Behaviour of subducted water and its role in magma genesis in the NE Japan arc: A combined geophysical and geochemical approach

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Water at subduction zones is carried to mantle depths by the subducting oceanic plate and then released by dehydration. It then migrates upwards and contributes to melting of the mantle wedge to form primary arc magma. The magma thus captures and transfers water to the crust, or outgasses water to the atmosphere. Water, either in fluids or melts in both the slab and the mantle, promotes the dissolution and mobilization of elements and affects the physical properties of the sub-arc slab, mantle, and seismicity. In this paper, I present a coherent model to explain the geophysical and geochemical role of water beneath NE Japan. I first investigate the seismic structures of the downgoing slab and sub-arc mantle and examine the role of subducted water in forming these structures. I then use the Arc Basalt Simulator version 5, a petrological–geochemical model developed to describe the geochemical behaviours of water and elements in the slab, mantle, and arc basalt. Parameters governing these petrogenetic processes are also estimated by the model and compared to geophysical observations. The combined approach shows that (1) subducted sediment and igneous oceanic crust are almost fully hydrated, whereas only partial hydration occurs in the oceanic mantle; (2) this high slab water content leads to melting of the slab sediment and the uppermost basalt layer beneath the arc; (3) the released water via slab liquid promotes 3–25% melting of the mantle wedge at a depth of 50–30 km at a mantle temperature of 1250–1350 _C; (4) virtually 89% of slab water is released, 22% of the water returns to the forearc, and 38% enters the arc crust with the magma; and (5) 11% of the subducted water retained beyond a depth of 180 km is held in the slab, and 29% in nominally anhydrous minerals in the wedge mantle.

Keywords: Subduction zone, Water cycle, Magma genesis

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Permeability and possibility of formation of supercritical geothermal resources in the ductile crust

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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. However, the hypothesis that the brittle–ductile transition (BDT) drastically reduces permeability implies that potentially exploitable geothermal resources (permeability $>10^{-16}$ m^2) could occur only in rocks with unusually high transition temperatures of >450˚C such as basalt. On the other hand, in contradition to this hypothesis, 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. Here we present experimental results suggesting that the BDT is not the first-order control on rock permeability, and that potentially exploitable resources may occur in rocks with much lower BDT temperatures, such as the granitic rocks with a transition temperature of ca. 360˚C that comprise the bulk of the continental crust. We find that permeability behavior for fractured granite samples at 350–500˚C under effective confining stress is characterized by a transition from a weakly stress-dependent and reversible behavior to a strongly stress-dependent and irreversible behavior at a specific, temperature-dependent effective confining stress level. This transition is induced by onset of plastic normal deformation of the fracture surface (elastic–plastic transition) and, importantly, causes no ‘jump’ in the permeability. Empirical equations for this permeability behavior suggest that potentially exploitable resources exceeding 450˚C may form at depths of 2–6 km even in the nominally ductile crust.

Keywords: permeabiliy, ductile crust, supercritical geothermal resource

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Effect of the hydraulic stimulation on hydraulic fracturing characteristics and gain in permeability of high-temperature ductile granite

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The creation of geothermal reservoirs in high temperature ductile rock has recently been suggested. However, the fracturing characteristics by the hydraulic stimulation under ductile condition of rock are not yet clear. In this study, hydraulic stimulation experiments on granite at temperatures of 200-450˚C have been conducted by injecting water into cylindrical granite having a borehole at a confining pressure of 40 MPa. Formation of fractures was observed at all temperatures, but fractures were formed in different manner depending on temperature, perhaps due to different water viscosities. At the lowest temperature fractures propagated linearly from the borehole, and the borehole pressure required for the fracturing was much larger than confining pressure, similarly to hydraulic stimulation at room temperature. However, these fracturing characteristics disappeared with increasing temperature. With increasing temperature, fracturing pattern shifted to formation of a larger number of shorter fractures, and the required borehole pressure became smaller with increasing temperature. Porosity and permeability increased significantly by hydraulic stimulation at all temperature, where permeability gain was high even at the highest temperature that exceeded the Brittle-Ductile Transition temperature.

Keywords: ductile rock, hydraulic stimulation

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Silica dissolution and precipitation in granite fracture and its implications to porosity evolution in deep geothermal reservoirs

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The solubility of silica in water changes significantly as function of pressure and temperature, and thus dissolution and precipitation of silica minerals could affect the spatial and temporal of porosity and permeability of the Earth’ s crust. A profile of silica solubility along the deep drilling well of the Kakkonda geothermal field (Saishu et al., 2014) revealed that the solubility reaches maximum at around 350 degreeC, and that it decreases to the local minimum at around 400 degreeC. The depths of maximum and minimum silica solubility correspond to those at prominent seismic reflectors and at permeable-impermeable boundary, respectively. To understand the long-term behaviors of the deep reservoirs, we conducted hydrothermal flow through experiments for dissolution and precipitation experiments with using granite fracture. We developed a new apparatus, which realizes experiments under supercritical conditions with confining pressure. The core of Aji granite (10 mm in diameter and 20 or 40 mm in length) with tensile fracture was covered by thin SUS jacket, which enables us to capture X-ray images repeatedly.

