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 CO_2. 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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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Natural analog of the deep geothermal reservoir -Hitachinai Granitic Rocks-

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In present, temperature of geothermal fields operating in Japan ranges from 200 to 300 °C, and depth ranges from 1000 to 2000 m. In operating geothermal reservoir, mechanical behaviors of the rocks is presumed to be brittle. New target of geothermal resources is in 2000-5000m depth and temperature is more than 350℃.In this region, the mechanical behavior of the rocks is considered to be ductile and it is expected to prevent induced seismicity. Furthermore, it is expected to high enthalpy in supercritical state.
Lithostatic-hydrostatic pressure transition zone that is important to the deep geothermal development is estimated by previous study related to the deep geothermal resource. Therefore the purpose of this study is obtaining an evidence of the transition and proposing the natural analog of the deep geothermal reservoirs. Thus, we investigated granitoid that is thought to be a heat source. And we also investigated mineral filling veins and alteration zone. Further, we analyzed chemical composition of minerals and the fluid inclusion of the rock samples.
Many volcanoes and calderas are distributed in Tohoku district. In previous study of the Koaizawa-Ohmizuhata granitic rocks located in west of Tazawa-ko lake in Akita Prefecture, Tohoku District, NE Japan, a granite–porphyry system is proposed as a natural analog of the deep geothermal reservoir. Fournier(1999) suggested that the veins including magmatic fluid formed under lithostatic pressure condition and the granite body is accompanied by alteration of porphyry-copper type with self-sealing zone.
In this study, we investigated the Hitachinai granitic rocks, located in north of Tazawa-ko lake complex rocks in central Akita Prefecture. It is expected the material evidence of the lithostatic-hydrostatic pressure boundary in the granite body.
As a result of field survey, silicified zone and argillized zone in alteration zone. Further, several kinds of mineral filling veins were observed with it, too. Mainly, those were quartz vein, glassy vein and hydrothermal breccia vein. We evaluated depth and temperature of geothermal fluids. Which of magmatic fluid or hydrothermal fluid participates in the vein formation is thought that related to the stage to change from lithostatic to hydrostatic pressure, and we expect that it leads to new knowledge of the deep geothermal reservoir. In this presentation, we estimate geothermal potential based on petrologic, mineralogic and fluid inclusion study of host granitic rocks and mineral filling veins.

Keywords: the deep geothermal reservoir, brittle-ductile transition zone, geothermalfluids, mineral filling veins

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Channeling flow generated by dissolution of granite fracture under hydrothermal conditions.

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Fractures act as dominant fluid pathways within the crust, and provide significant influences on transport of energy and heat. As silica solubility increases with increasing pressure and temperature, dissolution and precipitation of silica would provide significant effects on fracture permeability in the crust. Even for mineral dissolution within a single fracture, dissolution at free (non-contact) areas increases the aperture, whereas that at the contact areas decreases the aperture; therefore it is not clear how fracture permeability evolves by mineral dissolution under confining pressure.
The aim of this study is, based on the hydrothermal flow-through experiments, to reveal a porosity structure and permeability evolution during the dissolution of granite fracture. We developed a novel reactor, which enables us flow-through experiment under confining pressure at sub to supercritical condition (up to 350 ℃, and examined the porosity structure by X-ray CT repeatedly. In the experiments, fine-grained Aji granite core (Φ10 mm, 400 mm in length) was used. We conducted two series of hydrothermal experiments. First one is fluid flow through a slit (parallel plates) in the rock core. The analyses of solution chemistry passing through the slit and surface morphology revealed that quartz dissolved preferentially; Qtz was dissolved about five times greater than plagioclase.
Second experiments were performed with a tensile fracture introduced by Brazilian test, in which there was no shear displacement. In this fracture, very fine-grained gouge (granite powder) existed within some parts of the core sample. This experiment was conducted in three steps; at all steps, the fluid pressure was 20 MPa and confining pressure was 40 MPa (the effective pressure of 20 MPa). The first step was the flow through experiment (0.5 ml/min) at room temperature. At this stage (0-140h), fracture permeability decreased from 2.3×10^{-10} to 6.7×10^{-12} (m^2), which is consistent with decrease in mean aperture from 65 to 36 μm revealed by X-ray CT images. At the second step (140-290 h), the core sample was set without fluid flow (stagnant fluid) at 350 ℃. At this stage, permeability continuously decreased from 6.7×10^{-12} to 4.0×10^{-12} (m^2), corresponding to the decrease in aperture from 36 to 21μm. During the interval of stages 1 and 2, the aperture decreased uniformly for the entire fracture plane. These finings indicate that the aperture decrease attributes to the compaction of gouges within the fractures. At the final stag (290-300 h), flow though experiment (0.5 ml/min) was conducted at 350 ℃. At this stage, permeability recovered immediately toward 8.5×10^{-12} (m^2), and complex aperture structure was developed by mineral dissolution. Preferential dissolution occasionally occurred at the quartz grains as found in the experiment with a slit, but an interesting feature is that connected porosity network was developed regardless the minerals on the fracture plane. A flow simulation with using the X-ray CT-based 2D aperture distribution indicates that the preferential flow path (channeling flow) was developed along this porosity network. We interpret that this flow path was developed by preferential dissolution of gauge in the fracture. In contrast, the preferential dissolution of quartz does not contribute the flow due to the isolated distribution of quartz in granite. In natural settings, gauge was produced in fractures during fracturing or faulting of a rock. Our experiments suggest that, even when the initial aperture was very small for these gauge regions, the preferential dissolution occur due to significant surface areas of the gauges, which would significant effects on the formation of the preferential flow path under hydrothermal conditions.

