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研究課題名（和文）コンドライトの融解で探る初期惑星の形成と分化

研究課題名（英文）Making of proto-planets by melting of chondrite at high-pressure

研究代表者
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研究成果の概要（和文）：本研究では，コンドライト隕石の融解温度と相関係を高圧実験によって決定した．目的は，核形成，マントル全岩組成，始原マントルの酸化還元状態など，岩石型惑星形成初期の物質分化過程の理解である．融解実験は，天然の炭素質コンドライト隕石（CI2，タギシュ・レイク）とエンスタタイトコンドライト隕石（EH，サハラ）に対してマルチアンビル型高圧合成装置を用いて行い，両隕石の融点への揮発物質の影響を見積もった．これにより，鉄-ニッケル硫化物と炭素・水和物の共存安定性を考慮した，岩石型始原惑星の集積や核分離のモデル化に有用な相平衡関係を確立した．これは岩石型惑星の始原マントルの進化過程へも重要な示唆を与える．

研究成果の概要（英文）：We investigated the melting temperatures and phase relations of chondrite materials at high-pressure. The objective of this study is to understand early planetary differentiation processes such as core formation, mantle bulk composition and redox state of primordial mantle in early terrestrial planets. Melting experiments were carried out on natural carbonaceous (origin: Tagish Lake) and enstatite (origin: Sahara) chondrites at high pressure and temperatures using the multi-anvil apparatus. Our results show the effect of volatile on the melting temperature of Tagish Lake (CI2) and Sahara (EH3) with respect to Allende (CV3) meteorite and KLB1, respectively. We established the phase equilibria which can be used to derive a model of accretion and possible core segregation that takes into consideration the stability of carbon and hydrous species along with a Fe-Ni sulfide melt. This result leads to important implications for the evolution of the primordial mantle of terrestrial planets.

研究分野： Planetary Science

キーワード： chondrite　melting temperature　high pressure　magma ocean　planetary accretion

１．研究開始当初の背景

Magma ocean is an inevitable stage of rocky planets formation where silicate and metals are melted together during accretionary processes that involved chondritic material. Knowledge of the melting temperature and phase relations of chondrite-like materials at high pressure are an important step to understand early planetary differentiation and core formation, as well as bulk composition and redox state of the primordial mantle in early terrestrial planets. Whether the bulk composition of Earth resulted from the heterogeneous or homogeneous accretion of chondrites has been highly debated; to date, however, there is no firm conclusion about the origin and composition of the Earth's building blocks.

２．研究の目的

The aim of this study is to examine the bulk composition of primary mantle and core of proto-planets by means of melting experiments on natural chondrites at high pressures relevant to those expected in an Earth-size magma ocean. We investigated the melting temperature and phase relations of Tagish Lake volatile-rich carbonaceous chondrite (CC) and Sahara enstatite chondrite (EC) as candidate end member of the Earth's building blocks. CC and EC are among a variety of other species, interesting because composition of CC is close to that of the bulk silicate Earth (BSE) while they contain larger quantities of volatiles and high oxidation state in contrast to the more reduced EC models, which on the other hand has strong isotopic similarities with BSE. Natural EC and CC are therefore valid analogue starting materials to investigate the formation of Earth-like planets under various oxygen fugacity conditions, and infer the effect of volatiles on planetary differentiation processes.

３．研究の方法

We performed experiments at 5, 12, 21, 25, 30 and 50 GPa, and temperatures between 1400 and 2200°C using the multi anvil apparatus. Sample consisted of a finely powdered natural CC from Tagish Lake (TL, Ontario, Canada) and EC from Sahara (Ref. N° 97072). TL meteorite is known to contain large amount of carbon compared with other CC and falls in the field of CI2 compositions. In contrast, Sahara 97072 is made of ~26% Fe-Ni-S and ~74% silicates and

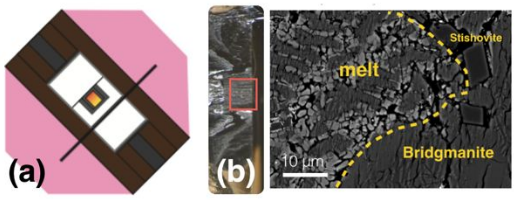

Fig.1 ***(a) HP cell assembly (b) Example of Cross-section of the recovered EC sample prepared by Ar-milling polisher.***

fall in the EH3 compositions. Samples were grinded into fine powder and packed into a graphite (Gr) capsule, which was surrounded by a rhenium (Re) shield. The Gr-Re capsule is then placed at the center of the HP cell, which consisted of (Mg,Co)O and MgO pressure media, equipped with a Re cylindrical heater and $LaCrO_3$ insulator (Fig. 1a). Temperature was monitored by a W/Re thermocouple while pressure was determined from the Load/P relation of the HP cell, on the basis of in situ X-ray diffraction in a previous measurements at SPring-8.HP melting experiments were conducted at the GRC using tungsten carbide (WC) anvils up to ~25 GPa and sintered diamond anvils for pressures higher than 30 GPa. Generally, sample was compressed to a target load, then heating was carried out at ~1000 °C for 1 hour to transform Gr capsule into diamond and prevent melt from leaking at higher T. The temperature was then raised to the target T and kept for ~1 to 5 minutes before quenching to room temperature. After HP experiments, samples were recovered to atmospheric conditions and polished for textural and chemical characterization of the mineral phases using FESEM and electron microprobe on accurately polished surfaces using the Ar-milling cross-section polisher to preserve textural features (Fig. 1b).

