

MINERALOGY OF STARDUST COMETARY GRAIN T112: SIMILARITY TO AMOEBOID OLIVINE AGGREGATES.

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Introduction:

The successful analysis of comet 81P/Wild 2 particles returned by the Stardust mission has revealed that the Wild 2 dust contains abundant silicate grains that are much larger than interstellar grains and appear to have formed in the inner regions of the solar nebula [1]. Wild 2 particles include minerals which are isotopically and mineralogically similar to CAIs [e.g., 2], chondrules [e.g., 3], and amoeboid olivine aggregates (AOAs) [e.g., 4] in chondrites. In this study, we have examined the mineralogy of the Track 112 particle and compared the possible relationships between T112 and AOAs.

Results and Discussion:

Our two TEM grids from T112 are dominated by 4 micron -sized forsteritic olivine. Submicron sized chromite is associated with the olivine. The olivine from T112 is near end-member forsterite, but shows a slight enrichment of Fe toward the grain rim. In the least metamorphosed chondrites, most AOAs consist of forsterite. Enrichment of olivine in fayalite component is correlated with petrologic subtype of a host meteorite [5]. In CV chondrites, Fe-enrichment is distinct in Allende (petrologic type >3.6). The Fe enrichment on the rim of T112 olivine may have been caused by a minor degree of thermal processing after the condensation of forsterite.

From EDS analyses, the chromite grains have high Cr₂O₃ content (up to 65 wt. %), and yield Al-absent compositions with intermediate Mg# ; however, it is likely that some Mg detected by EDS is from neighboring olivine and that the grains are closer to pure chromite in composition. Chromite is a minor phase in Wild 2 particles. Cr-rich spinels have been identified in the chondrule-like particle Torajiro [3] and associated with Coki-B Kool fragments (T141 [6]); however, these spinels have significant Al₂O₃.

Three possibilities for the formation of chromite can be considered: (i) direct condensation from a gas; (ii) crystallization from chondrule melt; (iii) metamorphism/aqueous alteration. (i) Modeling by [7] predicts that Cr-rich spinel crystallizes in mixed vapor + silicate liquid + refractory solid reactions at high temperatures in dust enriched systems, but always with significant Al₂O₃. (ii) This modeling [7] also shows that chromite is stable with silicate liquid at high dust enrichment, but textures of T112 particle do not appear to be typical of chondrules. Furthermore, the 16O-rich composition of olivine in the potted butt sample from (T112) is more consistent with AOAs than chondrules. (iii) Tiny Cr-rich grains surrounding olivine in type 3 ordinary chondrites were identified by [8] as products of incipient metamorphism. The T112 chromite might have a similar origin.

The forsteritic, 16O-rich composition of T112 olivine suggests a condensation origin. Slight enrichment in Fa-content along the olivine rim suggests some metamorphism. At this point, we consider metamorphism the most likely origin of T112 chromite.

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Keywords: meteorites, carbonaceous chondrites, cometary dust

Oxygen isotopic distribution of Fluffy Type A CAI from Efremovka

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A formation process of planetesimals from dust grains is most uncertain part in the planetary formation theory. The dust grains in the micron-to-centimeter size range are preserved in chondrite. Especially, "fluffy" shaped Type A Ca-Al-rich inclusions (FTA CAIs) are aggregates of domains that contain micron-sized grains thought to be condensed from the nebular gas. In the CAI-forming region, distinct ¹⁶O-rich and ¹⁶O-poor gaseous reservoirs are considered to be co-existed (Yurimoto et al. 2008). In this paper, we study petrology and oxygen isotopic distribution of a FTA CAI from Efremovka CV3 chondrite in order to reveal the growth process and the environment of the grain size evolution.

FE-SEM-EDS-EBSD system (JEOL JSM-7000F; Oxford INCA Energy; HKL Channel 5) was used for petrologic study. Oxygen isotopic compositions have been measured by SIMS (Cameca ims-1270).

The CAI is 1 cm x 4 mm in size with "fluffy" shape and surrounded by the Wark-Lovering rim (WL rim). The CAI is divided into two domains that named as domain-1 and domain-2. The WL rim surrounds each domain.

