初期地球のコマチアイト熱水系における流体の化学的性質に関する実験的研究
Experimental study on chemical nature of fluids in komatiite-hosted hydrothermal system on the early Earth

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H_2-rich hydrothermal fluids generated through the serpentinization of ultramafic rocks would have driven prebiotic chemical evolution and the development of biotic energy metabolisms (e.g., Amend and McCollom 2009; Shibuya et al., 2016). Hydrothermal systems on Early Earth could be different from modern equivalents, for example in terms of CO_2 content and pH value in parent seawater. Previous works demonstrated that carbonate formation during the serpentinization of olivine under CO_2-rich conditions and ferrous iron incorporation into the carbonate minerals suppress H_2 generation in fluids (Jones et al., 2010; Klein and McCollom, 2013; Neubeck et al., 2014). Some experiments recently were performed in komatiite-CO_2-H_2O systems (Lazar et al. 2012; Hao and Li 2015), but H_2 generation in fluids was not the objective in these experiments. Therefore, the potential for hydrogen generation through the serpentinization of komatiites over a wide temperature range has not yet been experimentally evaluated under CO_2-rich conditions.

To understand the chemical nature of hydrothermal fluids in the komatiite-hosted seafloor hydrothermal system in the Hadean, we conducted hydrothermal serpentinization experiments involving synthetic komatiite and a CO_2-rich acidic NaCl fluid (pH = 4.9 at 25 ˚C) at 100, 250, 300, and 350 ˚C, 500 bars. H_2 concentrations in fluids increase as the temperature is raised, and the maximum H_2 concentration at 350 ˚C was 2.9 mmol/kg. During the experiments, the total carbonic acid concentrations (ΣCO_2) in fluids decreased from starting values, which is consistent with the carbonate mineral formation in the serpentinized/carbonated komatiites. Precipitated carbonate minerals at 100, 250, 300, and 350 ˚C were ankerite/magnesite, dolomite, dolomite/calcite, and calcite, respectively. These carbonate mineral formation are thermodynamically consistent with Mg/Ca ratios in fluids. Ferrous iron contents in the carbonate minerals decrease with increasing temperature. The negative correlation between ferrous iron content in carbonate mineral and H_2 concentration in fluid suggests that the incorporation of ferrous iron into the carbonate mineral likely limited iron oxidation and consequent H_2 generation in the fluid. Fluid H_2 concentrations in the experiments at 350 ˚C are almost same as that of Kairei hydrothermal field (Central Indian Ridge) (Takai et al., 2004; Gallant and Von Damm, 2006; Kumagai et al., 2008; Nakamura et al., 2009), where hydrogenotrophic methanogens dominate in the prosperous microbial ecosystem. Even under CO_2-rich conditions, the high-temperature serpentinization of komatiite would provide H_2-rich hydrothermal environments that were necessary for the emergence and early evolution of life. In contrast, as considering that carbonate mineral becomes more stable and involve more ferrous iron with decreasing temperature, H_2-rich fluids may not have been generated by serpentinization at temperatures below 300 ˚C in komatiite-hosted hydrothermal systems on the Hadean Earth.

Chemical compositions of fluids have another implication for the Early Earth. The precipitated carbonate species strongly influenced Mg concentration in the hydrothermal fluid. At 350 ˚C, Mg-poor calcite is stable and Mg concentration is at most 1.2 mmol/kg. On the other hand, Mg-rich carbonate minerals such as magnesite and dolomite are stable below 300 ˚C, and Mg concentrations are at least 10 times higher than that at 350 ˚C. Therefore, in contrast to modern seafloor hydrothermal systems(e.g., Alt, 1995), the reactions between komatiite and CO_2-rich seawater at temperature range 100-300 ˚C could have been the source of Mg for the Hadean ocean.

