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Abstracts

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Progress in classification of Antarctic meteorites in China

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Meteorite classification not only involves identifying whether a sample is indeed a meteorite, but also requires obtaining petrological, mineralogical, and geochemical data to classify the type of meteorite, followed by securing approval from the Nomenclature Committee of the Meteoritical Society. Therefore, meteorite classification serves as a fundamental basis for Antarctic meteorite research.

In December 1998, during the inland comprehensive survey conducted by China's 15th Antarctic Scientific Expedition Team (hereinafter referred to as the "Expedition Team") in the Grove Mountains, four meteorites were discovered, three of which were ordinary chondrites and one an iron meteorite. Shortly afterward, during the 1999-2000 period, China's 16th Antarctic Scientific Expedition Team discovered 28 meteorites in the Grove Mountains, including one Martian meteorite and one HED meteorite. This marked the confirmation of the Grove Mountains as the first meteorite-enriched region discovered by China in Antarctica, with a wide variety of meteorite types found. Subsequently, China continued meteorite collection efforts in the Grove Mountains through five additional Antarctic expeditions, ultimately collecting a total of 12,665 meteorites. As a result, China now possesses a significant number of Antarctic meteorites that require classification, making the classification work both extensive and challenging. Based on different periods and participating institutions, the classification work of Antarctic meteorites in China can be roughly divided into three stages.

Stage 1: The classification tasks were assigned and funded by the Chinese Arctic and Antarctic Administration of the State Oceanic Administration. In 2000, Peking University and the Institute of Geology and Geophysics at the Chinese Academy of Sciences (CAS) conducted the first classification study on four meteorite samples, among which three were classified as chondrites and one as an iron meteorite. Subsequently, during the 2001-2002 Antarctic scientific expedition, China classified 28 meteorite samples discovered during the 16th Antarctic Expedition. This classification work was carried out independently by four institutions: the Guangzhou Institute of Geochemistry (CAS), the Institute of Geology and Geophysics (CAS), the National Astronomical Observatories (CAS), and Nanjing University. Through the efforts of this stage, China initially established a systematic process and standards for the classification of Chinese antarctic meteorites.

Stage 2: After 2005, the Ministry of Science and Technology of China, relying on the National Natural Science Resource Sharing Platform project, assigned basic meteorite classification tasks through the Chinese Arctic and Antarctic Administration and the Polar Research Institute of China. These tasks included the classification of 51 samples from the 4,448 meteorites discovered during the 19th Antarctic Expedition in 2005. From 2006 to 2008, China began large-scale systematic classification of Antarctic meteorites and established the Antarctic Meteorite Resource Sharing Platform. This project was carried out with the participation of eight institutions: the Institute of Geology and Geophysics (CAS), the Guangzhou Institute of Geochemistry (CAS), the National Astronomical Observatories (CAS), the Institute of Geochemistry (CAS), the Purple Mountain Observatory (CAS), Nanjing University, the Beijing Planetarium, and Guilin University of Technology. Stage 3: Beginning in 2012, China has continuously carried out Antarctic meteorite classification work on an annual basis. This phase was jointly funded by the National Natural Science Resource Sharing Platform project and the Polar Research Institute of China, with Guilin University of Technology leading the effort. A total of 3,760 meteorites were classified during this phase. To facilitate the development of the Antarctic Meteorite Repository and the sharing of meteorite data, Guilin University of Technology gradually refined various classification standards, including but not limited to: thin section preparation standards, digital photography standards, electron backscatter imaging standards, and compositional analysis standards.

Through the classification work conducted across these three stages, China has successfully classified a total of 6,193 meteorites. Among these, 73 were identified as unordinary chondrites (Table 1). These special meteorites represent a wide range of known meteorite types but make up a relatively small proportion (1.18%), which is significantly lower than the proportion found in other Antarctic regions (8.36%).

Acknowledgements

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Table 1. The number and types of unordinary chondrite meteorites in China's Antarctic meteorites						
Туре	Number	Group	Meteorites			
	0	<u>CN</u>	GRV 020005, GRV 020017, GRV 020025, GRV 021536, GRV 021580, GRV 050179,			
Carbonaceous chondrites	9	СМ	GRV 050384, GRV 13051, GRV 130434			
	1	СК	GRV 020015			
	1	СО	GRV 021579			
	4	CR	GRV 021710, GRV 021767, GRV 021768, GRV 021769			
	7	CV	GRV 021865, GRV 021992, GRV 022459, GRV 023154, GRV 023155, GRV 023158,			
			GRV 023159			
	3	Unclassified	GRV 020736, GRV 150256, GRV 150190			
Martian meteorites	2	Shergottite	GRV 99027, GRV 020090			
	3	Eucrite	GRV 99018, GRV 051523, GRV 13001			
HED meteorites	1	Howardite	GRV 150277			
	1	Diogenite	GRV 150230			
Lunar meteorite	1	Polymict breccia	GRV 150357			
···			GRV 021512, GRV 021729, GRV 021788, GRV 022835, GRV 022888, GRV 022931,			
Ureilite	11		GRV 024237, GRV 024516, GRV 052382, GRV 052408, GRV 090312			
Enstatite chondrite	2		GRV 021692, GRV 13100			
D: '/'	1	Acapulcoite	GRV 021663 (Later as classified as Winonaite)			
Plillitve	1	Winonaite	GRV 022890			
achondinte	1	Unclassified	GRV 022905			
Turan masta arita	6	IAB	GRV 98003, GRV 090327, GRV 090333			
non meteorne		Unclassified	GRV 090018, GRV 150481, GRV 150136			
Pallasite	1		GRV 020099			
	17		GRV 020124, GRV 020171, GRV 020175, GRV 020281, GRV 021525, GRV 021553,			
Mesosiderite			GRV 050212, GRV 054854, GRV 055055, GRV 055153, GRV 055364, GRV 090994,			
			GRV 020362, GRV 020518, GRV 020649, GRV 020733, GRV 020906			
T (1	= -					

Total

73

Oxygen isotope analyses of chondrules from CA chondrites Asuka-9003 and 09535

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Introduction:

A current model explaining the whole-rock isotope dichotomy is the accretion of non-carbonaceous chondrites (NCs) and carbonaceous chondrites (CCs) parent asteroids inside and outside, respectively, of the early formed proto-Jupiter (Desch et al., 2018). Bulk chondrule data from different classes of chondrites distribute at the specific locations in the oxygen threeisotope diagram near those of their host meteorites (Clayton, 1993). These data have been interpreted as indicating a close relationship between the regions where chondrules formed and where they accreted to make asteroidal parent bodies. Chondrules in NCs mostly plot above or near the terrestrial fractionation (TF) line. In contrast, CCs chondrules typically plot close to the carbonaceous chondrite anhydrous mineral (CCAM) line (Clayton, 1993), but some CCs chondrules plot on or above the TF line (e.g., Ushikubo et al., 2012; Tenner et al., 2017; Schrader et al., 2020), suggesting that those chondrules might be related to OC-like materials. However, the extent of radial migration and mixing of materials in the early Solar System remains poorly understood.

Asuka (A)-9003 and A-09535 represent a new type of carbonaceous chondrite, designated CA (Kimura et al., 2022). These CA chondrites have unique features: they share similarly high chondrule/matrix ratios with ordinary chondrites but resemble CO and CV chondrites in terms of the abundances of refractory inclusions (4–6 vol%) and oxygen isotopic compositions (Kimura et al., 2022). With characteristic features of both NCs and CCs, the CA chondrites are in some sense transitional between materials that accreted in the inner solar system and those from the outer solar system. Thus, analysis of their components could help shed light on complex histories of material transport before their accretion into the parent bodies. Here we present the results of petrological characterizations and oxygen isotopic analyses of chondrules in CA chondrites. **Methods:**

Chondrules studied were identified in polished thin sections of Asuka-9003 and 09535, on loan from the National Institute of Polar Research. The petrographic observation and chemical analysis were performed by scanning electron microscopy (Tescan Vega) equipped with an energy dispersive spectrometer. The oxygen isotope analyses were carried out on the UCLA CAMECA ims-1290 ion microprobe in multicollection mode. Because of grain size or avoiding veins and small metal grains, we used a ~50 pA and a ~4 nA Cs⁺ primary ion beam focused to ~4 and ~15 μ m spots, respectively. **Results and discussion:**

The selected 68 (36 from A-9003 and 32 from A-09535) chondrules are all Type I, with Mg# (= $100 \times \text{molar Mg/(Mg} + \text{Fe}) \ge 90$, and are mostly dominated by a porphyritic texture. Based on the proportion of olivine and pyroxene, they are further divided into type A (>80% olivine), type AB (20–80% olivine), and type B (<20% olivine). Six of 36 chondrules in A-9003 are classified as type A, 19 are type AB, and 11 are type B. In comparison, there are 2 type A, 17 type AB, and 13 type B among the chondrules analyzed in A-09535.

A-9003 and A-09535 have the bulk oxygen isotopic composition of $\Delta^{17}O = -4.65\%$ and -4.89%, respectively (Kimura et al., 2022). Our in-situ measurements revealed that $\Delta^{17}O$ values of olivine and pyroxene in individual chondrules vary from +1.1% to -22.6‰ for A-9003 and +1.3‰ to -8.7‰ for A-09535. One olivine grain in an A-9003 chondrule is much more ¹⁶O-rich ($\Delta^{17}O \sim -23\%$) than the average $\Delta^{17}O$ values (-3 to -7‰) obtained from other chondrules, indicating that it could be a relict grain. Such ¹⁶O-rich olivine grains are observed in chondrules from both NCs and CCs, but are less abundant in NC chondrules than in CC chondrules (e.g., Yurimoto and Wasson, 2002; Kita et al., 2010). Five chondrules in A9003 and A09535 plot on or above the TF line, and the rest of the chondrules (~90%) are characterized by $\Delta^{17}O < 0\%$. Based on these data, we infer that CA chondrites likely accreted material primarily derived from the CC reservoir. Materials from the OC region may also have been preserved in some chondrules with heavier oxygen isotopic compositions, but effects of water ice on such compositions cannot be ruled out.

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OAo3

Alkaline-rich accessory minerals in Ryugu grain and Orgueil CI chondrite

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The petrological, mineralogical, and geochemical characteristics of Ryugu grains are most similar to those of CI chondrites (Ito et al., 2022; Nakamura et al., 2023; Yokoyama et al., 2022). The major constituent minerals of CI chondrites are well studied, which allows to infer the global state of aqueous alteration that occurred on the parent body. In contrast, an accessory mineral gives an indication of local heterogeneous aqueous alteration in the parent body and/or the mixing of material of different origin. An alkaline element such as sodium (Na) and potassium (K) in CI chondrites is depleted compared to ordinary chondrites due to strong aqueous alteration on the parent body (Wasson and Kallemeyn, 1988; Zolotov, 2012). In CI chondrites, most Na and K are present as interlayer cations of saponite. Na- and/or K-rich accessory minerals may provide a new clue to the heterogeneity of the CI chondrite parent body. By combining a SEM equipped with a field emission electron gun (FEG), which can produce a highly brilliant electron beam, and a highly sensitive energy dispersive X-ray spectrometer (EDS), an accessory mineral in a meteorite can be found efficiently. In this study, one of the CI chondrites, Orgueil, was investigated together with Ryugu grains by FEG-SEM-EDS and FIB-assisted FEG-TEM/STEM-EDS to describe the Na-and/or K-rich accessory minerals.