In the domain-1, melilite crystals near the WL rim show reverse zoning and are observed as a layer of ~40 micron in width. The reverse zoning is typically ak30 in the center and ak15 at the grain boundary. Melilite crystals inside of the layer show oscillatory zoning, initially started as reverse zoning and changed to normal zoning. The compositions are ak35 in the center, ak30 at intermediate, and ak40 at the grain boundary. The oxygen isotopic compositions of the melilite crystals in the domain-1 are distributed homogeneously, $\delta^{18}\text{O} = 5\text{-}10$ permil. In the domain-2, melilite crystals positioned shallower than ~150 micron in depth from the WL rim show reverse zoning that are typically ak15 in the center and ak5 at the grain boundary. The oxygen isotopic compositions of these crystals are distributed along CCAM line ranging between $\delta^{18}\text{O} = -40$ and 0 permil and change from ¹⁶O-rich to ¹⁶O-poor with the distance from WL rim.

Reversely zoned melilite crystals in FTA CAIs are readily explained by the condensation from a solar nebular gas with falling pressure (MacPherson and Grossman 1984). The reversely zoned melilite crystals in the domain-1 and the domain-2 were also condensed from the nebular gas with decreasing pressure. The oscillatory zoned melilite crystals may be the result of overgrowth of normal zoning on the grain boundary of partially molten reversely zoned melilite crystals. The homogeneous oxygen isotopic composition in the domain-1 indicates melilite crystals were formed in a ¹⁶O-poor nebular gas. On the other hand, the oxygen isotopic distributions observed in the domain-2 suggests that the gas was changed from ¹⁶O-poor to ¹⁶O-rich during the condensation of melilite.

Typical compositions of the reversely zoned melilite crystals in the domain-1 and the domain-2 are ak30-15 and ak15-5. They formed below the eutectic temperature of melilite and fassaite. According to Yoneda and Grossman (1995), these crystals condensed below 1570 K and lower pressure than 10^{-2} atm. If the temperature is constant, the pressure of the gas surrounding the reversely zoned melilite crystals in the domain-2 is about 1.5-2 times lower than that of domain-1. For example if the temperature is 1400 K, the pressure was changed from 3.2×10^{-4} atm to 2.2×10^{-4} atm for domain-1, and from 2.2×10^{-4} atm to 9.7×10^{-5} atm for domain-2. However these conditions seem to be occurred continuously, the oxygen isotopic compositions of the melilite grains in each domain indicate that they were formed in the different nebular environment and incorporated into the FTA CAI.

In this study, we revealed that the micron-sized dust grains that were condensed from gas experienced different nebular environment during the accumulation to millimeter-sized domains. These domains were accreted together to form the centimeter-sized FTA CAI.

Keywords: Fluffy Type A CAI, melilite, chemical zoning, dust coagulation, oxygen isotopes, solar nebula

Oxygen isotopic distribution of a porous Type A CAI from Ningqiang chondrite

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Ca-Al-rich Inclusions (CAIs) have been reported oldest age in the solar system and large mass-independent fractionation for oxygen isotopic compositions. Fine grained CAIs, which are thought to be condensed from gas, often contain micron-sized voids (Lin and Kimura, 2003; Wasson et al., 2000). However, coarse-grained compact CAIs are usually unporous. We found a porous CAI having many micron-sized voids from Ningqiang C3-ungrouped chondrite. We studied petrology and oxygen isotopic distribution of the CAI in order to reveal the formation process of micron-sized voids.

Petrographic observation and chemical analysis were performed by FESEM-EDS (JEOL JSM-7000F + Oxford INCA Energy). Crystal orientation analysis was performed by EBSD (HKL Cannel 5). Oxygen isotopic composition was analyzed by SIMS (CAMECA, ims-1270).

A coarse grained CAI analyzed in this study has about 2x2 mm in size with rounded shape but with irregular portion in part. The CAI is mainly composed of melilite, diopside, spinel and perovskite. The CAI has a porous structure with voids occupying nearly 30% in volume. The CAI is rimmed by Wark-Lovering rim composed of melilite, spinel, anorthite and diopside layers. The CAI is classified into type A CAI with high perovskite abundance by the bulk composition and mineralogy.

