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

PPS22-01 Room:415 Time:May 1 09:00-09:15

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.

Keywords: Chelyabinsk meteorites, Meteoroid impacts, Inhomogeneity

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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.

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Keywords: ordinary chondrite, type 7, thermal metamorphism

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PPS22-03 Room:415 Time:May 1 09:30-09:45

Origin of eclogitic clasts in a CR2 chondrite: Evidence of frequent collisions and disruptions of large planetesimals?

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Achondritic clasts found in the Northwest Africa 801 (NWA801) CR2 chondrite have significant importance in planetary science (Sugiura et al., 2008; Kimura et al., 2010, 2013): (i) it provides strong evidence that achondrites formed earlier than chondrites, (ii) the clasts contain eclogitic high mineral assemblages (garnet and omphacite), suggesting formation at a high pressure (~3 GPa and ~1000 C; Kimura et al., 2013), and (iii) the clasts contain two lithologies, graphite-bearing (GBL) and graphite-free (GFL), and the presence of graphite in GBL implies some relations to ureilite.

We performed ion microprobe studies of oxygen isotopes and rare earth element (REE) abundances for selected minerals in the clasts (Hiyagon et al., 2014). Based on the newly obtained data and diffusion calculations, we discuss possible origin of the clasts, esp., whether they formed under a static high pressure in a large planetesimal or formed under a shock high pressure.

Key observations are as follows. (1) Olivine (ol) grains in the clasts (~20 micrometers in size) are chemically homogeneous with Mg# 66-68. (2) Most of orthopyroxene (opx) grains (~20 micrometers in size) are homogeneous with Mg# 70-75, but a few large opx grains (50-80 micrometers in size) have Mg-rich cores with Mg# 78-87. (3) Various geothermobarometers (7 equations for mineral pairs of opx-cpx, garnet-cpx, garnet-opx and garnet-olivine) consistently give a high P-T condition of 940-1080 C and 2.8-4.2 GPa. (4) All the oxygen isotopic data of ol and opx fall on a correlation line with a slope of ~0.6. Data for GFL (ol) are homogeneous with delta18O ~+5 permil, located close to the CCAM line and the ureilite field, but data for GBL (ol +opx) are variable with delta18O from +2.4 to +4.3 permil. (5) Major host minerals of REEs are chlorapatite (both LREEs and HREEs) and garnet (for HREEs). The estimated bulk REE patterns for GBL and GFL are almost flat (unfractionated) with ~1.2 x CI and ~1.8 x CI, respectively.

We consider that the presence/absence of graphite in the two lithologies may be due to absence/presence of smelting reactions, FeO (in silicates) + C (graphite) = Fe (metal) + CO (gas). This means that GBL might form at a deeper portion and GFL might form at a shallower portion, respectively, of a planetesimal.

We consider two different models: a shock high-P model and a static high-P model. Based on careful diffusion calculations, we argue that (1) almost homogeneous Fe/Mg ratios in ol and opx (with some Mg-rich cores) can be explained by heating at 1000 C for 120-800 years, (2) oxygen isotopic variations in GBL must have established before homogenization of Fe/Mg ratios in olivine, (3) consistency of different geothermobarometers requires equilibration of different elements among different mineral pairs, strongly suggesting a static high-P model, (4) in a static high-P model, ~3 GPa corresponds to the pressure at the center of a large planetesimal with a radius of ~1500 km, almost the size of the Moon, (5) consistency of different geothermobarometers also suggests a rapid cooling after heating several hundreds of years at ~1000 C at ~3 GPa, suggesting possibe disruption of the parent body.

In conclusion, the present results suggest frequent collisions and disruptions of a large planetesimals at a certain stage of the solar system evolution.

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Keywords: eclogite, CR chondrite, oxygen isotopes, rare earth elements, collisions of planetesimals, diffusion

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PPS22-04 Room:415 Time:May 1 09:45-10:00

