Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

PPS22-01 Room:A02 Time:May 28 09:00-09:30

# Formation ages and places of hydrated chondrite parent bodies

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When and where hydrated chondrite parent bodies accreted is a key question to understand the origin of chondritic water and the dynamical processes of the solar system evolution.

The ages of aqueous alteration can be inferred from $^{53}$Mn-$^{53}$Cr systematics of aqueously-formed secondary minerals (carbonates in CM, CI, and CR chondrites and fayalite in CV, CO, and ordinary chondrites). The $^{53}$Mn-$^{53}$Cr ages of carbonates and fayalite in carbonaceous chondrites (CCs) are similar, 3.5 – 5 Myr after the birth of the solar system (represented by CAIs in CVs) (Fujiya et al., 2013; Doyle et al., submitted). Fayalite in ordinary chondrites (OCs) seems to have formed slightly earlier ($\sim$1 Myr) than that in CCs. These observations are consistent with $^{26}$Al-$^{26}$Mg ages of chondrules (e.g., Kita and Ushikubo, 2012). The $^{53}$Mn-$^{53}$Cr ages of aqueous alteration indicate that water activity on CC and OC parent bodies started almost contemporaneously, and that the dominant heat source for aqueous alteration is the decay energy of $^{26}$Al (half-life: 0.7 Myr). Based on these ages, numerical simulations of the thermal history of CC and OC parent bodies suggest that they accreted 2.5 – 4 Myr after CAIs (Sugiura and Fujiya, 2014).

The formation places of chondrite parent bodies in the protoplanetary disk are more difficult to be inferred. The estimated water (ice) to rock mass ratios of CCs and OCs ($<$0.6) (e.g., Clayton and Mayeda, 1999), significantly lower than the solar value (1.2) (Lodders, 2003), suggest that CC and OC parent bodies accreted near from the snow line. The inferred D/H ratios and O isotopic compositions of water in CCs are likely to be significantly different from those of primordial (molecular cloud) water and/or most Oort-cloud comets measured so far, indicating that they must have recorded various degrees of isotopic re-equilibration between primordial water and nebular gas (Alexander et al., 2012; Krot et al., 2013). Model predictions on the location of the snow line 2.5 – 4 Myr after CAIs (e.g., Ciesla and Cuzzi; 2006) and both the temporal and the spatial distribution of H and O isotopic ratios of water in the protoplanetary disk (e.g., Yang et al., 2011, 2013) suggest that hydrated chondrite parent bodies accreted in the main asteroid belt. I am currently trying to constrain the contribution of C from cometary inorganic ice to the C inventory in CCs. Carbon isotopic ratios of carbonates in Murchison (CM) suggest that C reservoirs in primitive aqueous fluids were highly enriched in $^{13}$C with $\delta^{13}$C $>$70 ‰, which provides no evidence for C contribution from cometary ice (Fujiya et al., submitted).

Keywords: Hydrated chondrites, Formation ages, Formation places, Compositions of stable isotopes

Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

PPS22-02 Room:A02 Time:May 28 09:30-09:45

# Aqueously altered clasts in the NWA1232 CO3 carbonaceous chondrite

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CO parent bodies are generally believed to have escaped significant degree of brecciation. However, Northwest Africa 1232 (NWA1232) CO3 chondrite is a breccia consisting of three distinct lithologies (A, B, and C) that have experienced different degrees of thermal metamorphism [1,2]. Recently, we found that lithology A, which is the host lithology of NWA1232, contains numerous small clasts (100-1800 $\mu$m in diameter) of different metamorphic grades [3,4]. Most of the clasts show little evidence of thermal metamorphism and contain significant amounts of hydrous minerals. These characteristics have not been known in other CO3 chondrites and potentially provide new insights into the formation of CO3 chondrites. Here, we report the results of detailed mineralogical and petrographic study of the hydrous clasts in NWA 1232. We used SEM-EDS, TEM (STEM)-EDS, EPMA-WDS, and SR-XRD.

Small clasts occur abundantly throughout lithology A. Among them, hydrous clasts are most abundant and comprise ~2 vol.% of lithology A. Each of the clasts typically consists of one chondrule surrounded by a fine grained matrix, exhibiting the appearance of a chondrule with a rim. Some clasts contain multiple chondrules and CAIs embedded in a matrix.

Most chondrules in the clasts are Mg-rich Type I, and their olivine phenocrysts have homogeneous low Fe compositions (~$Fa_1$) and show almost no Fe-Mg zoning; these are similar to those in CO3.0 chondrites. Enstatite phenocrysts and mesostasis were partially replaced by fine grains (10-20 nm) of phyllosilicates and an Fe-Si-Mg-rich amorphous material. The amorphous material contains small amounts of fine olivine grains ($<$100 nm). High-resolution TEM observations reveal that the most abundant phyllosilicate exhibits ~0.7 nm basal spacing; thus, it is serpentine. Minor amounts of smectite with 1.0-1.1 nm basal spacing, were also observed. These phyllosilicates are compositionally indistinguishable from the amorphous material.

The rim-like matrix surrounding the chondrules mainly consists of an Fe-Si-Mg rich amorphous material, and contains relatively coarse grains (1-2 $\mu$m) of magnetite, forsteritic olivine, enstatite, fine grains (100-500 nm) of olivine, troilite, and finer grains (10-20 nm) of serpentine. The amorphous material is compositionally indistinguishable from the serpentine and mineralogically and compositionally similar to that within the chondrules.

Our results suggest that the clasts have experienced weak aqueous alteration in the meteorite parent body. However, the evidence of aqueous alteration was not observed in the outside of the clasts. These suggest that the clasts were formed and transported from a region in the parent body that was different from the region where the meteorite was finally lithified, and subsequently they were incorporated into lithology A. We note that the mineralogical and compositional characteristics of chondrules and matrix in the clasts are similar to those in the primitive CO3.0 chondrite ALHA77307 [5].

References: [1] Kiriishi and Tomeoka (2008), JMPS, 103, 161-165. [2] Umehara et al. (2009), JAMS Annual Meeting (abstract). [3] Kiriishi et al. (2009), JAMS Annual Meeting (abstract). [4] Matsumoto et al. (2014), JpGU Meeting (abstract). [5] Brearley (1993), GCA, 57, 1521-1550.

Keywords: CO chondrite, clast, brecciation, aqueous alteration, TEM, SR-XRD

PPS22-03 Room:A02 Time:May 28 09:45-10:00

# Hydrothermal alteration experiments of MgO-SiO2 amorphous silicates

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Hydrothermal alteration is one of the important processes for solid evolution in the early solar system. So far, many experiments have focused on reaction between aqueous fluids and meteorite itself or crystalline silicates, such as olivine and pyroxene (e.g., [1, 2]). Reaction with amorphous silicates is also important because interstellar dust as original building blocks of planetesimals is mostly amorphous [3] and primitive amorphous silicates are present in cometary dust as GEMS (e.g., [4]) and some carbonaceous chondrites (e.g., [5]). Hydrothermal alteration experiments with amorphous silicates were also carried out using natural GEMS [6] and synthetic materials with CI composition [7]. However, any experiments using amorphous silicates in a simple system have not been made. In this study, hydrothermal alteration experiments of amorphous silicates in the system MgO-$SiO_2$-H2O were carried out to understand basic features of hydrous layer silicate formation.

Nanoparticles of amorphous silicates ~10 nm in size with nearly enstatite and forsterite compositions (E and F: Mg/Si = 1.15 and 2.02) were synthesized by the induction thermal plasma method as starting materials. Intermediate compositions were also prepared by mixing E and F (ME, M and MF: Mg/Si=1.25, 1.5 and 1.75). Three types of experiments were made. (1) Synthetic experiments: Starting materials and pure water (water/rock ratio: W/R=5.0) were sealed and heated at 50, 100, 150 and 200$^o$C or held at room temperature for 0 to 1344 hrs. The run products were dried in vacuum and examined by powder X-ray diffraction (XRD) and SEM/EDX. (2) In-site experiments: Starting materials mixed with pure water (W/R=5.0) were exposed in water-saturated atmosphere at 60$^o$C and repeatedly measured by in-situ powder XRD (total duration: 9-292.5 hrs.). The final run products were dried in vacuum and measured again by powder XRD. (3) Swelling experiments: some dried run products were immersed in ethylene glycol, glycerol or water and measured by powder XRD to check swelling.

Layer silicates formed in all the run products even at room temperature. Brucite and sometimes magnesite were formed in runs using F. XRD reflection peaks of the layer silicates are week and broad particularly for the (001) peak suggesting that they are thin and have low crystallinity. The (001) lattice spacing and the chemical compositions of the run products together with the results of the swelling experiments indicate that the layer silicates are disordered mixed layer minerals of stevensite (Mg-smectite) or vermiculite, serpentine and talc. The (001) peak becomes sharper to some extent and shift to higher 2$\theta$ (smaller lattice spacing) with increasing run duration or temperature except for runs using E. The crystallinity and degree of mixing order also changed by drying process. The experimental results can be explained by that aqueous solutions of high degree of supersaturation with respect to layer silicate minerals formed by instantaneous dissolution of metastable amorphous silicate nanoparticles with high reactivity, and disordered mixed layer minerals metastably formed from these solutions. The presence of disordered mixed layer minerals in some carbonaceous chondrites, such as in CI [8], indicates that they formed from amorphous silicates. It should also be noted that we could not discuss hydrothermal conditions based on the present features of layer silicate minerals in meteorites, as they could be different from those during hydrothermal alteration.

