

“ハビタブル” とは何か：水惑星学の創成を目指して

What is “habitable”?: Toward development of aqua planetology

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Earth is an aqua planet that holds liquid water on the surface and can support life. On Earth, liquid water has played many essential roles in the biogeochemical cycles and interior evolution, which make our planet to have been habitable during its history. For instance, liquid water causes chemical weathering of lands, which in turn provides nutrients to life and can stabilize climate through the carbon cycle. The presence of water in the interior can also affect mantle convection in association with plate tectonics and continuous degassing. On the other hand, recent theoretical studies of planetary science suggest a possibility that the amount of water on Earth might have been determined stochastically in the planetary formation process. If Earth had possessed greater or less amounts of water on the surface, some of the essential roles that water plays on current Earth would not have worked effectively.

How was the amount of water on Earth determined? How would the biogeochemical cycles have changed if Earth had possessed different amounts of water? To answer these fundamental questions, it is required research at the interactions of geology, geochemistry, biosphere science, planetary science, and solar system exploration. Near-future spacecraft missions for volatile-rich asteroids, Mars, and icy satellites will provide unique observational constraints on water activity on planetary bodies with various amounts of water. Using the observational data, theory based on experiments and modeling could reconstruct water and geochemical cycles occurred on these bodies. Revealing cycles and fixation of water occurred within volatile-rich asteroids are key to determine the amounts of water delivered to Earth during its formation. Knowledge on geochemical cycles on early Mars and icy satellites will also allow to predict possible ecosystems and biomarkers occurred there, which are important for searching for life in future missions. This paper discusses a strategy how to develop the new fields of research, termed “aqua planetology”, at the interdisciplinary interactions. Aqua planetology aims at understanding the roles of liquid water on planetary bodies and tries to make a new definition of habitability on Earth and beyond.

キーワード：水惑星、地球型惑星、地球化学循環

Keywords: aqua planet, terrestrial planet, geochemical cycles

白馬八方の蛇紋岩温泉に由来する炭化水素の分子および分子内炭素安定同位体解析

Compound- and position-specific carbon isotopic study of hydrocarbons from serpentinite-hosted hot spring in Hakuba Happo, Japan

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Olivine is one of the major constituent minerals of various meteorites (Rubin, 1997). During serpentinization process of ultramafic rocks, water in contact with olivine is reduced to form molecular hydrogen (H₂) (e.g., McCollom and Bach, 2009). The highly reduced (H₂-rich) condition created by serpentinization is thermodynamically favorable for abiotic organic synthesis. Elevated concentrations of CH₄ and higher hydrocarbon gases have been observed in serpentinite-hosted systems, regardless of continental or seafloor setting (e.g., Charlou et al., 2002; Proskurowski et al., 2008; Etiope et al., 2011; Szponar et al., 2013). Abiotic synthesis has been invoked to account for the carbon isotopic distribution among low-molecular weight hydrocarbons (e.g., Proskurowski et al., 2008). However, uncertainties still remain regarding specific abiotic production mechanisms for serpentinite-hosted systems. In this study, we report a new geochemical study of hydrocarbon gases (methane, ethane, propane, butane, pentane) from the borehole well at the on-land hot spring associated with serpentinization in Hakuba Happo, Japan. We have conducted position-specific as well as compound-specific stable carbon isotopic analyses of hydrocarbons.