Sample plate C0105-042_000_00 (hereafter C0105-042), which was once analyzed by the Hayabusa2 Initial Analysis "Sand" team (Noguchi et al., 2024; Noguchi et al., 2023) and realocated by the approval of the 2nd AO, was used for this research. Ryugu small grains on sample plate C0105-042, averaging ~100 μ m in diameter, were collected from chamber C (C0105 aggregate grains collected from the second touchdown). There are more than 24 Ryugu small grains (from No. 1 to No. 24) on C0105-042. First, the surface morphology of grain C0105-042_No. 15 was observed by secondary electron imaging with a FEG-SEM. Then, a part of No. 15 grain was excavated by an FIB to prepare a TEM ultrathin film. TEM observations show that No. 15 grain consists of two different fragments. Both fragments consist mainly of Mg-Fe phyllisilicates, magnetite, and Fe-Ni sulfides (5C pyrrhotite). There is no clear difference in the chemical composition of Mg-Fe phyllosilicates between two fragments. However, one fragment contains Cu-bearing Fe-Ni sulfides (width < ~1.0 μ m) and K-Cu-bearing Fe-Ni sulfides (width < ~1.5 μ m). Based on selected area diffraction patterns, the former is cubanite (CuFe₂S₃) and the latter is djerfisherite K₆(Fe,Cu,Ni)₂₅S₂₆Cl (calculated *a* = 10.2Å).

Seven fragments of Orgueil CI chondrite (diameter $< \sim 1$ mm) were embedded in epoxy resin and polished under dry conditions. The detailed polishing procedure is described in Yamaguchi et al. (2023). The major constituent minerals of the seven fragments are Mg-Fe phyllosilicates, magnetite, iron-sulfides, and Ca-Mg carbonates, which are similar to Orgueil studied in previous studies (Gounelle and Zolensky, 2014). Mg-Al spinel, orthoclase, silica, and Na-sulfide/sulfate are present as accessory minerals in some fragments. Four Mg-Al spinel grains with dimensions $< \sim 10 \,\mu\text{m}$ are embedded in fine-grained Mg-Fe phyllosilicates. Zinner et al. (2005) and Liu et al. (2022) also found Mg-Al spinel in the Orgueil CI chondrite and considered it to be of pre-solar origin. There is no doubt that the spinel was originally contained in Orgueil, given its occurrence. On the other hand, we cannot exclude the possibility that silica and orthoclase are contaminants, since these grains are not embedded in the matrix of Orgueil, but are present only around Orgueil fragments. More careful investigation is required to know whether these minerals are intrinsic or contamination. Amoeboid material containing Na and S is found in several locations on the sample surface. No substances containing Na or S are used in the polishing process, and it is unlikely that the amoeboid material is a contaminant in the polishing process. The amoeboid material may be a deliquesced Na-sulfide/sulfate.

Mirabilite (Na₂SO₄ · 10H₂O) and metathénardite (Na₂SO₄) are the candidates for Na-sulfate. A mineral of Na-sulfide (Na₂S) has not been found in nature, however, it may be present when part of the Ca in an oldhamite (CaS) crystal is replaced by Na. In the present sample, it is difficult to clarify what kinds of minerals are originally present because Na-sulfide/sulfate is easily deliquesced under atmospheric conditions. Yamaguchi et al. (2023) found Na-rich hot spots in Ryugu C0014 grain, and they suggested that these spots are originally sodium hydroxide (NaOH). Calculations of chemical equilibria in closed waterrock-gas systems predict that the major species in solutions coexisting with CI chondrites are Na⁺, Cl⁻, K⁺, OH⁻, H₂, and CO₂ (Zolotov, 2012). Na-sulfide/sulfate in Orgueil CI and NaOH in Ryugu C0014 grain may be the remnants of the alkaline solutions.

Djerfisherite is found in enstatite chondrites and aubrites formed under reducing conditions (Lin, 2022; Weisberg and Kimura, 2012; Wilbur et al., 2024). There are two possible scenarios to explain the existence of djerfisherite in the Ryugu

grain: i) extrinsic and ii) intrinsic origin. In scenario 1, the fragment of djerfisherite derived from an enstatite chondrite or an aubrite was accumulated on the asteroid Ryugu. In scenario 2, the interior of asteroid Ryugu was in a reducing environment at some places where djerfisherite was formed. Although it is difficult to further discuss the origin of djerfisherite because oxygen isotope ratios have not been analyzed, there is no doubt that Ryugu asteroid also contains extrinsic material and/or material that is indicative of a local heterogeneous environment in the body. It is expected that more heterogeneous material will be found in Bennu's returned samples, which has a larger total volume than Ryugu.

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Prompt gamma-ray analysis of Antarctic meteorites (2) - CM chondrites

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Introduction

Mighei type carbonaceous chondrites (CM) make up the majority of carbonaceous chondrites in the Antarctic meteorite collection. CM chondrites have the second highest volatile element contents after CI chondrites. Almost all CM chondrites are characterized by aqueous alteration, and a number of meteorites have experienced dehydration caused by heating after aqueous alteration. These characteristics make CM chondrites the most appropriate research samples for discussing the processes of material evolution in the early solar system.

Ten CM chondrite samples were selected from the meteorite collection of the National Institute of Polar Research (NIPR) and their major elements were quantified by PGA. Petrological and mineralogical studies have been carried out on most of these meteorites, but there are limited reports of elemental analysis, especially of analytical data for the major elements. The aim of this study is to combine major element data with mineralogical/petrological knowledge to gain more insight into the formation process of CM chondrites.

Experimental

PGA was carried out using the JRR-3 research reactor of Japan Atomic Energy Agency. The ten CM chondrites analyzed in this study were Asuka (A) 12437, A 09474, A 12236, Yamato (Y) 984044, Y-793321, Y-791198, Y-82098, Y-791191, A-881655 and Y-82042, the first four being classified as CM, the next five as CM2 and the last Y-82042 as CM1/2. Eight of these meteorites have a recovered mass of less than 100 g. PGA is ideal for elemental analysis of such samples, as solid samples can be analyzed non-destructively and the effects of neutron irradiation are negligible. A similar analysis was applied to 12 meteorites classified as CY chondrites. The results were presented at the 2023 NIPR symposium on Antarctic meteorites and are currently being submitted as a paper (Ebihara et al., under review).

Results and Discussion

Eleven elements were determined by PGA: Ca, Ti, Si, Co, Ni, Fe, Cr, Mn, chlorine, S and H. In the analysis of the 'CY' chondrites, in addition to these elements, Al, Mg, B and Gd could be quantified, but contents of these elements could not be determined with sufficient accuracy due to the experimental conditions of this study. Among the analyzed meteorites, A 12236 and Y-793321 may be the two extremes. According to Kimura et al. (2020), A 12236 is rich in Fe-Ni metal and shows little phyllosilicate, meaning that aqueous alteration on the parent body was minimal and that it has not subsequently experienced significant heating and dehydration. On the other hand, Nakamura (2006) observed that Y-793321 has a regolith texture and was probably produced by impact in the surface layer of the parent body, during which it was heated to about 500°C, causing dehydration. Thus, the petrological and mineralogical features are significantly different between A 12236 and Y-793321. Nevertheless, no apparent differences were observed in major elemental composition from this study. In fact, with the exception of Cl and H, the major elemental compositions of the ten analyzed meteorites do not differ among within the limits of analytical error, which supports the claim of Rubin et al. (2007) that the CM material evolution occurred in an isochemically closed system. Large variations in chlorine and H contents were observed between the samples (1σ RSD: 44%, 47%). However, unlike in the case of 'CY', no positive correlation was observed between the two element contents. Chlorine is likely to have been added to the surface of meteorites after they fall on Antarctica. On the other hand, it is considered that weathering in Antarctica could also increase the H content in meteorites, but to a smaller extent than for chlorine. The major elemental composition of Y-82042 does not differ from other meteorite samples except for H. The H content of Y-82042 is higher than the CM meteorites analyzed and higher than the average value for CM (Wasson and Kallemeyn, 1988), which is consistent with the CM1/2 classification of this meteorite.

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Quantitative elemental mapping of chondrites using LA-ICP-TOF-MS

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Introduction

Elemental mapping has commonly been used for the screening of geological, biological, and other types of samples, using micro-X-ray fluorescence spectrometry (μ -XRF), scanning electron microscopy in combination with energy-dispersive X-ray spectrometry (SEM-EDS), or electron probe micro analysis (EPMA). Most of these techniques are valuable for major element distributions, but their application is rather qualitative and more limited for minor/trace elements due to their relatively high limits of detection. For trace element mapping, laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) has been widely used as a direct solid sampling micro-analytical technique [*e.g.*, 1]. Recently, time-of-flight (TOF) based ICP-mass spectrometers have been made commercially available and LA-ICP-TOF-MS provides rapid quasi-simultaneous detection of nearly the entire elemental mass spectrum for each individual laser pulse, exhibiting an ideal tool for fast elemental mapping applications including trace elements in a quantitative manner. Therefore, we invested significantly in applying this mapping technology to extraterrestrial materials for examining and improving the potential of LA-ICP-TOF-MS mapping, *i.e.*, to fundamentally evaluate how fast LA-ICP-TOF-MS mapping can be performed on meteorite samples containing relatively small mineral grains in terms of the spatial resolution and the ability for quantification [2].

Experimental

Polished thick sections (PTSs) were prepared for various petrologic types of ordinary chondrites and CM chondrites including finds and falls. Firstly, back-scattered electron (BSE) images and the X-ray maps of the major elements for the PTSs were obtained using a field emission (FE)-SEM-EDS at NIPR, Japan, and FE-EPMA at JAXA, Japan. The X-ray maps were also obtained using μ-XRF at the Vrije Universiteit Brussel (VUB), Belgium. Once their constituent minerals were identified based on the major element maps and BSE images obtained, EPMA and FE-EPMA were performed at NIPR and JAXA, respectively, to determine the major element abundances in each constituent mineral. Parallel to the EPMA analysis, the areas of interest on each PTS were defined for the subsequent LA-ICP-TOF-MS mapping. Finally, quantitative element mapping was conducted using LA-ICP-TOF-MS at Ghent University, Belgium. Additionally, the abundances of selected trace elements were determined for constituent minerals and cracks using single-point drilling for the minerals and line scans for the cracks by LA-ICP-sector field (SF)-MS at NIPR

Results and Discussion

To assess the reliability of the quantitative data as obtained using LA-ICP-TOF-MS mapping, the accuracy and precision were compared to data obtained using the more conventional spot analysis with EPMA and LA-ICP-SF-MS for major and trace elements, respectively. According to the results, first of all, LA-ICP-TOF-MS mapping reveals the elemental



Fig. 1. A combined X-ray elemental map of Asuka 09618 (H5) and a combined TOF elemental map of an area of interest.