Estimation of the size of the angrite parent body

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Angrites has very old crystallization age yielding 4557 - 4564Ma (Brennecka and Wadhwa, 2012; Kleine et al., 2012) and are igneous rocks come from differentiated planetesimal or protoplanet (e.g. Prinz and Weisberg 1995; Baker et al., 2005; Weiss et al., 2008). Angrites preserve information on such differentiated planets, and are one of the best targets for studying processed operated in the early stages of planetary evolution of the solar system. However, the angrite parent body has not been found, and we have scarce knowledge on its planet size, which is one of the most important information in planetary science. The radius of angrite parent body is believed to be larger than 100 ? 200km because of the operation of dynamo, which requires prolonged high temperature of the planet interior due to heat production of ^{26}Al decay to achieve its core formation (Weiss et al., 2008; Elkins-Tanton et al., 2011). The upper limit of radius is not constrained at all, although 2440km is proposed based on ambiguous evidence for Mercury as the angrite parent body (Papike et al., 2003; Kuehner et al., 2006). The radius of the angrite parent body, particularly its upper limit, needs to be further constrained. In this study, we try to constrain the upper limit of the planet size from the presence of spherical voids as large as 25mm in D'Orbigny angrite.

D'Orbigny has many spherical voids suggesting that they formed in 100% molten magma before crystallization. The vesicles are deformed while ascending in the melt depending on several physical parameters such as, melt viscosity and the size of vesicles. There are two dimensionless numbers that determine the shape, Reynolds number and Eotvos (or Bond) number. Reynolds number is a ratio of inertia force and viscous force and Eotvos number is a ratio of buoyancy force and surface tension. These two numbers depends on gravity of the parental body, and the gravity depends on the radius of the parental body. Therefore, spherical shape of the largest void enables us to estimate the upper limit of the radius of the angrite parent body. The boundary conditions for spherical and nonspherical regimes have been determined by Bhaga and Weber (1981) based on fluid dynamic experiments and by Hua and Lou (2007) based on numerical simulations.

Spherical voids in D'Orbigny are armored by fine-grained olivine and plagioclase crystals, where are the first liquidus phases, suggesting that the spherical shape was frozen by heterogeneous nucleation and growth of these phases on the bubble wall. In order to know relationship between Reynolds and Eotvos numbers for D'Orbigny, accurate estimation of density and viscosity is very important, which are strongly dependent on temperature of shape freezing. The temperature was estimated by MELTS (Ghiorso and Sack, 1995) as metastable olivine liquidus for the D'Obigny bulk composition to be ˜1100 ℃, from which the density and viscosity of D'Obigny magma are estimated to be ˜3000 kg/m^3 and ˜1.0 Pa s, respectively. Surface tension of the melt is 0.35N/m according to Walker and Mullins (1981), which is corrected by 50% occupation of olivine and plagioclase on the bubble-melt interface. We assume the average density of the parent body as 4000kg/m^3 for the planet having core, such as asteroid 4 Vesta (Zuber et al., 2011). By using these parameters, we estimated the upper limit of radius to be 700$\pm$100 km, which is clearly much smaller than that of Mercury.

Keywords: angite, planetesimal, parent body radius, parent body internal structure, D'Orbigny, protoplanet

PPS22-05 Room:415 Time:May 1 10:00-10:15

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).

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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 90020 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 92023 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.

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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

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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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Keywords: EPMA, Bulk composition, Apollo 16, Impact melt clast

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Formation processes of silica polymorphs in lunar meteorites

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Asteroid and meteorite collisions lead to formation of impact craters and thick regoliths on the Moon and also contribute to revolution of the Earth, e.g. Giant impact, the late heavy bombardments and the origin of life. Although lunar meteorites and Apollo samples have experienced such impact events during the ejection from the lunar surface or formation of immense basin, they were believed to contain few high-pressure mineral because of the volatilization during collision in the high vacuum (Papike 1998; Lucey et al., 2006). Recently, Ohtani et al. (2011) and Miyahara et al. (2013) discovered high-pressure silica polymorphs (coesite, stishovite and seifertite) in lunar meteorites, Asuka-881757 and NWA4734. Their existences provide constraints on the shock condition and give us valuable information on impact history on the Moon and the Earth.

The shock condition of meteorites has been estimated based on the pressure-temperature phase diagram obtained from high-pressure experiments using shock gun, multi-anvil press and diamond anvil cell (DAC) for various types of minerals including in silica polymorphs. There have been many investigations of the high-pressure experiments for quartz and amorphous silica glass, but not for the other polymorphs, regardless of dominant occurrence of cristobalite and tridymite in lunar meteorites. Since the transition pressure to high-pressure phase depends on a type of starting material (Kubo et al. 2012; Bl$\ddot{a}\beta$, 2013), it is necessary for understanding the detailed impact history of the Moon to conduct the high-pressure experiments for various types of silica polymorphs.

