Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

PPS22-01 会場:415 時間:5 月 1 日 09:00-09:15

チェリャビンスク隕石の組成・組織の不均質性
Compositional and textural inhomogeneity of Chelyabinsk meteorites

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Meteorites are important sources of information on composition and age of the solar system materials. However, collected meteorites are likely biased and unrepresentative of the near-Earth meteoroid population. Mineralogy and reflectance spectra of meteorites are used to link specific classes of meteorites and asteroids, but are not definitive enough. Meteorites of which fall were witnessed are rare and substantial case when meteorites and their parent bodies are directly linked, and both orbital and material data of the near-Earth bodies are known. The fireball was eye-witnessed near Chelyabinsk city of Russia in 15 February 2013, and associated meteorites of total mass of 4-6 ton, were subsequently recovered. Survey of physical and chemical nature of small bodies with an Earth-crossing orbit is crucial in understanding the origin and evolution of the near-Earth materials and in planetary defense. While near-Earth objects (NEO) >1 km dia. have been largely identified by NEO survey programs, most NEOs <?100 m dia. remain unknown. Thus, it is important to study the Chelyabinsk-sized objects. We present mineralogy and reflectance spectra of several chips of Chelyabinsk meteorites, which indicate chemical and spectral inhomogeneity, suggesting the complex history of the parent body.

キーワード: チェリャビンスク隕石, 隕石衝突, 不均質性
Keywords: Chelyabinsk meteorites, Meteoroid impacts, Inhomogeneity

PPS22-02 会場:415 時間:5 月 1 日 09:15-09:30

岩石学的タイプ 7 コンドライトの特徴と分類
Classification and petrologic features of chondrites of petrologic type 7

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Chondrites are classified into petrologic types 1-6, which distinguish the degrees of aqueous alteration (types 1-2), and thermal metamorphism (types 4-6). In addition, a petrographic type 7 has also been proposed to indicate an even higher degree of thermal metamorphism [1]. Such chondrites contain only relict chondrules, and plagioclase is commonly coarse-grained. Low-Ca pyroxene contains >1% CaO. However, most of these chondrites may actually be melt rocks or melt breccias [2], and the occurrence of a type 7 is controversial problem. However, LEW 88663 seems to be a genuine type 7 chondrite [3], not a melt rock.

Here we report the preliminary results of our petrographic study on ordinary chondrites classified as type 7, to explore their thermal history, classification, and genetic relationships to melt breccia and others.

Many chondrites are classified as type 7 in NIPR and other collections (77 chondrites at present). However, the detailed petrography has been rarely reported for these chondrites. Here we studied 4 H7, 4 L7, and 4 LL7 in NIPR collections. We also examined Uden (LL7).

All of the chondrites studied here show a well recrystallized texture. Triple junctions among olivine and pyroxene is commonly observed. However, Y-790124 and -790446 include many chondrules, indicative of type 6. A-880844 and -880993 contain clasts of various petrologic types, and are genomict breccias (H5-6 and LL4-6, respectively). Although Y-790144 does not seemto contain any chondrules, it is shock-darkened chondrite, and has lost its original texture.

Y-74160 has been extensively studied [e.g., 4]. This chondrite, Y-791067, and Uden consist of clasts among fine-grained matrix. The clasts comprise coarse-grained olivine, low-Ca pyroxene, and plagioclase. Olivine is typically included as chadacryst in pyroxene. The matrix is also highly recrystallized. Friedrich et al. [5] suggested that Y-74160 and Uden were subjected to Fe-FeS mobilization. These chondrites experienced partial melting, recrystallization, and brecciation, and may be classified as recrystallized breccias.

On the other hand, five chondrites, Y-75008, -790120, and -790960 (H7s), Y-82088 (L7), and Y-82067 (LL7), contain no or only a few relic chondrule in each section. They show highly recrystallized texture, and are not subjected to brecciation and melting. Y-82067 has composition identical to equilibrated LL chondrites [5]. These five chondrites are temporarily classified as type 7, if type 7 chondrite is defined to have experienced only a high degree of thermal metamorphism.

We are now examining modal mineral abundances and conducting mineral analyses, which will shed light on the classification criteria for type 7 chondrites.