Fig. 2. A BSE image and (semi-)quantitative element maps for Asuka 12236 (CM2.9) (a) BSE image of the region analyzed. (b) Combined RGB elemental map with red: Ca, green: Si, and blue: Na. (c) Aluminum distribution map. (d) Neodymium distribution map. Scale bars for (c) and (d) are in wt.% and ppm, respectively.

distributions among the constituent minerals of meteorite samples at sufficiently high spatial resolution (Fig. 1). For example, trace element mapping using LA-ICP-TOF-MS represents the first instance in which elemental depositions within cracks or grain boundaries were visually confirmed [3]. As such, LA-ICP-TOF-MS mapping demonstrates the capability to determine elemental distributions in cracks and along grain boundaries where conventional spot analyses cannot be applied readily. In terms of quantitative capabilities, overall, major and trace element abundances determined using LA-ICP-TOF-MS are in good agreement with up to 30% relative uncertainty compared to the values obtained based on the spot analyses and relative to literature values [3 and references therein]. In particular, the main host phase(s) of an element can readily be identified and the major and trace element abundances in the phase(s) can be quantified at an accuracy level approaching that of the spot analyses. Moreover, follow-up analysis such as backscatter electron (BSE) imaging, EPMA, and LA-spot analysis on the regions studied using LA-ICP-TOF-MS mapping shows that the LA-ICP-TOF-MS imaging process does not inflict changes on the material surface. This is because only a single laser shot is fired per pixel position for fast mapping, which minimizes sample consumption to only a top sample surface layer of approximately 100 nm.

In our ongoing study, LA-ICP-TOF-MS mapping aids in visualizing the elemental distribution even in CM chondrites, which consist of the relatively small size of minerals ($<50 \ \mu$ m) containing inclusions ($<10 \ \mu$ m) and have a high matrix/chondrule ratio, with obvious identification of zones enriched and depleted in specific elements [Fig. 2]. According to the preliminary results, Al-rich phases in CM chondrites are enriched in rare earth elements (REEs) as high as those of Caphosphates. Moreover, the other refractory lithophile elements are also abundant in these phases. Given the modal abundances of these phases, expectedly Ca, Al-rich inclusions ($\sim 1 \ vol.\%$ in total; [4]), such Al-rich phases constitute the main host of refractory lithophile elements in Spite of the existence of Ca-phosphates even for REEs. Therefore, our study shows that LA-ICP-TOF-MS mapping can be performed for a large surface area (cm² order), at high spatial resolution (5×5 μ m/pixel), and at a high scan speed (up to 1000 pixel/s = 5000 μ m/s) with the negligible effect of the ablation on the surface, and constitutes a powerful screening tool for extraterrestrial samples in order to reveal the elemental distribution even in the case of chondrites with a high matrix abundance.

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Petrology and Mineralogy of Beardsley (H5) Chondrite

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Introduction: Alkaline element enrichment has been identified in the interstitial glasses of several igneous clasts in brecciated LL chondrites such as Yamato (Y)-74442 (LL4), Bhola (LL3-6), and Krähenberg (LL5) [1,2]. These igneous clasts have seemed to have formed during impact melting event(s) with alkali-rich precursor(s) [1,2]. Alkaline-bearing minerals such as halite (NaCl) and sylvite (KCl) have only been identified in three brecciated H chondrites, Zag (H3-6), Monahans (1998) (H5) and Sidi El Habib 001 (H5) [3-5]. Beardsley (H5) is also recognized as alkaline-rich chondrite (up to 8 wt.% of K_2O in its matrix) [7], although the rock contains neither halite nor sylvite.

The origin of these alkali-rich materials is still unclear. Zolensky *et al.* [4] found inclusions (sodium chloride-potassium chloride brines) embedded in halite and sylvite in Monahans (1998) and suggested that the minerals may have originated from icy objects (ejected by cryovolcanism). On the other hand, the Cs/Ba abundances of Zag and Beardsley chondrites are similar to those of CAI in carbonaceous meteorites, suggesting that primitive aqueous alteration on their parent bodies [6]. Therefore, these chondrites are important for elucidating the elemental distribution and/or fractionation process in the solar nebula. Despite unique chemical characteristics of Beardsley chondrite, however, detailed petrological study of the chondrite is still lacking. In this study, we conduct petrological and mineralogical studies for Beardsley to understand the petrogenesis of the chondrite.

Sample and method: A fragment of Beardsley is allocated from Arizona State University. We made a polished thin section, and a polished thick section for petrological and mineralogical works. These were observed under an optical microscope and a scanning electron microscope (SEM: JEOL JSM-6490 with accelerating voltage of 15 kV). Elemental distribution maps of major elements were obtained using an EDS (OXFORD INSTRUMENTS INCA x-sight) attached to the SEM. Major chemical compositions of constituent minerals were analyzed using an electron probe microanalyzer (EPMA: JEOL JXA-8230, acceleration voltage 15 kV). All analyses were conducted at Okayama University of Science.

Results: Beardsley consists of two different lithologies of brown and gray without clear boundaries by macroscopic observation. The brown lithology mostly consists of coarse-grained pyroxene $(270 - 530 \ \mu\text{m})$, olivine $(120 - 470 \ \mu\text{m})$, Fe-Ni metal $(120 - 440 \ \mu\text{m})$ and troilite $(50 - 260 \ \mu\text{m})$ embedded in fine-grained glassy matrix. The minor minerals of Beardsley include several phosphate minerals (up to 200 \ mm) that formed chloro-apatite on the outside of the merrillite (Fig.1).

The gray lithology also contains coarse-grained pyroxene grains, however, these grains show overgrown texture at the rim of the grain surrounded by glassy matrix. The compositions of the host pyroxene and overgrown pyroxene were $En_{81.1-82.3}Fs_{15.4-17.2}Wo_{1.2-3.6}$ and $En_{48.3-51.7}Fs_{5.6-6.9}Wo_{41.5-46.4}$, respectively. Euhedral to subhedral pyroxene grains are embedded in glassy matrix were found in intersitis of fractures.

In contrast to the brown lithology, submicron-sized Fe-Ni metal droplets were ubiquitous in the coarse-grained fragments. We observed the formation of plessite in some of the metal at the gray lithology. The plessite was present in two forms: one made of typical fine-grained texture, and the other show stretched texture (Fig.2).

Potassium was mostly identified at the feldspathic glass matrix with K₂O contents of up to 2.3 wt.%. We also found relict potassium bearing minerals with relatively high amount of K contents than glassy matrix.



Figure 1. We identified to chloro-apatite with merrillite in Beardsley. Cl-ap. = Chloro-apatite. Merr. = Merrillite.



Figure 2. This plessite can be seen both stretched by force of the impact and normal granular state.

Beardsley contains a few unique lithic fragments (clasts). One of the clasts composed of fine-grained euhedral pyroxene and feldspathic glass with low Fe content (Fig.3A). The pyroxene composition consisted of Mg-rich ($En_{80.2-82.4}Fs_{16.2-18.4}Wo_{0.9-1.6}$) and Ca-rich ($En_{49.2-50.3}Fs_{6.1-6.3}Wo_{43.5-44.8}$) areas. Another clast contains numerous submicron-sized euhedral chromite and olivine grains embedded in feldspathic glass (Fig.3B, C).

Discussion and summary: The brown lithology contains coarse grained Fe-Ni metals with rusty rims, that are brown in color due to alteration [7,8]. The pyroxene grains of the lithology have a homogeneous composition; therefore, the brown lithology is a relict host phase of the Beardsley chondrite. On the other hand, the gray lithology has abundant submicron metal grains occurring in coarse lithic fragments of olivine and pyroxene and shows weak darkening. Overgrowths of pyroxene are found at the rim of fractures and have large compositional gaps from the host minerals. Interstitial materials in fractures are euhedral to subhedral pyroxene and feldspathic glass indicating that pyroxene grains crystallized from secondary melt. In addition, the deformed plessite in the gray lithology is also thought to have been stretched by shear stress during impact (Fig.2). Collectively, the gray lithology experienced incomplete melting during the impact event like Yamato-791088 type impact melt rock [9].

We found two lithic clasts in the sections. Each of the clasts has unique characteristics and differs from the Beardsley host materials (Fig.3). Both clasts have fine-grained euhedral to subhedral minerals of pyroxene or olivine, and oxide minerals embedded in glassy matrix also indicating products of impact melts. These clasts are thought to have formed as the melt droplets from different source materials. In conclusion, the Beardsley chondrite experienced incomplete melting with melt clasts derived from different impact events.

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Figure 3. Two lithic clasts in Beardsley. A) Elemental distribution map obtained by EDS. Red indicates K, green indicates Mg, and blue indicates Ca. A lithic fragment (surrounded by dotted line) consists mostly fine-grained Mg-rich pyroxene embedded in feldspathic glass (low-K).

B) Numerous submicron-sized euhedral chromite and olivine-bearing feldspar phases. Overall view.

C) Enlarged view of the part shown in B (white box). The euhedral minerals identified were inferred to be olivine and chromite based on the elemental contents by EDS.

Isotopic and organic molecular distributions of Asuka 12 CM chondrites

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Introduction: The Asuka 12 CM meteorites (Asuka 12085, 12169, and 12236) were reported by Kimura et al [1] as the most primitive CM (3.0-2.8) chondrites. The minimum aqueously altered CM chondrites have been studied for amino acids [2], presolr grains [3] and bulk carbon and hydrogen isotopic compositions [4]. The D-richment of Asuka 12236 could show the most primitive signature of H-bearing materials including water [4]. The hot water extract of Asuka 12236 yielded more abundant amino acids (up to \sim 360 ppm) than aqueously altered CM meteorites such as Murchison [2]. However, other soluble organic compounds in the Asuka 12 chondrites are largely unknown. CM chondrites contain a suit of homologous CHN and CHN₂ compounds including alkylated pyridines and imidazoles [5]. In this study, the Asuka 12 chondrites were examined for isotopic compositions and molecular occurrence for soluble organic matter.

Sample and Methods: Fragments of three Asuka 12 CM chondrites; Asuka 12085 (CM2.8), Asuka 12169 (CM3.0), and Asuka 12236 (CM2.9), were powdered using a quartz mortar and pestle in a clean room. A part of the sample powder was subjected to an elemental analyzer-isotope ratio mass spectrometer to determine bulk carbon (δ^{13} C) and nitrogen (δ^{15} N) isotopic compositions. Each sample powder was sequentially extracted with hexane, dichloromethane and methanol by sonication. The methanol extract was analyzed by nanoLC using a C18 column coupled with a high-resolution mass spectrometer (HRMS) through a nanoESI interface [6].

Results and Discussion: Bulk C and N contents ranged from ~1.7 to ~1.9wt% and from ~0.09 to ~0.12wt%, respectively, which are consistent with the previous study [4]. The isotopic compositions showed a little variation ranging from -2.3 to -0.9‰ for δ^{13} C values and from +53.2 to +54.3‰ for δ^{15} N values (Fig. 1). Both C and N became slightly more enriched in contents and heavy isotopes with increasing the grade of alteration. The isotope behavior implies that ¹³C- and ¹⁵N-rich components might be lost during the aqueous alteration.