In this study, silica polymorphs in various types of lunar meteorites (anorthositic breccia, basalt, and gabbro and basalt clast-dominated breccia) were described using Raman spectroscopy, Scanning and Transmission Electron Microscope and X-ray diffraction analysis and the obtained results were compared with the data of high-pressure experiments for various types of silica polymorphs to clarify the phase transition process, interpret the formation process on the Moon and constrain shock pressure and temperature that the lunar meteorites have experienced.

Keywords: Lunar meteorite, Silica polymorph, High-pressure mineral, Collision, Shock experiment, Static compression experiment

PPS22-10 Room:415 Time:May 1 11:45-12:00

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.

Keywords: Stishvite, Apollo mission, Impact, High pressure and temperature, Lunar sample

PPS22-11 Room:415 Time:May 1 12:00-12:30

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.

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

PPS22-P01 Room:Poster Time:May 1 18:15-19:30

Laboratory impact experiments of rock projectiles onto simulated asteroid regolith: Impactor fragmentation and capture

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We conducted laboratory impact experiments of rock projectiles onto target consist of silica sand used as simulated regolith surface. We investigate the relationship between degree of projectile fragmentation and impact velocity and particle size of silica sand.

Laboratory impact experiments have been performed to study the degree of target fragmentation, however, much less attention has been paid to the fate of the impactors. Experiments with impact velocity lower than 1 km/s were conducted using a powder gun and a gas gun at Kobe University, while experiments with higher impact velocity up to 5 km/s were conducted using a two-stage light-gas gun at Institute of Space and Astronautical Science. We collected the projectile fragments in the sand and weighed the mass of the largest fragments.

Destruction of rock projectiles is found to occur when the peak pressure is about equal to the dynamic tensile strength of the rock in the low velocity impact experiments (Nagaoka et al., 2014, MAPS). The largest fragment mass fractions in the high velocity impact experiments are higher than the expected from the result of low velocity impact experiments. The discrepancy is larger for the target with smaller silica sand particles. The larger fragments consist of multiple fragments and silica sand particles which were consolidated into larger particles by compression and the heating due to compaction of silica sand.

Keywords: meteorites, impact process, asteroids

PPS22-P02 Room:Poster Time:May 1 18:15-19:30

Secondary Ion Mass Spectrometry (SHRIMP) U-Pb dating of Chelyabinsk meteorite

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On Feburuary 15,2013, a meteorite fell into the area of Chelyabinsk in Russia .The petrographic and chemical analysis of the Chelyabinsk meteorite unambiguously classifies it as an LL5 ordinary chondrite (Galimov et al.2013). The reported Sm-Nd age of 3.7 Ga and Rb-Sr age of 0.29 Ga suggest that the Chelyabinsk meteorites could have suffered from the secondary event possibly due to shock metamorphism.For further understanding of the thermal history of Chelyabinsk meteorite, we carried out an in-situ U-Pb dating of phosphates of which closure temperatures is high (~600 ℃), using Hiroshima-SHRIMP.(Sensitive High-Resolution Ion MicroProbe).

Keywords: Chelyabinsk meteorite, SHRIMP, phosphate, U-Pb dating

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PPS22-P03 Room:Poster Time:May 1 18:15-19:30

Crystallization and subsolidus processes of the NWA 6704 ungrouped achondrite

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Introduction: NWA 6704 is an unique ungrouped achondrite. It consists of low-Ca pyroxene, less abundant olivine and plagioclase, minor chromite and merrilite, and trace awaruite, heazlewoodite, and pentlandite (1, 2). Although its bulk oxygen isotopic ratio is within the ranges of the acapulucoite-lodranite and CR chondrites, its petrography and mineralogy are evidently different from both of them (1). The U-Pb dating of this meteorite gives a $^{207}Pb/^{206}Pb$ date of 4563.75 +/- 0.41 Ma (3). To deduce its formation processes is important to understand formation of its parent body that may have predated the formation of chondrite parent bodies.

Methods: Polished thin sections were investigated by optical microscopes, electron microprobe analyzer (EPMA), field-emission scanning electron microscope (FE-SEM), Raman spectroscopy, and electron backscattered diffraction (EBSD).