The gas samples were collected from Hakuba Happo hot spring that lies on an serpentinized ultramafic rock body. Highly-alkaline hot spring water with temperature of around 50°C mainly contains N₂, H₂ and CH₄ gases (Homma and Tsukahara, 2008; Suda et al., 2014). The concentrations of C₁ to C₅ hydrocarbons were determined by Gas Chromatography. A compound-specific carbon isotope measurement for C₁-C₅ hydrocarbons was performed by GC-C-IRMS coupled with an on-line pre-concentration system. A position-specific ¹³C composition in propane molecule (C₃H₈) was measured using the GC-Py-GC-C-IRMS (Gilbert et al., 2016) coupled with an on-line pre-concentration system. The straight chain alkanes (*n*-alkanes) for the Happo sample show an isotopic depletion in ¹³C with increasing carbon number ($\delta^{13}\text{C}_1 > \delta^{13}\text{C}_2 > \delta^{13}\text{C}_3 > \dots$). This ¹³C depletion trend is very similar to those of some seafloor serpentinite-hosted hydrothermal systems (Proskurowski et al., 2008; Charlou et al., 2010), and undisputed abiogenic origin for the Murchison meteorite (Yuen et al., 1984). The observed isotopic trend can be explained by a simple polymerization model developed in this study. Our model assumes that, for any particular alkane, (i) all of the subsequently added carbon atoms that are bonded to the growing carbon chain have the same isotopic composition, and (ii) those are depleted in ¹³C with respect to the first carbon atom that initiates the carbon chain. The fit of this model suggests that *n*-alkanes for the Happo sample can be formed via polymerization from single-carbon compound (potentially methane) with a constant kinetic isotopic fractionation of $-8.9 \pm 1.0\%$. To understand the type of polymerization mechanism, we next focus on the position-specific carbon isotopic compositions of

hydrocarbons. For the first time, we applied a new method, namely position-specific ^{13}C analysis of propane, to a natural sample derived from a serpentinite-hosted system. The difference of $\delta^{13}\text{C}$ values between terminal and central carbon atom positions of propane molecule for the Happo sample was $-1.2 \pm 0.9\%$. We show the important potential of the position-specific ^{13}C analysis to identify different polymerization mechanisms that can not be discriminated by compound-specific isotopic analysis.

キーワード：蛇紋岩、炭化水素、分子内同位体分析、安定炭素同位体

Keywords: serpentinite, hydrocarbon, position-specific isotope analysis, stable carbon isotope

土星衛星エンセラダス地下海における蛇紋岩化作用とハビタビリティ Serpentinization and habitability in the Enceladus' subsurface ocean

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Saturn's moon, Enceladus, is presently discharging water-vapor plume from its south pole. The discovery of silica nanoparticles in the plume strongly suggested the presence of ongoing hydrothermal activities at the bottom of the subsurface ocean (Hsu et al., 2015). In this work, to estimate the composition of hydrothermal fluids, we conducted thermodynamic modeling of chondrite-seawater reactions at 100 to 300 degrees C and 100 bars with four representative initial seawater compositions; pH = 5.6-13.2 and DIC = 70-320 mmolal (Marion et al., 2012; Postberg et al., 2009; Hsu et al., 2015; Sekine et al., 2015; Glein et al., 2015).

The results show that the chondritic core is serpentinized by the interaction with seawater, generating chemically-varied hydrothermal fluid in all cases. Although SiO₂ concentration in the hydrothermal fluid partially depends on the initial seawater composition, it generally increases with increasing temperature of chondrite-seawater reactions. However, the SiO₂ concentration in hydrothermal fluids even at 300 degrees C does not exceed the solubility of silica in seawater in the cases with seawater pH values higher than 9.0 because NaHSiO₃(aq) increases with increasing pH when Na is the primary cation in seawater (e.g., silica solubility is 1.8 mmolal at pH = 8.5 and 216 mmolal at pH = 10.5). Therefore, pH of seawater is estimated to be less than 9.0 to keep the silica-saturated seawater by subseafloor hydrothermal activities. Taking into account the observation of Na₂CO₃ in the plume (Postberg et al., 2009), the most reasonable pH of Enceladus' seawater would be fall within the range between 8.5 and 9.0.

Molecular hydrogen (H₂) concentration in the hydrothermal fluid also changes with the initial seawater composition and the temperature of chondrite-seawater reactions. Based on the modeling of the mixing between seawater and hydrothermal fluid, we calculated the Gibbs free energies of hydrogenotrophic methanogenesis and acetogenesis in the mixing zone at the seafloor. As a result, it was revealed that these redox reactions are endergonic under all assumed conditions. Especially, H₂ concentration in hydrothermal fluid exceeds 50 mmolal at 300 degrees C, which can generate relatively high energies comparable to those of O₂-respiring microbial metabolic reactions (e.g., aerobic sulfide oxidation and hydrogen oxidation) in terrestrial seafloor hydrothermal systems. The results suggest that these hydrogen-based redox reactions can assure the energetic habitability of potential living forms in the hydrothermal systems within Enceladus.