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Keywords: hydrous layer silicate, hydrous alteration, carbonaceous chondrites, induction thermal plasma method, disordered mixed layer minerals

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PPS22-04 Room:A02 Time:May 28 10:00-10:15

# Hydrothermal and heating experiments: Implications for formation process of nepheline in carbonaceous chondrite

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Nepheline ($NaAlSiO_4$) and sodalite ($Na_4Al_3Si_3O_{12}Cl$) are widely distributed in chondrules and matrices of CO/CV chondrites (Kimura et al. 2014; Matsumoto et al. 2014). Because of the low condensation temperatures of such Na-rich minerals, these are likely not primary phases condensed from the solar nebula, but are secondary phases altered from melilite or plagioclase. According to previous petrographic studies (e.g. Russell et al., 1998; Tomeoka and Itoh, 2004), nepheline and sodalite are considered to form by hydrothermal processes on their parent body. Because of the high volatility and high mobility, Na element is potentially a powerful indicator reflecting aqueous environments of the chondrite parent bodies. In this study, we performed hydrothermal alteration experiments to understand the formation process of Na-rich minerals in chondrite parent bodies.

We used i) synthetic melilite (gehlenite, $Ca_2Al_2SiO_7$) + $SiO_2$, and ii) natural plagioclase ($An_{48}$) as starting materials. Four reaction solutions of 1N (mol/l)-NaOH (pH 0), $H_2O$ (pH 7), 0.1N-NaOH (pH 13) and 1N-NaOH (pH 14) were reacted with three different water/rock ratios (10, 100 and 1000). $Na^+$ concentration in all solutions was maintained at 1 mol/l by addition of NaCl. Hydrothermal alteration experiments were performed with a PTFE reaction vessel loaded into steel autoclave and were carried out at temperature at 200 ℃ and pressure of 1.5 MPa for run duration time of 168 hours. The recovered samples were analyzed by XRD, SEM, TEM, and TG-DTA.

In the experiments using melilite+$SiO_2$ with W/R = 100 and pH 7-14 solutions, hydrogrossulor ($Ca_3Al_2[SiO_4]_{1.6}[O_4H_4]_{1.3}$) formed as a secondary phase with low $SiO_2$ contents, while analcime ($NaAlSi_2O_6H_2O$), nepheline-hydrate ($NaAlSiO_4H_2O$), basic-cancrinite ($Na_8Al_6Si_6O_{24}[OH]_2\bullet 2H_2O$) and tobermorite ($Ca_5Si_6O_{16}[OH]_2\bullet 4H_2O$) formed with high $SiO_2$ contents. Although no secondary phase was observed at high W/R (=1000), analcime and basic-cancrinite occurred at low W/R (=10). Under the pH 0 solution, melilite was dissolved and no secondary phases formed. In the experiments using plagioclase with W/R = 100 and pH 0-7 solutions, no secondary phases formed. On the other hand, under pH 13-14 solutions, analcime and nepheline-hydrate formed with W/R = 10 and 100.

A TG-DTA of nepheline-hydrate at heating rate 5 ℃/min in air showed that the dehydration started at ˜100 ℃ and finished at ˜800 ℃. From the DTA and XRD data of this condition, nepheline-hydrate is considered to be transformed into nepheline at ˜800 ℃. From the TG-DTAs of nepheline-hydrate with different heating rates, we estimated that nepheline-hydrate could alter to nepheline for at least ˜$10^3$ years at 400 ℃. A TG-DTA of analcime at heating rate 2 ℃/min in air showed that dehydration started at ˜120 ℃ and finished at ˜500 ℃. The XRD data showed analcime is transformed into nepheline and amorphous material below 1000 ℃, although we failed to estimate the required time of the transformation because of the DTA curves of analcime were too complicated.

The present results show melilite and plagioclase are easily altered into hydrous minerals like nepheline-hydrate and analcime in $Na^+$-rich high alkali solutions. Because the experimental condition demonstrated in the present study seems to be comparable to actual carbonaceous chondrite parent body, we infer that nepheline in carbonaceous chondrite formed initially as intermediate products like nepheline-hydrate and analcime during aqueous alteration, and these hydrous minerals was subsequently dehydrated to nepheline.

Keywords: nepheline, melilite, aqueous alteration, hydrothermal experiments, dehydration heating experiments, carbonaceous chondrite

PPS22-05 Room:A02 Time:May 28 10:15-10:30

# Microtextures in the MAC 88107 carbonaceous chondrite: Is this meteorite really a primary accretionary rock?

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MAC 88107 is an ungrouped carbonaceous chondrite having intermediate properties between the CM and CO groups [1]. Carbonaceous chondrites generally consist of chondrules and inclusions embedded in a fine-grained matrix, which constitutes >30 vol.% of the meteorites. In contrast, MAC 88107 virtually has no matrix and consists mainly of chondrules and inclusions surrounded by rims. The rims are thought to have formed by accretion of dust onto the surface of chondrules and inclusions while floating in the solar nebula [2]. Thus, meteorites like MAC 88107 are thought to be “primary accretionary rocks” , which formed directly from the solar nebular [2]. However, recent studies of chondrules/rims in the Mokoia CV chondrite show abundant evidence for rim formation within the meteorite parent body [3,4]. Based on the model proposed by [3, 4], the rims are remnants of former matrix adhering to chondrules and inclusions.

To reevaluate the formation processes of MAC 88107, we performed detailed observation and analyses of this meteorite using SEM-EDS, STEM-EDS, and SR-XRD.

The rims in MAC 88107 mainly consist of extremely fine-grained material (<1$\mu$m) with small fragments (1-10 $\mu$m) of forsterite, enstatite, and magnetite-fayalite-hedenbergite aggregates. Our STEM observations and SR-XRD measurements reveal that the extremely fine-grained material consists mostly of an amorphous material with minor amounts of phyllosilicate, olivine, pyroxene, pentlandite, and magnetite.

Many rims in MAC 88107 contain characteristic veins (~10 $\mu$m in width) consisting of coarse grains (1-15 $\mu$m) of magnetite, fayalite, and hedenbergite. Krot et al. (2000) [1] suggested that these veins were formed during fluid-assisted oxidation of metal-sulfide nodules in chondrule peripheries. The oxidation was associated with a volume increase, induced high stresses in adjacent rims, and eventually broke to form fractures, which were subsequently filled with growing magnetite. However this model cannot explain the presence of veins in rims around CAIs which have no opaque nodules. If the veins were originated from cracks formed by brecciation of the present meteorite lithology, there should have been veins penetrating multiple chondrules/rims. However such vein is absent. These facts suggest that the veins were formed from cracks that resulted from brecciation of a precursor lithology of the chondrules/rims.

Characteristic layers, 5-30 $\mu$m in width, occur between neighboring rims. These layers consist of relatively coarse-grained magnetite, fayalite, and hedenbergite. Krot et al. (2000) [1] termed them “inter-rim layers” . The mineralogy and texture of inter-rim layers resemble to those of veins in the rims.

We found several clasts which contain multiple chondrules in MAC 88107. These clasts are 150-500 $\mu$m in diameter and have round shapes. They contact with adjacent chondrules or rims directly or through inter-rim layers. The chondrules in the clasts have no rims. The matrices of the clasts have mineralogy and texture similar to the chondrule rims in the outside of the clasts. These observations suggest that the chondrules/rims are actually clasts that resulted from brecciation of a precursor lithology and subsequent transportation and abrasion.

From these results, we suggest that MAC 88107 was formed through the following processes: (1) formation of chondrule/rim clasts by brecciation of a precursor lithology, (2) transportation and abrasion, and (3) accumulation and lithification of those clasts.

References:
[1] Krot et al. (2000) MAPS 35, 1365?1386. [2] Metzler et al. (1992), GCA 56, 2873?2897. [3] Tomeoka and Ohnishi (2010), GCA 74, 4438?4453. [4] Tomeoka and Ohnishi (2014), GCA 137, 18?34.

Keywords: MAC 88107, Primary accretionary rock, Carbonaceous chondrite, Brecciation, Aqueous alteration, Chondrule rims

Japan Geoscience Union Meeting 2015
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PPS22-06 Room:A02 Time:May 28 10:30-10:45

# Estimation of the equilibrium form of olivine from negative crystals in an equilibrated chondrite

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Olivine is one of the most common minerals both in the solar system and the interstellar and circumstellar environments. Adsorption of hydrogen atoms and water molecules onto the olivine surfaces may play a significant role in the formation of hydrogen molecules in the interstellar medium and the origin of water in the earth [2,3]. The crystal orientations of the olivine surfaces may affect adsorption efficiency and reaction rates, and thus it is important to understand crystal forms of olivine. Although the equilibrium form of olivine has been investigated based on the surface energies of olivine obtained by Ab initio calculations [1], it has not been confirmed by observations of naturally occurred olivine.

Many voids with facets (negative crystals) several um in size have been identified within olivine grains in HAYABUSA samples and equilibrated chondrites [4]. These negative crystals appear to be the equilibrium form because equilibrated chondrites have experienced thermal metamorphism at ˜800$^{o}$C. In this study, we analyze the three-dimensional shapes of negative crystals in an olivine grain to obtain the equilibrium form of olivine using micro-sampling with focused ion beam (FIB) and micro-tomography [5]. The results are compared with the estimated equilibrium form by the Ab initio calculations.

A thin section of Tuxtuac meteorite (LL5) was used in this study. A negative-crystal-rich region of an olivine grain was identified by an optical microscope. The 30x30x60 um$^3$ sized micro-sample was prepared by an FIB technique (FEI Quanta 200 3DS). X-ray microtomography was performed at the SPring-8 BL47XU beamline at (7 keV, 70.5 nm/voxel). Negative crystals were extracted three-dimensionally by binarization of the CT images. The orientation of the host olivine crystal was determined with an FE-SEM/EBSD (JEOL 7001F/HKL CHANNEL5) and face angles of the negative crystals were measured using the 3D-CT images. Crystal plane indices of negative crystals were determined from the obtained crystal orientation and face angles.

