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

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

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

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.

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

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

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

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

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

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

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

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

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

"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