References: [1] Dodd et al. (1975) GCA, 39, 1585-1594. [2] Huss et al. (2006) in Meteorites and the Early Solar System II. [3] Mittlefehldt and Lindstrom (2001) MAPS, 36, 439-457. [4] Takeda et al. (1984) EPSL, 71, 329-339. [5] Friedrich et al. (2014) submitted to GCA.

キーワード: 普通コンドライト, タイプ 7 , 熱変成作用
Keywords: ordinary chondrite, type 7, thermal metamorphism

PPS22-03 会場:415 時間:5 月 1 日 09:30-09:45

CR2 コンドライト中に見つかったエクロジャイト的クラストの起源：巨大な微惑星の頻繁な衝突破壊の証拠？
Origin of eclogitic clasts in a CR2 chondrite: Evidence of frequent collisions and disruptions of large planetesimals?

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NWA801 (CR2) コンドライト中に見つかったエコンドライト的クラストは、惑星科学において次のような重要性を持つ (Sugiura et al., 2008; Kimura et al., 2010, 2013): (i) エコンドライトがコンドライトより早く形成された強い証拠である、(ii) クラストにはエクロジャイト的な鉱物相（ザクロ石とオンファス輝石）が含まれており、高圧で生成されたことが示唆される (~3 GPa, ~1000 C; Kimura et al., 2013)、(iii) クラストにはグラファイトを含む岩相 (GBL) と含まない岩相 (GFL) が含まれており、GBL におけるグラファイトの存在はユレイライトとの関連性を示唆する。

我々はクラスト中のいくつかの鉱物に対してイオンマイクロプローブによる酸素同位体分析、希土類元素分析をおこなった (Hiyagon et al., 2014)。本講演では、新しく得られたデータおよび拡散計算をもとに、クラストが巨大微惑星内部での高圧により作られたのか、衝撃圧によりつくられたのかについて議論する。

鍵となる観測事実は次のとおりである。(1) オリビン粒子（~20 ミクロン）は化学的にほぼ均一で Mg# 66-68 を示す。(2) ほとんどの opx（~20 ミクロン）は均一で Mg# 70-75 であるが、大きな opx 粒子 (50-80 ミクロン) には Mg に富むコア（Mg# 78-87）がある。(3) 異なる地質温度圧力計（opx-cpx, garnet-cpx, garnet-opx, garnet-ol の鉱物ペアに対する７つの式）が整合的な温度圧力 (940-1080 C, 2.8-4.2 GPa) を示す。(4) すべての酸素同位体データ (ol +opx) は傾き~0.6 の相関線上に乗る。GFL のデータ (ol) は均一で CCAM line の近くにプロットされ (delta18O ~+5 パーミル) るが、GBL のデータ (ol +opx) は delta18O が+2.4 から+4.4 パーミルまでばらついている。(5) 希土類元素を含む主要な鉱物はクロルアパタイト（軽希土類、重希土類とも）およびザクロ石（重希土類）である。GBL および GFL の希土類元素バルク組成の推定値は、それぞれ~1.2 x CI, ~1.8 x CI の存在度でほとんどフラットなパターンである（分別を示さない）。

二つの岩相のグラファイトの有無は、smelting と呼ばれる反応、FeO (silicate) + C (graphite) = Fe (metal)+ CO (gas)、の有無が関与していると考えられる。すなわち、GBL は微惑星の深い場所で、GFL は微惑星の浅い場所で生成された可能性がある。

我々は、衝撃圧縮モデルおよび静水圧モデルの二つのモデルについて考察する。拡散の計算に基づいて、次のような議論をおこなった。(1) オリビンおよび opx のほとんど均一な Fe/Mg 比（一部の opx には Mg に富むコアが見られる）を説明するためには、~1000 C で 120-800 年間の加熱が必要である。(2)GBL に見られる酸素同位体不均一は、オリビンの Fe/Mg 比が均一化する前につくられている必要がある、(3) 異なる地質温度圧計が整合的な温度圧力を示すためには、異なる鉱物ペア間の異なる元素の分配が平衡に達している必要がある。このことは、静水圧的な高圧モデルを強く示唆する。(5) 異なる地質温度圧力計の示す値の整合性はまた、数百年間の加熱の後に急冷されたことを示唆するが、このことは微惑星の破壊を示唆しているかもしれない。

本研究の結果は、太陽系の進化過程のある段階での、巨大微惑星の頻繁な衝突と破壊を示唆しているのかもしれない。

参考文献：Kimura M. et al. (2010) (abstract) Meteoritics and Planetary Science 45, A105; Kimura M. et al. (2013) American Mineralogist, 98, 387-393; Sugiura N. et al. (2008) (abstract) Meteoritics and Planetary Science 43, A149. Hiyagon H. et al. (2014) in preparation.