Results: The most abundant mineral in NWA 6704 is orthopyroxene containing blobs of augite. Both Raman spectroscopy and EBSD data indicate that this pyroxene is orthopyroxene. The texture of the blob-bearing orthopyroxene is very similar to Kintokisan-type orthopyroxene (inverted pigeonite) (4). We call it early formed (ef-) pigeonite. There are another less abundant low-Ca pyroxenes: augite blob-free orthopyroxene, and pigeonite containing sub-micrometer-size augite exsolution lamellae. Here we call them primary orthopyroxene and later formed (lf-) pigeonite. Lf-pigeonite occurs as coherent overgrowth of the primary orthopyroxene and discrete grains in the interstices of large ef-pigeonite. Lf-pigeonite also occur as inclusions in olivine. Based on the EBSD data, modal abundances of ef-pigeonite, olivine, lf-pigeonite, primary orthopyroxene, feldspar, chromite, awaruite are 67.2, 16.8, 3.4, 0.6, 10.9, 0.4, and 0.4 vol.%, respectively. Crystallization sequence estimated based on the petrography is following: primary orthopyroxene =>awaruite =>ef-pigeonite =>chromite =>lf-pigeonite =>olivine =>augite (quite rare crystallized from melt) =>heazlewoodite =>pentlandite =>merrilite =>feldspar. Early formed pigeonite (blob-bearing orthopyroxene) shows a LPO of the [010] axis. Lf-pigeonite contains complex exsolution lamellae of augite. The thickest lamellae have ˜0.2 micrometer in width and 1-2 micrometer wavelength. Finest lamellae have <0.1 micrometer thick and ˜0.2 micrometer wavelength.

Discussion: Because [010] lattice preferred orientation of pyroxene in terrestrial rocks has been interpreted as settling of tabular pyroxene crystals in a stagnant magma chamber (5), ef-pigeonite could have settled in a stagnant magma chamber. Presence of Fe^{3+} in chromite and high NiO concentration in olivine (0.89 wt.% on average) suggest that this meteorite crystallized under an oxidized condition. About 1100 ^oC equilibrium temperature was estimated by using two pyroxene geothermometry and ˜950 ^oC by using olivine-spinel geothermometry. These high temperatures suggest that the meteorite cooled rapidly in this range of temperature. Multiple exsolution lamellae with thickness and wavelength similar to this meteorite were observed in Zagami martian meteorite. Its cooling rate between 1100 ^oC to 950 ^oC was estimated to be ˜0.02 ^oC/hr (6). This meteorite could be cooled as slow as Zagami did. Further studies are needed to clarify if a monotonous cooling can accomplish both high equilibrium temperatures estimated by geothermometers and sub-micrometer-size exsolution lamellae in lf-pigeonite. NWA 6704 has petrography similar to that of NWA 6693. However, there is a stark difference between these two meteorites. Blob-bearing orthopyroxene is the most abundant pyroxene in the former. On the other hand, low-Ca pigeonite is the most abundant in the latter. Therefore, it is possible that NWA 6704 is not mere a pair of NWA 6693.

References: (1) Irvine et al. (2011), (2) Warren et al. (2012), (3) Iizuka et al. (2013), (4) Ishii and Takeda (1974), (5) Jackson (1961), (6) Brearley (1991).

Keywords: NWA 6704, achondrite

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PPS22-P04 Room:Poster Time:May 1 18:15-19:30

Petrologic type from plagioclase size distribution

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Ordinary chondrites are classified into petrologic types 3-6, reflecting thermal metamorphism. One of the criteria to classify types 5 and 6 is the size distribution of plagioclase. The size, 50 microns, has been commonly used to classify types 5 and 6. However, no any statistic study for plagioclase size has been conducted. Here we measured the size distribution, and discuss the classification of types 5 and 6. We studied 26 thin sections of types 5 and 6 from the H, L, and LL chondrite groups. Our study indicates that plagioclase of 50 microns are commonly encountered both in types 5 and 6. However, plagioclase of 80-100 microns is more abundant in type 6 than type 5. We also noticed that the size distribution of plagioclase in H6 is similar to that in type H5. The different criteria to classify H from L and LL are necessary.

