, pressure, and salinity. The salinity and fluid fraction of NaCl-H_2O fluid are discussed for explaining the observed highly conductive zone in the crust.

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Keywords: Water, Seismogenic zone, Salinity, MD simulation

Development of the Stokes-Darcy coupled flow code for simulating the geothermal system in geological time scale.

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The geothermal systems of subduction zones are of great interest as a resource of geothermal energy. In order to evaluate the sustainability and assess the environmental impact of geothermal systems it is important to model their formation and their dynamic evolution. We use numerical simulations to quantitatively investigate the dynamics of crustal deformation coupled with fluid and melt generation for periods ranging from tens of thousands up to millions years. Numerical codes solving Darcy’s and Stokes equations are commonly used to simulate fluid flow in porous media and solid crust deformation in the geological time scale (e.g. Bauville et.al. 2015), respectively. However, these earlier numerical simulations did not address both the solid rock deformation and porous fluid flow in a coupled manner without large simplification.
This presentation reports the preliminary results of the development of a coupled simulation code solving Stokes and Darcy equations. The governing equations are based on the work of Katz et. al (2007) which deals with compaction pressure in addition to the hydrostatic and dynamic pressure. Our implementation is designed to include concepts of fracture network commonly used in the engineering field of ground water simulation. We use a hybrid discretization scheme with 1) finite difference method with marker in cell scheme for the Stokes part and 2) finite volume method with unstructured grid for the Darcy part. The non-linear equations of the system are solved by a JFNK frame work (Furuichi and May, 2015). We will perform a series of numerical experiments to demonstrate the feasibility of our developed code.

Keywords: Stokes flow, Darcy flow, nonlinear solver