キーワード: エクロジャイト, CR コンドライト, 酸素同位体, 希土類元素, 微惑星衝突, 拡散
Keywords: eclogite, CR chondrite, oxygen isotopes, rare earth elements, collisions of planetesimals, diffusion

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

PPS22-04 会場:415 時間:5 月 1 日 09:45-10:00

アングライト母天体の半径の推定
Estimation of the size of the angrite parent body

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アングライト隕石は非常に古い結晶化年代 (4557 - 4564Ma) を持つ隕石であり（Brennecka and Wadhwa, 2012; Kleine et al., 2012）、分化した原始惑星のマグマ固結物（e.g. Prinz and Weisberg 1995; Baker et al., 2005; Weiss et al., 2008; Suzuki, et al., 2012）と考えられている。このため、アングライト隕石は太陽系最初期の分化した微惑星?原始惑星の情報を持つと考えられ、惑星の形成や分化を明らかにする上で重要である。しかし、その母天体は見つかっておらず、その形成進化過程を知る上できわめて重要な情報である天体サイズは不明である。アングライト母天体の半径の下限値は、ダイナモの存在から示唆される核形成のためには、^{26}Al の壊変による発熱で充分長期間にわたって天体内部が高温に保たれている必要があることから半径 100~200km 以上とされている（Weiss et al., 2008; Elkins-Tanton et al., 2011）。一方、半径の上限値は、揮発性成分に乏しいこと（Papike et al., 2003）や、スピネルの反応組織を高圧条件での反応であると考え（Kuehner et al., 2006）から、水星サイズ（半径 2440km）という主張もあるが、まったく制約されていないと言って良い。このため、アングライト母天体半径により強い制約を課す必要がある。

本研究では、アングライト隕石の一つである D'Orbigny に含まれる真球状気泡（Varela et al., 2005; McCoy et al., 2006）に着目して、アングライト母天体の半径の推定を行った。真球状の気泡サイズは 0.3 ? 25 mm（McCoy et al., 2006; Kurat et al., 2004）で、周囲は細粒の初期晶出相である olivine と plagioclase にのみ囲まれており、これらの結晶化開始時に気泡の形が凍結されたことがわかる。冷却速度を計算すると数度/時という速い速度が推定され、D'Orbigny は母天体表層で固化されたと考えて良い。また、気泡の濃集層が存在することから気泡がメルト中を運動していたと考えられる。上昇する気泡の形を支配する無次元数には、慣性力と粘性力の比を代表するレイノルズ数、浮力と表面張力の比を代表するエトベス数、気液密度比、気液粘性率比があり、中でもレイノルズ数とエトベス数は天体の重力に依存するため、母天体の半径の制約に用いる事が出来る。上昇している気泡が球状になるか非球状になるかを分けるレイノルズ数とエトベス数の関係は、Bhaga and Weber (1981) の実験や Hua and Lou (2007) の数値計算結果により推定されている。D'Orbigny マグマのレイノルズ数とエトベス数を計算するにはメルトの密度や粘性を推定する必要がある。特に重要なのは、これらに大きな影響を与える気泡凍結時の温度である。これは、最初に結晶化した olivine の準安定リキダス温度とし、MELTS (Ghiorso and Sack, 1995) を用いて推定した。この他、最大気泡直径 25mm、表面張力を 0.35N/m（Walker and Mullins, 1981）、凍結時の気泡表面の結晶被覆率を 0.5、金属核を持つ天体である 4 Vesta 程度の母天体密度 4000kg/m^3 (Zuber et al., 2011) を用いて、D'Orbigny マグマのアングライト母天体表層でのレイノルズ数とエトベス数の関係を求めた。これらと、球状・非球状領域の境界線との交点から、母天体の半径の上限を 700 ± 100km と推定した。これは、先行研究で主張されていた水星の半径よりかなり小さな値である。

