深部地熱貯留層のナチュラルアナログ -秋田県比立内花崗岩体-
Natural analog of the deep geothermal reservoir -Hitachinai Granitic Rocks-

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現在、日本における地熱開発は温度が200-300℃、深度が1000-2000mの岩石が脆性的な領域で行われている。近年、再生可能エネルギーによる発電量の増加が期待される中で、純国産エネルギーで二酸化炭素排出量の少ない地熱発電でもより大きな発電が望まれている。
そこで本研究では、さらに大きなエネルギーを得るために既存の地熱開発よりも深部である、温度が350℃以上、深度が2000-5000mの領域を対象にしている。この領域では岩石が延性的な挙動をすると考えられ、誘発地震発生の可能性が低いことや流体が超臨界状態でありエンタルピーが高いことが期待できる。
これまで深部地熱資源に関する地球科学的な研究から、深部地熱資源は静岩圧下で存在すると考えられているため、深部地熱開発を目指す上で重要な静岩圧-静水圧境界の詳細な情報が求められている。そこで本研究の目的はその境界の物質的な証拠を明らかにし、深部地熱資源のナチュラルアナログを提示することとした。そのため花崗岩質岩体周辺のフィールド調査や岩体周辺の鉱物脈や変質帯、流体包有物などの地球化学的な検討を行う。
東北地方には火山やカルデラが多く存在しており、その下部に深部熱源として花崗岩があると考えられている。先行研究では秋田県田沢湖の西に位置する小相沢・大水端花崗岩体の研究が行われており、花崗岩-斑岩の系が超臨界地熱資源のナチュラルアナログとして提示されている。また、Fournier(1999)では静岩圧平衡のもとマグマ性流体を含み形成した脈がセルフシーリング帯とともに存在していることや斑岩銅鉱床型の変質帯を伴っていることが示されている。
そこで本研究では、花崗岩体と縁辺部の安山岩や玄武岩との接触部分にある鉱物脈や変質帯が深部地熱貯留層のアナロジーとなるか検討するために、秋田県中央部に位置する田沢湖複合岩体の北端、比立内花崗岩体を対象として研究をおこなった。ここでは熱源と考えられる花崗岩体とその縁辺部にある鉱物脈や変質帯には静岩圧-静水圧境界の物質的な証拠が期待できる。
フィールド調査の結果、変質部には珪化帯や粘土化帯がみられ、それに伴い数種類の鉱物脈もみられた。主に肉眼で白色の石英脈と暗灰色のガラス質脈、及び熱水角礫岩脈である。本研究では深部熱源と考えられる花崗岩とその周囲の岩石、及びそれらに伴う鉱物脈の主要成分、微量成分などの組成分析や流体包有物分析から、地熱流体が存在した深度や温度を推測し、また元素移動を考慮することで各鉱物脈の形成がどの段階なのかを考察する。脈形成にマグマ性流体もしくは熱水のどちらが関与しているのかは、静岩圧から静水圧へ遷移する段階と関連していると考えられ、深部地熱貯留層の新たな知見につながっていくことが期待できる。今回の発表では深部熱源である花崗岩の定置深度及び温度、さらに各鉱物脈の形成温度圧力条件、鉱物脈の分布から深部地熱貯留層の熱エネルギーなどのポテンシャルについて検討した。

キーワード：深部地熱貯留層、脆性-延性境界、地熱流体、鉱物脈
Keywords: the deep geothermal reservoir, brittle-ductile transition zone, geothermalfluids, mineral filling veins

水熱条件下における花崗岩き裂の溶解によるチャネリングフロー
Channeling flow generated by dissolution of granite fracture under hydrothermal conditions.

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

that, even when the initial aperture was very small for these gauge regions, the preferential dissolution occur due to significant surface areas of the gauges, which would significant effects on the formation of the preferential flow path under hydrothermal conditions.