Two types of void are observed in the CAI. We categorized small void and large void by their size and shapes. The small voids are three micrometers or smaller in size. The voids distributed in regions near the Wark-Lovering rim and in 50-100 micron sized regions consist of 5 micron sized melilite crystals with few micron sized perovskite crystals. Melilite crystals in the regions show reverse zoning, i.e., Mg-rich interior and Al-rich rim. The oxygen isotopic compositions of the melilite varies from $\delta^{18}\text{O} = -40$ permil to $\delta^{18}\text{O} = 0$ permil. Reversely zoned melilites in type A CAIs are believed to be condensed from gas (MacPherson and Grossman, 1984). Therefore, it is suggested that melilite in the regions did not experience melting, and small void was formed during the process of condensation and accumulation of melilite and perovskite.

The large voids have roundish irregular shape and distributed inside of 300 micron sized melilite crystals. In a single crystal of melilite crystals void-rich areas are gehlenitic (ak2-5) and void-free areas are akermanitic (ak15-24). Oxygen isotopic compositions of the melilite crystals at the void-rich areas were $\delta^{18}\text{O} = -5$ permil and the void-free areas were $\delta^{18}\text{O} = -20 \sim -10$ permil. Nepheline was sometimes observed at the area with voids. The mineral layer of diopside and anorthite exists at walls of some voids. Fine grained porous CAIs in Ningqiang are thought to be formed by an aqueous alteration on its parent body (Sugita et al., 2009). If the large voids in the CAI were formed by the aqueous alteration, it is required that voids were preferentially formed at gehlenitic area or that melilite compositions became gehlenitic during the void formation. We will study the relation between chemical zoning and crystals growth of melilite in order to clarify formation processes of the large voids in this CAI.

Keywords: void, CAI, oxygen isotopic composition, Ningqiang, melilite

Rapid cooling of chondrule to reproduce olivine bars observed in barred olivine chondrules

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Chondrules are millimeter-sized and spherical-shaped crystalline grains consisting mainly of silicate material. Since chondrules occupy about 80 vol.% of chondritic meteorites in abundant cases, they must have great information about the early history of our solar system. They are considered to have formed from molten droplets about 4.6 billion years ago in the solar nebula; it is believed that they melted and cooled again to get solidified in a short period of time. They have various solidification textures that record the solidification process. Barred olivine (BO) chondrules show a unique texture characterized by parallel set(s) of olivine bars in a thin section. BO chondrule usually has an olivine crystal, which is termed as rim, which covers the chondrule surface. This olivine rim has the same crystallographic orientation as inner olivine bars, which connect to the rim. It is considered that the crystallographically continuous structure was formed by morphologic instability during olivine growth, like dendritic crystals. However, initial process of the morphologic instability that produces the olivine bars has not been investigated in details.

We investigated the initial process of formation of BO texture based on numerical simulation of solidification of chondrule melt. The thermodynamically consistent phase-field model for a binary alloy based on the entropy functional is adopted here. We adopted Mg_2SiO_4 - Fe_2SiO_4 binary system in which only olivine is considered as a solid phase. We carried out a numerical simulation of a molten olivine droplet solidifying from a platy seed crystal at droplet surface. Under an extremely rapid cooling condition, in which the cooling rate is 5000 K/s, the platy seed crystal overgrew keeping its flat interface at the beginning of solidification, and then changed to cell-like pattern due to morphological instability. The initial stage before the instability can be considered as the formation of olivine rim, and the cell-like pattern as that of olivine bars. In this case, the average width of bars is about 5 micrometer in numerical result, which is comparable to that observed in natural BO chondrules ranging from 5 to 100 micrometer. If we consider that the bar width is proportional to a root of the cooling rate, the required cooling rate to reproduce 100 micrometer thickness is evaluated as $12.5 \text{ K/s} = 45000 \text{ K/hr}$, which is much faster than the canonical value of 1000 K/hr inferred from traditional experiments. We also found that the rim and olivine bars showed zoning profile in Fe/(Mg+Fe) value, which was similar to that of laboratory-synthesized BO chondrules.

Our numerical simulation of solidification of chondrule melt suggested that the cooling rate should be much faster than that inferred from traditional experiments to produce olivine bars of 5 ? 100 micrometer in width such as observed in natural BO chondrules.