The nanoLC/HRMS analysis identified alkylated Nheterocyclic homologous compounds (shown as C_nH_mN and $C_nH_mN_2$) in the methanol extract of A-12236. These include extensively alkylated pyridines ($C_nH_{2n-5}N$) and imidazoles ($C_nH_{2n-2}N_2$) homologues in the range up to C_{33} with the maxima of C_{13} . The relative contents are almost identical between alkylated pyridines and imidazoles homologues in A-12236, while alkylpyridines are more abundant than alkylimidazoles in other CM chondrites such as the Murchison meteorite [5]. Even though both alkylated N-heterocycles could be produced from simple aldehydes (i.e. formaldehyde and acetaldehyde) and ammonia [5], the relative contribution of the synthetic mechanisms may be different depending on the degree of aqueous alteration.

Further studies are needed to clarify organic molecular distributions with respect to alteration processes within the parent bodies of CM chondrites.



Fig. 1. Bulk δ^{13} C– δ^{15} N values of the Asuka 12 CM chondrites.

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The distribution of nitrogen heterocyclic molecules extracted from the Kaba CV3 carbonaceous chondrite using methanol

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The Kaba meteorite, a carbonaceous chondrite, has long been a subject of interest for scientists studying the composition and distribution of organic compounds in extraterrestrial materials. Recent analyses have revealed the presence of various heterocyclic molecules, including alkylpyridines, which may provide clues about the potential prebiotic chemistry that occurred in the Early Solar System. Furthermore, the identification of alkylpyridines in the Kaba meteorite aligns with findings from other meteorites, suggesting that such compounds are not unique to this specimen but may instead represent a more widespread distribution of organic molecules in carbonaceous chondrites (Imae et al., 2013). This raises interesting questions about the processes involved in the synthesis and preservation of these organic compounds during the formation of the Solar System, as evidence suggests that similar organic structures are found in other carbonaceous meteorites as well (Imae et al., 2013). Moreover, the survival of these compounds during the meteorite's atmospheric entry highlights the potential for complex organic chemistry to endure even under extreme conditions, underscoring the significance of carbonaceous meteorites as reservoirs of prebiotic material that may have contributed to the origin of life on Earth (Bonner 1996, Breslow & Cheng, 2009).

One of the key features of the Kaba meteorite is the presence of alkylpyridines, a class of heterocyclic organic compounds (Bonner, 1996, Murchie et al., 2009, Breslow & Cheng, 2009, Toxværd, 2013). These compounds are of particular interest due to their potential role in prebiotic chemistry, as they may serve as building blocks for more complex organic molecules that are essential for life, highlighting the importance of extraterrestrial sources in understanding the origin of homochirality in biological systems (Breslow & Cheng, 2009). The formation of chiral molecules in extraterrestrial environments suggests that these organic compounds could have provided critical precursors for the biochemical pathways that led to life on Earth, particularly through processes such as asymmetric photolysis in interstellar settings, which could yield enantiomeric excesses in the organic materials that eventually accreted into the solar system (Bonner, 1996, Breslow & Cheng, 2009).

The identification of alkylpyridines in the Kaba meteorite contributes to a growing body of evidence that suggests the widespread distribution of heterocyclic molecules in carbonaceous chondrites (Bonner 1996, Breslow & Cheng, 2009, Toxværd, 2013). This distribution implies that these organic compounds could have formed under various conditions in space and subsequently been delivered to early Earth, where they may have played a crucial role in shaping prebiotic chemistry and supporting the complex processes necessary for the emergence of life (Bonner 1996, Breslow & Cheng, 2009, Toxværd, 2013). The presence of these compounds in the Kaba meteorite, as well as in other carbonaceous meteorites, suggests that similar prebiotic chemistry may have occurred in different regions of the solar system, potentially providing a diverse source of organic material for the development of life on Earth (Bonner 1996, Gleiser & Walker 2008, Breslow & Cheng, 2009, Toxværd, 2013). In addition, the detection of alkylpyridines and other organic molecules in meteorites like Kaba raises intriguing possibilities regarding their synthesis mechanisms, as well as their implications for the origins of homochirality and the conditions necessary for life to arise in the broader cosmic context.

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Reproduction experiments on the chondrule formation of the E3 chondrites

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Introduction

The detailed mechanism of chondrule formation remains unresolved, despite the numerous models proposed to date [e.g., 1]. However, certain constraints on the formation process, such as peak temperature, precursor material, cooling rate, gas interaction, and chronology, are well-established. E3 chondrites predominantly consist of type IB chondrules and metal nodules, exhibiting a unique assemblage that is distinctly different from those of C and O chondrites. Experimental investigations into the formation of E3 chondrite chondrules, including the associated nodules, may provide new constraints on the chondrule formation environment and offer a unique perspective on their origin. In the present study, we explore the formation of reduced E3 chondrite chondrules using a newly developed experimental technique, building on preliminary work related to the sulfidation of Mg-silicates [2].

Experiments

Anhydrous carbonaceous chondrites may serve as potential precursors for EH3 chondrites, as relict forsterites have been identified within them [3, 4]. The starting material, NWA 1465 anhydrous carbonaceous chondrite (fragment or sintered pellet of powder), was placed in a graphite capsule along with a troilite grain in another graphite capsule. The assembly was then double-sealed under vacuum in silica glass tube (Fig. 1). Argon gas was flowed through the system during heating to prevent the silica glass from breaking in the vertical electric furnace. Chromium or silicon was added in additional graphite capsules to explore different behaviors under varying sulfur and oxygen partial pressures (Table 1). The maximum heating temperature was typically ~1417°C, with a cooling rate of ~100°C/h. The heating duration at maximum temperature ranged from 3 to 10 minutes. To date, four experimental runs have been successfully recovered, as summarized in Table 1. The experimental charges were extracted from the silica glass tube by crushing and were then dry-polished after being embedded in epoxy resin. The polished sections were carbon-coated and subsequently observed and analyzed using a field emission scanning electron microscope (FE-SEM, JSM-7100F, JEOL) with energy dispersive spectrometry (EDS, Oxford AZtecEnergy X-Max^N 50) and an electron probe microanalyzer (EPMA, JXA-8200, JEOL).



Fig. 1. *Experimental assembly (Run# N65Tr-C4) using a doubly evacuated silica tube method. The starting material of NWA 1465 (rectangular shape) and troilite (circle) are placed in separate graphite capsules within the inner silica glass tube.*

Table 1. Experimental conditions for the double-sealed under vacuum in silica glass tube.							
Run#	Starting materials		Maximum temperature (°C)	Cooling rate (°C/h)	Duration at peak temperature (min.)	Main products	Other products
N65Tr-C3	NWA 1465, grain	Tro	1417	100	3	En, Gl	Tro, Kam, Tae, Ca-px, Fo
N65Tr-C4	NWA 1465, sintered pellet	Tro	1417	100	9	En, Gl	Nng, Old, Tro, Kam, Phos, Fo, Silica
N65TrCr-C1	NWA 1465, grain	Tro and Cr	1417	100	10	En, Gl	Tro, Dbr, Kam, Tae
N65TrSi-C1*	NWA 1465, grain	Tro and Si	1417	100	10	En, Gl	Old, Tro, (Fe,Ni)S, Tae, Phos
N65=NWA 1465 (Ung C3). En=enstatite. Gl=glass. Tro=troilite. Kam=kamacite. Tae=taenite. Ca-px=Ca-rich pyroxene. Nng=niningerite. Old=oldhamite. Phos=phosphide bearing Ni&Fe. Fo=forsterite. Dbr=daubréelite.							

*N65TrSi-C1: Silica glass was broken during the cooling.

Results

Type IB chondrule textures were commonly reproduced from the starting material of NWA 1465. This is attributed to the melting that occurred under Si-rich gas conditions in the silica glass tube [e.g., 5, 6]. Niningerite and oldhamite were observed in run# N65Tr-C4 (Table 1; Fig. 2). In contrast, in run# N65Tr-C3, which had a shorter duration at peak temperature than N65Tr-C4, neither niningerite nor oldhamite was observed. The Cr- and Si-buffered conditions appeared to behave differently than predicted by thermochemical models (Fig. 3). Cr was oxidized during heating, preventing it from acting as a buffer as anticipated. Oldhamite was abundantly observed, but niningerite was absent in N65TrSi-C1 (Fig. 2e). Troilite and daubréelite lamellae were commonly observed, but neither niningerite nor oldhamite was detected in N65TrCr-C1 (Fig. 2f).



Fig. 2. Images of the run products. (a) N65Tr-C3: Low magnification BSE image showing the overall texture. The silicate portion corresponds to E3 chondrite chondrule, and the metallic portion corresponds to E3 chondrite nodule. (b)-(d) N65Tr-C4: (b) Type IB chondrule texture. (c) Oldhamite within troilite. (d) Niningerite coexisting with troilite. (e)-(f) N65TrSi-C1: (e) Oldhamite as droplets and dendrites. (f) Cr-rich sulfide (darker portion, possibly daubréelite) coexisting with troilite (brighter portion) displaying lamella texture. Tro = troilite. Fe =

Fe metal. Phos = (Ni, Fe) phosphide. Gl = glass. En = enstatite. Old = oldhamite. Nng = niningerite. Dbr = daubréelite. Kam = kamacite.

Discussion

The results from run# N65Tr-C4 show similarities in mineral assemblages and textures to EH3 chondrites, supporting the hypothesis that anhydrous carbonaceous chondrites may have been their precursors. However, the absence of niningerite and oldhamite in run# N65Tr-C3 suggests that sulfur absorption or sulfidation during the isothermal heating at peak temperature may be critical for the subsequent crystallization of these minerals. The experiments also showed a separation between the silicate and metal portions, suggesting the formation of two immiscible melts during heating (Fig. 2a). This may

support the hypothesis of simultaneous formation of chondrules and nodules [7]. However, a force would be required for complete separation during heating, implying that the heating mechanism could be related to shock. It is considered that the pS₂ and pO₂ under the experimental conditions of run# N65Tr-C4 (region B in Fig. 3), which is under the trolite buffer affected graphite capsule, are slightly higher than those in EH3 chondrite chondrules (region C in Fig. 3), based on the Si bearing kamacite in EH3. While it was initially assumed that the Cr- and Sibuffered conditions in runs N65TrCr-C1 and N65TrSi-C1 would correspond to regions A and C respectively, further examination is required.

Fig. 3. Stability fields of niningerite by sulfidation of enstatite, using thermochemical calculations, buffered by troilite (B region), and affected by the C-CO buffer. These fields may apply to the chondrule formation conditions of E3 chondrites. Buffers for pyrrhotite, $Cr-Cr_2O_3$, and Si-SiO₂ are also shown. The C region may correspond to the chondrule formation conditions for E3 chondrites.



Summary and perspectives

Experiments on E3 chondrite chondrule formation were successfully conducted. The results suggest that E3 chondrite chondrules may have formed in a closed system environment, interacting with Si-rich and S-rich gas, with metal nodules separating from the silicate melt during formation. This indicates that a dynamic environment, such as shock heating of precursor materials, may be necessary for their formation. Future work will focus on detailed comparisons of the compositions and textures of the experimentally produced minerals with those of natural E3 chondrites.