In the dissolution experiments at T = 350 degreeC and P_{fluid} = 20 MPa, the output solution of dissolution of granite plates contains 90 ppm of Si, 4-10 ppm of Al, Na and K, indicating that the dissolved quartz volume was at least 2 times greater than feldspars. This is consistent with the formation of pockets on quartz surfaces. Then we conducted the dissolution experiments with a sample with a tensile fracture with effective confining pressure of 20 MPa. The permeability decreased at initial 1 hour, and then increased about one-order within 10 hours. The average aperture increased from 0.02 to 0.06 mm. The 2D aperture maps before and after the experiments by X-ray CT indicate that quartz grains on the fracture surface was dissolved preferentially, but more interestingly a large connected pore was produced along the wall of the reaction tube, which acts as preferential flow path. Such large pores were produce by dissolution of gauges (fine powders of granites), which generated in the time of tensile fracturing. The gauges in natural fractures and faults posses huge surface areas, and the dissolution of such particles could change the porosity of the rocks fractures. Our experiments revealed that preferential dissolution of quartz and gauges within granite fracture produce heterogeneous apertures with fluid pockets. Such a pockets would be sustained by less-reactive feldspars grains, which correspond to fluid pockets as observed as seismic reflectors.

In the precipitation experiments T = 400 degreeC, P_{fluid} = 25 MPa, we used a high supersaturated solution (saturation ration $C_{Si}/C_{Si,Qtz,eq}$ = 5.2). To reveal the effects of mineral precipitation clearly on porosity and permeability evolutions, the applied effective confining pressure was samll (< 1MPa). Within 10 hour, permeability decreased in one order, and experiment was stopped when fluid pressure difference reached at 10 MPa. Most of the parts of the fracture shows a homogeneous decrease in aperture from 0.05 to 0.02 mm, but it is not enough to explain the signify permeability drop. Instead, at the inlet of the fracture (< 2mm from the inlet), preferential precipitation of silica was observed. Silica precipitation occurs not only as overgrowth of pre-existing quartz surface, but also precipitation as fine grained quartz crystals and amorphous silica covering fracture surfaces uniformly; accordingly, fracture was clogged effectively. The influx of high Si solution in our experiments may correspond to downward-flow along the geotherm with a significant solubility drop, or fluid pressure drop by breakage of impermeable layer. Our results suggest that, in such situations, self-sealing by silica plays a primary control to formation and maintenance of impermeable layers, but that such impermeable layer could be thin.

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Saishu, H., Okamoto, A., Tsuchiya, N., 2014. Terra Nova, 26, 253-259.

Keywords: silica, hydrothermal flow-through experiments, X-ray CT

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Depth distribution and fluid saturation of the fossil calderas and their relations with geofluid activities at NE Japan

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Arc magma is the main source of geofluid, and their depth distribution and H_2O content are important for understanding the dynamics of the upper crust. After the 2011 Great Tohoku-oki Earthquake, many earthquake swarms are observed under fossil calderas distributed in NE Japan (Okada et al., 2015). Shirasawa, Fukano, and Kawasaki calderas are ones of these calderas, and located approximately 15 km east from the present volcanic front. Especially under Shirasawa caldera, seismic reflectors and seismic low-velocity areas had been observed, indicating presence of geofluids. To understand the physico-chemical conditions under the fossil caldera, petrologic investigations are conducted using melt inclusions in the sediments of the fossil calderas. Depth distribution of the magma chambers, degree of H_2O saturation of the melt, and their relation with geophysical observations are revealed.
Melt inclusions in quartz obtained from these calderas are low-alkaline rhyolite, and its major and trace element compositional trends can be explained by fractionation of plagioclase±quartz. Entrapment pressure of melt was estimated from the pressure dependency of eutectic composition of plagioclase–quartz, and are 30–300 MPa, indicating the depth of magma chamber at 1–11 km. The H_2O contents of the melt inclusion are 2.8–5.5 wt%, with <38 ppm of CO_2. The pressure–H_2O content relations are close to solubility curve of H_2O in rhyolite melt, indicating that melt was water-saturated at least at the depth range of 1–6 km.
The depth distribution of magma chambers (1–11 km) and depth of water-saturation (1–6km) corresponds to a low V_s, V_p and high Poisson ‘s ratio region (5–10 km) and seismic reflectors (2–5 km), respectively. Therefore, these regions are expected to be a geofluid reservoir consists of tonalitic plutonic rocks. Earthquake swarms occur beneath Shiraswa and Fukano calderas at the depth of 7–12 km, indicating that supply of geofluid under these tonalite fluid reserviors.

Keywords: Fossil caldera, Geofluid, Melt inclusion, Arc magma

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Variation of the brittle-ductile transition beneath New Zealand's geothermal systems: Imaging using 3-D passive seismic attenuation