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Keywords: Channeling flow, dissolution, hydrothermal

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Mechanical and Hydraulic Characteristics of Rock Fracture Under Brittle-Ductile Transition

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A new concept of Enhanced Geothermal System (EGS), in which geothermal fluids are produced from a fractured reservoir created artificially within an originally semi-brittle or ductile basement, has been proposed . To assess the potential of the new geothermal system, the “Japan Beyond-Brittle Project (JBBP)”has also been recently initiated, and the author have conducted fundamental investigations on mechanical and hydraulic characteristics of the new type of reservoir, in which the rock is first experiences hydraulically and/or thermally induced brittle failure, and then subjected to the temperature and pressure conditions where the rock exhibits semi-brittle or ductile stress-strain behavior at the natural condition. Kawarago tuff have been used in the present study, because brittle, semi-brittle and ductile stress-stain behaviors of the tuff specimen can be controlled only with confining stress level at the room temperature . At confining stresses up to 40 MPa, tri-axial compression and fluid flow experiments have been conducted on the specimens without and with thermal fracture.

Keywords: brittle-ductile transition zone, EGS, Mechanical Characteristics, Hydraulic Characteristics

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The formation rate of quartz vein along seismogenic megasplay fault Nobeoka Thrust, southwestern Japan

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Precipitation of minerals has a role to fill the fractures, to form mineral veins, and to affect spatial and temporal change of the permeability of the Earth’s crust. However, the change of permeability of crustal rocks has been discussed based on the geophysical properties, not on the geochemical reactions as dissolution-precipitation of minerals. Based on the ubiquitous observation of quartz veins and silica sinters, silica polymorphs are one of the most effective minerals on permeability change. Okamoto et al. (2012) and Saishu et al. (2012) revealed that precipitated silica minerals and precipitation rate depend on the concentrations of minor components in the fluid by the precipitation experiments at 430 ℃ and 30 MPa. Saishu et al. (2014) also revealed that the depth of the local minimum of quarts solubility where the quartz precipitation is dominant reaction correlates to that of the permeable-impermeable boundary at the Kakkonda geothermal field.

Fault zones including the damage zone and the fault core have a controlling influence on the crust’s mechanical and fluid flow properties. In the Nankai subduction zone, southwestern Japan, the velocity structures indicate the contrast of the pore fluid pressure between hanging wall and footwall of the megasplay fault (Tsuji et al., 2014). At Nobeoka Thrust, a major fault bounding the northern and southern Shimanto belt of the Cretaceous-Tertiary accretionary complex in Kyushu, southwestern Japan, the microchemical features of syn-tectonic mineral veins along fault zones of the Nobeoka Thrust provide evidence of temporal fluctuations in redox state during repeated earthquake cycles within a seismogenic megasplay fault in an ancient subduction zone (Yamaguchi et al. 2011). The measurement of the strike, dip, width and length of the quartz veins that fill mode I cracks (extension quartz veins) around the fault zone of the Nobeoka Thrust indicated that the fluid driving pressure ratio P* at the time of fracture opening are 0.15-0.40 in the hanging wall and footwall, respectively (Otsubo et al., 2015). Otsubo et al. (2015) suggested two possible explanations for the observed spatial variations in P*: spatial variations in pore fluid pressure P_f are directly responsible for P* variations, or P* variations are controlled by differences in mechanical properties between the hanging wall and footwall.