Keywords: chondrule, solidification texture, crystal growth, zoning profile

Artificial micrometeorites from powdered Allende meteorite

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Micrometeorites (MMs) are extraterrestrial dust particles that have been captured by the Earth and are thought to be derived from asteroids and comets. Depending on their velocity, mass and entry angle, MMs have undergone various degrees of heating during their deceleration in the atmospheric entry within a few seconds. This heating may lead to significant textural, mineralogical and chemical modifications in MMs.

In this study, we carried out immediate heating and quenching experiments on fine particles to represent for atmospheric entry of MMs. The experimental system is reported by Isobe and Gondo (2012). We used powdered Allende meteorite (typical CV3 chondrite) with approximately 100 micron meters in diameter as the starting material.

The run products show analogues textures to MMs including scoriaceous, porphyritic olivine and dendritic magnetite. Fe sulfide occurs on melted particle surfaces. Immiscibility between sulfide melt and silicate melt may induce sulfide melt discharge from silicate melt. The surface distribution of iron sulfide in MMs has not been reported. Sulfide on MMs may be removed by abrasion in the upper atmosphere. This process may be constant source of sulfur species other than volcanic activity to the upper atmosphere. Maximum temperature and thermal history of particles were estimated from compositions of melt and minerals. Analogy of the run products to MMs are discussed on textural, mineralogical and chemical modifications during atmospheric entry.

Keywords: micrometeorite, heating / quenching experiment, Allende meteorite, atmospheric entry

Correlations between D and ^{15}N -rich organic matters in a carbonaceous chondrite

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Carbonaceous chondrites contain organic matters that are enriched in D and/or ^{15}N [1-2]. The D and/or ^{15}N -rich organic matters are believed to have formed in molecular cloud or outer protoplanetary disk in early solar system [1-2], however, relationship between the D and ^{15}N enrichment is unclear. Previous study suggests that there are good correlation between D-rich and ^{15}N -rich region in organic matters of carbonaceous chondrite [1], but other studies suggest that the D and ^{15}N enrichment are not correlated [2].

In this study, we tried to analyze D and ^{15}N -rich organic matters in carbonaceous chondrite by in-situ analysis. We determined spatial distribution of D and ^{15}N enrichments of organic matters in NWA 801 CR2 chondrite by isotope imaging. Our previous study reported that the NWA 801 contains many D-rich organic matters [4]. The isotope imaging was performed using isotope microscope of Hokkaido university (Cameca ims-1270 + SCAPS [5]). The sample surface was homogeneously irradiated over a field area with a broad Cs^+ primary beam of ~ 50 micron in diameter. Secondary ion images of H^- , D^- , $^{12}\text{C}^-$, $^{12}\text{C}^{14}\text{N}^-$ and $^{12}\text{C}^{15}\text{N}^-$ were obtained from a field. We obtained $^{12}\text{C}^-$ images before and after the analysis for a field to check whether carbonaceous matter was disappeared during the isotope analysis. Total integration time for a field was ~ 10 minutes. After the isotope analysis, morphological observations of isotopically anomalous materials were performed by FE-SEM-EDS (JEOL JSM-7000F, Oxford INCA Energy).

Seven D-rich materials and six ^{15}N -rich materials were found in NWA 801 matrix of approximately 0.2 mm^2 . ^{12}C were detected from the five D-rich materials and six ^{15}N -rich materials during measurements. The continuously D and ^{15}N enrichments were observed from different spots. Hydrogen isotopic compositions of the D-rich carbonaceous matters are 2,300-7,900 permil in delta-D. Nitrogen isotopic compositions of the ^{15}N -rich carbonaceous matters are 1,100-1,200 permil in delta- ^{15}N . The morphologies of D-rich or ^{15}N -rich carbonaceous matters are determined by FE-SEM analysis. The D-rich and ^{15}N rich matters have similar morphology, which are round or irregular shaped carbonaceous globules, or aggregate of some carbonaceous globules.

The carbonaceous matters with D or ^{15}N enrichment might be organic matters that have formed in molecular cloud and/or outer protoplanetary disk in early solar system. Large D-rich and ^{15}N enrichment believed to have occurred in extremely cold region [6, 7]. The D or ^{15}N enrichments signatures suggest that they have survived through alteration on parent body of NWA 801. The lack of correlation between D and ^{15}N anomalies may be due to different origin for D and ^{15}N -rich carriers.