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We image seismic properties Vp, Vs and Qp in the Taupo Volcanic Zone (TVZ), New Zealand, across a region encompassing the Wairakei, Rotokawa, and Waimangu high-temperature geothermal systems, as part of a multi-disciplinary research programme to investigate untapped deep geothermal resource. The TVZ contains more than 20 high-temperature geothermal systems, which together discharge ~4.2 GW of heat at the surface. This study of seismic properties is complementary to a magnetotelluric study investigating electrical conductivity in the same region (Bertrand et al., GRL 2012 and JVGR 2015).
Seismic data used for the imaging include data from a 38-site broadband seismic array deployed across the region between 2009 and 2011, as well as from an 11-site broadband array deployed since 2015. We supplement these new data with legacy seismic data recorded by previous arrays, including the “TVZ95” array, the 2001 “CNIPSE” array, as well as by data recorded by the national GeoNet seismometer network.
We have inverted these data to derive the spatial and depth variation of seismic properties Vp, Vs, and Q (1/attenuation), especially focusing on resolving the properties in the 2-8 km depth range. Our derived 3-D Vp, Vp/Vs, and Q volumes show heterogeneity at a range of length scales, with strong lateral changes, especially for Q. The revised 3D velocity model has also enabled us to relocate all seismicity in the area, providing the best dataset to date of earthquake locations in the TVZ; we observe some areas where the inferred brittle-ductile transition appears to be shallower than 6 km, while seismicity locally extends down to ~10 km beneath the Wairakei and Te Mihi systems.

Keywords: New Zealand, geothermal , seismic attenuation

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Molecular dynamics simulations of NaCl-H_2O fluid at elevated temperatures and pressures

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Fluids in the crust have large effects on the mass transfer, heat transport, and physicochemical properties of rocks. We have investigated the physical properties of aqueous fluids for developing the database used to model the distribution of fluids based on the geophysical observations. This study contributes to understanding the fundamental physical chemistry for characterizing the properties of aqueous fluids. Major components of fluid in the crust are estimated to be H_2O, NaCl and CO_2. Here we discuss the properties of NaCl-H_2O fluid.
Density and electrical conductivity of NaCl-H_2O fluids were calculated by classical molecular dynamics (MD) simulations from 673 to 2000 K, 0.2 to 2 GPa, and 0 to 10 wt% NaCl (to 22 wt% for the density) [1, 2]. These wide ranges of temperature, pressure, salt concentrations can be sufficient to discuss the fluids in the crust. Some highly conductive zones in the crust observed by the magnetotelluic technique can be interpreted by the presence of NaCl-H_2O fluid with the salinity lower than 7.0 wt%.
Our MD simulations can provide a plausible model to explain the density, electrical conductivity, dielectric constant of the fluid by the behavior of ions and H_2O molecules in the fluid. The behavior is discussed for developing the physical chemistry of aqueous fluids at elevated temperatures and pressures.

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Keywords: Supercritical fluid, Electrical conductivity, Density, Dielectric constant, Salt water

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Hypersaline hot spring water with similar hydrochemical facies but different origin from Arima-type thermal water - Yokawa Hot Spring, Hyogo Prefecture, Japan

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Saline hot spring water and its associated gases were sampled from some hot springs in Arima and surrounding areas in southwestern Hyogo Prefecture. Results show the discharge of hypersaline hot spring water with similar hydrochemical facies but different isotopic characteristics from Arima-type thermal water (e.g., δ D- δ^{18}O of water, He isotopic composition) at Yokawa Hot Spring. Deep-seated saline water beneath Yokawa Hot Spring has many similarities to diagenetic fluid under plain areas in the sedimentary basin, but the water has different HCO_3 concentrations and major components of associated gases. Its hydrochemical facies has become Na-Cl-HCO_3 type. Elucidating the origin of carbonate components of the Yokawa Hot Spring water is expected to be important to ascertain why differences exist in hydrochemical facies and gas composition. For the Yokawa Hot Spring water, estimates of the origin of CO_2 and He in associated gases using isotope data suggest that the source of these gas components is not deeper than the crust.

Keywords: Yokawa Hot Spring, Arima-type thermal water, Hydrochemical facies, Isotopic nature

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Technical issues toward supercritical geothermal drilling

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Supercritical geothermal fluids are expected as next generation, frontier geothermal resources in Japan. Extremely high formation temperature has been recognized as one of the critical issues in drilling supercritical geothermal wells. From the previous experiences such as at Kakkonda WD-1a or IDDP wells, downhole temperature should be maintained below at most 200 degree C by effectively circulating drilling fluid during drilling because of the relatively low temperature limits in downhole equipment and materials that are currently available. In this presentation, the authors raise another possible critical issue that has not been pointed out so far. Subnormal formation pressure, and frequent and severe lost circulations are encountered in typical geothermal fields. The low formation pore pressure in supercritical geothermal formation implies that the formation fracture pressure can be also considerably lower than expected. Our estimate is that the downhole circulating pressure of cooled drilling fluid may possibly exceed the fracture pressure at depth beyond brittle-ductile transition. The fracturing of formation induced by higher downhole circulating pressure than the formation fracture pressure is a potential risk of borehole instability, packoff, stuck pipe and unsuccessful termination of the drilling in the worst case.

Keywords: supercritical geothermal, drilling

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Data-driven analysis for evaluating crustal energy in island arc

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For exploiting the crustal energy in island arc, it is important to quantitatively evaluate the constitute materials, stress state, fracture distribution and fluid-rock interactions. We will introduce data-driven analysis by which we can understand complex processes in geosystems.