キーワード：エンセラダス、熱水系、蛇紋岩化作用、ハビタビリティ

Keywords: Enceladus, hydrothermal system, serpentinization, habitability

Experimental investigations on hydrothermal reactions within large icy satellites and Martian crustal rocks using a 130-MPa hydrothermal autoclave

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Geochemical cycles of carbon (C) and sulfur (S) within interior oceans on icy satellites are key to understand the chemical evolution of the oceans and potential habitability (Gaido et al., 1999). Knowledge on geochemical cycles of C and S on early Mars is also critical for its chemical and climate evolution of the surface environment (Halevy et al., 2007). In the geochemical cycles on these bodies, oxidizing C- and S-bearing species, CO₂ and SO₂, could have been reduced to CH₄ and H₂S, respectively, by reactions with H₂ under hydrothermal conditions at water-rock interfaces. For instance, CH₄ in Titan's atmosphere could have been generated through high-temperature water-rock interactions in its interior during the formation and early evolution (Atreya et al., 2006). On Europa, H₂SO₄ and CO₂ on the surface might have been transported into the subsurface ocean and could have reduced in the interface between the ocean and rock components, which, in turn, may control redox state of the oceans and availability of metabolic energy for microbial life (e.g. Zolotov and Shock, 2004; Vance et al., 2016). On Mars, CH₄ could have been produced through hydrothermal reactions within deep crustal rocks, which may explain the detection of a trace amount of CH₄ on Mars (Webster et al., 2015).

Despite the importance of hydrothermal reactions of CO₂ and SO₂, kinetics of these reactions under the conditions corresponding to the interiors of icy satellites and Mars' crustal rocks are poorly constrained. This is because the previous experimental studies have mainly focused on the reactions in hydrothermal systems on Earth, where pressure typically reaches at ~30–50 MPa (e.g. McCollom et al., 2001). On the other hand, hydrothermal reactions within icy satellites and Mars' crustal rocks are proposed to occur at higher pressures (e.g., > 100 MPa) (Vance et al., 2016). In fact, recent experimental studies suggested the presence of pressure dependence on reaction products of the hydrothermal reactions (Lazar et al., 2015). However, both kinetics and reaction mechanisms remains unclear because they have used closed-system hydrothermal autoclaves, which is incapable of tracing time variations of dissolved species during the experiments.

In the present study, we have developed a 130-MPa hydrothermal apparatus that allows to perform on-line sampling using a flexible gold reaction cell, based on the experimental apparatus for investigations of Earth's hydrothermal systems (e.g., McCollom and Seewald, 2003, Shibuya et al., 2013). During the experiments on hydrothermal reactions of CO₂ and SO₂, we measure time variations of dissolved gas species. Based on the results, we discuss the reaction mechanisms and implications for the aqueous environments on icy satellites and early Mars.

キーワード：熱水反応、地球化学の物質循環、氷衛星、火星

Keywords: hydrothermal reaction, geochemical cycle, icy satellite, mars

地球型惑星形成：水星と金星への水供給の検証

Terrestrial Planet Formation: Delivery of Water to Mercury and Venus

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(英文のアブストラクトをご参照ください)

キーワード：惑星形成、水、地球型惑星、水星、太陽系、金星

Keywords: planet formation, water, terrestrial planets, Mercury, solar system, Venus