キーワード：komatiite、CO2-rich condition、early Earth、hydrothermal alteration、serpentinization、experiment
Keywords: komatiite, CO2-rich condition, early Earth, hydrothermal alteration, serpentinization, experiment

Short peptides formed under Enceladus hydrothermal condition

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Enceladus is one the sixth largest moon of the moons of Saturn, and it has been known to harbor interior ocean beneath the icy crust. , which hold important factors necessary for life such as organic compounds, liquid water, and high temperature condition. The mass spectrometry data and the presence of nanometer sized silica particles obtained by *Cassini* spacecraft indicates the presence of salty, and most likely alkaline ocean containing various simple organic compounds. While geochemical and other radiation related processes for the *in situ* production of organics remain elusive, thermally unaltered carbonaceous chondrites, consisting the main body of Enceladus are known to be enriched with organic matters such as simple amino acids. potentially including the Therefore we Enceladus alkaline seawater, we hypothesized that an ongoing chemical evolution and polymerization of amino acids coupled with water-rock interaction under simulated Enceladus hydrothermal condition. Serpentinization coupled may contribute to dehydration may lead to condensation of surface localized amino acids leading to peptide formation. Short peptide is significant important for primitive life in terms of initial chemical evolution In order to test this hypothesis, we have developed the Enceladus hydrothermal reactor based on the chemical constraints obtained through previous experimental and theoretical studies. We have added six different abiotically available L-amino acids (Gly, Ala, Asp, Glu, Ser, Val) that are and introduced a thermal fluctuation system simulating the periodic tidal heating of the interior chondritic core. The pH monitoring and H_2 and CO_2 Gas Chromatography (GC) data clearly indicated the occurrence of serpentinization / carbonation reaction. Organic compounds data estimated by Orbitrap Fusion suggest the interaction between amino acids, aqueous alteration reaction and thermal cycling processes for the role of abiotic peptide formation under alkaline hydrothermal condition. Here, we discuss the interaction between aqueous alteration reactions and thermal cycling processes for the role of abiotic peptide formation under the Enceladus hydrothermal condition.

キーワード：エンセラダス、アミノ酸、ペプチド合成、熱水反応実験
Keywords: Enceladus, Amino acid, Peptide synthesis, Hydrothermal reactor

Geo-electrochemical CO production: Implications for the autotrophic origin of life

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Hydrothermal activities on the primitive Earth were considered to be much greater than the present level, and hydrothermally produced geo-electrochemical potential may have facilitated CO_2 reduction and the formation of organic compounds that preceded the origin of life. To test the possibility, we examined electrochemical CO_2 reduction on low-crystalline sulfides of various metals (Ag, Cd, Co, Cu, Fe, Mn, Mo, Ni, Pb, W, or Zn) in the simulated ancient seawater. Results showed that CdS and Ag_2S have excellent catalytic efficiency for the CO_2 reduction to CO, together with the H_2 evolution. At potentials below -1.0 V (versus the standard hydrogen electrode), the CO production on CdS and Ag_2S accounted for around 40 and 30 % of the total electric current, respectively. The threshold potential could be readily generated in the H_2-rich, high-temperature and alkaline hydrothermal vents that were probably widespread over the early ocean floor. The electrochemical production of CO, a crucial energy and carbon sources for abiotic and biotic organic synthesis, could have been a key initial step of the prebiotic CO_2 fixation in the early ocean hydrothermal systems, and provided the materials for the origin and early evolution of life.

堆積物中の吸着重元素分布を利用した水質復元：鉄酸化物による微量ウラン吸着の表面錯体モデリング

Reconstruction of Water Quality from Adsorbed Heavy Elements in Sediment: Surface Complexation Modeling of Trace Uranyl Adsorption on Iron Oxide

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地球誕生以来, 地球表層環境はさまざまな変化を遂げてきた. 地球上の生命にとって水は必須であり, 環境変化に伴って地球上の水の性質(つまり水質)がどのように応答したかを理解することは生命の起源や進化を理解する上で必須である. また地球以外の天体のおける生命存在の可能性を評価する上でも, その天体で生じた水質変遷の理解は必須であろう. 水の化学的性質を示す最も重要かつ基本的なパラメータはpHである. pH は水中における元素の化学的挙動(溶解・沈殿・錯形成)をコントロールし, 水を介したエネルギーと物質の移動を支配する. 地質学では過去の水質を当時の堆積物や化石(地質記録)に残された何らかの代替指標(プロキシ)を読み解くことにより復元するが, 汎用的に利用できるpH のプロキシは現在のところない.