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Carbon signatures in grassy dark clasts in howardite meteorites

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Xenoliths in HED meteorites can help understand the relationships with different meteorite parent bodies and the formation processes of the protoplanetary body. Numerous types of xenoliths were reported among the crustal materials. For example, howardite and eucrite polymict breccias contain foreign meteorite clasts, mainly CM and CR chondrites, lithic debris formed during regolith gardening of the parent body, and impact melt clasts. Some xenoliths, especially carbonaceous chondrite clasts, may contain the petrological/chemical evidence of delivered volatile gases to the HED parent body (Barrat et al. 2011, Warren et al. 2017, Shisseh et al. 2023). Previously, to better understand the volatile rock interactions, we studied the textures, compositions, and Raman spectra of the carbonaceous chondrite clasts found in howardites. We found that Raman spectra of their insoluble organic matter were little affected by metamorphism on the HED parent body (Isa et al., 2023). In this study, using techniques similar to those used in the previous study, we examined the nature of glassy or glass-rich dark clasts in HED to better understand the volatile rock interactions.

Twenty howardites were examined: A-881170, ALH 78006, Y 000426, Y 000428, Y 000523, Y 000527, Y 000528, Y 000577, Y 000596, Y 000605, Y 000705, Y 000706, Y 001380, Y 002797, Y 002895, Y 003125, Y 791192, Y 793173, Y-984079, and NWA 6695. We located several dark grassy clasts, for example, in Y 000706 (Figure 1). We used Ramman spectroscopy to investigate carbons and full-width, half-maximum (FWHM) of the D1- and GL-bands were determined. We confirmed carbon peaks, which G-band or D-band shapes are distinct from organics in carbonaceous chondrite materials, within the impact melt clast. In the impact melt clast, we also confirmed pyroxene, metal, relict chondritic olivine phenocryst. The carbon peaks are likely inorganic carbon that was initially chondritic organic prior to the. The sharp G-band indicates possible graphite.

We plan to investigate other dark grassy clasts found by OMs further using EPMA and Raman spectroscopy.



Figure 1. BSE image of grassy clast in Y 000706. The dark gray phenocrysts are pyroxene. The white veins are metal, partially oxidized. The carbon peak was found within the clast.

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Silica minerals in eucrites: Implication for crystallization and metamorphic history of Vestan crust

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Introduction

Silica minerals are the most common rock-forming minerals on Earth. These minerals are known to have various polymorphs under different temperature and pressure conditions [1]. Therefore, understanding the characteristics of silica minerals is crucial for elucidating the thermal and shock history of the rocks. In this study, we focused on eucrite meteorites, which are rich in silica minerals (< 10 vol.%) [2]. Eucrites are believed to originate from the crustal material of a 4 Vesta, and silica minerals in these meteorites are thought to have crystallized from residual melts during the last stages of magma crystallization [3].

Samples and methods

We studied 13 basaltic eucrites and 4 cumulate eucrites, including nine Antarctic meteorites: Asuka (A) -881747, A-87272, Yamato (Y)-75011, Y-790266, Y-791195, Y-792510, Y 983366, Y 980433 and Elephant Moraine (EET) 90020, and eight non-Antarctic meteorites: Northwest Africa (NWA) 5356, NWA 7188, Agoult, Cachari, Moama, Moore County, Millbillillie, and Stannern. Samples of Antarctic meteorites were obtained from National Institute of Polar Research, Tokyo (NIPR) and NASA/Johnson Space Center (JSC), and those of non-Antarctic meteorites were obtained from meteorite dealers. An optical microscope, in Via Raman microscope (Renishow), a field emission scanning electron microscope (FE-SEM: JEOL JSM-7100) equipped with an energy dispersive spectrometer (EDS: Oxford AZtec Energy) and a color-cathodoluminescence imaging system (ChromaCL2: GATAN) at NIPR were used in this study. Color CL images were obtained by a CL microscope (luminoscope, ELM-3) at Okayama University of Science. Chemical compositions were obtained using an electron probe microanalyzer (FE-EPMA: JEOL JXA-8200) at NIPR and a Field-emission electron probe microanalyzer (FE-EPMA: JEOL JXA-8200) at NIPR and a Field-emission electron probe microanalyzer (FE-EPMA: JEOL JXA-1400) at ISAS/JAXA.

Results and discussion

Crystallization of silica minerals

Silica minerals in eucrites exhibit various combinations, and their proportions change continuously. Therefore, in this study, we distinguished the occurrence of silica minrals into quartz dominant eucrites (Si-I type), quartz and tridymite dominant eucirtes (Si-II type), and tridymite dominant eucrites (Si-III type). Quartz and cristobalite in Si-I type coexists with opaque minerals (troilite, ilmenite, baddeleyite) and phosphate. This occurrence of quartz suggests that it crystallized as mesostasis during the last stage of crystallization process from eucritic magma. Moreover, the coexistence with cristobalite suggests that these portion crystallized during a rapid cooling process. Most of tridymite in Si-II type shows lathy shape with no opaques and phosphate. On the other hand, quartz occurs as fine-grained aggregates coexists with opaque minerals and phosphates around the tridymite grain. Most of tridymite in Si-III shows similar features to the tridymite in Si-II type. This occurrence of tridymite suggests that it underwent euhedral crystal growth from magma when there was a relatively abundant presence of melt in the surrounding environment. We also observed an increase in plagioclase size (thickness) from Si-I to Si-III. The thickness of plagioclase is related to the crystallization rates [4]. This suggests that the crystallization rate decreases from Si-I to Si-III. Focusing on minor elements for each silica polymorph from WDS analysis, a trend was observed where the amounts of alkali elements (i.e., Na₂O, K₂O) and Al₂O₃ increase in the order of quartz, cristobalite, and tridymite. This suggests that tridymite crystallized from a melt richer in alkalis and Al₂O₃. Powell et al. [5] suggest that immiscible melts (enriched in Si, K and Al) can form in eucrite magma under slow cooling rates. Such immiscible melt is considered to the most likely candidate for the crystallization of euhedral tridymite. Hence, on the basis of these suggestion, we propose the formation model of the silica minerals as following process. Cristobalite and quartz in Si-I and II crystallized from rapidly cooled eucritic magma. In that case, immiscible melts were not formed, and quartz and cristobalite crystallized at the last stage of the crystallization process coexistence with mesostasis material. Tridymite in Si-II and III crystallized from Alkali and Al₂O₃ rich immiscible melt produced by slowly cooled eucritic magma. The presence of Si-II eucrites, which exhibit intermediate characteristics between Si-I and Si-III, is particularly interesting. The existence of such samples suggests that there were abrupt changes in cooling rates during the crystallization process. In basaltic and gabbroic rocks like eucrites, such rapid changes in cooling rates could be associated with the extrusion of magma onto the surface of the parent body.

Shock effects of silica minerals

The shock degree of eucrites is determined based on the mineralogical features of pyroxene and plagioclase [4]. Shock degree E eucrites, show that most of their plagioclase converted into maskelynite, and comparisons with the run products of shock recovery experiments suggest a shock pressure of \sim 30 GPa [6]. On the other hand, plagioclase in shock degree D eucrites converted maskelynite only around shock vein. Kubo et al. [7] suggest that high-temperature condition reduce the maskelynization pressure. The fact suggests that the host potion of shock degree D eucrites undergo the shock pressures lower than maskelynization pressure at room temperature (i.e., < 20 GPa). The high-pressure polymorphs of silica minerals (i.e., coesite and stishovite) are observed only in samples with shock degrees D and E, indicating shock pressures of > \sim 8-13 GPa. Hence, the shock pressure of shock degree D eucrites is constrained to \sim 8-20 GPa. Shock metamorphic grade of shock melt veins, but no high-pressure minerals are found in these samples. Therefore, the shock metamorphic grade of shock degree C eucrites is constrained to \sim 8 GPa.

In this study, as evidence of shock metamorphism other than high-pressure minerals, we found that silica glass (probably diaplectic glass) and MX tridymite, coexistence with MC tridymite in shock degree D and E eucrites. These silica glass and MX tridymite seems to be present as replacements of euhedral MC tridymite. Moreover, these silica glass and MX tridymite have similar chemical composition with MC tridymite. Hence, the silica glass and MX tridymite is concluded to shock induced products. In fact, MX tridymite is formed when MC tridymite is stressed such as crushing in a mortar [8]. Thus, the presence of MX tridymite with silica glass implies that the MX tridymite corresponds to the transition phase that occurred during the conversion from MC tridymite into silica glass by shock metamorphism. The fact that such MX tridymite and silica glass are not found in shock degree C eucrites suggests that the vitrification pressure of MC tridymite is between 8 and 20 GPa. **Summary**

Silica minerals in eucrites provide information about the formation and metamorphic history of their parent bodies. Quartz and cristobalite crystallize from rapidly cooled melts, while tridymite is characterized as a silica phase that crystallizes from immiscible melts (Si, Al, K rich) formed during slow cooling processes. High-pressure minerals such as coesite and stishovite are observed in eucrites with shock degrees \geq D. In addition, the vitrification of tridymite is also observed in eucrites with shock degrees >D. Since silica minerals are relatively rare in planetary materials but have been recognized as component minerals in other achondrites such as lunar and Martian meteorites, our results may also be applicable to the comparative studies on the formation of silica minerals among different bodies.

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OAo12

Late-stage Igneous Glasses in Terrestrial vs. Lunar Gabbros: Comparison of Magmatic Evolution in Lunar Meteorite NWA 773 Clan with Murotomisaki Sill, Japan

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Introduction: Late-stage igneous glasses occur in both the NWA 773 clan of lunar meteorites [1,2] and a gabbroic sill from Murotomisaki, Japan [3-5]. Both the NWA 773 clan and the Murotomisaki Gabbroic sill (MGS) are dominated by mafic lithologies. Feldspathic glasses are relatively rare, but offer a window into late-stage magmatic evolution and provide an opportunity to compare igneous processing in lunar vs. terrestrial settings.

Methods: Textures and major element compositions of minerals and glasses reported in this study come from two polished thin sections (pts) of NWA 773 and one pts of the MGS labelled Muro-14. Based on work by [3,4,5, and references cited therein], the MGS crystallized from chilled margins inward. The interior of the sill evolved primarily by olivine settling, olivine crystal growth and gravitational separation of feldspar combined with fluxing by aqueous fluid, all accompanying crystallization of gabbroic rocks rich in pyroxene and plagioclase feldspar. Sample Muro-14 is a coarse-grained pyroxene-feldspar gabbro from the MGS Middle Zone of [5]. Glass and mineral compositions were determined by electron probe micro-analysis (EPMA) using the JEOL JXA-8900 instrument at Waseda University. Glass inclusions along with minerals in NWA 773 were analyzed using 15 kV, 20 nA and a spot size of 1 to 2 μ m; we are aware of the potential problems of alkali-loss during analysis of feldspathic glass [6], but decided to use a small spot size to minimize beam overlap with adjacent phases. Feldspathic glass in Muro-14 was analyzed using 15 kV, 10 nA and a spot size of 5x7 μ m. Five replicate analyses using these conditions on the same spot in Muro-14 feldspathic glass show that minor Na-loss is detected between the 1st and 2nd analysis (12.5 vs. 11.5 wt% Na₂O) and a more accentuated decrease in detected Na (with increase in Si and Al) occurs between the 2nd and 3rd analysis (8.8 wt% Na₂O). After the 3rd replicate, minimal decreases in Na were detected in analyses #4 and #5 (8.4 and 8.6 wt% Na₂O, respectively). In this study, we do not apply a correction to our reported analytical results; rather, we acknowledge that our analyses of the Muro-14 glass may be biased, yielding Na₂O concentrations slightly lower than the true compositions.