Other than these carbonaceous matters, two D-rich materials have not detected for ^{12}C peak in isotopography. Possibility of the carbonaceous matters for the D-rich materials are ruled out, because carbon was not detected in $^{12}\text{C}^-$ images obtained before and after the measurement. N related peaks were not detected at the D-rich spots. Hydrogen isotopic compositions of these D-rich materials are 3,400 and 3,800 permil. Si, O, Mg, Fe and Al were detected from these D-rich materials by the X-ray analysis. The results suggest that the D-rich materials are silicates and plausibly phyllosilicate because previous study revealed that phyllosilicates in Rennazo CR2 chondrite were enriched in deuterium [7].

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Keywords: D and ^{15}N -rich organic matters, Carbonaceous chondrite, Correlation of D and ^{15}N enrichment, Isotope imaging

The observation of shock textures in fragments of Kilabo, LL6 ordinary chondrites

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The Hayabusa space-craft reached S-type asteroid 25143 Itokawa in 2005 [1]. As a result of observations of telescope and a series of remote sensing researches, it is estimated that Itokawa has compositions similar to L or LL5 to 6 ordinary chondrites [2,3,4]. Then Hayabusa could have retrieved samples of Itokawa back to the Earth from the asteroid surface called MUSES-Sea Regio in 2010. Initial analyses showed that those samples collected by Hayabusa correspond to LL4 to 6 ordinary chondrites because analyses data of mineralogy, chemical compositions and oxygen isotopic ratios are consistent with LL4 to 6 chondrites [5,6,7,8,9,10].

The size of Itokawa samples analyzed by initial analysis is mainly as small as a few tens of micrometers. Sample size has problems because it is difficult for us to understand which processes and which parts of host rocks did micrometer sized samples come from on the surface of Itokawa. Therefore it is also difficult to extend their mineralogy and textures to those of larger scale.

On the other hand, many meteorites fallen to the Earth have been analyzed although their parent bodies are unknown other than the Moon and the Mars. But analyses of meteorites have not focused on micrometer sized samples so far. To study micrometer sized samples of meteorites in detail is important for extending their tiny samples to understanding of larger scale information about Itokawa samples. Furthermore, we may get new knowledge about meteorites from analyses of micrometer samples.

In this study, using the LL6 ordinary chondrite named Kilabo, we focused on shock textures in micrometer sized grains of Kilabo. Shock textures are generally observed in ordinary chondrites and caused by impact on the surface of asteroid [11]. As a result of initial analyses, Itokawa is supposed to be accumulated fragments of bigger parent body crushed by impact [5] and shapes of returned samples are also seems to be affected by impact [9]. This study observed shock textures in micrometer and millimeter samples of meteorites and compared both of them.

The results of the comparison showed that planar fractures, which typically observed in olivine and feldspar as shock textures, were found in real micrometer samples at 54% while they are found in millimeter samples at only 39%. In contrast, few micrometer samples have a melt texture caused by impact while Kilabo was reported that it has many shock veins by previous study [12].

These results suggest that micrometer grains broken from bigger chondritic materials are selective in specific textures in host materials. It is possible that these specific textures are also present in surface materials of Itokawa and also affect to brecciations on asteroid surface. Therefore micrometer samples made by brecciations may not be reflected mineralogy and textures of host rock because some shock textures occur in specific minerals.

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Keywords: Meteorite, Hayabusa, Itokawa, Shock metamorphism, Ordinary Chondrite

H₂O contents and hydrogen isotopic composition of apatite crystals in L, LL5-6 ordinary chondrites

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Introduction: Ordinary chondrites of petrologic types 4 to 6 exhibit a sequence of progressive chemical and textural equilibration. However, the conditions and environment of metamorphism are not well constrained. The role of fluids is poorly understood, although there is evidence that fluids were present (Li et al., 2000; Dunn et al., 2010; Jones et al., 2011). The secondary phosphate minerals apatite and merrillite can be used to interpret the conditions of the metamorphic environment, since they can potentially preserve a record of interactions with parent body fluids (Jones et al., 2011). In this study, we report the petrography, H₂O contents and hydrogen isotopes in chlorapatite from L, LL5-6 ordinary chondrites using secondary ion mass spectrometry (SIMS).