We identified seven negative crystals 2-4 um in size. They aligned in the same plane within the olivine crystal suggesting that they are a healed crack as well as those in the HAYABUSA samples [5]. All negative crystals have developed facets of the same crystal orientations and have similar morphology, and some edges were rounded, which indicate that the morphology of the negative crystals almost represents the equilibrium form of olivine. The (100), (001), and (011) facets were observed and (100) facet was most well-developed. The other facets seem to be (001), (102), and (343) planes although these facets were small with respect to the spatial resolution of the micro-tomography.

Forsterite surface energies determined by Ab initio calculation increase in order of (010), (120), (001), (101), (111), (021), and (110) [1]. The observed (010), (120), and (001) planes have low surface energies while the surface energy of the (100) plane is high [6] and those of (011), (102), and (343) are probably high as well. The possible interpretations of unexpected facet planes with high energies are (1) changing surface energy due to adsorption of molecules onto the crystal surface, (2) temperature dependence of the surface free energy, and (3) kinetic effect. If surface energies change due to adsorption of molecules, anisotropy of the surface structures would play an important role for surface stability. Evaporation rate of forsterite along the a-axis in hydrogen gas at less than 1400$^{o}$C is smaller than those along the b- and c-axes [7], which is consistent with this study.

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Keywords: equilibrium form, negative crystal, equilibrated chondrite, olivine, Ab initio, surface energy

Japan Geoscience Union Meeting 2015
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PPS22-07 Room:A02 Time:May 28 11:00-11:15

# An experimental study on the formation of the type I chondrules

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Introduction: Chondrules have been reproduced at 1 bar under the IW-0.5 oxygen pressure, where FeO-rich, type II chondrules are produced. Although type I chondrules have been experimentally examined by Cohen and Hewins (2004), the charge was quenched and dissimilar to natural chondrules. In the present study, chondrules were reproduced under the condition of the IW-3 to -5 with the various cooling rates mainly of 100 oC/h, where FeO-poor, type I chondrules are produced.

Experiments: Three kinds of sintered pellets of homogenized powders with chondritic compositions were prepared as starting materials of the present experiments; (1) Allende CV3.2, (2) NWA 1465 (a carbonaceous chondrite), and (3) powder mixtures including iron, olivine, enstatite, anorthite, and diopside. The peak temperatures of the runs 1200-1550 oC and the cooling rates 80-10000 oC/h. Two cases were considered in the use of silica powder as Si-rich gas source and in the absent of the silica powder. The furnace was low pressure type controlling below the atmospheric pressure under the reduced condition, whose pressure was controlled to be mainly 100 Pa. The capsule made of alumina has an orifice (1 mm) on the top and the charge is held using the Mo-wire of 0.2 mm in diameter in the capsule. Silica was put on the bottom of the capsule for its use The vapor pressure from the charge and silica in the capsule is about 1 Pa at ˜1450 oC of the peak temperature. When the furnace total pressure is controlled to be 100 Pa using the hydrogen gas, the hydrogen gas enters into the capsule balancing the outside of the capsule. The oxygen pressure is IW-3 in the case of the existence of silica powder, and IW-4 in the absence of the silica powder at 1450 oC. The starting materials (1) and (2) correspond to the metallic iron poor starting materials and the runs of 53 times were carried out (23 times with Si-rich gas and 30 times without Si-rich gas). The starting material (3) corresponds to the metallic iron rich starting materials and the runs of 21 times were carried out (11 times with Si-rich gas and 10 times without Si-rich gas). The polished sections were made from the run produces, and observed and analyzed using an electron probe micro analyzer (EPMA, JXA-8200).

Results and discussion: Poikilitically enclosed rounded forsteritic olivines in porphyritic enstatites formed from metallic iron poor starting materials at the peak temperature of 1450 oC and the cooling rate of 100 oC/h, which is similar to type I chondrules. The rounded olivines are relict phase, dusty olivines and forsterites, common in chondrules. The texture of the runs with Si-rich gas source is similar to the type I chondrules. Although kamacite droplets enclosed in olivines and pyroxenes are usually abundant in type I chondrules, they are not common in the run products. The iron content of the run products decreased. Since the volume of the absorption of iron into the Mo wire is much less than the volume of compositional change, the significant of the iron oxide component directly evaporated but not the reduction into metallic iron.

Metallic iron melt tends to aggregate into a clump at the peak temperature more than 1500 oC from metallic iron rich starting materials. The metallic iron was dispersed in the charge due to the low melting degree at the peak temperature less than 1500 oC, but the iron was deficient on the charge surface, suggesting the evaporation of iron. The textures are not similar to chondrules.

Considering the present experimental results, we may prefer the metal-deficient precursors for the type I chondrules rather than metal-bearing precursors. However, the origin of kamacite droplets enclosed in Mg-rich olivine and pyroxenes in type I chondrules is still unclear. They may be originated from the injection during the chodnrule melting or the iron vapor was saturated during the chondrule melting.

Reference: Cohen B. A. and Hewins R. H. 2004. GCA, 68, 1677-1689.

Keywords: chondrule, type I, chondrule formation, reproduction, experimental study

Japan Geoscience Union Meeting 2015
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PPS22-08 Room:A02 Time:May 28 11:15-11:30

# Cosmic-ray exposure age and heliocentric distance of the parent body of the rumuruti chondrite PRE 95410

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We measured concentrations and isotopic ratios of noble gases in the rumuruti (R) chondrite Mt. Prestrud (PRE) 95410. This meteorite contains high concentrations of solar and cosmogenic noble gases, from which solar gas implantation rate (concentrations of solar noble gases implanted per unit time) can be estimated. By comparing the solar gas implantation rates between PRE 95410 and lunar regolith samples, the parent-body heliocentric distance of the meteorite can be obtained, as solar wind flux is inversely related to the square of heliocentric distance. Based on the exposure model of solar noble gases and galactic cosmic rays, we calculated the exposure age on its parent body (15.4±5.2 Ma), exposure age in space after ejection from the parent body (9.5±1.3 Ma), and heliocentric distance of the parent body (1.3±0.2 AU) . The calculated exposure age in space is consistent with the peak of space exposure age distribution of other R chondrites. The derived heliocentric distance suggests the location of parent body when constituents of the PRE 95410 meteorite were exposed to the solar wind. From the previous studies of mineralogy and chemistry, R chondrites might have formed between the regions where ordinary and carbonaceous chondrites formed (2-4 AU). Hence the heliocentric distance of the PRE 95410 parent body studied in this work is not consistent with the formation region. This may imply that the parent body of the PRE 95410 migrated from the R chondrite formation region to the inner area where irradiated by solar wind before the ejection of the meteorite (9.5±1.3 Ma). Kr isotopic ratios show excesses of 80Kr and 82Kr produced by neutron capture reaction on Br during space exposure. The minimum radius of the PRE 95410 meteoroid was calculated as 53 cm from the abundances of neutron-induced Kr.

Keywords: Rumuruti chondrite, noble gas analysis, cosmic-ray exposure age, heliocentric distance

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PPS22-09 Room:A02 Time:May 28 11:30-11:45

# Nucleosynthetic Strontium Isotope Anomalies in Carbonaceous Chondrites

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We present precise Sr isotopic compositions in samples from sequential acid leaching experiments for three carbonaceous chondrites, Allende, Murchison, and Tagish Lake, together with those in the bulk aliquots of these meteorites. The chondritic acid leachates and residues were characterized by Sr isotope anomalies with variable $\mu^{84}$Sr values ($10^6$ relative deviation from a standard material) ranging from +120 to -4700 ppm, documenting multiple nucleosynthetic sources within a single meteorite. In addition, the $\mu^{84}$Sr patterns across leaching samples for individual chondrites differed from one another. The highest $\mu^{84}$Sr values were observed for leaching Step 3 ($HCl+H_2O$, 75 ℃) for Allende and Murchison likely because of the incorporation of calcium and aluminum-rich inclusions (CAIs). In contrast, extremely low $\mu^{84}$Sr values were observed in the later fractions (Steps 6 and 7) for Murchison and Tagish Lake, suggesting the existence of s-process-enriched presolar SiC grains derived from AGB stars.

A $\mu^{84}$Sr-$\epsilon^{54}$Cr diagram was prepared with the CAIs and bulk aliquots of carbonaceous chondrites and other meteorites (non-carbonaceous) that were plotted separately; however, they still formed a global positive correlation. CAIs presented the highest $\mu^{84}$Sr and $\epsilon^{54}$Cr values, whereas carbonaceous chondrites and noncarbonaceous meteorites had intermediate and the lowest $\mu^{84}$Sr and $\epsilon^{54}$Cr values, respectively. The positive trend was interpreted as resulting from global thermal processing in which sublimation of high $\mu^{84}$Sr and $\epsilon^{54}$Cr carriers generated the excess $\mu^{84}$Sr and $\epsilon^{54}$Cr signatures in CAIs, while noncarbonaceous planetesimals accreted from materials that underwent significant thermal processing and thus had relatively low $\mu^{84}$Sr and $\epsilon^{54}$Cr values. Apart from the global trend, the carbonaceous chondrites and noncarbonaceous meteorites both exhibited intrinsic variations that highlight an isotopic dichotomy similar to that observed in other isotope combinations (e.g., $\epsilon^{54}$Cr-$\epsilon^{50}$Ti, $\epsilon^{54}$Cr-$\triangle^{17}$O). A plausible scenario for creation of the intrinsic variations involves local thermal processing (e.g., flash heating for chondrule formation) caused by additional selective destruction of presolar grains different than that caused by global thermal processing. The existence of such a global positive trend and local variations for two meteorite groups suggests a complicated dynamic history for the dust grains with respect to thermal processing, material transportation, and mixing in the protoplanetary disk prior to planetesimal formation.