キーワード: アングライト, 微惑星, 母天体半径, 微惑星内部構造, ドビグニー, 原始惑星
Keywords: angite, planetesimal, parent body radius, parent body internal structure, D'Orbigny, protoplanet

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

PPS22-05 会場:415 時間:5 月 1 日 10:00-10:15

Almahata Sittaおよび南極産ユレイライトに見られるα鉄、γ鉄、鉄化合物の結晶化実験

Crystallization experiment of alpha-Fe, gamma-Fe and iron compounds found in the Almahata Sitta and Antarctic ureilites

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Ureilites are ultramafic achondrites whose origin and petrogenesis are still controversial. The cooling rate of ureilites estimated from silicates is approximately a few degrees per hour, and it was considered to reflect catastrophic disruption of the ureilite parent body. Ureilites were broken into meter-sized fragments and then formed daughter body(ies) by re-accumulation.

Fe-Ni metal is one of the major components of all types of ureilites. Almahata Sitta, having fallen on the earth in October 2008, was classified as a polymict ureilite and ureilitic fragments from the Almahata Sitta contain abundant Fe-Ni metal. In previous studies, some grain boundary metals in Almahata Sitta ureilites show unique textures, not found in main group ureilites. These textures show characteristic assemblages with various combinations of α-iron (bcc), γ-iron (fcc), cohenite ($[Fe,Ni]_3C$) and schreibersite ($[Fe,Ni]_3P$).

Those metal textures resemble the product by steelmaking process in the earth, for example martensite (α-iron and γ-iron). Generally, these textures require rapid cooling equivalent to quenching by water (>100 ℃/s). However, the cooling rate estimated from silicates (ca. several ℃/h) is much slower than that in producing the martensite. Thus, these metal textures may record the event separated from the event that recorded in the silicates, that is, disruption of parent body. Therefore, studying these complicated metal textures will contribute to a better understanding of the formation and origin of metal in ureilites with the information about their thermal histories.

Those metal textures were only found in Almahata Sitta fragment #44, in previous studies, but we found similar assemblages composed of iron metal and its compounds in other fragments of Almahata Sitta and Antarctic ureilites. Forms and abundances are variable depending on samples, but it is suggested that those mineral assemblages in Fe-Ni metal are commonly found in ureilites.

To estimate the cooling rate which can form these iron and iron compounds textures, we performed cooling experiments by the electric furnace to heat and quench metal whose compositions correspond to metals showing complex metal phase assemblages in Almahata Sitta ureilite. The results suggest that those metal textures can be achieved in the cooling rate faster than the lowest limit between 10 ℃/s and 0.83 ℃/s, whose chemical composition is $Fe_{79.2}Ni_{3.4}P_{2.5}Si_{2.7}C_{12.2}$. At lower cooling rate (0.83 or 0.04 ℃/s) and 10 ℃/s of other starting material ($Fe_{86.4}Ni_{2.8}P_{0.7}Si_{4.1}C_{6.0}$), interstitial schreibersite among rounded iron was detected and neither cohenite nor γ-iron has been formed. In the carbon-free composition ($Fe_{91.2}Ni_{3.9}P_{0.5}Si_{4.4}$), similar textures were not generated at all cooling rates. This cooling rate, forming metal textures, is much faster than that estimated from silicates, and thus it is concluded that the event recorded by the silicates and the event formed the metal textures were truly separated.

Before disruption of ureilite parent body, primary metals probably melted and mixed with surrounding materials (graphite, phosphide and other iron compounds) to various extents at high temperature. The iron phase was considered to be uniformly γ-iron. Then, the ureilite parent body was destroyed and silicate minerals obtained cooling rate by quenching. Later, daughter body(ies) formed by accumulation of meter-size fragments. If daughter body(ies) was either shocked while still hot or heated by shock and then disrupted into smaller fragments (cm-size), the formation of iron textures may be achieved by super rapid cooling exceeding 1 ℃/s. The metal grains without γ-iron would experience relatively slow cooling due to larger fragment size. Consequently, it is considered that the complex coexistences of iron and iron compounds found in ureilites have recorded temperature change and fragmentation process due to the impacts on the parent body and daughter body(ies).