Analytical methods: 10 thin sections of Carnegie (L6) and thick section (Barwell (L5), Mocs (L5-6), Carnegie (L6), Ensisheim(LL6)) mounted one inch with San carlos Olivine were used in this study. Apatite grains were identified using elemental X-ray mapping, using scanning electron microscope (FE-SEM JEOL JSM 7000-F) and energy dispersive X-ray spectrometry (EDS Oxford INCA Energy) at Hokkaido University. Quantitative analyses were also performed using FE-SEM-EDS system.

The Hokudai isotope microscope system (Cameca ims-1270 SIMS instrument at Hokkaido University) was applied to determine D/H ratio and H₂O contents of apatite. The meteorite and standard sample were kept pumping about two months in the ultra-high vacuum chamber in order to reduce the surface adsorbed water on the samples. The Dorang apatite (0.0478wt%) and Linopolis apatite (1.28wt%) were used to estimate the H₂O content using the calibration curve with H/18O ratio. In the same analytical session, the H/18O ratio of San carlos olivine crystals were also measured to compare with those of chlorapatite from ordinary chondrites. The hydrogen isotopic compositions was calculated using Dorango apatite (dDSMOW =-121permil). The overall analytical errors were about 20permil (2sigma). The detail analytical conditions are shown in Greenwood et al. (2011).

Results and Discussion:

H₂O content of apatite grain can only be estimated in Ensisheim (LL6) by SIMS because it is difficult to avoid cracks or metamorphic phases. H₂O contents of apatite are estimated to be 18-35ppm. These results are much smaller than those based on a deficit. This difference is consists with that of Jones et al. (2011). In addition, the H/18O ratio of apatite grain from Ensisheim is about five times higher than those of San carlos olivine. In the future, H₂O content of the apatite in chondrites will be estimated using a lower water content of standard.

The hydrogen isotopic compositions of apatite grains in the LL6 Ensisheim chondrite are likely to be D-rich. However, it is difficult to estimate these values quantitatively because of low water content. In the future, we will develop to measure the hydrogen isotopic compositions of such a low water content in apatite grains.

Keywords: ordinary chondrite, apatite crystal, H₂O, hydrogen isotopic composition, SIMS

Water Content of the 4.56Ga D'Orbigny Parent Body Estimated from Phosphate

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Behavior of water in the formation of planets is essential to understand the origin of the terrestrial water (Albarede, 2009) and evolution of planets. We estimated the water content of the parent body of D'Orbigny meteorite, a ~4.56Ga angrite, as 0.001~0.006wt% combining the water content of phosphate and petrological and mineralogical information on melting and crystallization history of D'Orbigny. This study shows that a planetesimal contains a minor but an appreciable amount of water in the very early stage of the solar system evolution.

At first, we have estimated the timing of phosphate crystallization to estimate the water content of D'Orbigny parent body from phosphate, an accessory mineral. D'Orbigny consists chiefly of plagioclase, clinopyroxene and olivine with ophitic texture accompanying many spherical voids and druses (Kurat et al., 2001; Mittlefehldt et al., 2002). Phosphate is always found in interstices of the major constituent minerals, and Fe and Ca in olivine and Fe, Al and Ti in clinopyroxene are extremely enriched to almost Mg-free composition toward the interstices, and intergrowth of olivine and kirschsteinite is developed. The interior of the intergrowth is systematically occupied by skeletal phosphate, ulvospinel, troilite, and rounded voids. This microstructure indicates that the phosphate crystallized from a residual melt before formation of troilite and voids (vesicles) in the waning stage of crystallization.

We analyzed 3 coarse grains of phosphate with a NanoSIMS to determine the hydrogen concentration and hydrogen isotopic composition. The average water content and isotopic composition is obtained to be 0.03wt% and D/H=2.9x10⁻⁴, respectively. This D/H ratio is near the lower limit of D/H of comets and Martian meteorites (Canup and Righter et al., 2000). This implies that the water in the D'Orbigny parent body had a similar origin as that of comets and that the D'Orbigny parent body could be a planetesimal that accreted to form Mars.