Keywords: Sr isotopes, presolar grains, acid leaching, chondrites, nucleosynthesis, thermal processing

Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

PPS22-10 Room:A02 Time:May 28 11:45-12:00

# High precision neodymium isotopic analysis of chondrites with complete sample digestion

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A variety of isotope anomalies have been discovered in bulk chondrites and differentiated meteorites (e.g., Cr, Mo [1, 2]). These results point to the existence of planetary-scale isotope heterogeneities for refractory heavy elements, which are most likely due to the heterogeneous distribution of presolar grains (e.g., SiC, graphite) in the protosolar nebula before the onset of planetesimal formation.

High precision Nd isotope analyses in meteorites have been the center of interest in recent cosmochemistry community. One of the most remarkable results is that chondrites possess $^{142}$Nd/$^{144}$Nd ratios $\sim$20 ppm lower than those in terrestrial rocks [3]. The anomaly was interpreted to be caused by the Sm-Nd fractionation via early differentiation of the terrestrial mantle. On the other hand, variations in stable Nd isotopes (e.g., $^{148,150}$Nd/$^{144}$Nd) have been documented in chondrites [4]. Although the authors concluded that the observed variation was due to incomplete digestion of presolar grain-bearing samples, the existence of Nd isotope anomalies in bulk aliquots of chondrites remains unclear unless high precision Nd isotope data with complete sample digestion become available.

In this study, we revisit high precision Nd isotope analysis of chondrites coupled with a new sample digestion technique that confirms complete dissolution of acid resistant presolar grains. We also develop a modified dynamic multicollection method using TIMS to improve the analytical reproducibilities.

We investigated two carbonaceous chondrites (Murchison, CM2; Allende, CV3), five ordinary chondrites (Kesen, H4; Chergach, H5; Saratov, L4; Hamlet, LL4; St.Severlin, LL6). The ordinary and Rumuruti chondrites with a petrologic grade greater than 3 were dissolved by a conventional acid digestion method using $HNO_3$ + HF + $HClO_4$ [5]. For carbonaceous chondrites, each sample was digested using a high-pressure digestion system (DAB-2, Berghof) with HF + $HNO_3$ + $H_2SO_4$ to completely dissolve acid resistant presolar grains [6].

The Nd isotope compositions were measured by TIMS (Triton-plus, Tokyo Tech). In previous studies, Nd isotope compositions of bulk meteorites have been commonly measured in the “static-multicollection” mode, which may be affected by the time-related deterioration of Faraday cups [7]. In contrast, the “multi-static” [8] or “dynamic-multicollection” methods can reduce the effect of cup deterioration by acquiring Nd isotopes with multiple lines of different cup configurations within a single analytical cycle. In this study, we developed a modified “dynamic-multicollection” method.

In contrast to the static mode, the dynamic method achieved improved reproducibilities as follows; $^{142}$Nd/$^{144}$Nd: 2.8 ppm, $^{148}$Nd/$^{144}$Nd: 4.5 ppm, and $^{150}$Nd/$^{144}$Nd: 9.2 ppm. It should be noted that improvements of reproducibilities are evident for $^{148}$Nd/$^{144}$Nd and $^{150}$Nd/$^{144}$Nd ratios even compared to those obtained in the multi-static method (6 ppm and 19 ppm, respectively) conducted in [8].

All samples have $\mu^{142}$Nd values 20 – 30 ppm lower than the terrestrial value. In contrast, all but one sample (Allende) have $\mu^{148}$Nd values indistinguishable from the terrestrial value. Likewise, $\mu^{150}$Nd values in chondrites are generally within the range of the terrestrial component. Although the data points are limited, this study suggests that stable Nd isotopes were homogenously distributed in the protosolar nebula, at least for carbonaceous, ordinary, and Rumuruti chondrites.

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Keywords: isotopic heterogeneity, isotopic anomaly, chondrite, neodymium, TIMS, presolar grain

PPS22-11 Room:A02 Time:May 28 12:00-12:15

# Chemical composition of a precursor material of an Allende F(UN) CAI estimated from a mass dependent fractionation

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Calcium-aluminum-rich inclusions (CAIs) are considered to be the oldest solid materials in the solar system [e.g., 1, 2]. Some CAIs show mineralogy, texture, and isotopic signature that have experienced melting, evaporation and recrystallization [e.g., 3, 4]. These CAIs have lost primordial chemical compositions caused by evaporative loss of less refractory elements such as magnesium and silicon from the melt. Hence, in order to understand the origin and evolution of such ‘igneous’ and isotopically fractionated CAIs, estimations of primordial compositions of these CAIs are required.

Estimations of primordial compositions of ‘normal’ igneous CAIs have been conducted by determination of mass dependent isotopic fractionation degrees in Mg and Si [5, 6], but those of igneous CAIs with *F*ractionation and *U*nknown *N*uclear effects (FUN [e.g., 7]) have been poorly carried out. FUN CAIs are amongst solar system materials with extreme mass dependent isotopic fractionations in Mg, O, and Si. The origin of FUN CAIs is still not well understood, but they must have information about an earliest stage of the solar system evolution. Here we report chemical and Si isotopic compositions of a CAI from Allende, called AL1B-F. AL1B-F is a forsterite-bearing CAI which shows large mass dependent isotopic fractionations in oxygen and magnesium [8]. These fractionation signatures indicate that AL1B-F is related to FUN CAIs.

FEG-EPMA (JEOL JXA-8530F, the Univ. of Tokyo) was used for petrologic studies. Silicon isotopic compositions have been measured by the NanoSIMS installed at Atmosphere and Ocean Research Institute, the Univ. of Tokyo.

AL1B-F is composed of two parts, a forsterite-rich core and a spinel-rich mantle. Among these two parts are filled with abundant secondary minerals (e.g., sodalite and nepheline). Silicon isotopes of forsterites and Al-Ti-rich pyroxenes in AL1B-F show a large mass dependent isotopic fractionation of up to $\sim$22 ‰/amu.

In order to estimate the primordial composition of AL1B-F, we combined Si and previously measured Mg and O isotopic data [8]. If we assume that mass dependent isotopic fractionations in AL1B-F were resulted from simple one-stage evaporation event, $\sim$80% of Mg and $\sim$75% of Si must have been lost (evaporated) from the molten precursor of AL1B-F based on the experimentally determined isotopic fractionation factors [9]. Because of the presence of abundant secondary minerals, it is not possible to precisely determine the bulk chemical composition of the present AL1B-F. If we assume, however, that secondary minerals in AL1B-F are alteration products of primary melilites with Ak mole% of, e.g., $\sim$89, which is a composition of melilites in the Vigarano forsterite-bearing FUN CAI 1623-5 [10], the estimated precursor composition for AL1B-F would be $\sim$34 wt% MgO and $\sim$50 wt% $SiO_2$. The result suggests that the precursor of AL1B-F also have a Mg- and Si-rich composition like C1, 1623-5, and CMS-1 FUN CAIs [9, 11].

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Keywords: FUN CAI, mass dependent isotopic fractionation, silicon isotopes, ion microprobe

Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

PPS22-12 Room:A02 Time:May 28 12:15-12:30

# Oxygen isotopic distribution of Type B1 CAI from the Vigarano

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Ca-Al-rich inclusions (CAIs) in meteorites are the oldest objects in the Solar System. Heterogeneous oxygen isotope distributions among inter- and intra-crystals have been observed for CAIs (e.g., Yurimoto et al., 1998). The heterogeneous oxygen isotope distributions of CAI minerals are interpreted to be the result of thermal processes in the solar nebular with different oxygen isotopic compositions, which are multiple melting, condensation, and solid-state diffusion processes, as well as aqueous and thermal metamorphism/alteration on the parent body (Yurimoto et al., 2008). However, most efficient processes to form oxygen isotopic compositions were different at each mineral and each CAI. In this study, we have conducted systematic oxygen isotope measurements for a large area in a CAI and compared with the petrography, in order to understand the processes to form the heterogeneous oxygen isotope distributions.

A type B1 CAI from the Vigarano was examined. FE-SEM-EDS system (JEOL JSM-7000F; Oxford X-Max 150) was used for petrographic observations. Oxygen isotopic compositions were measured using SIMS of Hokkaido University (Cameca ims-1280HR). Secondary ions ($^{16}O^-$, $^{17}O^-$, and $^{18}O^-$) were measured simultaneously in a multicollection mode. We selected three regions with sizes of 1 x 1 mm and measured oxygen isotopes of 40 x 40 points every 25 micrometers. Measurement time for each spot was 55 seconds including 10 seconds of ion counting time, pre-sputtering, and stage moving.

The CAI is 6.5 x 3 mm and has an irregular and a wrinkled surface. The CAI has a core-mantle structure. The core consists of spinel, melilite, anorthite, and Al-Ti-rich augite, while the mantle is composed mainly of melilite. The Wark-Lovering rim surrounds the CAI. The CAI is a fragment and an entire shape is unclear. A bulk chemical composition corresponds to those for typical Type B1 CAIs (Grossman, 1975). Crystallization sequences from a melt of the CAI composition were spinel, melilite, anorthite, and fassaite (Stolper, 1982).

The oxygen isotopic compositions of minerals in the CAI are distributed along the CCAM line in a three oxygen isotope diagram. Spinel shows a $^{16}$O-rich composition ($\delta^{18}O \sim$ -45 permil), while melilite shows a $^{16}$O-poor composition ($\delta^{18}O \sim 11$ permil). Anorthite has bimodal distributions of oxygen isotopic compositions. Fassaite shows mainly a $^{16}$O-rich composition and less spots having a $^{16}$O-poor composition.

The oxygen isotopic compositions of mineral measured are not readily explained by crystallization sequences from the melt, indicating that the heterogeneous oxygen isotope distributions are the results of either multiple re-melting events or any other processes except for the melting event.