Keywords: data-driven analysis, Bayesian estimation, sparse modeling

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Contribution of “Supercritical Geothermal Power Generation” to national energy-environmental policy

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Nationalwide potential of “Supercritical Geothermal Power Generation” has been roughly estimated to reach hundreds GW, although there are a lot of scientific unknowns and necessary technological breakthroughs. The member of this project expect that a number of commercial power plans will start operation and their total capacity reaches to 50-100 GW in 2050th. This strongly contributes to energy security and reduction of CO2. In 2016, Japanese government has identified Supercritical Geothermal Power Generation as one of the eight most prioritized technologies to drastically reduce CO2 emission in 2050 in their the National Energy and Environment Strategy for Technological Innovation towards 2050 (NESTI 2050), and started various supports to the project.

Keywords: Supercritical geothermal

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"Island Arc Crustal Energy"- Grant-in-Aid for Scientific Research on Innovative Areas in KAKENHI-

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Subduction system of oceanic plate is reconsidered as an energy system, which means inputs of energy and material and outputs of energy and material such as volcano, earthquake, terrestrial heat flow and geofluid flow. We have to estimate energy balance , material balance in subduction system, and then we consider geothermal energy for human beings and social relationship between earth scientific energy and social acceptance. We are planning to apply Grant-in-Aid for Scientific Research on Innovative Areas in Application Procedures for Grants-in-Aid for Scientific Research-KAKENHI after FY 2018.
Structure
General Management
A group
Island Arc Crustal Energy System
A-1:Geomaterial energy system
A-2: Terrestrial measurement energy system
B Group Island Arc material System
B-1: Chemical circulation
B-2: Transport Phenomena
C Group Technology o for Island Arc Crustal Energy
C-1: Exploration Technology
C-2:Drilling Technology
C-3: Simulation Technology
D Social Acceptance of Island Arc Crustal Energy
D-1: SLO (Social License to Operate)
D-2: Energy Economics

Keywords: Island Arc Crustal Energy, Grant-in-Aid for Scientific Research on Innovative Areas, Grants-in-Aid for Scientific Research-KAKENHI

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Molecular dynamics simulation to reveal slip and lubrication behaviors of interfacial water on quartz at high temperature conditions

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Water-rock interaction has many important roles in Earth’ s events such as earthquake. The relationship between fault friction and geofluid has been studied as represented by Sibson *et al.* (1988). The frictional strength of fault under the presence of fluid is controlled by phenomena occurring at the interfaces of mineral surface and fluids. Such interfaces can be understood from micro- and nano-scale approaches. The physicochemical properties of interfacial water on a solid surface have been studied by both theoretical and experimental methods. In our previous molecular dynamics study (Ishikawa *et al.*, 2016), interfacial water on quartz at 298-573 K showed layered structure and lower self-diffusion coefficient than that of bulk water. This indicates that, even at high temperature condition like underground environment, physicochemical properties of interfacial water on mineral could be different from bulk water. This interfacial water may alter the frictional strength of faults. In this study, we performed molecular dynamics simulations to understand the effects of interfacial water on the friction between quartz surfaces at 298-573K.
We prepared the system of confined water between two quartz surfaces characterized by the termination of silanol (Si-OH). The thickness of confined water layer ranges from 0.3 to 3 nm. In the simulation, surface force balance (SFB) system was used (Leng and Cummings, 2006). One quartz surface was fixed and the other surface was moving with constant velocity. The shear force of moving surface was calculated to obtain the friction coefficient.
In our presentation, we will show the lubrication behavior of interfacial water at 298-573 K and the discussion of frictional behavior on fault with pressurization.

Sibson *et al.* (1988) *Geology*
Ishikawa *et al.* (2016) *J. Mineral. Petrol. Sci.*
Leng and Cummings (2006) *J. Chem. Phys.*

Keywords: Molecular dynamics, interfacial water, friction

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Molecular simulation of density fluctuation of H_2O and H_2O-NaCl solutions under supercritical conditions

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Supercritical fluids, which the density of the liquid phase and the vapor phase are equal, have characteristic properties on chemical reactivity, solubility, and ionic product. The fluids are under the condition higher temperature and higher pressure than the critical point. Geofluids, which is mainly composed in H_2O-NaCl are sometimes identified as supercritical state in deep areas such as earth's crust, deep-sea hydrothermal vents and deep-drilling for geothermal well. The physicochemical properties of supercritical geofluids are important to understand these areas.
Molecules of supercritical fluid are heterogeneously distributed, and forming density fluctuation. The characteristic properties of supercritical fluids are said to be mainly due to the density fluctuation. Direct observation on the density fluctuation is obtained by small-angle X-ray scattering (SAXS) (Nishikawa *et al*., 1996) and visible light spectroscopy (Tsuchiya and Hirano, 2007; Sekiguchi *et al*., 2013). On the other hand, molecular dynamics simulations of supercritical fluids have been performed focused on the molecular cluster size (Istok *et al*., 2008). Here, we performed molecular dynamics simulations of H_2O system and H_2O-NaCl system at high temperature conditions around the critical point.
H_2O molecules and H_2O-NaCl molecules were prepared in a cubic box. In order to evaluate the density fluctuation, "bin analysis method" was used. This method divides the cubic box into small cubes with equal volumes, and the number of molecules in each boxes was counted at each time steps. The distribution of the number of molecules in each small boxes has a normal distribution and some amount of standard deviation. Large standard deviation means that the density fluctuation is large. As the result of the simulations, the density fluctuation of H_2O and H_2O-NaCl was maxima around the critical point.
In our poster, we will show the behavior of NaCl concentration dependence, and discuss about the effect of Na^+ and Cl^- ion.