天然水にはさまざまな微量元素が含まれる. 微量元素はpHをはじめとする水質条件に依存し鉱物表面に吸着する性質がある. したがって鉱物に吸着した微量元素には, 吸着当時の水質情報が保存されていると考えることができる. 「表面錯体モデリング」と呼ばれる熱力学的吸着モデルは, 水質条件の関数として重元素の吸着挙動を理論的に予測することができる. 表面錯体モデリングを逆方向に適用すると, 微量元素の吸着挙動から水質を予測できる可能性がある. 本研究は堆積物に残された微量元素情報から表面錯体モデリングを用いて, 吸着時の水質を復元する手法を構築することを目的としている.

天然水に比較的高濃度に含まれる重元素にウラン(U)があげられる. Uは熱力学的には酸素分圧がおおよそ10^{-50}気圧以上の条件で6価の価数を持つU(VI)として存在する. U(VI)は溶解度が高く移動性が高いが, 鉄酸化物に強く吸着する性質がある. U(VI)の鉄酸化物への吸着は自然界では頻繁に認められている. 例えば, 大陸内部古代湖フブスグル湖の湖底堆積物コア中ではU濃度は年代によって変動することが確認されているが, 変動するU濃度は鉄酸化物への吸着・脱離過程により説明される可能性が指摘されている.

本研究では, 自然界に近い水質条件で鉄酸化物による微量Uの室内吸着実験を行い, その実験結果を表面錯体モデリングによりモデル化した. 構築した表面錯体モデリングにより, 古代湖堆積物のU分布を利用した古水質復元を試みた.

キーワード：吸着、微量重元素、鉄酸化物
Keywords: adsorption, trace heavy element, iron oxide

EXPERIMENTAL STUDY ON MANGANESE OXIDE FORMATION: INTERPRETAION OF MANGANESE OXIDE ON GALE CRATER AND OXIDIZING ENVIRONMENT ON EARLY MARS.

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The Curiosity rover has found Mn enrichments within sandstones in the Kimberley region of the Gale crater on Mars [1]. These enrichments were detected within fracture-filling materials, *i.e.*, veins, crosscutting the surrounding sandstones, implying that Mn was once concentrated in subsurface fluids and then precipitated within ancient aquifers [1]. The chemical composition analysis for the Mn-rich materials also show that the abundance of Mn is coupled with those of transition trace metals, particularly Ni and Zn; meanwhile, Si, Ca, Cl and/or S are inversely correlated or not correlated with Mn [1]. This indicates that Mn exists as oxides in the fracture-filling materials, rather than silicate, carbonate, or chloride [1]. Since oxidation of Mn requires high levels of redox potential [2], the findings of Mn oxides indicate a possible coexistence of a highly oxidizing atmosphere and wet conditions on early Mars [1]. However, the pO_2 level at the time of deposition of Mn oxides remains poorly constrained.
In the present study, we conducted laboratory experiments in order to constrain the pO_2 level at the time of deposition of the Mn oxides based on the elemental pattern of coprecipitation of Mn oxides. In the experiments, we synthesized MnO_2, Mn_3O_4, and $Mn(OH)_2$ from solutions of dissolved Mn, Ni, Zn, and Cr using different oxidants, such as $KMnO_4$ [8] or H_2O_2 [9]. After the reactions, filtered solutions and solid precipitates were collected. The recovered solid precipitates were analyzed with X-ray absorption fine structure (XAFS) and X-ray diffraction (XRD). In addition, concentrations of dissolved Mn, Cr, Ni, and Zn in the remnant solution samples were measured using inductively coupled plasma atomic emission spectroscopy (ICP-AES). We found that only formation of MnO_2 can explain the enrichments of Mn together with Ni and Zn, which is consistent with the pattern of trace metal enrichments of the Mn oxides in the Gale crater. On the other hand, formations of Mn_3O_4 or $Mn(OH)_2$ cannot account for the observations. Given that precipitation of MnO_2 requires a high level of O_2 (>0.01 bar), our results strongly suggest the presence of an O_2-rich atmosphere on early Mars at the time when groundwater was active within the Gale crater. These results, in turn, imply effective formation of O_2 via H_2O photolysis and/or ineffective loss of O_2 due to limited amounts of reductants on early Mars.