PPS22-06 会場:415 時間:5 月 1 日 10:15-10:45

原始惑星おける初期衝突現象：玄武岩質隕石からの事実
Early impact events on differentiated protoplanets: Evidence from basaltic achondrites

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Impact events are a ubiquitous geological process on planetesimals and protoplanets, evidenced by the presence of shock and brecciated textures in asteroidal meteorites. However, evidence for early impact events were obliterated by overprints of later thermal events such as volcanism and thermal metamorphism. We investigated early impact events in these meteorites on the basis of mineralogical and geochemical data.

At present, there are ~5 eucrites which were derived from distinct protoplanets. An anomalous eucrite, Ibitira, is a strongly recrystallized rock. Low-Ca pyroxene shows homogeneous compositions, indicating that these rocks experienced prolonged thermal metamorphism (~900-1000 C), as did most basaltic eucrites. The presence of unequilibrated pyroxenes related to oxide grains can be explained by short reheating event (and partial melting) and rapid cooling. Normal eucrites, EET 92023 and Y 86763, and a cumulate eucrite Moore County seem to have experienced a similar history. Most likely explanation for this thermal history is that they were excavated by impact from hot interior.

Anomalous cumulate eucrites Dho 700 and EET 92023 are medium-grained granular rocks similar to cumulate eucrites. Anomalous basaltic eucrite, NWA 011 shows a recrystallized texture. These rocks are crystalline (unbrecciated) but contain significant amounts of impactor materials. Dho 700 and EET 90020 contain taenite which is not common in pristine eucrites. The high abundances of siderophile elements are explained by addition of ~1% iron meteorites. Thus, these rocks experienced impact event before or during crystallization and thermal metamorphism.

All anomalous eucrites studied here show crystalline textures, but have evidence for impact melting or brecciation before thermal events. These meteorites record early collisional history possibly during the stage of runaway growth.

PPS22-07 会場:415 時間:5 月 1 日 11:00-11:15

火星起源隕石 Tissint の衝撃組織の特徴
Shock features in a Martian meteorite, Tissint

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Tissint is the fifth fall Martian meteorite collected in Morocco on 2011 [1]. The nomination of a fall Martian meteorite is since 1962. Tissint will bring new clues for Martian evolution because it is less contaminated with terrestrial materials. Tissint is a member of shergottite. Many shergottites experienced a heavy shock event on Mars [e.g., Ref. 2]. We expected that Tissint should be also heavily shocked. A high-pressure polymorph is one of clear evidences for such a dynamic event. Accordingly, we described shock features, especially a high-pressure polymorph by FEG-SEM, EMPA, Raman spectroscopy and FIB-TEM techniques to clarify shock history recorded in Tissint.

We prepared several petrographic thin sections of Tissint for this study. EMPA analysis show that Tissint studied here consists mainly of olivine (Fa_{18-66}), pigeonite or augite ($En_{43-62}Fs_{23-37}Wo_{10-34}$) and labradoritic feldspar ($An_{62-66}Ab_{34-37}Or_{0-1}$). There are many melt-pockets, which is suggestive of a heavy shock event. FEG-SEM and FIB-TEM observations show that olivine grains entrained in the melt-pockets dissociated into silicate-perovskite (now almost amorphous or poorly-crystallized) and magnesiowustite, which is found in a Martian meteorite DaG 735 for the first time [3]. Silicate-perovskite and magnesiowustite show equigranular texture and less than ˜100 nm in dimension. We also identified ringwoodite lamella in some olivine grains adjacent to the melt-pockets. TEM images show that ringwoodite has a dimension of less than ˜500 nm. Raman spectroscopy analysis indicates that most feldspar now transforms into maskelynite. Jadeite-like crystals appear in some feldspar grain adjacent to the melt-pockets.

