

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

延性地殻における透水性と超臨界地熱資源の形成可能性

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 $>10^{-16} \text{ m}^2$) could occur only in rocks with unusually high transition temperatures of $>450^\circ\text{C}$ such as basalt. On the other hand, in contradiction 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 $350\text{--}500^\circ\text{C}$ 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.

キーワード：透水性、延性地殻、超臨界地熱資源

Keywords: permeability, ductile crust, supercritical geothermal resource

高温延性花崗岩の水圧破砕特性と透水性向上に対する水圧刺激の効果 Effect of the hydraulic stimulation on hydraulic fracturing characteristics and gain in permeability of high-temperature ductile granite

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高温延性岩体中への地熱貯留槽の造成が提案されている。しかしながら、延性条件下の岩石に対する水圧刺激による破壊特性は未解明である。そこで本研究では、温度200℃～450℃、封圧40 MPaの条件下で、中心にボアホールを有する花崗岩円柱供試体に対して水圧刺激実験を行った。その結果、全ての温度環境においてき裂の生成が確認され、生成されるき裂の形態は温度によって異なることを明らかにした。主なこの原因は、破砕流体の粘度が温度によって変化するためである。200℃の条件においては、線形に連続したき裂が生成され、このときの破砕水圧は封圧よりも大きかった。なお、この結果は室温環境下と同じであった。一方、450℃の条件においては、多くの離散き裂が供試体全体に亘ってクラウド状に生成され、この時の破砕水圧は封圧と同程度であった。空隙率および透水性はすべての温度環境下において増加した。このことから、脆性-延性遷移温度を超える高温条件下においても、水圧刺激によって十分な透水性を持った地熱貯留槽の造成の可能性あるとした。

キーワード：延性岩体、水圧刺激

Keywords: ductile rock, hydraulic stimulation

花崗岩亀裂におけるシリカの溶解・析出と深部地熱貯留層の間隙変化 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 $P_{\text{fluid}} = 20$ 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, $P_{\text{fluid}} = 25$ MPa, we used a high supersaturated solution (saturation ration $C_{\text{Si}}/C_{\text{Si,Qtz,eq}} = 5.2$). To reveal the effects of mineral precipitation clearly on porosity and permeability evolutions, the applied effective confining pressure was samll (< 1 MPa). 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 (< 2 mm 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.

キーワード：シリカ、熱水流通実験、X線CT

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

東北日本の古カルデラのマグマ溜まり深度・流体飽和度と地殻流体活動の関連

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

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島弧マグマは地殻への水流体供給の主要なソースであり、そのマグマ溜まり深度や含水量の把握は、上部地殻のダイナミクスを理解する上で重要である。特に2011年の東北沖大地震以降、多くの群発地震が古カルデラ下で発生しており、流体活動が示唆されている(Okada et al., 2015)。白沢・深野・川崎カルデラは、そのようなカルデラの一つであり、現在の火山フロントの約15 km東側に位置する古カルデラ群である。特に、白沢カルデラ下では地震波反射面や地震波低速度異常が観測され、現在でも地殻流体の供給が続いていると示唆される。このような古カルデラ下の物質科学的な実態を明らかにするために、古カルデラ堆積物中のメルト包有物の解析を行い、マグマ溜まりの深度分布・メルトの流体飽和度を明らかにし、地球物理観測との比較を行った。

これらカルデラの石英中のメルト包有物は、低アルカリ流紋岩に分類され、その主要・微量元素組成は斜長石±石英の分化トレンドで説明できる。斜長石-石英間の共有点組成の圧力依存性からメルトの捕獲深度を推定すると、白沢カルデラは30-300 MPaに集中し、主要なマグマ溜まりは深さ1-11 kmにあったと推測される。また、メルト包有物の含水量は2.8-5.5 wt%、CO₂含有量は38 ppm以下である。捕獲圧力-含水量関係は流紋岩質メルトの飽和含水量曲線に一致し、少なくとも深度1-6 kmではメルトはH₂Oに飽和していたことが明らかになった。