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Istok *et al*. (2008) *J. Phys. Chem.*

Keywords: supercritical water, Molecular dynamics

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Permeability evolution in high-temperature fractured granite by water-rock reaction at elastic and plastic conditions

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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. Moreover, a recent study on permeability of fractured granite at temperatures exceeding the brittle-ductile transition (BDT) temperature of ca. 360˚C has suggested that potentially exploitable supercritical geothermal resources may form even in the ductile granitic crust. This is because high permeability may be created by tensile fracturing such as hydraulic fracturing in the ductile crust, in which shear fracturing may not be likely, and the created permeability may not be destroyed even though a transition from elastic to plastic deformation of fracture surfaces (elastic-plastic transition) leads to strongly stress-dependent and irreversible permeability. However, there is still concern about viability of permeability because previous studies have suggested that fracture permeability reduction occurs with time at high temperature and high effective confining stress conditions due to pressure solution at bridging asperities within the fracture, and an increase of permeability reduction rate by the elastic-plastic transition is also suggested. In the present study, hydrothermal flow-through experiments have been conducted on granite samples containing a single tensile fracture at 400°C, a pore pressure of 10 MPa, and effective confining stresses of 18, 30 and 50 MPa, with a flow rate of 0.1 g/min, where the elastic-plastic transition stress at 400°C is 40 MPa. Permeability reduction was observed at 30 and 50 MPa, where the permeability reduction was faster for the higher stress level. On the other hand, permeability increased at 18 MPa. Permeability reduction rate was positively correlated with effective confining stress, as expected from the theory of pressure solution. However, the increase of the reduction rate from 30 MPa to 50 MPa (elastic to plastic conditions) was larger than that from 18 MPa to 30 MPa (elastic to elastic conditions). These results imply that dissolution was dominant reaction in these experiments, and permeability increased and decreased respectively at the lowest and other stress levels depending on influence of the pressure solution. Moreover, these results imply an acceleration of permeability reduction rate (i.e, pressure solution) by the elastic-plastic transition. The permeability reduction rate at the plastic condition seemed to be several times larger than that at the elastic condition.

Keywords: permeabiliy, ductile crust, supercritical geothermal resource

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Permeability enhancement of granite fracture followed by seismic slip in laboratory experiments

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Hydraulic stimulation for the fractured reservoirs such as geothermal and hydrocarbon reservoirs is now a well-known operation for enhancing or maintaining the permeability of reservoir [*Evans et al.*, 2005; *Hä ring et al.*, 2008]. In this operation, as a massive amount of pressurized fluid is injected into the targeted reservoir, preexistent fractures undergo slip/shearing. At the period of fracture slip/shearing, seismicity is triggered in both seismic and aseismic modes [*Ellsworth*, 2013]. Here, considering the fact that the crustal permeability is the essential factor for controlling the fluid flow in the Earth's crust [*Ingebritsen and Manning*, 2010] and the permeability change of rock fracture is closely related to the changes in pore pressure and effective normal stress of rock fracture, it is no wonder that we come to interest in the relationship among frictional strength evolution, fracture permeability evolution, and the manner of seismicity (i.e., seismic or aseismic) during slip/shearing. Although such a relation is fundamental for defining the impact of the hydraulic stimulation or for simulating the nucleation of seismicity adequately [*McClure and Horne*, 2012; *Norbeck and Horne*, 2016], this relation has rarely been investigated and is still poorly understood.

The present study explores this relationship via the laboratory shear-flow concurrent experiments on the Westerly granite fracture. The novelty of our experiment is the fact that the shear velocity is precisely controlled during the fracture permeability measurements. Experimental results demonstrate the possibility that the permeability enhancement of rock fracture is created by frictional shearing of velocity-weakening (potentially unstable slip). To proceed our discussions on this link, we further evaluate the state of contacting asperities and of fracture surface asperities via statistically equivalent digital rock fracture modeling. By combining the experimental study with the numerical study, we can first discuss the aforementioned relationship, and successfully propose the two plausible mechanisms constraining the relationship; change in contacts distribution and shear-induced dilation at the moment of the instantaneous shear velocity jump. Though we haven't completely specified the mechanism that indeed controls the link between mechanical and hydraulic properties of rock fracture herein, these mechanisms should be taken into account in interpreting the field observation such as the abrupt permeability increase of natural fault at the moment of seismic slips [e.g., *Guglielmi et al.*, 2015].

Keywords: fracture permeability, seismic slip, contacts asperities, frictional coefficient

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Slip characteristic of rock fracture in brittle-ductile zone

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The geothermal energy using the fracture-type reservoir in the continent crust more than temperature of brittle-ductile transition (350 ℃ - 400 ℃) is suggested. When using this fracture-type reservoir, there is a possibility of aseismic slip rather than seismic slip. However, characteristic and influence on permeability of the aseismic slip is unknown. Therefore, in this study, to clarify the occurrence condition, characteristics, influence on permeability of aseismic slip, injection-induced slip experiment using cylindrical specimen with 60 ˚tilted crack was conducted at elastic-plastic deformation condition. As a result, the slip behavior suggested the occurrence of aseismic slip under both conditions of elastic deformation condition and plastic deformation condition. The magnitude of slip under elastic deformation condition was bigger than that under plastic deformation condition. In addition, the penetration rate increased by 24 times under the elastic deformation condition and 2 times under the plastic deformation condition.