Keywords: CAI, meteorite, oxygen isotope, SIMS

Japan Geoscience Union Meeting 2015
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PPS22-13 Room:A02 Time:May 28 12:30-12:45

# Al-Mg chronology and oxygen isotope distributions of multiple melting for a Type C CAI from the Allende

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Ca-Al-rich inclusions (CAIs) in meteorites have undergone multiple melting processes in the early solar nebula, which indicates that transient heating events repeatedly occurred in the early Solar System (e.g., Yurimoto et al., 1998). A relative chronometer with Al-Mg systematics for the CAIs could be applied to determine the time interval of heating events. To determine the time interval of heating events for the CAIs, detailed histories of multiple melting events in the CAIs should be well understood. We have carried out a coordinated study of detailed petrographic observations and in-situ oxygen and Al-Mg isotope measurements for a Type C CAI, EK1-04-2, from Allende CV3. Precise petrographic observations and oxygen isotopic measurements were performed to understand the individual melting processes that occurred in the CAI. Investigation of the Al-Mg systematics was performed for minerals formed by different melting and recrystallization processes to determine the age differences of individual CAI melting events.

The CAI consists mainly of spinel, anorthite, olivine, and pyroxene, and has a core and mantle structure. Petrography of the core suggests that the crystallization sequences of the core minerals are spinel, anorthite, olivine, and pyroxene. The mantle has the same mineral assemblages as the core, and shows incomplete melting and solidification textures.

Oxygen isotopic compositions of the minerals are distributed along with a carbonaceous chondrite anhydrous mineral (CCAM) line ($\delta^{18}$O = -44 to +9 ‰), which indicates to preserve a chemical disequilibrium status in the CAI. Spinel shows $^{16}$O-rich signature ($\delta^{18}$O ˜-43 ‰), while anorthite shows $^{16}$O-poor signature ($\delta^{18}$O ˜+8 ‰). Olivine and pyroxene in the core have the same oxygen isotopic composition ($\delta^{18}$O ˜-15 ‰), which indicates their equilibrium. Olivine and pyroxene in the mantle have variable oxygen isotopic compositions and are slightly depleted in $^{16}$O ($\delta^{18}$O = -13 to -4 ‰) compared with the same minerals in the core. The $^{26}$Al-Mg systematics is consistent with the disequilibrium status observed according to the petrography and oxygen isotopes. Spinel is plotted on a line of $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 = (3.5\pm0.2) \times 10^{-5}$, anorthite is $(-1\pm5) \times 10^{-7}$, and olivine and pyroxene in the core are $(-1\pm7) \times 10^{-6}$. Plots of olivine and pyroxene in the mantle are scattered below the isochron of these minerals in the core.

The coordinated study of the oxygen and magnesium isotopes and the petrography indicates that the EK1-04-2 Type C CAI underwent multiple heating events after a precursor CAI formation. The precursor CAI was formed at 0.43 Myr after the formation of the Solar System defined by canonical CAI formation. At least 1.6 Myr after the precursor CAI formation, the CAI was partially melted and the partial melting melt exchanged oxygen isotopes with surrounding $^{16}$O-poor nebular gas. $^{16}$O-poor olivine and pyroxene in the core were recrystallized from the partial melting melt. Subsequently, Al-rich chondrules accreted on the CAI, and the CAI experienced partial melting again and recrystallized to form the mantle. The oxygen and magnesium isotopes in anorthite were redistributed during thermal metamorphism in the Allende parent body. Our study reveals that the CAI had been retained in the solar nebula for at least 1.6 Myr and underwent multiple melting events in the nebula, and oxygen and $^{26}$Al-Mg systematics has been partially disturbed depending on crystal sizes by metamorphism on the parent body.

PPS22-14 Room:A02 Time:May 28 14:15-14:45

# Mixing of exogenic impactor materials on the surface of asteroids: Disruption, penetration, and consolidation

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Dawn observation found dark materials on the surface of the hypothesized HED meteorites' parent body, asteroid 4 Vesta. The dark materials are interpreted to be fragments of carbonaceous chondrite impactors, while HED meteorites were known to include carbonaceous chondrite clasts. Meteorite fall named Almahata Sitta, originally was an asteroid 2008 $TC_3$, is a polymict ureilite with various foreign materials such as enstatite chondrites, ordinary chondrites, one carbonaceous chondrite, etc. Dust particles returned from comet 81P/Wild 2, a Jupiter-Family Comet (JFC) contained materials condensed at high temperature formed near the Sun. It shows that materials of different temperature histories were mixed into the comet at some point during its formation and evolution. Mixing process of materials of different origins occurred ubiquitously or repeatedly on small bodies.

We performed impact experiments of simulated small bodies as targets using various impactors including rocks, metals, and porous sintered materials in order to examine the degree of disruption, penetration, and consolidation of impactors in relation with the material properties and impact velocity for the purpose of understanding the mixing process of materials due to collsion. We found that (1) degree of impactor's disruption can be described by the ratio of initial pressure to dynamic strength of the impactor, (2) penetration depth of silicate impactor is only up to 100 times of its size even when it collides with an icy body of 90% porosity, however, (3) impactor with large porosity can survive with larger fraction and can penetrate deeper, probably because local microscopic collapse of pores inhibits growth of overall fracture, and (4) when impacted on fine regolith at high velocity, mutual consolidation of impactor fragments and also with regolith particles occurs owing to temperature increase due to compaction of pores in regolith.

We will summarize these results in relation with porosity, size of impacting body, and impact velocity and will discuss them in comparison with observational evidences, especially, of asteroids.

Keywords: asteroids, collision, laboratory experiments, meteorites, regolith

PPS22-15 Room:A02 Time:May 28 14:45-15:00

# Experimental confirmation of ringwoodite crystallization from shock-induced melts

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Many high-pressure phases have been identified in meteorites that experienced heavy collisions. The presence of high-pressure phase may provide an estimate of pressure condition. However, the dynamic formation conditions may not be equal to those at static pressures and there is no firm experimental report to indicate the ringwoodite formation at dynamic pressures, although there are Hugoniot data and trials to synthesize ringwoodite by shock compressions. We tried to confirm the ringwoodite formation by hypervelocity impacts from two powdered mixtures of biotite and cristobalite (sample A) and phlogopite and cristobalite (sample B) for Fe-rich and Mg-rich ringwoodites, respectively. When we used stainless steel containers for recovery, the container had reacted with the biotite melt to form chromite spinels. No spinel phase was observed in sample B. When we used copper containers for sample A, X-ray diffraction data on the recovered samples indicated a spinel phase (a =0.8257 nm). Because the lattice constant is greater than that of Fe2SiO4 (ahrensite) and significantly less than those of magnesioferrite and magnetite, the composition can be a Fe-rich ringwoodite. However, detailed scanning electron microscopy indicated no obvious crystals on the polished surface where there were many spherical voids. Finally the Raman spectroscopy investigations detected spectra similar to Fe-rich ringwoodite in the voids. We will try to investigate the spinel phase using analytical transmission electron microscopy.

The present experimental results confirm the formation of ringwoodite from shock-induced melts. Further studies need to provide Mg-rich ringwoodite formation and the minimum dynamic pressures required to the formation. If such experiments are extended to the other high-pressure phases present in meteorites, the shock pressure estimation will be more powerful and helpful than the present.

Keywords: ringwoodite, shock-induced melt, crystallization, recovery shots

Japan Geoscience Union Meeting 2015
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PPS22-16 Room:A02 Time:May 28 15:00-15:15

# Formation of metastable lingunite

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Lingunite (hollandite-type NaAlSi3O8) has been frequently found in shocked meteorites with other high-pressure minerals (Liu and El Goresy, 2007). According to the laser-heated diamond anvil cell (LHDAC) experiment by Liu (1978), following the decomposition of albite (NaAlSi3O8) into jadeite (NaAlSi2O6) plus silica (SiO2) at 2-3 GPa, these phases recombine to form lingunite in the range of pressure between 21 and 24 GPa, and then it decomposes again into calcium ferrite-type NaAlSiO4 plus stishovite at pressures above 24 GPa. Similarly, Tutti (2007) observed lingunite as a minor phase at 21-23 GPa and 2273K using LHDAC. In contrast to these LHDAC studies, high-pressure experiments using multi-anvil type (MA) apparatus revealed that the maximum solubility of NaAlSi3O8 component in hollandite structure is limited to ˜50 mol% at 14-25 GPa and 1073-2673K (Yagi et al., 1994, Liu, 2006) and NaAlSi3O8 lingunite is not stable at least up to 2273K (Akaogi et al., 2010). This contradiction has not been solved yet, which makes it dif?cult to understand the shock conditions for the presence of lingunite in shocked meteorites.

To investigate the lingunite puzzle, we focused on the formation process of lingunite by conducting time-series experiments. We performed high-pressure experiments at 18-27 GPa and 1073-2023K using both LHDAC and MA apparatus. Powders of natural albite, oligoclase and labradorite are used as starting materials. Existing phases were identified by X-ray diffraction method.

The quenching experiments using MA apparatus revealed that lingunite does not form in 5 min, but forms in 60 min as a single phase from oligoclase at 20 GPa and 1473K. In situ X-ray diffraction study indicated that oligoclase becomes amorphous with increasing pressure and temperature. At 22 GPa and 1473K, lingunite first crystallizes from the complete amorphous oligoclase in 100 sec, and it decomposes into stishovite and CAS phase in 60 min. These results suggest that lingunite forms as a metastable phase by solid-state reaction after the amorphization of oligoclase, which might have also occurred with maskelynite in shocked chondritic meteorites (Tomioka et al., 2000). In contrast, lingunite was not observed when albite and labradorite were used as starting materials. The amorphization pressure increases with increasing albite component. The pressure condition for complete amorphization of albite is higher than that for the lingunite formation. No lingunite observed from the albite sample in this study implies that the complete amorphization is required for the metastable formation of lingunite by solid-state reaction. In the case of labradorite, lingunite was not formed even after the complete amorphization. This is consistent with the observation that lingunite with labradorite composition in martian shocked meteorites crystallized not by solid-state reaction but from plagioclase melt (e.g., El Goresy et al., 2013).