The water content of the D'Orbigny parent body is estimated from that of phosphate on the basis of the following petrologic evaluation. At first, D'Orbigny is inferred to have been liquid magma solidified in a closed system but not a cumulate, which is supported by ophitic texture and continuous Fe-increase and Mg-decrease in olivine and clinopyroxene towards the interstices. Then, the crystallinity at the phosphate crystallization is calculated to be 98 vol.% from the volume of troilite and voids, which further implies that the water content of the D'Orbigny melt is 0.003~0.012wt% on the basis of the water partition coefficient between apatite and melt (McCubbin et al., 2011). On the other hand, the meteorite contains much larger spherical voids and druses, which suggest that the melt was vesiculated at the early stage of crystallization. Assuming that water is the most dominant gaseous component and that the vesicles maintained equilibrium with the melt, the water held in the vesicles is calculated to correspond to 0.0005~0.0038 wt% in the melt by using the ideal gas equation and the volume fraction of spherical voids and druses. The sum of the two estimates is the initial water content of the melt. The water content of the parent body (mantle) is further estimated to be 0.001~0.006 wt% on the assumption that the melting degree was high enough (30~40 %) to consume pyroxenes, because the REE pattern of D'Orbigny is unfractionated. The estimate is comparable to 2~13 % of the water content of the Earth (0.046 wt%), if the Earth's interior has an equivalent amount of water to the amount of the seawater (Hirschmann, 2006). This study shows a planetesimal, which accreted to form solid planets, contained a little amount of water in the very early stage of planet formation. Application of this approach to various types of meteorites may pave the way for better understanding of the water origin and transporation in the planetary formation process.

Na-metasomatism in the Ningqiang carbonaceous chondrite : A TEM and SR-XRD study

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Ca-Al-rich inclusions (CAIs) and chondrules in carbonaceous chondrites are known to be an initial condensate from the early solar nebula at high temperatures. However, they often include various amounts of nepheline ($[\text{Na,K}]\text{AlSiO}_4$), which condenses under relatively low temperatures. The nepheline in CAIs and chondrules is, therefore, widely believed to be a secondary mineral which have formed by replacing the primary condensate phases through the process called Na-metasomatism. Recent studies [1,2] showed that a degree of Na-metasomatism is correlated with the petrologic subtype, and thus suggested that the Na-metasomatism occurred on the meteorite parent bodies. In the case, matrix, the major part of meteorite parent bodies, could not have escaped the process. Nonetheless, previous studies did not refer to the Na-metasomatism in the matrix. The Ningqiang carbonaceous chondrite is known to be rich in bulk Na content compared to typical CV chondrites [3], and its CAIs include large amount of nepheline [4]. Here, we will report detailed mineralogical characteristics of the chondrules and the matrix in the Ningqiang chondrite concerning its signature of the Na-metasomatism. The sample used in this study is one polished thin section of the Ningqiang chondrite ($\sim 560 \text{ mm}^2$ total area). They were examined with a scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometer (EDS), a transmission electron microscope (TEM) equipped with an EDS, and a synchrotron radiation X-ray diffraction (SR-XRD).

The SEM and TEM observations revealed that more than 90 percent of the chondrules (39/41) include nepheline by replacement of plagioclase in their mesostasis. Small amounts of sodalite have been also observed. In many chondrules, plagioclase has been completely replaced by nepheline and sodalite, suggesting that the degrees of Na-metasomatism of the chondrules are probably high. The SR-XRD and X-ray mapping analyses revealed that about 10 vol.% of the matrix is composed of nepheline and sodalite. The abundance of nepheline and sodalite in the matrix is so large as not to be seen in other chondrites. These minerals are distributed throughout the matrix as fine grains (< 10 micron). The estimated value of bulk Na content ($\sim 4 \text{ mg/g}$) from the matrix volume (~ 40 vol.%) and the nepheline/sodalite abundance is consistent with the previous study ($\sim 3.76 \text{ mg/g}$) [3]. These mean that nepheline and sodalite are the major host minerals of Na content of the Ningqiang chondrite.

In the Ningqiang chondrite, the most of CAIs and chondrules, and matrix include abundant nepheline and sodalite. These results indicate that Na-metasomatism on the Ningqiang parent body has extensively and ubiquitously taken place. Na-metasomatism might be an ordinary process which has occurred on many meteorite parent bodies. Although the most of previous studies had found the evidence of Na-metasomatism in CAIs and chondrules, further studies that focus on matrix may also give a new clue to solve the process of Na-metasomatism.

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