In this study, the amount and rate of silica precipitation for the formation of the extension quartz veins of the Nobeoka Thrust were calculated to consider the relationship between the time frequency of fracture opening-closing and the precipitation of silica minerals. The initial pressure was lithostatic condition. Basically, the larger pressure drop enhances the larger amount of silica precipitation and the faster sealing of cracks. However, the precipitation rate depends not only PT conditions but also the host rock and fluid compositions etc. The time for the formation of quartz vein at Nobeoka Thurust was estimated in the various models, for example, that pressure drop from lithostatic to lithostatic, hydrostatic, and atmospheric pressure.

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Keywords: Nobeoka Thurust, Quartz vein, Precipitation rate

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Availability of magnetoelluric resistivety survey to explore deep geothermal resources

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A supercritical geothermal resource, which exists at a deeper part than a brittle-ductile transition, can be one of the dominant renewable energy sources in a volcanic zone. In order to find an appropriate field for utilizing this resource, highly accurate geophysical explorations should be required. A resistiveity exploration including the magnetotelluric (MT) method is considered to be a powerful tool for this purpose because resistivity is very sensitive to existence and connectivity of fluids in rocks. We estimated an availability of the MT method to explore such a deep geothermal resource, applying the 3-D resistivity simulation.
We composed 3-D resistivity models to demonstrate geothermal fluids beneath old calderas in NE Japan, which included surrounding seawater and sediments. At first, the conventional MT method examined different bottom depths of the conductive body (=fluids zone). The MT responses from these different cases were compared. All models showed considerable response changes, which were more than 20% compared with the non-conductor model. The existence of the conductor itself can be identified by inversion analysis. However, the change was less than 5%, comparing the response between the models with the 6km and 10 km bottom depths. It might be difficult to identify this difference by any resistivity inversions because the estimated changes were smaller than observational errors.
Next, we calculated the MT responses in the situation that both the electric and magnetic fields were measured in the earth. The different measurement depths were examined. The calculated responses showed the highest change in the case that the measurement depth was deeper than an overlying conductive layer (e.g. sediments). This situation is similar to marine electromagnetic explorations. However, it is technically too difficult to measure the electric field in the earth.
Finally, we calculated the MT like response in the situation that the magnetic field was measured in the earth, while the electric field was on the surface. This trial also showed the highest response change in the case that the magnetic measurement depth exceeded a conductive layer. Thus, the downhole magnetic field measurement can drastically improve the accuracy of the MT method. A development of the magnetometer to be available under the condition in high- temperature and pressure should be required in order to realize this method.

Keywords: geothermal, resistivity structure, magnetotelluric method

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Physicochemical properties of water confined between quartz surfaces at elevated temperatures by molecular dynamics simulation

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Interfacial water, of which physicochemical properties were different from bulk water, was recognized in the vicinity of solid surface. The physical properties of interfacial water show unique characteristics, for example the self-diffusion coefficient, thermal expansion coefficient and freezing point. The property of interfacial water is essential for understanding geophysical and geochemical phenomena.

Although the phenomena of interfacial water have been studied theoretically and experimentally, the dynamics of the interface at high temperature and pressure remains unclear. In this study, we performed the molecular dynamics (MD) simulations to understand the structure and dynamics of water confined between quartz surfaces at 298-573 K, 10 MPa.

We tested some systems of water confined between quartz surfaces characterized by the termination of silanol (Si-OH) group. At low temperature, the density profiles showed several layered structures near the surface, and the self-diffusion coefficient was reduced in 1.0 nm distance from the surface. At high temperatures, the layered structures were disappeared and the self-diffusion coefficient was reduced in 1.5 nm.

The activation energies of the diffusion process in confined geometries were calculated based on the Arrhenius theory, and these values were close to that of bulk water. This implied that the diffusion mechanism in confined geometries is similar that in bulk and the activation energy may be interpreted by the dissociation energy of hydrogen bond.

Based on these results, the relationship of between geophysical phenomena and interfacial water will be discussed.

Keywords: interfacial water, quartz, Molecular dynamics, self-diffusion coefficient

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