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# Shock-metamorphosed zircons from the Jack Hills metaconglomerate in the Narryer Gneiss Complex, Western Australia

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An intense flux of extraterrestrial bodies into inner solar system during ca. 3.8-4.1, called as Late Heavy Bombardment (LHB), has been hypothesized originally from studies of the Moon. Extraterrestrial impacts by meteoritic bodies and comets on the early Earth play a significant role for the initial state of crustal, atmospheric and biological evolution. Considering the planetary size, the Earth should have suffered approximately 20 times the impact flux compared to the Moon. Ancient terrestrial evidence of impact in the early Earth is, however, scarcely preserved due to surface erosion, sedimentary burial and tectonic destruction. To date, the oldest impact structure on the Earth is the 2.02 Ga Vredefort Dome, South Africa, and another oldest evidence of impact is 3.47-3.24 Ga spherule layers in the Barberton Greenstone Belt, South Africa. The impact chronology from these spherule layers suggest that the impact flux was significantly higher 3.5 Ga than today, but there are no terrestrial evidence of impact prior 3.5 Ga.

Geological information during Hadean era (before 4.0 Ga) can be deduced from detrital zircons as old as 4.4 Ga preserved in metasedimentary rocks at Jack Hills in the Narryer Gneiss Complex, Western Australia. Previous studies have reported that the Jack Hills metasedimentary rocks contain detrital zircons with ages continuously spanning from ca. 3.0 up to 4.4 Ga, but evidence of impact, such as shock-metamorphosed minerals, have not been confirmed. In the study we first report shock-metamorphosed detrital zircons from the Jack Hills metaconglomerate, in the Narryer Gneiss complex, Western Australia. A total of 8993 detrital zircons were investigated for the surface and internal structure using a scanning electron microscope and optical microscope with/without acid treatment, and four types of shock-metamorphosed zircons were currently identified; (1) curvi-planar (non-planar) feature ($n = 6$), (2) multiple sets of planar feature ($n = 7$), (3) partly granular (polycrystalline) texture ($n = 2$), and (4) fully granular texture ($n = 10$). Of these four, multiple sets of planar feature are proved for diagnostic evidence for impact origin, and now observed as annealed (decorated) planar feature, probably due to post-impact thermal heating or regional metamorphic overprint. Coarse polycrystalline zircon represents several micro-meter sized crystallites in a glassy $ZrSiO_4$ matrix that may resulted from shock-induced amorphization and subsequent recrystallization. This grain shows abundant micro-vesicles and tiny $ThSiO_4$ phase suggesting incipient melting and degassing.

Shock-metamorphosed zircons are often utilized for impact-dating due to their partly or completely Pb-loss (age resetting). Therefore, impact age determinations on shock-metamorphosed detrital zircons from the Jack Hills metaconglomerate would provide significant clues not only for the deciphering the impact history on the early Earth but also for the verifying LHB hypothesis.

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# Shock P-T history of Martian meteorites as revelaed by electron microscopy of ”brown” olivine

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Introduction: Most Martian meteorites are heavily shocked and exhibit various shock features. Among these shock features, olivine darkening (”brown” olivine) is unique in Martian meteorites. Detailed observation of brown olivine by TEM reveals that olivine darkening is due to the presence of iron nano-particles (Fe metal and/or magnetite) ranging 5-20 nm in size in olivine. Although nano-particles are considered to be formed by heavy shock metamorphism, their formation processes and conditions are not well understood and there is a possibility to obtain new constraints on shock events on Mars. In this study, we observed and compared Martian meteorites containing brown olivine with those without brown olivine and heavily-shocked chondrite for revealing their darkening processes and conditions and seeking singularities of planetary shock events on Mars.

Sample: Eight shergottites (NWA 1950, LAR 06319, LEW 88516, Y984028, NWA 1068, RBT 04261, LAR 12095 and Tissint) and one L chondrite (NWA 4719) were observed in this study. Four shergottites (NWA 1950, LAR 06319, LEW 88516, Y984028) contain darkened olivine. Olivine grains in other samples are almost colorless although they are certainly heavily shocked.

Results and Discussion: Observation of brown olivine by optical microscopy reveals heterogeneous coloration on the scale of tens of $\mu$m. In three shergottites (LAR 06319, LEW 88516, Y984028) olivine around shock melts is recrystallized and not darkened.

The brown areas look brighter in BSE images and have fewer cracks and low crystallinity by EBSD compared to the colorless areas. Observation at high magnifications reveals that some brighter areas of NWA 1950 are composed of abundant lenticular areas with submicron-sized Fe particles around them. Shergottites with brown olivine contain no high pressure minerals although they show similar lamellar textures to olivine with high pressure polymorphs.

In contrast, shergottites without brown olivine contain high pressure minerals and also partially darkened areas in olivine adjacent to shock melt veins. These darkened areas show similar microstructures to those of brown olivine, and therefore their formation processes seem to be identical and olivine darkening (formation of iron nano-particles) requires high temperature because darkened areas are present only near shock melts in these meteorites without brown olivine. It is conceivable that the heterogeneity of olivine darkening corresponds to temperature difference. Since temperature heterogeneity is vanished within about $<$1 sec, iron nano-particles need to be formed in such a short time. The absence of Si-rich phases means that mechanism of nano-particle formation is similar to the initial process found in olivine reduction experiments whose rate is limited by atomic diffusion rates. Atomic diffusion in olivine is too slow to reflect temperature heterogeneity to their color distribution in such a short time, and therefore rapid diffusion, for example transformation to high pressure minerals, is needed. Lenticular areas in brown olivine with low crystallinity may have been a high pressure mineral and, if that is the case, it seems easy to reflect temperature heterogeneity to their coloration. Thus, Martian meteorites with brown olivine have undergone such a high pressure-temperature condition in a short time (˜a few ms) on which most olivine in the meteorites is transformed to high pressure polymorphs. Temperature increase throughout meteorite induces a slow cooling of shock melt and it seems also related to recrystallization of olivine and back-transformation of high pressure minerals around shock melt.

This condition may be induced by an extremely strong shock event and meteorites with brown olivine have undergone such stronger shock than those containing high pressure minerals and colorless olivine. Thus, the collisional events ejecting rocks from Mars may be extremely strong compared to those affecting the other meteorites.

Keywords: Mars, Martian meteorite, High pressure mineral, shock, brown olivine

PPS22-19 Room:A02 Time:May 28 15:45-16:00

# Pressure dependence of cathodoluminescence spectra of shocked quartz.

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Impact cratering is a ubiquitous process on both terrestrial planets and small bodies in the solar system. Study on impact craters on the Earth provides a unique opportunity to constrain planetary-scale impact phenomena. In particular, reconstruction of distribution and shock pressure recorded on the shock-metamorphosed minerals would provide vital information on partition of the impact energy and cratering mechanism on Earth.

Quartz, which is one of the most abundant and widely distributed rock-forming minerals on the Earth, has been conventionally used to evaluate shock pressure on the minerals. However, the precious shock estimations using quartz, such as PDFs, are rather qualitative, hence it is required for more detailed evaluation of shock pressure to develop new advanced method. Recently, cathodoluminescence (CL), emissions of photon from materials in ultraviolet to infrared wavelength regions, especially CL of quartz is expected to be used as shock barometer because of change of luminescent properties with shock metamorphism, but systematic study focused on pressure dependence of CL spectra have never been reported. In this study, we conducted a series of systematic shock recovery experiments of impact on quartz crystals and analyzed recovered samples to evaluate the CL spectral features and their dependence on shock pressure.

The shock recovery experiments were performed on natural and synthesis quartz crystals in the National Institute for Material Science (NIMS) using a one stage propellant gun. The velocity range of flyer plate was 0.5 to 1.8 km/s, which produces peak shock pressure from 5 to 40 GPa. Recovered samples were polished to make thin sections, and then are coated by carbon for CL analysis. CL measurements of grain by grain were conducted at Okayama University of Science using a SEM-CL (SEM combined with a grating monochromator) instrument.

Based on CL measurements of over a hundred shock-recovered quartz grains, we found drastic change in spectral pattern with an increase in shock pressure. The starting material of synthetic and natural quartz has only one broad emission peak around 630 nm, but another broad peak around 450-460 nm (blue emission) appears from the shock-recovered samples at 10 to 20 GPa. At higher pressure, the CL intensity of blue emission of shocked quartz increases drastically up to 100 times as large as that of the starting materials. On the other hand, CL emission intensity around 630 nm changes less than 3 times in spite of the pressure increase.

CL spectra of quartz with $\beta$-form (e.g., quartz from Goroku, Sendai) show extremely intense blue emission and unique luminescent properties depending on temperature (e.g. activation energy) similar to quartz from terrestrial impact craters, suggesting probably relationship of the blue CL with defects associated with Daufine twins formed as a result of $\alpha$-$\beta$ transition. On the other hand, Daufine twins are also confirmed in the experimentally shocked quartz under TEM observation. Therefore, the rise of blue emission intensity in our measurements suggests generation and density increase of defects related to Daufine twins with ascending shock pressure. Quantitative evaluation of this relationship presumably enables us to construct a new quantitative pressure barometer or thermometer for shocked quartz grains.