Considering the dissociation reaction of olivine into silicate-perovskite and magnesiowustite, shock pressure condition recorded in Tissint is beyond ˜23 GPa based on phase diagram deduced from static synthetic experiments [4]. Phase transformation from olivine to ringwoodite also occurs besides the olivine dissociation reaction. Phase transformation from olivine to ringwoodite occurs instead of olivine dissociation reaction with decreasing temperature but under same pressure condition [5], which is due to thermal gradient in the olivine grains adjacent to the melt-pockets although pressure condition should be almost homogeneous. The nucleation and grain growth of a high-pressure polymorph is kinetically controlled. Baziotis et al. (2013)[6] propose that Tissint experienced the largest impact event among known Martian meteorites because ringwoodite appear to be a huge single crystal based on their SEM observations. However, our TEM images clearly depict that ringwoodite is a fine-grained grain assemblage, suggesting that it is unlikely that Tissint experienced the largest impact event.

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Keywords: Tissint, Martian meteorite, Shock, High-pressure polymorph

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

PPS22-08 会場:415 時間:5 月 1 日 11:15-11:30

EPMA を用いたアポロ衝撃溶融岩片の全岩組成の推定
Estimation of bulk major element composition for Centimeter-Sized Impact Melt Clasts in Lunar Rocks using EPMA

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Most of lunar surface rocks are brecciated and mixed with various types of rock fragments and impact melt clasts during multiple impact events. We are testing the Late Stage Heavy Bombardment on the Moon surface [1-3] using Apollo 16 centimeter-sized impact melt clasts in ancient regolith breccias. Bulk composition is a key to understand original (pre-impact) lithologies where the clasts come from [4, 5]. Large-sized impact melt rocks (>5 cm) have been classified into 4 major group (Group 1 to 4) according to Sm and Sc compositions [6]. We compiled major element compositions of the previously classified impact melt rocks [6] and found that we can classify major impact melt groups even when we use major element compositions. However, our samples, centimeter-sized impact melt clasts, are highly restricted on their masses and makes us difficult to obtain bulk composition using conventional techniques (e.g. INAA and XRF). Defocused beam analyses (DBA) with EPMA is used to estimate the bulk compositions for limited mass samples using petrological sections, however, nobody tested accuracy of DBA techniques using certified geochemical standard.

We use a thin section of BCR-2 (fine-grained basalt supplied from USGS) and tested accuracy of DBA method using an EPMA (CAMECA SX-100) at NASA Johnson Space Center. We measured 12 elements (Na, Mg, Si, Al, P, K, Ca, Ti, Fe, Mn, Cr, and Ni) at >250 points with 20 micrometer beam diameter. We corrected density effect following the Warren (1997) method [7]. Averaged SiO_2 and FeO have larger difference from USGS values (+4.4 wt.% for SiO_2, -4.68 Wt.% for FeO) relative to other elements (up to +/- 2.4 wt.%). Although there are major changes in SiO_2 and FeO values after correct the density effect (difference from USGS values are up to -4.1 Wt.% for SiO_2 and up to +4.6 Wt.% for FeO), we suggest the DBA compositions can useable for the fine-grained materials to estimate the bulk major element composition for Apollo 16 impact melt clasts.

We estimated the bulk composition by averaged DBA method for two impact melt clasts in an Apollo 16 ancient regolith breccia 61135 which have optically different 5 regions (Clast1 R1, R2, and R3; and Clast 2 R1 and R2) to reveal the original lithology of the impact melt clasts. Five regions from the two impact melt clasts can be divided into three chemical groups of high-K, low-K and intermediate compositions. Clast 1 R3 has high K (K_2O=0.72 wt.%) and P (P_2O_5=0.35 wt.%), and low Al (Al_2O_3=20.7 wt.%) and Ca (CaO=12.0 wt.%). On the other hand, Clast 1 R1 and R2 have low K (K_2O=0.31-0.27 wt.%) and P (P_2O_5=0.08-0.07 wt.%) with high Al (Al_2O_3=26.1-25.2 wt.%) and Ca (CaO=14.5-14.0 wt.%). Clast 2, in both dark and bright regions, has an intermediate composition between high-K and low-K melts (e.g. K_2O=˜0.46, P_2O_5=˜0.16 wt.%, Al_2O_3=˜22.9 wt.%, CaO=˜12.8 wt.%). The bulk Mg# of the 5 regions are similar (Mg#=80-78).