水素-水蒸気大気下での海洋形成条件

Formation condition of oceans under hydrogen-rich atmospheres

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海洋を形成するためには、液体の水が存在できる地表温度・水蒸気分圧が必要である。その条件は現在の地球のような惑星を想定した、水蒸気-二酸化炭素-窒素大気についてよく調べられている。一方、惑星形成の過程では円盤ガスの捕獲や金属鉄との化学反応により、初期の惑星大気は水素を大量に含みうる。水素-ヘリウム大気を考慮した先行研究では、40 barの水素大気をもつスーパーアースは、太陽のようなG型星から10 AU離れても水素の衝突誘起吸収により地表温度が280 K以上に保たれることが示されている(Pierrehumbert and Gaidos, 2011)。また、十分な集積熱や潮汐加熱がある場合、浮遊惑星や巨大惑星の衛星でも温暖に保たれる可能性がある(Stevenson, 1999; Peters and Turner, 2013)。

本発表では、非灰色一次元放射対流平衡計算を行い、様々な大気量・地表の水素モル分率に対して水素-水蒸気大気の構造、また液体の水が地表に存在できる条件の検討を行った。その結果、地球質量の惑星に対して、数barの水素があればH₂O-CO₂で求められたハビタブルゾーンの外側でも温暖な条件が保たれることがわかった。これは、水素による大気中の平均分子量が減少する効果で、大気スケールハイトが増加し、その結果、純粋な水蒸気大気と比べて水蒸気の気柱質量が増加することによる。一方で、これは、地表の水蒸気分圧を海洋形成に十分な値に保つには、水素を加えることでより多くの水が必要であることを意味する。本発表では、放射対流平衡計算の結果に基づき、海洋が形成するのに必要な水量・水素量・軌道距離の関係を示す。

キーワード：還元的な大気、海洋形成、初期表層環境、ハビタブルゾーン

Keywords: Reducing atmospheres, Formation of oceans, Early surface environment, Habitable zone

プレートテクトニクスを起動したABEL Bombardment : スタグナント リッドテクトニクスからプレートテクトニクスへ

ABEL Bombardment as the trigger to initiate plate tectonics of Earth: From stagnant lid to plate tectonics

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プレートテクトニクスがいつ開始したかは、長い間の議論だった。ここでは、地球と月の地質、ならびに小惑星帯の記録に基づき、プレートテクトニクスの開始は冥王代中期(4.37-4.20Ga)だったことを解説する。プレートテクトニクスの引き金となったのは、4.37-4.20Ga に断続的に起きたABEL Bombardmentと呼ばれる炭素質隕石の飛来である。ABEL Bombardmentによって、それまで無水だった還元的地球（エンスタタイトコンドライト起源）に初めて大気・海洋成分がもたらされた。隕石衝突に伴う衝撃変成作用により炭素質隕石も地球表層の岩石も一瞬にして蒸発したと考えられる。アノーソサイトからなる珪長質の上部地殻（厚さ約21 km）と50 km に達する厚いKREEP玄武岩の下部地殻からなる原初大陸は、水を含む揮発性成分の二次的付加に伴って再結晶作用を起こし、大規模なエクロジャイト化が進行した。エクロジャイト化は強力なスラブ引っ張り力を生じ、これによりプレートテクトニクスが開始した。もう一つの重要な要素は、隕石爆撃の規模である。直径1000 km に達する隕石が衝突すると、太平洋サイズのクレーターが形成される。このような巨大隕石は、それまでのスタグナントリッドテクトニクスを破壊した。爆撃による海洋地殻の形成に伴って、バイモダルナリソスフェアが形成され、スラブ引っ張り力によってプレートテクトニクスが機能し始めた。ABEL Bombardmentによって、大気・海洋が地球で初めて誕生し、プレートテクトニクスを可能にしたことの重要性を考慮すると、冥王代は次の3期に分けることができるだろう。(1) 初期冥王代 (4.57-4.37Ga), (2) 中期冥王代 (4.37-4.20Ga), and (3) 後期冥王代 (4.20-4.00Ga)である。

キーワード : ABEL Bombardment、大気海洋成分の二次的付加、プレートテクトニクスの開始、エクロジャイト化

Keywords: ABEL Bombardment, secondary accretion of volatiles, initiation of plate tectonics, eclogitization