Keywords: shock metamorphism, shocked quartz, cathodoluminescence

Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

PPS22-20 Room:A02 Time:May 28 16:15-16:30

# High-pressure polymorphs in Gujba CB type carbonaceous chondrite.

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One of the most unambiguous evidences for shock metamorphism is a dense polymorph, high-pressure polymorph in and around the shock-melt veins and/or melt-pockets of shocked meteorites. Now, the existences of high-pressure polymorphs have been reported from ordinary chondrite, enstatite chondrite, ureilite, eucrite, iron meteorite, lunar meteorite, Apollo sample and Martian meteorite (e.g., Ohtani et al., 2004; Miyahara et al., 2014). On the other hand, it is widely accepted that carbonaceous chondrites were less shocked than ordinary chondrites, implying that high-pressure polymorphs would not be included in carbonaceous chondrites. However, Hollister et al. (2014) identified ringwoodite and stishovite from Khatyrka CV type carbonaceous chondrite. Shock metamorphism in carbonaceous chondrites may be overlooked or underestimated. CB type carbonaceous chondrite is a unique grouplet because it consists mainly of metallic Fe-Ni and chondrtic fragment (Weisberg et al., 2001). Although the origin of CB type carbonaceous chondrite has been under debated, some previous studies propose that it may be formed through a planetesimal collision (Weisberg et al., 2010). In this study, we investigated a high-pressure polymorph in CB type carbonaceous chondrite, Gujba to clarify its shock metamorphism history and origin using FEG-SEM, EPMA and laser Raman spectroscope.

We prepared a polished Gujba sample for this study. Gujba studied here consists of metal and chondritic fragment. Shock-melt veins occur widely between the chondritic fragments and metals. The major constituent minerals of the chondritic fragments are low-Ca pyroxene ($Fs_{1-5}$, $En_{89-98}$, $Wo_{0-6}$), Mg-rich olivine ($Fa_{1-18}$, $Fo_{82-99}$) and Ca pyroxene ($Fs_{1-13}$, $En_{41-66}$, $Wo_{32-57}$) based on EPMA analysis. Many mineral fragments and fine-grained chondritic fragments are entrained in the shock-melt veins. We confirmed the existences of many kinds of high-pressure polymorphs from such fragments and chondritic fragments adjacent to the shock-melt veins. Raman spectroscopy analyses indicate that olivine entrained in the shock-melt veins transform into wadsleyite. A small amount of ringwoodite is accompanied with some wadsleyite. Low-Ca pyroxene is replaced with akimotoite, majorite or probably bridgmanite. Minor Fe-rich olivine ($Fa_{39-40}$) and albitic feldspar ($Ab_{82}An_{13}Or_5$) are entrained in the shock-melt veins. Lamellar ringwoodite occurs in the Fe-rich olivine. The albitic feldspar is replaced with jadeite, lingunite or maskelynite. We also clarified the distributions of these high-pressure polymorphs in Gujba studied here. High-pressure polymorphs occur ubiquitously in and around the shock-melt veins, indicating that the parent-body of Gujba was heavily shocked. The metals, which consist of kamacite and minor FeS, show evidence for melting. Alternatively, we can also infer that Gujba is a part of shock-met veins induced by a collision.

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Keywords: carbonaceous chondrite, high-pressure polymorph, shock metamorphism

**Japan Geoscience Union Meeting 2015**
(May 24th - 28th at Makuhari, Chiba, Japan)

PPS22-21 Room:A02 Time:May 28 16:30-16:45

# Symmetry of majorite garnet in shocked chondrites revisited: A TEM study

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Majorite is a garnet-structured mineral with a composition on the join (Mg,Fe)$SiO_3$-$(Mg,Fe)_3Al_2Si_3O_{12}$, which contains Si in the octahedral sites. Al-free majorite samples synthesized by Kawai-type multianvil apparatus are known to have a tetragonal symmetry (space group $I4_1/a$) [1]. However, all of natural Al-free majorite samples found in shocked chondrites have been reported to be cubic ($Ia$-$3d$) [2]. Single-crystal X-ray study of a synthetic $MgSiO_3$ majorite clarified the tetragonal distortion of majorite is caused by Mg-Si ordering in the octahedral sites [3]. Subsequent microstructural observations of synthetic Al-free majorite by TEM concluded that the tetragonal phase is formed from the cubic phase through the cation ordering even upon rapid quenching ($10^3$ ℃/sec) and the symmetry reduction phase derives modulated and twinning structures [4]. On the contrary, cubic (Mg,Fe)$SiO_3$ majorite in shocked chondrites is inferred to have been preserved due to higher cooling rate than that in high-pressure synthesis where the cation ordering is inhibited.

Due to very small tetragonal distortion from the cubic phase ($c/a$ = 0.99) and very week extra reflections for the tetragonal phase, it is difficult to judge the symmetry of small amount of natural majorite samples by powder X-ray diffractometry. For the symmetry analyses of submicron-sized grains, single-crystal electron diffraction is a suitable method, since the intensities of weak reflections to diagnose the tetragonal symmetry are enhanced by the effect of dynamical diffraction. In this study, we revisit symmetries of majorite grains in shocked ordinary chondrites (Tenham; L6, Y-75100; H6) and also synthetic (Mg,Fe)$SiO_3$ majorite by TEM. The intensity of $\{101\}$ reflections, which appears only for the $I4_1/a$ tetragonal phase, is under investigation by selected are electron diffraction.

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Keywords: majorite, shock metamorphism, high-pressure phase transition, TEM

Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

PPS22-22 Room:A02 Time:May 28 16:45-17:00

# Basin forming event on Vesta: Petrologic evidence from a diogenite, NWA 5480

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The HED (Howardite, Eucrite, Diogenite) meteorites are the largest group of achondrites, and are derived from the regolith and crustal lithologies of asteroid 4-Vesta, which is the only surviving differentiated protoplanet in the Solar System. Diogenites are considered to have been derived from intrusions from within the curst or from a deep global layer. Some of them display high levels of platinum group element (PGE) concentrations that have been attributed to impact events on the parent body.

NWA 5480 is an unusual olivine diogenite. It has a heterogeneous crystalline texture. Irregular and subrounded clasts of dunite and fragments of olivine and chromite are set in an igneous matrix mainly composed of Low-Ca pyroxene. In some cases, large dunite clasts are intersected by pyroxene matrix. Flow textures are observed near some clasts. Olivine, chromite, and pyroxene show minor chemical zoning, implying relatively rapid cooling compared to typical diogenites. NWA 5480 contains a significant amount of PGE (CI x ˜0.001 for Ir) with chondritic relative proportions. All these line of evidence support that NWA 5480 is an impact melt breccia from a target composed of olivine and pyroxene-rich lithologies.

Upon heating of olivine diogenites, low-Ca pyroxene is the earliest phase to melt, and olivine and chromite are the last at >˜1600 C. The irregular and rounded shape resulted from resorption, and pyroxene veins and flow textures formed by violent mixing during impact melting. The pyroxene matrix crystallized from impact melts. Cooling rates estimated from the shape of Ca zoning of profiles near the rims in olivine fragments could be several tens of C/year, corresponding to burial depths less than a few km in impact melt sheet. An impact crater with diameter >a few hundreds km would be needed to produce impact melt sheet >a few km in thickness. Thus, we suggest that NWA 5480 was derived from impact melts from a very large crater of Vesta. The bulk chemical compositions indicate that the target was an area where olivine and orthopyroxene-rich rocks are largely exposed. However, there are no such areas on Vesta except minor olivine spots. Thus, it is likely that NWA 5480 sampled a part of large impact melt sheet (>a few km thick) formed by melting of deep crustal materials rich in olivine and orthopyroxene. One of the best candidates is the Rheasilvia basin (˜500 km diameter), where orthopyroxene-rich materials were observed in the crater floor.

Keywords: diogenite, Vesta, impact melt breccia, impact crater

PPS22-23 Room:A02 Time:May 28 17:00-17:15

# 147Sm-143Nd and 146Sm-142Nd chronology of a basaltic eucrite, NWA 7188

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Eucrites are achondritic meteorites originating from the Vesta's crust. They can be petrographically classified into basaltic and cumulate eucrites. Determination of precise ages for eucrites will constrain the period of igneous activity and the following thermal metamorphism of Vesta and may further provide insights into its differentiation and thermal history. We investigate the long-lived $^{147}$Sm-$^{143}$Nd ($T_{1/2}$ = $1.06\times10^{11}$ yr) and the short-lived $^{146}$Sm-$^{142}$Nd ($T_{1/2}$ = $6.8\times10^{7}$ yr [1]) systematics of a basaltic eucrite, NWA 7188 and compare the results with the ages obtained in previous chorological studies on cumulate and basaltic eucrites. To obtain highly precise age data, we developed the techniques for determining Nd and Sm concentrations and Nd isotope compositions in meteorite samples.

NWA 7188 was crushed and sieved into four sizes; G1) 500 — 1700 $\mu$m, G2) 250 — 500 $\mu$m, G3) 106 — 250 $\mu$m, and G4) $\leq$106 $\mu$m. G3 and G4 were separated into pyroxene and plagioclase grains by handpicking. We determined the $^{147}$Sm-$^{143}$Nd and $^{146}$Sm-$^{142}$Nd ages of NWA 7188 using G1, G3-px, G4-px, G3-pl, and G4-pl. These were dissolved using a mixture of concentrated pure acids ($HClO_4$, HF, and $HNO_3$). After the sample digestion, ~ 10% of the solution was removed and mixed with $^{149}$Sm- and $^{145}$Nd-enriched spikes to determine the Sm and Nd concentrations by ID-ICP-MS (X-series Ⅱ, Thermo). The remainder of the sample solution was used for highly precise Nd isotope analysis by TIMS (TRITON plus) with the dynamic multicollection mode. Nd was separated by a three-step column chemistry procedure; 1) major elements were removed by passing through a cation exchange resin, 2) Ce was removed using the LN resin (Eichrom) by oxidizing $Ce^{3+}$ into $Ce^{4+}$ using $KBrO_3$ [2] and 3) Nd was separated from Sm using the LN resin. We achieved Ce/Nd = ~ $3\times10^{-5}$ and Sm/Nd = ~ $4\times10^{-5}$ with $\geq$91% Nd recovery.