白沢カルデラの南西に位置する深野・川崎カルデラのメルト捕獲深度も約30-300MPaに集中し、同カルデラのマグマ溜まり深度も1-11 kmであったと推測される。

これらのマグマ溜まり深度分布(1-11 km)・流体飽和深度(1-6 km)は、白沢カルデラ直下の反射法地震探査の顕著な反射面(2-5 km; Sato et al., 2002)、地震波トモグラフィーの低V_p、V_s・高ポアソン比の領域(5-10 km)に対応しており、トーナライト質のマグマ溜まりの残渣あるいは集積岩が流体貯留層となっていると考えられる。また、マグマ溜まりの最深部(白沢カルデラ~11 km、深野カルデラ~11 km)はそれぞれ群発地震の深度(白沢カルデラ8-12 km; 深野カルデラ7-12 km)と一致し、マグマ溜まり残渣の底へ現在でも流体供給があると推測される。

キーワード：古カルデラ、地殻流体、メルト包有物、島弧マグマ

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 V_p , V_s and Q_p 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 V_p , V_s , and Q ($1/\text{attenuation}$), especially focusing on resolving the properties in the 2-8 km depth range. Our derived 3-D V_p , V_p/V_s , 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

高温高圧下におけるNaCl-H₂O流体の分子動力学計算

Molecular dynamics simulations of NaCl-H₂O fluid at elevated temperatures and pressures

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地殻における流体は、物質移動・熱輸送・岩石物性に影響を与えており、その性質を知ることが重要である。我々は地殻における流体の物性を知ること、①地震波や電磁気観測の結果を流体の存在として説明できるかどうかの流体物性の提供、②流体の性質を記述するための物理化学の発展、という二つの研究課題に取り組んできた。地殻における流体の主成分はH₂O, NaCl, CO₂と考えられており、この主成分で構成される流体の物性が第一に必要とされる。本研究ではNaCl-H₂O流体に関する研究成果を議論する。

①の研究課題については、我々の分子動力学（MD）計算から、NaCl-H₂O流体の密度・電気伝導度について、673 ~ 2000 K, 0.2 ~ 2 GPa, 0 ~ 10 wt% NaCl（密度に関しては22 wt%まで）を推定した[1, 2]。これらのデータベースを利用して、地震波や電磁気観測の結果と比較することで地殻における流体の存在形態をある程度推定することが可能となった。

②の研究課題については、イオンや分子を直接取り扱うMD計算の解析結果を用いることで、尤もらしいモデルを構築できる。本発表では、NaCl-H₂O流体の密度・電気伝導度・誘電率がミクロなイオン・分子のどのような挙動によって決まるかについて議論する。

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キーワード：超臨界流体、電気伝導度、密度、誘電率、塩水

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

有馬型熱水と水質がよく似た起源の異なる温泉—兵庫県の吉川温泉 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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有馬温泉の北西15kmほどに位置する吉川（よかわ）温泉の地下に賦存される流体は、水質とガス組成に見られる特徴（CO₂に富むNa-Cl型高塩分）から、一見すると有馬型熱水と同じ起源を有するよう思えるが、水の同位体組成やHe同位体組成などが有馬型熱水のそれとは異なる。同位体を用いた付随ガスのCO₂やHeの起源の推定結果は、これら温泉ガス成分の供給源が地殻より深いところにはなく、吉川温泉は有馬温泉に代表されるようなプレート脱水流体に由来する温泉ではないことを示唆している。これは、CO₂に富んだNa-Cl組成の高塩分温泉水であってもプレート脱水流体とは無関係であるものが存在することを示し、主要化学組成（水質）の類似性だけによって地質学的研究から見た地下深部流体と温泉とを結びつける行為に警鐘を鳴らす情報であると考えられる。

キーワード：吉川温泉、有馬型熱水、水質、同位体的性質

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

超臨界地熱掘削へ向けた技術課題

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.

キーワード：超臨界地熱、掘削

Keywords: supercritical geothermal, drilling

島弧地殻エネルギーを評価するためのデータ駆動型解析 Data-driven analysis for evaluating crustal energy in island arc

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島弧-沈み込みシステムの地熱エネルギーの開発のためには、脆性-延性境界および以深の構成物質、応力状態、き裂分布、脆性破壊現象、岩石-水相互作用などの定量的な理解が必須である。これらの複雑な地球プロセスを理解するために、最新の情報処理技術を取り入れたデータ解析手法であるデータ駆動型解析について紹介する。

キーワード：データ駆動型解析、ベイズ推定、疎性モデリング

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

超臨界地熱発電のエネルギー・環境政策への寄与 Contribution of “Supercritical Geothermal Power Generation” to national energy-environmental policy

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Nationwide 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.