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キーワード：初期火星、惑星環境、大気進化

Keywords: Early Mars, Planetary environment, Atmospheric evolution

Cycles and escape of water on Earth and Mars: implications from hydrogen isotopic compositions

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The presence of water influences the tectonics and mantle convection and therefore changes the chemical reactions occurring on planetary surfaces, the volatile cycles among different reservoirs, and the thermal evolution of planets. Because Earth is the only planet known to be sustaining oceans through its history and Mars probably lost the liquid water that once existed on its surface, comparative planetology of these planets would help us to understand the sustainability of water on terrestrial planets.

As hydrogen isotope (D/H) compositions vary among different sources of water and fractionate through planetary processes, the origins and evolution of water can be constrained by D/H data. The D/H ratios of the terrestrial water and the primitive Martian water are nearly identical, suggesting their common origins (Usui et al. 2012). The D/H ratios of surficial water on present-day Mars are ~6 times higher than the primitive value, suggesting significant water loss through its history (Villanueva et al. 2015).

By combining theoretical models of cycles of water among different reservoirs with D/H data, we constrained the cycles and escape of water on Earth and Mars. The small difference in D/H ratios of the oceans and mantle of Earth can be understood as resulting from a balance between the fractionation due to the ingassing and outgassing processes, suggesting an efficient water cycle (Kurokawa et al. in prep). On the other hand, the D/H ratios of different water reservoirs on Mars are likely to be quite inhomogeneous (Usui et al. 2015), suggesting the less efficient, limited cycles of water at least from ~4 Ga to present (Kurokawa et al. 2016). An increase in the D/H ratios of the terrestrial oceans from Archean to present (Pope et al. 2012) is likely to be a signature of the evolution toward a steady state, rather than that of the water loss (Kurokawa et al. in prep). In contrast, our study demonstrated that water loss from Mars before ~4 Ga was more significant than during the rest of its history. Our model suggested that a significant fraction of paleo-oceans is stored as ground ice on present-day Mars (Kurokawa et al. 2014).

The fates of Earth and Mars probably diverged very early (~4 Ga) in their evolutions.

キーワード：地球、火星、同位体、水循環、大気散逸
Keywords: Earth, Mars, Isotopes, Water cycle, Atmospheric escape

“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 (H_2) (e.g., McCollom and Bach, 2009). The highly reduced (H_2-rich) condition created by serpentinization is thermodynamically favorable for abiotic organic synthesis. Elevated concentrations of CH_4 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 N_2, H_2 and CH_4 gases (Homma and Tsukahara, 2008; Suda et al., 2014). The concentrations of C_1 to C_5 hydrocarbons were determined by Gas Chromatography. A compound-specific carbon isotope measurement for C_1-C_5 hydrocarbons was performed by GC-C-IRMS coupled with an on-line pre-concentration system. A position-specific ^{13}C composition in propane molecule (C_3H_8) 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 ^{13}C with increasing carbon number ($\delta^{13}C_1 > \delta^{13}C_2 > \delta^{13}C_3 > ...$). This ^{13}C 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 ^{13}C 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 ±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 $\delta^{13}C$ values between terminal and central carbon atom positions of propane molecule for the Happo sample was -1.2 ±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 Na2CO2 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-respirating 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, CO_2 and SO_2, could have been reduced to CH_4 and H_2S, respectively, by reactions with H_2 under hydrothermal conditions at water-rock interfaces. For instance, CH_4 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, H_2SO_4 and CO_2 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, CH_4 could have been produced through hydrothermal reactions within deep crustal rocks, which may explain the detection of a trace amount of CH_4 on Mars (Webster et al., 2015).

Despite the importance of hydrothermal reactions of CO_2 and SO_2, 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 CO_2 and SO_2, 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、地球化学的物質循環、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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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H_2O-CO_2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21ｋｍ）と50ｋｍ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1000ｋｍ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、バイモーダルな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