Keywords: Slip characteristic, brittle-ductile transition zone

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Mechanical properties of granites after triaxial deformation and fracturing in hydrothermal conditions under supercritical state

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In order to extract geothermal energy effectively and safely from magma and/or adjacent hot rock, we need to tackle many issues which require new technology development, such as a technique to control a risk from induced-earthquakes. On a development of induced-earthquake mitigation technology, it is required to comprehensively understand roles of factors on occurrences of the induced-earthquake (e.g., regional and local stress conditions, strength of the hot rock, pore pressure of supercritical fluid, crack density or porosity, permeability and fluid-rock reaction) and their intercorrelations (*e.g., Asanuma et al., 2012*).

Our purpose of this first series of the experiments is to clarify a relationship between the rock strength and the crack density under the supercritical fluid conditions. Although in this abstract we only show a preliminary result of triaxial deformation experiment on intact granite rock strength under high-temperature (250 –650°C), high-pressure (104 MPa) condition at a constant load-point velocity (0.1 μm/sec) using a gas-rig at GSJ/AIST, we at JpGU meeting will report alteration of the granite rock strength relevant to crack density increase. We used Oshima granite as the specimen for the deformation, which has initially less than 0.2 % of the porosity and 4.29±0.55 km/s in V_p (dry) and 2.49±0.19 km/s in V_s (dry), respectively. All experimental products showed the brittle feature having several oblique fracture surfaces with c.a. 35° to cylindrical axis of the specimen, but the amount of stress drop became smaller at higher temperature and/or at lower pore pressure. Estimated Young's modulus increased with decreasing the temperature from 35.9 GPa at 650°C to 57.4 GPa at 250°C. At 550 °C, the stress drop accelerated the deformation with 8~10 times faster velocity than that at load-point. In contrast, at 650 °C, the velocity during stress drop kept the velocity within the same order of the load-point velocity. Therefore, the deformation mechanism may start to be changed from brittle to ductile when the temperature exceeds 650 °C, even though the brittle fracture is observed.

Highly dense cracked granite specimens were formed by a rapid decompression treatment using an autoclave settled at Tohoku University (*Hirano et al., 2016JpGU*), caused by a reduction of the fluid pressure within several seconds from vapor/supercritical state (10 –48 MPa, 550 °C) to ambient pressure. X-ray CT scanning on the specimens after the rapid decompression treatment let us recognize that numerous microcracks developed mainly along grain boundaries. Using X-ray CT images, we also have a plan to evaluate the fracture density for the fractured granite rock specimens. The rapid decompression treatment imposed the porosity increasing towards 3.75 % and V_p and V_s decreasing towards 1.37±0.52 km/s and 0.97±0.25 km/s on the specimens, respectively. In future, we will compare the strength for the intact granite rocks resulted from the triaxial deformation experiments with that for the fractured granite rocks to create the relationship between the granite strength and the fracture density under the supercritical conditions.

Keywords: Supercritical geothermal resources, Rapid decompression fracturing, Brittle-ductile transition zone, Granite

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Real-time measurements of permeability of Aji granite during triaxial compression tests

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Hot dry rock power generation, one kind of the geothermal generation, is a generation system which uses technique to create an artificial geothermal fluid reservoir by the hydraulic fracturing of bedrock. This generation system is expected to generate more electricity compared with conventional geothermal generation because it can develop a much wider range of sites. In the reservoir, water transportation is restricted by the permeability of host rock (Townend and Zoback, 2000). Therefore, it is important to know how the permeability varies with deformation of host rock. Permeability variations in the process of deformation of granite have presented by Zoback and Byerlee (1975) and Mitchell and Faulkner (2008). However, there are some problems in their studies. First, permeability of prefailure sample was not measured. Second, their results of measurements are not continuous. Third, their results lack accuracy. This study aims to improve these problems and measure permeability in the process of granite deformation during triaxial compression tests.

Aji granite which was formed into cylindrical shape (20 mm long and 40 mm in diameter) was used as a specimen and a nitrogen gas was used as the pore fluid. The triaxial compression tests were conducted with Intra-Vessel Deformation and Fluid-Flow Apparatus (IVA) at constant pore pressure (1.5MPa), confining pressure (20 or 40MPa), displacement rate (0.02 or 0.04mm/min) and room temperature. All the experiments were performed by using a flow method and the permeability was calculated from the flow rate which was measured in every ten seconds. In addition, strain measurements by a strain gauge were performed at the same time. The relationship between the permeability and inelastic volumetric strain was investigated.

The experimental results showed that the permeability initially decreased and began to increase from the onset of dilatancy. Regardless of the experimental condition, variation of the permeability had this tendency. This indicates that as the sample initially stressed, preexisting cracks closed and new cracks were created by inelastic deformation with increasing differential stress. The permeability increased along with inelastic volumetric strain. As samples approached brittle failure, the permeability increased remarkably. The previous research reported that mean crack diameter increased in the prefailure stage (Takemura and Oda, 2004). Therefore, the permeability enhancement in the prefailure stage is due to the increase in crack diameter.