キーワード：超臨界地熱

Keywords: Supercritical geothermal

「島弧地殻エネルギー」－科研費新学術領域研究への申請に向けて－ "Island Arc Crustal Energy"- Grant-in-Aid for Scientific Research on Innovative Areas in KAKENHI-

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沈み込みシステムをエネルギーシステムの視点から捉え直し、海洋プレートの沈み込みにともなう、エネルギーのインプット、物質のインプット、そして、火山、地震、地殻熱流量、地殻流体の流動などによるエネルギーのアウトプット、物質のアウトプットを推定し、沈み込みシステムのエネルギー収支、人類が使える地熱エネルギー、火山エネルギーおよび地球科学的エネルギーと社会との関係性についての新学術領域を創設する。2018年度の科研費新学術領域研究への申請を考える。

総括班

A班：島弧地殻エネルギーシステム

A-1：地球物質エネルギーシステム

A-2：地球計測エネルギーシステム

B班：島弧物質循環システム

B-1：化学的物質循環

B-2：移動現象

C班：島弧地殻エネルギーの開発技術

C-1：島弧地殻探査

C-2：島弧地殻掘削

C-3：地殻流体流動

D班：島弧地殻エネルギーの社会受容性

D-1：社会ライセンス(SLO)

D-2：エネルギー経済

キーワード：島弧地殻エネルギー、新学術領域、科研費

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

キーワード：分子動力学、界面水、摩擦

Keywords: Molecular dynamics, interfacial water, friction

Molecular simulation of density fluctuation of H₂O and H₂O-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 H₂O-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 H₂O system and H₂O-NaCl system at high temperature conditions around the critical point.

H₂O molecules and H₂O-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 H₂O and H₂O-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.

Nishikawa K. and Tanaka I. (1996) *J. Phys Chem.*

Tsuchiya N. and Hirano N. (2007) *Island Arc*

Sekiguchi *et al.* (2013) *J. Mineral. Petrol. Sci.*

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

キーワード：超臨界水、分子動力学

Keywords: supercritical water, Molecular dynamics

高温き裂性花崗岩の弾性および塑性条件下における水-岩石反応にともなう透水性変化

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.

キーワード：透水性、延性地殻、超臨界地熱資源

Keywords: permeability, ductile crust, supercritical geothermal resource

室内実験で観測された地震性滑りにともなう花崗岩き裂の浸透率上昇 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; Häring *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].

キーワード：き裂浸透率、地震性滑り、アスペリティ、摩擦係数

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

脆性－延性領域における岩石き裂のすべり特性 Slip characteristic of rock fracture in brittle-ductile zone

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大陸地殻の脆性－延性遷移温度（350℃～400℃）以上の岩体中のき裂型貯留層を利用した地熱発電が提案されている。このき裂型貯留層を利用する場合、き裂が地震性滑りではなく非地震性滑りを生じる可能性がある。しかし非地震性滑りが生じたときのき裂浸透率の増減といった滑り特性は明らかになっていない。そこで本研究では非地震性滑りの発生条件、特性、浸透率に与える影響を明らかにするために60°傾いたき裂を有する円柱供試体を用いて弾性～塑性変形条件下でのすべり実験を行った。その結果、すべり挙動は350℃（弾性変形条件）、450℃（塑性変形条件）のどちらの条件でも非地震性のすべりの発生を示唆した。すべり量は弾性変形条件の方が塑性変形条件と比較して多かった。また、浸透率は弾性変形条件では24倍、塑性変形条件では2倍増加した。

キーワード：すべり特性、脆性－延性遷移領域

Keywords: Slip characteristic, brittle-ductile transition zone

三軸変形実験ならびに急減圧実験にみる超臨界高温岩体（花崗岩）の物理特性

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.

キーワード：超臨界地熱発電、急減圧破碎、脆性－延性遷移領域、花崗岩

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

庵治花崗岩の三軸圧縮試験における浸透率のリアルタイム測定 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.

キーワード：浸透率、ダイラタンシー、非弾性体積歪み

Keywords: Permeability, Dilatancy, Inelastic volumetric strain

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 bottomhole decompression condition is milder than that of previous studies. In this study, rapid decompression experiment at 500, 550 and 600 °C 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 °C 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.

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.

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 km²), the Budar (ca. 42 km²), the Mandakh (length stretched around 45 km), the Mogoit (ca. 40 km²)). 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 phenocrysts, which have an apparently poikilitic and perthitic 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 SiO₂ 66 %, high Al₂O₃ 14.4 %, Na₂O+K₂O>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

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

References

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