Results and Discussion: Late-stage magmatic evolution in the NWA 773 clan is exemplified by: (1) incompatible element-rich, intercumulus pockets in olivine cumulate gabbro (OCG), a characteristic lithology of the NWA 773 clan; and (2) breccia clasts dominated by fayalite, ilmenite, Ca-phosphate(s), and glass and/or feldspar+silica (Fig. 1a). The intercumulus pockets are crystalline, whereas the fayalite-rich clasts (<u>a</u>lkali-<u>r</u>ich phase <u>fe</u>rroan clasts referred to as ARFe by [1]) typically have feldspathic glass. Glass in the NWA 773 ARFe clasts occurs as rounded inclusions in fayalite and ilmenite (Fig. 1a). Analyses of the NWA 773 glass indicate silica-rich compositions, with most results in the rhyolite field of the total-alkalis vs. silica diagram of [7] (Fig. 2). Discrepant analyses may be due to beam overlap with microlites of feldspar or silica. The NWA 773 glasses are K-rich, with most atomic K/(K+Na) values >0.8. Analytical totals are near 100%, indicating that major elements were for the most part detected (i.e., H₂O, if present, is only minor). In some cases, the glass inclusions occur in an ARFe domain in part of a composite clast with pyroxene exhibiting increasing Fe/(Fe+Mg) and Ti/(Ti+Cr) with proximity to the ARFe domain (see Fig. 6 of [1]). The pyroxene zoning and textures of glass inclusions hosted by fayalite and ilmenite, combined with experimental data of [8], led [1] to infer that glass inclusions in the NWA 773 ARFe clasts formed by silicate liquid immiscibility (SLI) after extreme Mg-depletion of the crystallizing system.

The feldspathic glass in MGS sample Muro-14 is distinct from the NWA 773 glass in both texture and composition. The Muro-14 feldspathic glass occurs in elongate veins, mostly along the borders of coarse crystals of plagioclase feldspar and pyroxene (Fig. 1b). Though the glasses from both Muro-14 and NWA 773 are late-stage features, the Muro-14 feldspathic glass does not have the extreme silica-enrichment observed in NWA 773; silica concentrations in the Muro-14 glass fall within 52 to 56 wt% SiO₂ (Fig. 2). Furthermore, the Muro-14 glasses are sodic rather than K-rich, with atomic K/(Na+K) values of essentially 0, and the Muro-14 glasses appear to be hydrous, with EPMA analytical totals of approximately 90 wt%. The low-K (actually, K-absent) compositions of the Muro-14 glass may be connected to fluxing of aqueous fluid, which has been inferred independently for the MGS (e.g., [5]) and may have resulted in dissolution of K and transport of K atoms away from late-stage magnatic liquid. The lower SiO₂-content and inferred water-rich composition of the Muro-14 glass suggest a more fluid (less viscous) liquid compared to the NWA 773 feldspathic liquid, leading to emplacement in veins rather than in melt inclusions. Unlike the formation of NWA 773 glass, silicate liquid immiscibility was probably not important for the evolution of feldspathic glass in Muro-14. However, the specific mechanisms that led to compositional evolution, including the likely high water contents, of the feldspathic glass in Muro-14 have not been determined.



Figure 1. Back-scattered electron (BSE) images showing occurrences of feldspathic glass in an NWA 773 ARFe clast (a) and in Murotomisaki gabbroic sill sample Muro-14 (b). Abbreviations: apa = apatite; cpx = high-Ca pyroxene; Fa = fayalite; fsp = feldspar (including alkali & plagioclase solid solutions); ilm = ilmenite; mer = merrillite; pfs = plagioclase feldspar; sil = silica.



Figure 2. Total-alkali vs. silica (TAS) diagram of [7] showing compositions of feldspathic glasses from Murotomisaki gabbroic sill sample Muro-14 and from NWA 773.

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Stratigraphy of the poikilitic shergottite igneous body deciphered from petrographic and mineral compositional diversity

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Introduction: Recent discoveries of many poikilitic shergottites in Antarctica and the Sahara desert have revealed large petrological and geochemical diversity of the samples although this shergottite subgroup was originally thought to have similar characteristics in petrology and geochemistry [e.g., 1]. The major constituent minerals of poikilitic shergottites are olivine, pyroxene, and plagioclase (maskelynitized by impact), with large pyroxene oikocrysts reaching several mm in size surrounded by smaller olivine chadacrysts. The pyroxene oikocrysts consist of a core of low-Ca pyroxene, followed by pigeonite, and then a rim of augite, and are thought to have formed first in a deep magma reservoir, and finally by the magma containing them rising and intruding near the surface and solidifying to form the poikilitic shegottites [e.g., 2]. However, there has been little detailed discussion of the final magma crystallization process near the surface to form non-poikilitic regions. Therefore, this study aims to place constraints on the final crystallization process of the poikilitic shergottite igneous body by analyzing and comparing the petrography and mineral compositions of several poikilitic shergottites.

Samples and analytical methods: Elemental maps were obtained using electron microprobes (EPMA) (JEOL JXA-8900 at Univ. of Tokyo and JXA-8200 at NIPR). The elemental maps were then used for quantitative analysis to decide the analysis points of olivine, pyroxene, maskelynite, and spinel minerals in both poikilitic and non-poikilitic regions. The modal abundance of each mineral phase and the crystal size distribution (CSD) of olivine in the non-poikilitic regions were analyzed from the elemental maps using Image J.

Results: Analysis of all samples showed no significant differences in pyroxene major elemental composition between the samples, with the oikocryst core portion being $En_{69\pm8}Wo_{12\pm7}$ and the rim portion about $En_{51\pm5}Wo_{35\pm5}$. Maskelynite is present only in the non-poikilitic regions. Plagioclase crystallizes in the later stages of crystallization, which may reflect the degree of accumulation of other minerals at the time of final magma crystallization.

The cooling rate of the poikilitic shergottite parent magma after intrusion near the surface was determined by the Ti diffusion profile at the pyroxene oikocryst's augite rim [3]. These profiles are thought to have been formed after intrusion due to atomic diffusion between T-rich late-stage melt and pyroxene. The initial temperature of the parent magma was estimated from a pyroxene thermometer as 1200 °C and the solidification temperature as 1000 °C by MELTS [4]. To account for differences in crystal size for each sample, the diffusion equation was assumed to be 3-D spherically symmetric. Accordingly, the obtained cooling rate ranges from 0.17-1 °C/year (Fig. 1). For the olivine composition, samples such as NWA 12241, which are considered to have cooled relatively slowly (cooling rate of ~0.17 °C/year) and a magma residence time of ~120 days by CSD analysis, have a narrow composition range of Fo₆₂₋₇₀. On the other hand, samples such as NWA 13227 and NWA 14127, which are considered to have cooled relatively quickly (cooling rate of ~1 °C/year) and a magma residence time of ~40 days, have a wider compositional range of Fo₄₀₋₇₀. The other samples were intermediate between these samples in terms of cooling rate and mineral compositional range. A negative correlation between the magma cooling rate and the modal composition of maskelynite in the non-poikilitic regions was also observed (Fig. 2).

The size of poikilitic shergottite igneous body was estimated from the thermal diffusion equation. Thermal diffusion coefficients were set to $k = 0.30 \times 10^6 \text{ m}^2/\text{s}$ for intrusive magma [5] and $k = 0.44 \times 10^6 \text{ m}^2/\text{s}$ 1000 °C for country rock [6]. From the thermal diffusion equation, the igneous body size of poikilitic shergottite was estimated to be ~270 m by considering the thermal evolution of the intrusive magma with an initial temperature of 1200 °C and a solidification temperature of 1000 °C based on pyroxene thermometry (Fig. 3). Here, the magma is assumed to have intruded horizontally in an infinitely wide sheet with thickness, and the top and bottom surface of intrusive magma are assumed to be in contact with the country rock at 0 °C. The calculations also incorporated the effect of latent heat. For simplicity, the parent magma was assumed to be in the liquid phase above 1200 °C and in the solid phase below 1000 °C, with the proportion of the solid phase increasing linearly with decreasing temperature.

Discussion and Conclusion: For NWA 12241, which is considered to have the slowest cooling rate, the relatively large crystal size of olivine in the non-poikilitic regions and the narrow Mg-Fe composition range of olivine suggest that it was formed by magma that intruded near the surface from a deep magma reservoir and cooled slowly while accumulating other minerals near the central part of the intrusive igneous body. On the other hand, in the case of NWA 14127 and NWA 13227,

where the cooling rate is estimated to be the fastest, the relatively small crystal size and wide compositional range of olivine suggest that the intruding magma cooled and solidified before accumulating near the rock wall of the intrusive igneous body.

The present study suggests that the factors that cause variations in the petrography and mineral composition of poikilitic shergottites are differences in cooling rates and accumulation depths within the same intrusive body. Because poikilitic shergottites with different geochemical groups (depleted, intermediate, and enriched) exist and this igneous body model can also explain samples of different geochemical types, poikilitic shergottites parent bodies with similar stratigraphy, including poikilitic textures, may exist universally in the Martian crust.

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Fig. 1. Estimation of cooling rates by Ti element diffusion profiles at the augite rim in the NWA 12241 oikocryst. Calculations based on pyroxene thermometry and MELTS, assuming an initial temperature of 1200 °C and a solidification temperature of 1000°C.



Fig. 2. Relationship between cooling rate estimated from pyroxene Ti element diffusion profiles and modal abundance of maskelynite in non-poikilitic regions. The maskelynite abundance is considered to correlate with the accumulation depth.



Fig. 3. Estimation of the igneous body size of poikilitic shergottite by the thermal diffusion equation. Based on pyroxene thermometer and MELTS calculations, the initial and solidification temperatures of the magma are assumed to be 1200 °C and 1000 °C, respectively, and the center of the parent body is assumed to cool at 0.17 °C/year, the slowest cooling rate in the analyzed samples (NWA 12241). Note that calculations here assumed that the temperature drops linearly from 1200 °C to 1000 °C linearly, but in reality, it drops nonlinearly. thus, the actual igneous body size may be smaller than estimated.

OAo14

Investigation and Classification of mid-IR indicators of meteorites for future thermal infrared spectroscopic exploration: TIRI onboard Hera.

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Introduction:

The formation and evolution processes of the Solar System have been studied based on remote sensing observations of asteroids, primitive bodies that retain information about the early Solar System, and comparative analysis of asteroids with meteorites. Asteroids have been classified based on their reflectance spectra by spectroscopic observations, one of the most common methods of observation. On the other hand, asteroids have been altered by thermal metamorphism, e.g. by radioactive decay heat, since the early stages of their formation. To obtain information on the material properties of the initial stages of asteroids, it is necessary to understand the changes in the reflectance spectra due to thermal metamorphism. In particular, the mid-infrared region is useful in the discovery and preparation for exploration of 'truly primitive bodies' (un-thermal metamorphosed bodies) by ground-based telescope observations, since there is almost no absorption by the atmosphere. In this study, the following are carried out.