Keywords: Permeability, Dilatancy, Inelastic volumetric strain

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Fundamental study of flush fracturing of high temperature controlled by depressure rate

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Generating cracks to rock can be applied to deep drilling technology for seated geothermal development. Thermal stress derived from rapid decompression is considered to be effective for crack generation of rocks. But possible bottomehole decompression condition is milder than that of previous studies. In this study, rapid decompression experiment at 500, 550 and 600 ℃ for granite samples with water/rock ratio of 2.5, 0.5 and 0.2 was conducted. And after experiment porosity and P-wave velocity (V_p) were measured. As temperature and water/rock ratio increase, the temperature after decompression was decreased (ΔT as temperature difference of before/after decompression was increase.). Porosity is largely depending on temperature before decompression, in particular a-b phase transition of quartz has large influence. V_p is also depends on temperature before decompression. And V_p of sample at 600 ℃ decompression has same as water. Differences of water-saturated V_p and dry condition V_p shows the relationship of ΔT. Therefore ΔT affects the process of crack generation. When ΔT is small, micro crack is generated, and when ΔT is large, large aperture crack is generated. Elastic moduli were calculated from porosity and V_p. Young's modulus decreases as porosity increases and shows negative value in all after decompression samples, which indicates samples after decompression are no more elastic. This result shows that it is possible to generate small cracks to rock even if ΔT is small.

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Evaluation of Deep Geothermal Reservoir and Magma Process Revealed by Melt Inclusion-Example in Fukano Caldera, NE Japan-

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INTRODUCTION

The deep geothermal reservoir which located beneath the caldera is potential energy resources. Magma process and the formation of the caldera were important geological evidence to reveal deep-seated geothermal reservoir, and caldera fill sediments provide petrological evidence of volcanic activities. Melt inclusion is a reliable material that provides the thermal-chemical information of the magma chamber, as it preserves the composition of the magma before eruptions. This characteristic has been used by the petrologists to determine magma evolution and differentiation. In this study, melt inclusion is used to evaluate the properties of geothermal resources, including the depth, and differentiation process which were conduct in Fukano Caldera Northeast Japan.

Fukano caldera located in the West of Sendai City. This caldera activity started from 7-8 Ma based on stratigraphy and the fossil data (Otsuki et al. 1995). Fukano formation filled in Fukano Caldera is characterized by whitish to grayish white colored massive pyroclastic flow deposits which are composed of small amounts of pumice and volcanic lapilli with 10 to 20 mm in diameter. Tenjin tuff member is grayish white massive pumiceous pyroclastic flow deposit which is contained huge dark colored pumice blocks (size up to 30 cm) and also is intercalated with lake sediments (Takahashi & Nagahashi, 2004).

METHODS

Samples were taken from 20 locations that represent the products of Fukano caldera (Fukano Formation & Tenjin Tuff member). These samples can be categorized into welded tuff and pumice tuff. Quartz crystals were separated from the samples, which are then encased with resin plate. The melt inclusions in quartz crystals are then analyzed using electron probe micro analyzer (EPMA) for 10 elements. The depth of crystallization is determined by the percentage of Quartz (Qtz) –Albite (Ab) –Orthoclase (Or) that calculated from CIPW norm. The eutectic lines will be shifted with the pressure so that if the composition of the melt inclusions in quartz crystals plotted on the diagram, quartz crystallization pressure can be calculated, as well as the emplacement depth. The MI sample then analyzed using LA-ICP-MS for 44 elements. The incompatible elements were normalized with basaltic andesite from the nearby recent volcanic arc (Zao Volcano, Tatsumi et al. 2008) to determine the differentiation of the magma.

ANALYSIS AND RESULT

The samples from Fukano Caldera were classified into low-medium K, low alkali tholeiite dacite-rhyolite with the higher silica content in the sample from the northern part. The norm percentage, crystallization pressure, and depth for the northern part and southern part respectively of 126 melt inclusions are Qtz: 20-46%, Ab: 44-71%, Or: 5-13%, 11-1900 MPa, 0.4-200km and Qtz: 29-41%, Ab: 55-66%, Or: 3.5-8%, 76-660 MPa, 3-24 km. The samples are following plagioclase differentiation path.

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PRELIMINARY RESULT OF PETROCHEMICAL COMPARISON OF GRANITOIDS OF THE MANDAKH AREA IN SOUTH MONGOLIA

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The Mandakh granitoids in southern Mongolia is part of the Central Asian Orogenic Belt, a vast accretionary orogen that records the opening and closer of the Paleo-Asian Ocean in the late Proterozoic to Palaeozoic. Our research area is located in Mankdakh soum of Dornogovi province in the southeast Mongolia. In the around Mandakh area, several granitoids, such as the Narin khudag, the Bronze fox, the Mandakh, the Mogoit, the Budar and the Shuteen, show different age several from early Carboniferous to Permian.

The previous researchers have studied some intrusive bodies, for example the Narin khudag, the Bronze fox, the Mandakh (James H.S.Blight et al., 2010), Shuteen (Batkhishig, Iizumi, 2001). However, no detailed analyses of other granitoid complexes have been carried out, therefore, we studied petrochemical properties of granitoids (Bronze fox (ca. 10 km^2), the Budar (ca. 42 km^2), the Mandakh (length stretched around 45 km), the Mogoit (ca. 40 km^2)).The Harmagtai-Hongoot-Oyut and Tsagaan suvarga Cu-Mo porphyry ore bodies which were identified are distributed in and around the area as Middle Carboniferous to Early Permian and late-Devonian respectively.