If the melts in the two clasts are related, there are two possible origins: (1) A single impact event hit a complex lithological target and incompletely mixed the melts, to produce high-K, intermediate-K, and low-K melt fractions. (2) An impact produced either a high- or low-K melt. A second impact produced a melt at the other end of the K spectrum. The melts in Clast 1 represent those two end member melts. If the second impact melt digested older fragments of the first impact melt, then that may have produced the intermediate compositions of Clast 2. Alternatively, the melts are not related and require three or more impact events.

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キーワード: EPMA, 全岩組成, アポロ 16 号, 衝撃溶融岩片
Keywords: EPMA, Bulk composition, Apollo 16, Impact melt clast

PPS22-09 会場:415 時間:5 月 1 日 11:30-11:45

月隕石におけるシリカ多形の形成過程の解明
Formation processes of silica polymorphs in lunar meteorites

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月面に広く分布する大小様々なクレーターやレゴリスは、隕石や微惑星が月や地球にこれまでに幾度と無く衝突した痕跡であり、このような天体衝突が月や地球の進化、例えばジャイアント・インパクトによる初期地球や月の形成、さらには後期重爆撃期における大量の隕石群の衝突と生命の誕生に寄与したことが知られている。通常、天体衝突の際に発生した高温高圧条件により、惑星から放出された隕石には種々の高圧鉱物が存在する。しかし、月のような大気の無い天体の場合、高圧鉱物が隕石中に残存することは難しいと考えられてきた（Papike 1998; Lucey et al., 2006)。しかし、最近では月隕石である Asuka-881757 や NWA4734 からコーサイトやスティショバイト、ザイフェルタイトなどのシリカ鉱物の高圧相が発見されており、高圧相の生成条件から月面における天体衝突過程の詳細が明らかとなってきた（Ohtani et al. 2011; Miyahara et al. 2013)。

天体衝突時の変成条件は、衝撃銃を用いた動的圧縮実験とマルチアンビルプレスやダイヤモンドアンビルセル（DAC）による静的圧縮実験をもとに決定されている。シリカ鉱物の場合、石英やシリカガラスを出発試料とした高圧実験については数多くの研究がなされているものの、月面に存在すると考えられているクリストバライトやトリディマイトなどのシリカ多形については報告例が少ない。高圧相への転移圧力や温度は出発試料の結晶構造に依存することから（Kubo et al. 2012; Bl*äβ* 2013)、月面における衝突過程の詳細を明らかにするためには種々のシリカ多形に対する高圧実験が必須である。

本研究では、産状を異にする月隕石（斜長岩質礫岩、玄武岩および、斑れい岩質礫岩）を対象としたラマン分光分析、透過型および走査型電子顕微鏡観察ならびに X 線回折分析からシリカ鉱物の同定ならびに記載を行い、高圧実験の結果と比較することで、月面におけるシリカ鉱物の形成過程の解明ならびに各隕石が被った衝撃変成作用の圧力および温度条件の推定を行う。

キーワード: 月隕石, シリカ多形, 高圧鉱物, 天体衝突, 衝突実験, 静的圧縮実験
Keywords: Lunar meteorite, Silica polymorph, High-pressure mineral, Collision, Shock experiment, Static compression experiment

PPS22-10 会場:415 時間:5 月 1 日 11:45-12:00

Discovery of stishovite in an Apollo 15 sample and impact record on the Moon
Discovery of stishovite in an Apollo 15 sample and impact record on the Moon

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Thick regolith layers and many craters on the Moon indicate that the Moon has been heavily bombarded after the lunar formation. Short time intervals of high-pressure and high-temperature occurred on the lunar surface during the collision of asteroids on the Moon, and the constituent minerals of the Moon and asteroids transformed into high-pressure polymorphs during the high-pressure and high-temperature conditions. Although many brecciated lunar rocks have been recovered by the Apollo missions, any high-pressure polymorph has not been observed in Apollo samples so far. Silica is one of constituent minerals of terrestrial planets and asteroid. We investigated a lunar regolith collected by the Apollo 15 mission with a special interest on silica, because high-pressure polymorphs of silica are recently reported from shocked lunar meteorites (Ohtani et al., 2011; Miyahara et al., 2013). Here, we show stark evidence for stishovite from a sample collected by the Apollo 15 mission. X-ray diffraction analysis and transmission electron microscopic observations clearly confirmed the existence of a high-pressure polymorph of silica, stishovite, in the Apollo sample, which suggests that the lunar legolith preserves records of early shock events. Considering radio-isotope ages, lithologies, and shock features, stishovite was formed by an impact event in the near side Moon ca. 3.8-4.1 Ga ago.