キーワード：チャネリングフロー、溶解、水熱
Keywords: Channeling flow, dissolution, hydrothermal

脆性から延性挙動を示す条件下における岩石き裂の力学的・水理学的特性
Mechanical and Hydraulic Characteristics of Rock Fracture Under Brittle-Ductile Transition

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

キーワード：脆性－延性遷移領域、EGS、力学特性、水理学特性
Keywords: brittle-ductile transition zone, EGS, Mechanical Characteristics, Hydraulic Characteristics

延岡衝上断層のプレート沈み込み巨大分岐断層周辺における石英脈形成速度

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

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Precipitation of minerals has a role to fill the fractures, to form mineral veins, and to affect spatial and temporal change of the permeability of the Earth’s crust. However, the change of permeability of crustal rocks has been discussed based on the geophysical properties, not on the geochemical reactions as dissolution-precipitation of minerals. Based on the ubiquitous observation of quartz veins and silica sinters, silica polymorphs are one of the most effective minerals on permeability change. Okamoto et al. (2012) and Saishu et al. (2012) revealed that precipitated silica minerals and precipitation rate depend on the concentrations of minor components in the fluid by the precipitation experiments at 430 ℃ and 30 MPa. Saishu et al. (2014) also revealed that the depth of the local minimum of quarts solubility where the quartz precipitation is dominant reaction correlates to that of the permeable-impermeable boundary at the Kakkonda geothermal field.
Fault zones including the damage zone and the fault core have a controlling influence on the crust’s mechanical and fluid flow properties. In the Nankai subduction zone, southwestern Japan, the velocity structures indicate the contrast of the pore fluid pressure between hanging wall and footwall of the megasplay fault (Tsuji et al., 2014). At Nobeoka Thrust, a major fault bounding the northern and southern Shimanto belt of the Cretaceous-Tertiary accretionary complex in Kyushu, southwestern Japan, the microchemical features of syn-tectonic mineral veins along fault zones of the Nobeoka Thrust provide evidence of temporal fluctuations in redox state during repeated earthquake cycles within a seismogenic megasplay fault in an ancient subduction zone (Yamaguchi et al. 2011). The measurement of the strike, dip, width and length of the quartz veins that fill mode I cracks (extension quartz veins) around the fault zone of the Nobeoka Thrust indicated that the fluid driving pressure ratio P* at the time of fracture opening are 0.15-0.40 in the hanging wall and footwall, respectively (Otsubo et al., 2015). Otsubo et al. (2015) suggested two possible explanations for the observed spatial variations in P*: spatial variations in pore fluid pressure P_f are directly responsible for P* variations, or P* variations are controlled by differences in mechanical properties between the hanging wall and footwall.
In this study, the amount and rate of silica precipitation for the formation of the extension quartz veins of the Nobeoka Thrust were calculated to consider the relationship between the time frequency of fracture opening-closing and the precipitation of silica minerals. The initial pressure was lithostatic condition. Basically, the larger pressure drop enhances the larger amount of silica precipitation and the faster sealing of cracks. However, the precipitation rate depends not only PT conditions but also the host rock and fluid compositions etc. The time for the formation of quartz vein at Nobeoka Thurust was estimated in the various models, for example, that pressure drop from lithostatic to lithostatic, hydrostatic, and atmospheric pressure.
References: Okamoto et al. (2010) GCA., 74, 3692-3706; Otsubo et al., (2015) AGU abstract; Saishu et al. (2012), Am.Min., 97, 2060-2063; Saishu et al. (2014) Terra Nova, 26, 253-259; Tsuji et al. (2014) Earth Planet. Sci. Lett., 396, 165-178; Yamaguchi et al. (2011) Earth Planet. Sci. Lett.,

302, 369-377.

キーワード：延岡衝上断層、石英脈、析出反応速度
Keywords: Nobeoka Thurust, Quartz vein, Precipitation rate

深部地熱資源開発におけるMT法比抵抗探査の有効性の検討

Availability of magnetoelluric resistivety survey to explore deep geothermal resources

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

キーワード：地熱、比抵抗構造、マグネトテルリック法
Keywords: geothermal, resistivity structure, magnetotelluric method

分子動力学シミュレーションによる石英面間の高温の水の物理化学特性

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

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

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

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

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

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

キーワード：界面水、石英、分子動力学、自己拡散係数
Keywords: interfacial water, quartz, Molecular dynamics, self-diffusion coefficient