The Mandakh complex contains porphyritic structure granite and granodiorite but the Mogoit and The Bronze fox intrusions composed from granite and quartzmonzonite, have medium (5-10mm) and coarse (>10mm) grained textures, that vary from equigranular to crystal-crowded porphyritic. The samples collected from the Bronze fox, the Budar, the Mandakh, the Mogoit complexes consist of ca 3-5 mm- long euhedral plagioclase phenocrysts that are strongly altered to sericite. The groundmass contains 2-3 mm biotites and interstitial quartz. Additionally, a medium-grained granitoid densely packed with subhedral 3-5 mm K-feldspar penocrysts, which have an apparently poikilitic and pertitic texture. Accessory minerals include apatite, sphene and zircon. Intrusive rocks are immersed by K alteration and sericite-chlorite alteration assemblages.

The complexes of Mandakh area composed from high calc-alkaline, I-type. Furthermore those plutons are silica saturated SiO_2 66 %, high Al_2O_3 14.4 %, Na_2O+K_20>6 %, Y25 ppm, Nb 12.3 ppm, Rb 150.1 ppm, formed within an island arc setting.

Porphyry Cu-Mo deposits and occurrences are associated with typical calc-alkaline metaluminous, oxidized, I type, magnetite series granitoids, which is dominated granitoid type in Mongolia (Gerel. O., et al).The petrochemical figure of granitoids of the Mandakh area is commonly similar to the Carboniferous Shuteen Complex which is petrochemically similar to adakite-type rocks.

Keywords: Mongolia, granitoid of Mandakh , Central Asian Orogenic Belt

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Formation of mineralized quartz veins induced by flash evaporation from liquid to vapor under sub and supercritical conditions

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Fluid flow through faults and fractures in Earth's crust controls transport of elements, energy and heat, and it is associated with formation of many types of ore deposits. Since the solubility of silica in water drastically changes with temperature and pressure conditions, fluid flow and phase transition of aqueous fluids produce silica scales in pipelines of geothermal power plants and also mineralized quartz veins. A drop of fluid pressure and involving boiling could be a cause of precipitation of silica and metal species. Weatherley and Henley (2013) proposed a hypothesis of gold mineralization by “flash vaporization”, which is an instantaneous vaporization at fault jog induced by fault displacement. They suggested a possibility of the formation of gold-quartz veins at the time of earthquake. Since there are many similarities between conditions of superctical geothermal reservoir and hydrothermal ore deposits, the exploitation of supercritical geothermal reservoirs would provide us good opportunities for further understanding mechanism of hydrothermal ore deposits. However, to our knowledge, there have been no studies on precipitation of silica under such extremely high-supersaturated conditions, and its relation to ore formation. The aim of this study is to understand the mechanism of silica precipitation by flash vaporization and its relation to hydrothermal ore deposits. The reaction vessel (50 or 110 ml) has inner wall made of Ti, and P-T conditions were up to 450 and 50 MPa, respectively. Initially, we enclosed the fluids into the vessel, elevated pressure and temperature, and then, flashed fluids by opening the valve. Alumina filter with pore size of 10-30 micron was placed on the flow path to catch precipitates during vaporization.

In the experiments of silica precipitation by flashing, the input solution (Si = 370 ppm) was prepared by dissolution of composites of quartz and granite sand. The rapid decompression experiment was carried out by flashing from 30 MPa under liquid (200, 250, 300, 350˚C) and supercritical conditions (400, 450˚C).The pressure of the input solution was instantaneously decrease to the vapor conditions within a few seconds. In contrast to our previous studies of silica precipitation by flow-through apparatus (Okamoto et al. 2010), where phase transition of water occurred by increasing temperature, silica precipitates did not include quartz but occurred as spherical particles of amorphous silica with size of 1-3 micron, probably due to a lack of duration of transformation into more stable phases. The Si concentration of the output solution ranged from 10 to 60 ppm, which is lower than the solubility of silica on the saturated vapor pressure curve along the P-T path. These occurrences of silica indicate that metastable amorphous silica particles were formed by rapid decompression and transported from sub- to supercritical fluids, which leads to the formation of silica scales and clogs of fractures.

Next, we prepared the initial fluids (pH = 2, HCl added) with metal components, Cu (170 ppm) and Mo (30ppm), as well as silica (Si = 400 ppm). The input solution was kept four hours at 350˚C, 30 MPa, then was decompressed in two ways; first one is slow decompression by natural cooling, and the other was near adiabatic decompression by flash vaporization. As the result of slow decompression, the composition of the solution after the experiment does not change significantly (Si = 360 ppm, Cu = 130 ppm, Mo = 12 ppm). In contrast, in the rapid decompression experiment, each concentration decreased drastically to Si = 13 ppm, Cu = 4 ppm, Mo = 0.2 ppm, respectively. Our results indicate that mechanism and rate of the formation of mineralized quartz veins was highly depends of P-T-t path of the fluids, and that flashing from

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sub to supercritical conditions (phase transition of water) potentially plays roles of mineralizeation.

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Keywords: Flash vaporization, Supercritical fluid, Quartz vein

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