キーワード: スイテイショバイト, アポロミッション, 衝突, 高温高圧, 月試料
Keywords: Stishvite, Apollo mission, Impact, High pressure and temperature, Lunar sample

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

PPS22-11 会場:415 時間:5 月 1 日 12:00-12:30

高圧下でのシリカおよび斜長石の非平衡相転移に基づく隕石の衝撃条件の制約
Experimental constrains on shock conditions of meteorites based on non-equilibrium behaviors of silica and plagioclase

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Recent studies on shocked meteorites have revealed non-equilibrium behaviors of silica and plagioclase at high pressures. We focus on the following three points observed in meteorites to deduce the P-T-t shock conditions from high-pressure kinetic experiments. 1) The formation of seifertite as a high-pressure polymorph of silica, 2) The occurrence of jadeite from plagioclase that does not contain stishovite, 3) The formation of lingunite as a high-pressure polymorph of albite-rich plagioclase.

Seifertite is a polymorph of silica with alpha-PbO2 type structure that was found in shocked Martian and lunar meteorites (e.g., Sharp et al., Science1999; Miyahara et al., PNAS2013). Although this phase is thermodynamically stable at more than 90 GPa corresponding to the base of the lower mantle (Murakami et al., GRL2003), it has also been known that it metastably appears from cristobalite at around more than 40 GPa and room temperature (Dubrovinsky et al., CPL2001). We have carried out high-pressure and high-temperature in-situ XRD experiments of cristobalite using a Kawai-type multi-anvil (KMA) apparatus, and determined the formation kinetics of metastable seifertite and the following stable phase of stishovite. Because the activation energy for the seifertite formation is very low (~10 kJ/mol), which is consistent with the recently proposed formation mechanism (Blab, PCM2013), it can metastably appear at low T conditions beyond the negative PT boundary from ~10 GPa and 400C to ~30 GPa and room T. We found the clear difference in the formation kinetics between seifertite and stishovite, which enables to estimate the P-T-t shock conditions from the coexistence of these phases in various ratios in meteorites.

The occurrence of jadeite from plagioclase that does not contain stishovite has been often reported in shocked meteorites (e.g., Kimura et al., MAPS2000). In-situ XRD study using KMA apparatus have revealed that jadeite forms first from (amorphous) plagioclase, whereas the nucleation of other minerals such as stishovite or garnet is significantly delayed (Kubo et al., NGEO2010). The missing stishovite problem can be explained owing to the differences in crystallization kinetics of high-pressure phases from plagioclase. The hybrid shock indicator combining these non-equilibrium behaviors of silica and plagioclase mentioned above consistently and strongly constrains the P-T-t shock conditions of Martian meteorites.

The formation of lingunite (albite-rich hollandite) in shocked meteorites (e.g., Gillet et al., Science2000; Tomioka et al., GRL2000) has remained unsolved. This phase appears in lase-heated diamond anvil cell (LHDAC) experiments as a minor phase at around ~20-24 GPa and ~1000C (Liu, PEPI1978) and ~2000C (Tutti, PEPI07). However, KMA experiments indicate that the maximum solubility of NaAlSi3O8 component in hollandite structure is limited to ?50 mol% (Yagi et al., 1994, Liu, 2006). This clear contradiction may be due to the non-equilibrium origin. It has been suggested that the rapid T quenching in LHDAC experiments is important for the survival of lingunite metastably to the ambient condition. Our previous in-situ XRD study using KMA apparatus have indicated that lingunite is not formed at least ~1200C at these pressure conditions (Kubo et al., NGEO2010). We are also preliminarily conducting some LHDAC experiments, however we have not observed lingunite at least ~1400C. Further studies on the formation process of lingunite are needed to solve this problem, which may lead to construct another P-T-t shock indicator.