The $^{147}$Sm-$^{143}$Nd mineral isochron of NWA 7188 yields an age of 4203±970 Ma. In contrast, we obtained a much older $^{146}$Sm-$^{142}$Nd mineral isochron age of $4549\pm^{28}_{40}$ Ma when an initial solar system ratio of $^{146}$Sm/$^{144}$Sm = 0.0094 at 4568 Ma was applied [1]. It is presumed that thermal metamorphism on the Vesta has some effects on the $^{147}$Sm-$^{143}$Nd age while the $^{146}$Sm-$^{142}$Nd age represents the timing of the last Sm-Nd isotopic closure. Therefore, we use the $^{146}$Sm-$^{142}$Nd age of NWA 7188 in the following discussion.

The $^{146}$Sm-$^{142}$Nd age ($4549\pm^{28}_{40}$ Ma) for NWA 7188 is consistent with the $^{147}$Sm-$^{143}$Nd age for cumulate eucrites (4546±8 Ma [3]) within analytical uncertainties. This suggests that the parent body processes associated with the last Sm-Nd isotopic closure were contemporaneous for basaltic and cumulate eucrites. Likewise, the $^{146}$Sm-$^{142}$Nd age of NWA 7188 is not resolvable from the metamorphic age of Agoult [4]. According to the $^{53}$Mn-$^{53}$Cr systematics [5], the last global Mn/Cr fractionation in the mantle of the Vesta occurred at 4564.8±0.9 Ma, the timing when basaltic magmas have formed in the mantle. This implies that basaltic eucrites quenched rapidly on the surface of eucrite parent body, but thermal metamorphism may have affected both Sm-Nd and U-Pb systematics. No apparent age difference between basaltic and cumulate eucrites implies that both types of eucrites might have experienced similar cooling history as opposed to their petrographic distinction, or more likely that the time difference is too subtle to be resolved by the $^{146}$Sm-$^{142}$Nd system.

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Keywords: basaltic eucrite, Sm-Nd chronology, NWA 7188

Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

PPS22-24 Room:A02 Time:May 28 17:15-17:30

# Olivine petrofabric and chemical study of Divnoe ungrouped primitive achondrite

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Brachinite is a small group of achondrites mostly composed of olivine. Currently ~30 meteorites belong to brachinite, however, what are called “brachinite-like” but classified as “ungrouped” exist (e.g., Day et al. 2012; Keil 2014). Such “brachinite-like” meteorites have a similar rock texture, oxygen isotopic compositions or trace elements abundance to brachinite but do not perfectly match, and so they are classified as ungrouped. It is important to study these meteorites to understand the formation process of brachinite in general and their parental differentiated asteroid(s). Divnoe is one of such “brachinite-like” meteorite discovered in Russia in 1981 (Graham 1983; Petaev et al. 1994) and recently some meteorites similar to Divnoe have been found from hot and cold deserts (e.g., RBT 04239 and Tafassasset). These findings may establish a new achondrite group (“Divnoeite” ) including some of above “brachinite-like” meteorites (Gardner et al. 2007). In this study we analyzed Divnoe from mineralogical and chemical points of view to better understand its petrogenesis.

Divnoe is a medium- to coarse-grained achondrite (~0.5-2.0 mm in grain size) dominated by olivine ($Fo_{72-80}$) and apparent shape preferred orientation (SPO) of olivine grains is observed by optical microscopic observation. It is known that dislocation-creep controlled flow of upper mantle materials develops crystallographic preferred orientation (CPO) of olivine and seismic anisotropy in the Earth (Ohuchi 2013). Recently, Tkalcec et al. (2013) studied lattice preferred orientation (LPO) of olivine in diogenite and proposed solid-state plastic deformation in the dynamic interior of 4Vesta. Our EBSD (Electron Back Scatter Diffraction) analysis of Divnoe olivine grains shows that they are preferentially aligned along [001], which is parallel to elongation of olivine grains. The dimensions of [100] and [010] are randomly oriented. This observation indicates that CPO of Divnoe olivine was achieved when olivine grains accumulated in magma rather than plastic deformation after solidification in the interior of the parent body, which is consistent with previous study (Ando et al. 2003). Therefore, Divnoe is likely an olivine cumulate rock. However, we found that its bulk chemical composition has high abundance of siderophile elements (Ir, Pt: ~0.5 x CI), which is unusual for an olivine cumulate. Such high abundance of siderophile elements may be derived from addition of an iron meteorite component by impact. It is required to analyze other Divnoe-like meteorites to see whether (1) olivine SPO is present or not and (2) such chemical signature (e.g., enrichment of siderophiles) is similarly seen.

PPS22-25 Room:A02 Time:May 28 17:30-17:45

# Crystallization and cooling conditions for the diogenite formation in the turbulent magma ocean of the asteroid 4 Vesta

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The asteroid 4 Vesta has been completely differentiated to core and mantle despite its small size, of which surface materials are howardite-eucrite-diogenite (HED) meteorites that we know the detailed petrology, and therefor, is a good target for understanding differentiation of terrestrial planets. A new differentiation model for crust formation was developed by taking magma ocean fluid dynamics, chemical equilibrium, presence of $^{26}$Al, and cooling into consideration with special care to crystal separation. The role of crystal size, thickness of the conductive lib, and $fO_2$ are evaluated as parameters. Large crystals (1cm) settle and form a km-thick cumulate layer of orthopyroxene with Mg# of 0.70-0.90 in 20 thousand years, which almost agrees with the Mg# of diogenites, whereas thinner layers are formed if the grain size is smaller.

Keywords: magma ocean, Asteroid 4 Vesta, HED meteorites

Japan Geoscience Union Meeting 2015
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PPS22-26 Room:A02 Time:May 28 17:45-18:00

# A mineralogical and chemical study of primitive achondrite NWA 6704

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Introduction: Primitive achondrites provide unique insights into the early stage of growth and differentiation of planetesimals. Northwest Africa (NWA) 6704 is an ungrouped primitive achondrite found in Algeria in 2010. This meteorite is composed mainly of low-Ca pyroxene, olivine, feldspar, chromite, awaruite, heazlewoodite, pentlandite, and whitlockite. The U-Pb dating of this meteorite shows the crystallization age of 4563.75 ± 0.41 Ma (1). To better understand the formation process of this primitive meteorite, we carried out a mineralogical and chemical study of NWA 6704 using SEM-EDS, EPMA and LA-ICP-MS.

Results & Discussion: Seven polished thin sections (TS-1˜7; 10×18mm; 10×20mm; 9×10mm; 10×12mm; 10×11mm; 15×28mm; 19×28mm) have been investigated. The texture is best characterized by the existence of many orthopyroxene (Opx) megacrysts up to 1.56 cm in length ($Fs_{40-42}En_{53-57}Wo_{3-4}$). Olivine ($Fa_{50-53}$) typically occur as interstices associated with feldspar and have subhedral shapes, but locally occur as the vermicular olivine within the Opx. The vermicular olivine share the same optical extinction position under crossed-nicols and occurs only in one place near the center of each Opx crystal if present. Feldspar ($Ab_{91-93}An_{5-6}Or_{2-30}$) occurs in the Opx and the interstices as anhedral cuspate grains with extremely low dihedral angles and sharing the same optical extinxtion position over up to 1cm, which implies that it's pseudomorph of a melt-filled interstitial pore. Other phases include chromite (Cr# = 0.90-0.96) and awaruite (78-81 wt% Ni) also occur associated with feldspar. We estimated $fO_2$ of FMQ -2.6 using the Olv-Opx-Spl oxygen geobarometer (4).

The texture is properly represented by aggregate of large Opx hollow (skeletal) megacrysts with finer interstices. Other phases such as olivine are present in the hollow cores, and some of them are isolated from the interstices. The contiguity of feldspar in the Opx megacrysts with or without olivine in three dimensions is clearly demonstrated by the fact that the same optical extinction position are shared by feldspar isolated in the megacrysts and those present in the interstices. The distribution of the Opx hollow crystal and the vermicular olivine are highly heterogeneous. In TS-1 and TS-6, Opx $<$6.2 mm across are dominant and more than five of them include vermicular olivine; in TS-2˜5 and TS-7, Opx megacrysts up to 1.56cm across are common and only a few of them contain vermicular olivine. The vermicular olivine may be a decomposition product of the precursor pyroxene through the abrupt heating ($>$1400 ℃). There is a negative correlation between size of Opx and the number of vermicular-olivine bearing Opx. Given this fact, a new scenario can be derived: this vermicular olivine and its host acted as nuclei for crystallization of hollow Opx crystals, and the number of nuclei limits the size of Opx. Thus, more nuclei in a given area result in smaller grain size as seen in TS-1,6. The abnormally large size of Opx and its hollow morphology indicates that the initial crystallization occurred under rapid cooling. The SEM images, however, show that some pigeonite contain sub-micrometer-size augite ($Fs_{17}En_{45}Wo_{39}$) exsolution lamellae. We estimated equilibrium temperatures of 1050 ℃ using two-pyroxene geothermometry (3) and of 773 ℃ using Olv-Spl $FeMg_{-1}$ exchange thermometry (4). The cooling rate between 1100-950 ℃ was estimated to be ˜0.02 ℃/hr from the thickness and wavelength of multiple exsolution lamellae (5), indicating significant decrease in cooling rate at a later crystallization stage. The inferred thermal history suggests high internal temperature of the parent planetesimal due to $^{26}$Al decay, which was abruptly heated by impact followed by rapid cooling up to the ambient temperature to sustain slower cooling.

References: (1) Iizuka et al. (2013), (2) Warren et al. (2012), (3) Lindsley & Andersen (1983), (4) Ballhaus et al. (1991), (5) Jackson (1961)

Keywords: Primitive achondrite, NWA6704