Keywords: ordinary chondrite, petrologic type, plagioclase, thermal metamorphism

PPS22-P05 Room:Poster Time:May 1 18:15-19:30

Systematic isotopic studies of REE, Sr and Ba in eucrites

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The eucrites is meteorites that probably originate from the crust of asteroid 4-Vesta. Cosmochemical and chronological information of eucrites puts important constraints of on the evolutional history of the eucrite parent body (EPB). In this study, systematic istopic isotopic studies of Sr, Ba, Ce, Nd, Sm and Gd were performed on eight eucrites for better understanding of differentiation on the EPB. ^{138}Ce, ^{142}Nd, and ^{143}Nd include radiogenic components, and their isotopic variations correlate with La/Ce and Sm/Nd elemental ratios, respectively. The results were consistent with the isochron from previous studies (Makishima and Masuda, 1991; Boyet and Carlson, 2005; Andreasen and Sharma, 2007). The Rb-Sr chronometer consisting of ^{87}Sr/^{86}Sr and Rb/Sr for these eucrites is now in progress. Sm and Gd isotopic compositions of the eucrites showed the isotopic shifts caused by neutron caputure reactions due to cosmic rays irradiation. These isotopic shifts correspond to the neutron fluences ranging from 0.28 to 4.05 $\times$ 10^{15} n cm^{-2}, but these are almost consistent with their cosmic-ray exposure ages, suggesting no strong evidence of initial cosmic-ray irradiation on the surface of EPB. Most previous Ba isotopic studies of meteorites focused on the variation of r- and s-process nucleosynthetic components due to additional inputs in the early solar system. ^{135}Ba and ^{137}Ba isotopes are sensitive to s- and r-process variations, and often have deficits and/or excesses in chemical separates in carbonaceous chondrites due to the existence of presolar grains. In case of eucrites, there are no isotopic variations of all Ba isotopes, but some samples showed the slight excess of radiogenic ^{135}Ba probably from ^{135}Cs decay. Systematic isotopic data obtained in this study provide a hint to understand the evolution processes of differentiated meteorites. We are now applying this technique for the analyses of cumulate eucrites and diogenites.

Keywords: eucrite, REE, chronology, isotope

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PPS22-P06 Room:Poster Time:May 1 18:15-19:30

Preliminary experiments on the formation process of lingunite in shocked meteorites

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Albite-rich hollandite (lingunite) has been frequently found in shocked meteorites with other high-pressure minerals (Gillet et al., 2000; Tomioka et al., 2000). According to the laser-heated diamond anvil cell (LHDAC) experiments by Liu (1978), following the decomposition of albite ($NaAlSi_3O_8$) into jadeite ($NaAlSi_2O_6$) plus quartz (SiO_2) at 2-3 GPa, these phases recombine to form lingunite in the range of pressure between 21 and 24 GPa at about 1000 ℃, and then it decomposes again into calcium ferrite-type NaAlSiO4 plus stishovite at pressures above 24 GPa. Similarly, Tutti (2007) observed $NaAlSi_3O_8$ lingunite at 21-23 GPa and 2000 ℃ using LHDAC. In contrast to these LHDAC studies, high-pressure experiments using multi-anvil type (MA) apparatus revealed that the maximum solubility of $NaAlSi_3O_8$ component in hollandite structure is limited to ˜50 mol% at 14-25 GPa and 800-2400 ℃ (Yagi et al., 1994, Liu, 2006). This contradiction has not been solved yet, which makes it difficult to understand the shock conditions for the presence of lingunite in shocked meteorites. Tutti (2007) suggested that the stability of lingunite might be sensitive to temperature and could transform back when quenching rate is slow like MA experiments. However, the formation conditions of lingunite has not been well constrained even by LHDAC experiments.

To investigate the formation process of lingunite, we preliminarily carried out LHDAC experiments using a powder of natural albite as a starting material. The samples were compressed at room temperature, and then heated by the double-sided laser heating method using a Nd:YAG laser. The emission spectra were measured on both side of the heated sample, and used to estimate temperature. Heating duration at the maximum temperature was several minutes. Recovered samples were analyzed by X-ray diffraction method at BL-ARNE7 and BL-ARNE1 of photon factory, KEK. The results obtained suggest that jadeite and stishovite are present at 22 GPa and 1230 ℃. The assemblage changed into calcium ferrite-type structure and stishovite at 25 GPa and 1400 ℃. Hydrous aluminum silicate (phase egg) was also present in both samples probably due to the effect of absorbed water in the powdered stating material. We measured X-ray diffraction patterns at several points in the sample, which showed changes of the ratio of the constituent minerals due to the presence of pressure and temperature gradients, however we did not observe lingunite in any measured points. Although experimental conditions are still rather limited, our preliminary results suggest that the formation condition of lingunite is more than 1400 ℃ at these pressure ranges.

Keywords: lingunite, high pressure, LHDAC, shocked meteorite