Objectives:

- 1. To clarify the changes in the mid-infrared spectra of meteorites associated with different thermal metamorphic degrees. In particular, to find and organize spectral indicators for thermal metamorphism.
- 2. To prepare for estimation of composition and metamorphic degree of target bodies by TIRI¹: Thermal InfraRed Imager, an instrument on board Hera: the ESA-led S-type asteroid exploration mission. In particular, the identification of meteorite types by TIRI imaging is simulated and validated based on the spectral indicators found in 1.

Backgrounds:

- 1. Christianen Feature: CF (emissivity maximum at 7-9 μm) and Reststrahlen Feature: RF (emissivity minimum at 9-12 μm) are indicators of the mid-infrared region found in minerals, rocks, and meteorites. Their position depends mainly on SiO₂ content. In particular, the position of the CF shifts to shorter wavelength with increasing SiO₂ content² and also depends on the bond structure of SiO4 tetrahedra (CF positions: plagioclase: 7.91, pyroxene: 8.12, olivine: 8.47 μm)³.
- 2. An example of CF estimation from mid-infrared spectroscopic observations is the lunar surface observations by the Diviner Lunar Radiometer. The CF value maps of silicate minerals have been investigated by a quadratic fitting of three-band spectroscopic data³.

Methods:

- 1. Mid-IR spectral data of more than 200 meteorite samples (Table 1) of different compositions and metamorphic degrees are measured at NIPR using a handy FTIR (wavelength range: 2.5-15 μm, resolution: 8 cm⁻¹, reference material: Coarse Silver. The CF and RF are estimated by fitting analysis with multiple Gaussian functions.
- 2. Mid-IR spectral data of 22 samples (Table 2) were taken by TIRI PFM (6 bands: 7.8, 8.6, 9.6, 10.6, 11.6, 13.0 μm). The RF are estimated by quadratic fitting analysis. It is verified whether spectral imaging by TIRI can estimate the composition and metamorphic degree of the samples by comparing the results of the FTIR.

	Table 1. Samples used in Method 1.	Table 2. Samples used in Method 2.		
minerals	olivine, pyroxene, quartz, plagioclase	olivine, pyroxene, quartz, plagioclase		
rocks	anorthosite, hypersthene-augite andesite, olivine	anorthosite, hypersthene-augite andesite, olivine basalt,		
	basalt, peridotite, obsidian	peridotite, obsidian		
meteorites	petrologic types 3-7 ordinary chondrites (H, L,	NWA 7676 (LL3.5), NWA 7187 (L3.6), Chelyabinsk		
	LL), primitive achondrites (acapulcoites,	(LL5), NWA 5490 (L3.7), Mezo-Madaras (L3.7),		
	lodranites, ureilites, winonaites), differentiated	Bjurbole (LL4), Saratov (L4), Iran 006 (L6), Kilabo		
	achondrites (diogenites, eucrites),	(LL6), Allende (CV3), El Hammami (H5), SaU 001 (L5),		
	carbonaceous chondrites (CM2, CO3, CR2)	Kunashak (L6)		

Results & Discussion:

- 1. The positions of the CF and RF tended to differ for each meteorite type in Figure 1. For example, in ordinary chondrites, the CF and RF tend to shift to longer wavelength in the order of H < L < LL. In comparison with SiO₂ content, the difference between the CF and RF positions tended to widen with increasing SiO₂ content. This suggests that there may be some absorption bands due to Si-O bonds between the CF and RF. From the above, it is possible to estimate meteorite types (composition, especially SiO2 content) by estimating the positions of the CF and RF. The RF depth (peak intensity) tended to be larger in the order of carbonaceous chondrites < H < L < LL <achondrites in Figure 2. There is also a trend of a positive correlation with the thermal metamorphic degree. These suggest that the RF depth may depend on composition and thermal metamorphic degree. In particular, it has been reported⁴ that the RF depth becomes shallower with decreasing grain size in quartz and granite, and therefore the RF depth may be useful as an indicator reflecting the crystallinity, i.e. the thermal metamorphic degree.
- 2. In minerals and rocks, the RF positions obtained by FTIR and TIRI PFM are found to be generally consistent. Therefore, it is expected that spectral imaging with TIRI can provide information on the composition of target bodies. On the other hand, the results did not exactly match for meteorite samples. Possible reasons may be due to differences in composition of the different measurement locations by the two instruments and/or properties of the two instruments.

9 8.5 10.4 10.48 10.56 10.64 10.72 10.8 RF wavelength [μm]

Figure 1. RF position vs CF position of meteorites



Figure 2. RF position vs RF depth of meteorites

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Preliminary curation process for micrometeorites collected at Tottuki ice field, Antarctica

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Micrometeorites are small extraterrestrial materials, roughly less than 2 mm in diameter. Although micrometeorites can be collected from various locations on Earth, those collected in Antarctica are thought to have preserved their original mineralogy because they have been less affected by weathering alteration on Earth (e.g.,[1]-[4]). Japanese Antarctic Research Expedition (JARE) conducted systematic recovery of Antarctic micrometeorites in 1998 by JARE-39 and in 2000 by JARE-41. Micrometeorites were collected by on-site melting and filtration in the ice field at Tottuki area near the Syowa station and around the Yamato Mountains ([5], [6]). Since 2003, snow samples from the Dome Fuji station area have regularly been collected. The snow samples are melted and filtered in the laboratory, and the fluffier micrometeorites are also extracted. Fluffy micrometeorites containing primitive materials including carbon materials such as those originating from comets have been found in the snow ([7], [8]). Antarctic micrometeorites collected by JARE activity are still being used as samples to study the birth of the solar system and the physicochemical evolution of planets, satellites, and asteroids (e.g., [9]-[13]).

In this study, we will show the initial curation process of micrometeorite samples recovered at Tottuki and how they experience an initial description process within the National Institute of Polar Research, where they are catalogued and distributed to researchers. At the Tottuki ice field, ice of a maximum diameter of 3 m and a depth of 1.5 m was typically melted, and 10 tons of water equivalent was filtered for the present filter set as filter number 6 [6]. Collected filters in the field are differentiated by grain size (10, 40, 100, and 238 µm) and stored in glass petri dishes with lids, respectively. Almost all of the curation process takes place in a clean booth set up in a class 10,000 clean room to prevent contamination or sample loss.

First, possible micrometeorite particles are sorted under a microscope. Using a handling tool made from the processed tip of a small brush made of polyester-based material and ultrapure water, the micrometeorites are moved one by one to a holder for electron microscopic observation. The holder uses compressed carbon nanotube (CNT) tape fixed to a glass slide with carbon tape attached. The microstructure and chemical composition of the sample is obtained by scanning electron microscopy and energy dispersive X-ray spectrometry (SEM-EDX). Any obvious terrestrial material is excluded at this stage. In a clean booth, the sample is removed from the CNT using glass vacuum tweezers with a 20-50 µm tip diameter; one micrometeorite is moved to a glass slide with a single hole, covered with cover glass and fixed with mending tape. After giving it an official name, the data obtained by SEM-EDX are catalogued. The samples are stored in the clean room described above.

The current method picks up so-called spherules (cosmic spherules) selectively during the initial micrometeorite sorting process. This is because the number of samples of Antarctic micrometeorites is quite large, and we must first extract what we consider to be extraterrestrial material. The spherules were melted and rounded by the heat during atmospheric entry. In the future, we are interested in using machine learning to determine the number density of spherules for each grain size. In addition, many of the micrometeorites recovered from snow near Dome Fuji are irregularly shaped and retain their original mineralogy. We would like to develop a method to efficiently detect such micrometeorites from ice as well.



Figure 1. AMMs collected at Tottsuki area. a) Optical microscopic image of TT006cA0023. b) Back scattered electron image of a). c) EDX spectra image of entire area of particle in b). Si is the major element, and Ni is also present.

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Distribution of highly siderophile elements in CI-like materials.

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CY chondrite including Yamato (Y)- 82162, Y-980115, Y-86029, Y-86720, Y-86789, and Belgica (B)-86720, is a new proposed group of carbonaceous chondrites [1-3]. The CY chondrites have very similar mineralogical and chemical characteristics to CI (Ivuna-type) chondrites. However, they have heavier oxygen isotopic compositions and higher abundances of Fe-sulfides and phosphates than CI-chondrites, and are depleted in some volatile elements, including Bi, Cd, In, and Tl [4]. King et al. [4] argued that these features indicate that the CY chondrites have different parent body(ies) from CI chondrites and have experienced post-hydration heating alteration. However, the studies on CY chondrites are still limited, and parent body processes that explain similarities and differences between CY and CI chondrites are still unclear.

Recently, the Hayabusa2 mission brought samples from the Cb-type asteroid Ryugu back to Earth. Initial analysis of Ryugu samples revealed mineralogical, chemical, and isotopic similarities with CI chondrites [e.g., 5-6]. For a comprehensive understanding of CI-like materials, CY chondrites attract attention due to their similarities with CI chondrites, which are thought to be formed in the outer Solar System.

Variations of elemental abundances in planetary materials, along with their isotopic compositions, reflect not only the conditions and processes that the precursor materials underwent prior to accretion into larger bodies, but also the secondary processes in their accreted bodies such as aqueous alteration. Although previous studies on CI and CY chondrites used typically 50 mg to determine bulk elemental compositions, in order to discuss the detailed formation process, it is necessary to focus on the element distribution on smaller scale. Ryugu samples exhibit chemical and isotopic heterogeneities at the mm scale, which seems to stem from the aqueous alteration in its parent body [7]. In this study, we investigate the small-scale chemical heterogeneity in Ryugu samples, CI, and CY chondrites to gain better insights into the conditions and processes that these materials have undergone during their formation and evolution. For this purpose, we measured the abundances of highly siderophile elements (MSE; Re, Os, Ir, Ru, Pt, Rh, Pd, and Au), volatile chalcophile elements (VCE; S, Ge, As, Se, and Te), and other elements (Mg, Al, and Ca). The analyzed materials consisted of five samples of Ryugu particle aggregates (A0223) provided by JAXA, two particle aliquots of Ivuna, two samples of Orgueil chunks, and six samples of Y-980115 grains provided by NIPR. The typical amount of sample for a single measurement was ~1 mg.

Ryugu, CI, and CY samples give homogeneous relative abundances for most elements. Ryugu samples are enriched in Ca and Mn abundances, due to high abundances of carbonates in the Ryugu samples [6]. Y-980115 samples show depletions in Au. Gold could have been lost during heating event(s) on the parent body along with Bi, Zn, Cd, In, and Tl. The abundances of the Ryugu and CI samples do not show fractionation among highly siderophile elements, but their absolute abundances are variable (0.5-1.1xCI). Following the condensation model of the solar nebula, siderophile elements condense into FeNi-alloy phases [8]. Metal phases have not been identified via surface observation of 16 Ryugu particles, comprising a total of 55 mg [7]. Although FeNi-alloy phases would have been affected by aqueous alteration, the secondary host phases of HSE are not clear. Therefore, HSE abundances could reflect the accretion materials resulting in homogeneous relative siderophile element abundances of the sampled materials, and their resistance to aqueous process modification. The observed variable absolute HSE abundances of the Ryugu and CI samples would be controlled by the amount of the secondary host phases.