４．研究成果

Our results on EC showed the coexistence of high pressure mineral assemblages in equilibrium with Fe-Ni-S metal liquid (ML) and Si-rich melt (SM). Fig. 1 shows such textural features for EC recovered from 30 GPa and 2500 °C. Subsolidus phases below 25 GPa are similar to studies where CV3 Allende meteorite was used as starting material. Fig.2 shows that Mg/Si ratio of SM (Fig. 2 red dots) was substantially higher compared to previous experiments on less Si-rich synthetic chondrites (Fig2., blue dots), suggesting that excess Si in natural EC could be accommodated in SM.

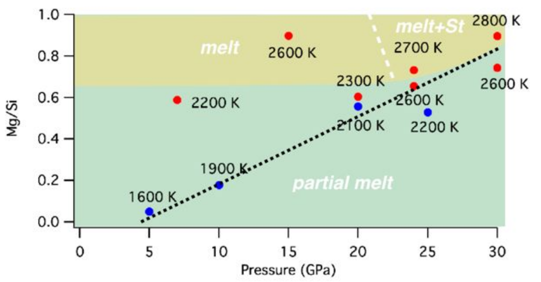

Fig.2 ***Variation of Mg/Si content of the silicate melt as function of P and T.***

In contrast, above 25 GPa, we found that stishovite (St) coexists with bridgmanite (Br) and Ca-perovskite (CPv) instead of MgO as reported by experiments on the more oxidized CV3 chondrite. At 30 GPa and 2600 °C, St is the last remaining phase coexisting with ML, implying that if EC materials contributed to the accretion of the proto-Earth, very high T would be required to melt completely EC and therefore it is likely that dense St would have crystallized in the primitive lower mantle just at the end of the magma ocean stage. This scenario implies that the proto-Earth lower mantle may have been stiffer than the less silica-rich pyrolitic mantle and therefore less inclined to internal convection, which could result in the formation of a Venus-like proto-planet.
Our results on TL show the coexistence of the main high pressure mineral assemblages in equilibrium with Fe-Ni-S metal liquid and $CO_2(+H_2O)$-rich melt over the entire temperature range (Fig. 3a and 3b). Subsolidus phases are characterized by the presence of carbonates with composition ranging between the Ca-, Fe- and Mg end members (Fig. 3b). Analyses of the quenched products revealed the presence of a $CO_2(+H_2O)$-rich melt with SiO_2 content as low as ~10 wt% enriched in Mg and Fe and coexisting with a metallic Fe-Ni-S such a that described in previous similar studies where CV3 Allende meteorite was used as starting material. The distribution of elements between metallic liquid and volatile-bearing melts results to be lower than previous experiments of CV3 Allende meteorite likely as a result of the more oxidized conditions, as well as the Fe-rich nature of the produced silicate melt. In addition, the distribution of Ni and Fe appears to be slightly pressure dependent. Our melting experiments show evidence that the oxygen fugacity of TL

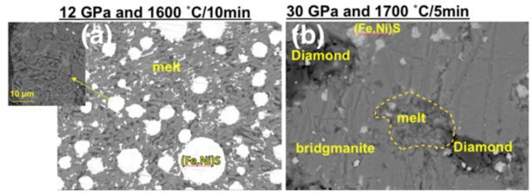

Fig.3 ***Backscattered Electron (BSE) images showing the texture of the recovered run products at (a) 5 GPa and (b) 30 GPa.***

remained intrinsically buffered by the coexistence of C/carbonate at HP-T, however, segregating Fe-Ni-S metallic liquid as representative of proto-cores with up to ~6 wt% O, similarly to what measured in metallic liquids produced by melting of CV3 Allende meteorite.
Results from melting experiments of TL meteorites are summarized in Fig. 4. Due to the large amount of volatile, the solidus and liquidus temperatures are much lower than CV3 Allende meteorites and KLB-1. Our results imply that, if CC material from the asteroid belt contributed to the accretion of Earth, this might have experience melting at much lower temperature during which volatiles such as C and H could be retained as deep volatile reservoirs. Current theories on the Earth's formation however favor the addition of oxidized chondritic material from the asteroid belt during a late-accretion stage. A scenario CC would Results on the phase equilibria of EC and TL can be used to derive a model of accretion and possible core segregation that takes into consideration the stability of carbon and hydrous species along with a Fe-Ni sulfide melt with important implications for the evolution of the mantle composition of terrestrial proto-planets.

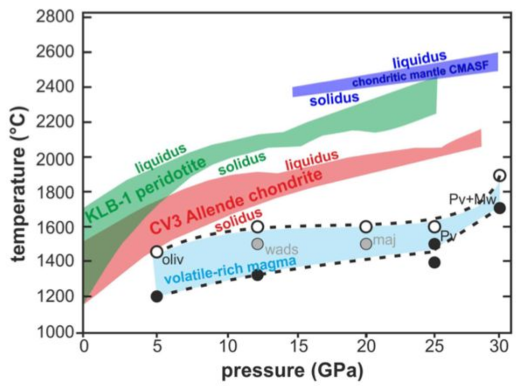

Fig. 3 P-T diagram comparing the melting intervals of TL with KLB-1 peridotite, Allende and synthetic chondritic mantle.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

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〔図書〕（計　０件）

〔産業財産権〕
○出願状況（計　０件）
○取得状況（計　０件）

〔その他〕

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