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

*Jun-Ichi Kimura[1]

1. Department of Solid Earth Geochemistry, Japan Agency for Marine-Earth Scienc and Technology

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

*渡邉 則昭[1]、沼倉 達矢[1]、坂口 清敏[1]、最首 花恵[2]、岡本 敦[1]、Steven E. Ingebritsen[3]、土屋 範芳[1]
*Noriaki Watanabe[1], Tatsuya Numakura[1], Kiyotoshi Sakaguchi[1], Hanae Saishu[2], Atsushi Okamoto[1], Steven E. Ingebritsen[3], Noriyoshi Tsuchiya[1]

1. 東北大学大学院環境科学研究科、2. 国立研究開発法人　産業技術総合研究所　再生可能エネルギー研究センター、3. 米国地質調査所
1. Graduate School of Environmental Studies, Tohoku University, 2. Renewable Energy Research Center, National Institute of Advanced Industrial Science and Technology (AIST), 3. US Geological Survey

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.

キーワード：透水性、延性地殻、超臨界地熱資源
Keywords: permeabiliy, 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

*坂口 清敏[1]、渡邉 則昭[1]
*Kiyotoshi Sakaguchi[1], Noriaki Watanabe[1]

1. 東北大学大学院環境科学研究科
1. Graduate School of Environmental Studies, Tohoku University

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，脆性ー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

*岡本 敦[1]、田中 寛人[1]、渡邉 則昭[1]
*Atsushi Okamoto[1], Hiroto Tanaka[1], Noriaki Watanabe[1]

1. 東北大学大学院環境科学研究科
1. Graduate School of Environmental Studies

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.

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

*宇野 正起[1]、山田 亮一[1]、ファジャール アマンダ[1]、奥村 聡[2]
*Masaoki Uno[1], Ryoichi Yamada[1], Amanda Febiani Fajar[1], Satoshi Okumura[2]

1. 東北大学大学院環境科学研究科、2. 東北大学大学院理学研究科地学専攻
1. Graduate School of Environmental Studies, Tohoku University, 2. Department of Earth Science, Graduate School of Science, Tohoku University

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．斜長石ー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%, CO_2含有量は38 ppm以下である．捕獲圧力ー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H_2O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

*Stephen C Bannister[1], Sandra Bourguignon[1], Ted Bertrand[1], Adrian Harvison[1], Cameron Asher[1]

1. GNS Science, New Zealand

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

高温高圧下におけるNaCl-H_2O流体の分子動力学計算
Molecular dynamics simulations of NaCl-H_2O fluid at elevated temperatures and pressures

*佐久間 博[1]、市來 雅啓[2]
*Hiroshi Sakuma[1], Masahiro Ichiki[2]

1. 物質・材料研究機構、2. 東北大学
1. National Institute for Materials Science, 2. Tohoku University

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で、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H_2O, NaCl, CO_2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-H_2O流体に関しての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-H_2O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-H_2O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。

References
Sakuma and Ichiki (2016) *Geofluids*, **16**, 89-102.
Sakuma and Ichiki (2016) *J. Geophys. Res. Solid Earth*, **121**, 577-594.

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

*大沢 信二[1]、網田 和宏[2]
*Shinji Ohsawa[1], Kazuhiro Amita[2]

1. 京都大学大学院理学研究科附属地球熱学研究施設（別府）、2. 秋田大学大学院工学資源学研究科附属理工学研究センター
1. Institute for Geothermal Sciences, Graduate School of Science, Kyoto University, 2. Research Center for Engineering Science, Graduate School of Engineering and Resource Science, Akita University

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（CO_2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に思えるが，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CO_2 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，CO_2 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

*長縄 成実[1]、ガザリ ヌラル アイミ[1]
*Shigemi Naganawa[1], Nurul Aimi Ghazali[1]

1. 国立大学法人東京大学
1. The University of Tokyo

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

*桑谷 立[1,2]、岩森 光[1,3]、駒井 武[4]
*Tatsu Kuwatani[1,2], Hikaru Iwamori[1,3], Takeshi Komai[4]

1. 国立研究開発法人海洋研究開発機構、2. 国立研究開発法人科学技術振興機構、3. 東京工業大学、4. 東北大学
1. Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 2. Japan Science and Technology Agency (JST), 3. Tokyo Institute of Technology, 4. Tohoku University

島弧ー沈み込みシステムの地熱エネルギーの開発のためには，脆性ー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，岩石ー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

*浅沼 宏[1]
*Hiroshi Asanuma[1]

1. 産業技術総合研究所・再生可能エネルギー研究センター
1. AIST

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 2050$^{th.}$ 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」ー科研費新学術領域研究への申請に向けてー
"Island Arc Crustal Energy"- Grant-in-Aid for Scientific Research on Innovative Areas in KAKENHI-

*土屋 範芳[1]、小川 康雄[2]、浅沼 宏[3]
*Noriyoshi Tsuchiya[1], Yasuo Ogawa[2], Hiroshi Asanuma[3]

1. 東北大学大学院環境科学研究科環境科学専攻、2. 東京工業大学火山流体研究センター、3. 産業総合技術研究所　福島再生可能エネルギー研究センター
1. Graduate School of Environmental Studies, Tohoku University, 2. Volcanic Fluid Research Center, Tokyo Institute of Technology, 3. AIST-FREA

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, Grants-in-Aid for Scientific Research-KAKENHI