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Macromolecular carbon of the Kaba CV3 carbonaceous chondrite: A Micro-Raman spectroscopical case study

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Introduction: The study of extraterrestrial materials, such as meteorites, provides invaluable insights into the chemical and mineralogical composition of the early solar system. One particularly intriguing class of meteorites is the carbonaceous chondrites, which are known to contain significant amounts of macromolecular carbon. The Kaba meteorite, a member of the CV carbonaceous chondrite group, is of particular interest as it contains a diverse suite of organic compounds and mineralogical features that can shed light on the origin and evolution of these materials (Bower et al., 2013, Tanbakouei et al., 2024).

Micro-Raman spectroscopy has emerged as a powerful, non-destructive technique for the in-situ analysis of carbonaceous materials in meteorites and microfossils (Bower et al., 2013). This method allows for the identification of distinct Raman signatures associated with different forms of carbon, including graphitic, disordered, and amorphous phases. By analyzing the characteristics of the Raman D and G bands, researchers can infer the thermal history, degree of structural organization, and potential biogenicity of the organic matter.

In this study, a Micro-Raman spectrometer was used to identify the crystallinity of the Macromolecular Carbon (MMC) of the Kaba meteorite. The purpose of the study above is to understand more about the formation mechanism of the carbonaceous matrix of the Kaba meteorite.

Sample and Experimental Procedure: *Kaba meteorite:* Kaba belongs to the oxidized subgroup of the CV3 carbonaceous chondrite class, which fell in Hungary (close to the village of Kaba) in 1857 (Busemann et al. 2007). It is one of the most primitive, least-metamorphosed carbonaceous chondrites. Therefore, the Kaba meteorite provides a good opportunity for Raman spectroscopical studies. A thin section was produced, in which the sample was mounted in non-radiative three-component epoxy material. It was polished in a silicon colloidal solution to avoid any carbon-related pollution (Fig. 1).



Figure 1. A polished thin section of the Kaba Meteorite shows the analyzed area.

Raman analysis: The analysis was performed using Ratatoskr, a customized WITec alpha-300 Raman imaging spectrometer in the Hlidskjalf Raman Laboratory at NASA Johnson Space Center.

Results and Discussion: The selected area (LAS01) shows macromolecular carbon (Fig. 2). Andradite, olivine, and gehlenite were also identified (Fig. 2).

Lighter colors indicate MMC with a more ordered crystalline structure than darker colors. The most parsimonious explanation for this is MMC, which has seen elevated temperatures relative to the darker-colored MMC. The MMC borders some chondrules and the gehlenite is more ordered than matrix MMC, as is some in discrete assemblages in the matrix (Fig. 3).



Figure 2 MMC (red), olivine (green), gehlenite (B) as well as andradite (cian) were identified by the 3D Raman mapping.



Figure 3 MMC G band position image, showing position of the G band derived from a Lorentzian fit. ("a.u" on the scale bar is arbitrary units, but the correct units are wavenumbers (cm⁻¹).

In this study, we employed micro-Raman spectroscopy to characterize the macromolecular carbon present in the Kaba carbonaceous chondrite. Our results reveal the presence of organic matter that has been amorphized, likely due to sputtering processes or irradiation during the formation of the meteorite parent body or during transport to Earth. The D band widths and peak metamorphic temperatures are strongly correlated, allowing for a straightforward estimation of the thermal history of the organic materials.

The Kaba meteorite was found to contain a diverse suite of organic compounds, including macromolecular carbon, as well as a range of mineralogical features. Micro-Raman spectroscopy analysis of the organic matter revealed the presence of amorphized carbon, suggesting that the parent body experienced thermal processing or irradiation during its formation or subsequent evolution (Busemann et al., 2007, Ferralis et al. 2016, Tanbakouei et al., 2024).

Summary: Raman mapping of the Kaba meteorite identified that the Macromolecular Carbon (MMC) is not homogeneous in its carbonaceous matrix, which might be due to the thermal metamorphism. However, some further studies must be applied to clarify the crystalline background of the MMC.

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Hyper-velocity impact phenomena caused by Giant Impact debris - Pressure and temperature conditions probed by impact melt breccia

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The Giant Impact (GI) hypothesis is considered the most likely explanation for the formation of the Moon. The numerical simulations of GI suggest that some of the debris from the collision between the proto-Earth and the proto-planet ware injected into the asteroid belt, where it collided with an asteroid at hypervelocity (>10 km/s) (Bottke et al. 2015). In addition, since S-type asteroids, which correspond to the parent bodies of ordinary chondrites, are abundant in the area of the asteroid belt near the Sun (DeMeo et al. 2013), it is highly likely that the impact fragments collided with the parent bodies of ordinary chondrites.

Meteorites undergo physical and chemical effects called shock metamorphism due to the transient high temperature and high pressure conditions experienced by the parent body during impact. Shock metamorphism in ordinary chondrites has been demonstrated by shock recovery experiments up to shock pressures of 40–50 GPa, corresponding to an impact velocity of 2–4 km/s (<u>Güldemeister et al. 2022</u>). However, widespread shock-induced melting at such pressures has not been confirmed. On the other hand, impact melt breccia (IMB) is a rock containing a large amount of breccia and melt, and if formed by an impact phenomenon, it is likely to have experienced extremely high temperature- and pressure-conditions. Therefore, we investigated the IMB of ordinary chondrites with a focus on shock metamorphism and examined the relationship with hypervelocity impacts to verify the GI hypothesis.

Nine ordinary chondrites (Y-790964, Y-790143, Y 983417, Y 001863, Y 002660, Y 000727, Y 000660, Y 000469, A 10043) classified in the IMB were selected for this study. The microstructures of petrographic thin sections were observed using a polarizing microscope and a field emission scanning electron microscope (FE-SEM). We also analyzed the chemical compositions of the major constituent minerals, olivine, pyroxene, and plagioclase, using an electron probe microanalyzer (EPMA). We identified the phases in the IMBs by a laser Raman spectrometer and a transmission electron microscope (TEM).

Based on the observations, the investigated IMBs were classified into three groups with different degrees of shock metamorphism, mainly based on the melt area ratios (> 60%, 20-60%, < 20%). Considering the volume ratios of the melts, Y-790964, Y-790143, Y 983417, and Y 001863 are expected to be the most strongly shocked. We will focus on these four IMB samples. Numerous bubbles, indicative of volatile degassing, were found throughout these samples. These samples have igneous rock-like textures in which the original constituent minerals were completely melted and then rapidly cooled, crystallizing in the order of olivine and pyroxene, with plagioclase filling the gaps. The Fe/Mg ratios of olivine in these four samples show greater variation compared to olivine in equilibrated ordinary chondrites. In addition, the olivine contains a small amount of calcium (< 0.32 wt% as CaO). The chemical compositions of pyroxene and plagioclase are also variable compared to those in equilibrated ordinary chondrites. A high-pressure mineral, which is clear evidence of high-pressure generation, is not found in these four IMBs.

The diverse compositions of olivine, pyroxene, and plagioclase in Y-790964, Y-790143, Y 983417, and Y 001863 are likely due to rapid cooling. These IMBs experienced extremely high temperatures that caused large-scale melting, and the melts were rapidly cooled in a compositionally heterogeneous state without sufficient mixing. This would have resulted in compositional diversification. Based on the synthesis experiments of olivine from melts, as the temperature of the melts increased, the abundance of calcium in olivine became larger (Kawasaki et al. 2001, Remmert et al. 2018). Calcium was probably more partitioned into the olivine crystallized from the high-temperature melts due to the slow diffusion rate of calcium in the melts. A high-pressure mineral indicating very high pressures (> 50 GPa) was not found in the investigated IMB samples, although Y-790964, Y-790143, Y 983417, and Y 001863 underwent large-scale melting probably induced by an intense impact. More detailed investigations are needed to clarify whether these IMBs were affected by a high-velocity impact.

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Mesosiderite reheating history as deduced from merrillite and associated minerals

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Mesosiderites formed by mixing of metal to silicates on an achondritic parent body. Subsequent to the mixing of metal, mesosiderites were thermally metamorphosed. The last significant reheating occurred at ~4525 Ma, but the reheating mechanism and the history are not well known.

Merrillite ($Ca_9NaMg(PO_4)_7$) is a representative mineral in mesosiderites that is several x10 times more abundant than in eucrites. It is produced by the reaction of P in metal and Ca in silicates. Hence it may tell us about the thermal history after the metal mixing. Usually, Ca in pyroxene is used for the merrillite formation, but Ca in plagioclase may also be used. If Ca in plagioclase is extensively consumed by the merrillite formation reaction, Al activities in the remaining silicates get high. This could induce formation of cordierite and high Al concentrations in chromite and pyroxene. Also, Na concentrations in merrillite may be affected by the disintegration of plagioclase.

Cordierite is a mineral that is stable in the absence of Ca in silicates. Therefore, it is a reliable proxy for extensive formation of merrillite using Ca in plagioclase. Here, we present SEM-EDS observations of cordierite-bearing, silicate-rich inclusions in a Bondoc nodule (metal-rich spheroidal material). Inclusions in a nodule is classified to globular or angular, based on the shape and also based on the presence/absence of glass (devitrified glass). Cordierite was found in both globular and angular inclusions, though the latter were more numerous. As expected, plagioclase is nearly absent in such cordierite-bearing inclusions.

Cr/(Cr+Al) ratios in chromite vary from 0.3 to 0.7 which are significantly lower than those (~0.8) in chromite in the Bondoc matrix. Al in pyroxene ranges from 0.4 to 2.2 (mol.%), which is higher than those (~0.4) in pyroxene in the Bondoc matrix. These high Al concentrations are explained by the extensive consumption of plagioclase due to the merrillite forming reaction. Na in merrillite ranges from 0.4~1.6 mol.%, which is generally higher than those in merrillite in the Bondoc matrix. This suggests that a significant fraction of merrillite in cordierite-bearing inclusions was produced from plagioclase, though the contribution of pyroxene is not negligible.

In addition to the above observations, we found (1) a couple of idiomorphic merrillite crystals in globular inclusions, (2) thin (~1 micron thick) lamellae in pyroxene, and (3) silicate inclusions are evenly distributed in the nodule. (1) and (2) are considered as evidence for short time scales during/after the last reheating event. (3) suggests that the nodule was initially an aggregate of solid metal grains with abundant pore spaces which were later filled by achondritic materials during gardening. Therefore, the metal was not a heat source at the time of the metal accretion.

Globular inclusions are fairly abundant in the Bondoc nodule, but is practically non-existent in general mesosiderites. This suggests that the nodule attained a higher temperature than the general mesosiderites. A plausible explanation is that the heat source (heating mechanism) depends on the metal fraction; the electromagnetic induction associated with super flares of the early sun is a plausible mechanism. If true, reheating of mesosiderites must have occurred many times, and we recognize only the last biggest reheating episode. It is known that the time scale of solar flares is several hours that is quite consistent with the inferred time scale of reheating of inclusions in the nodule. Mesosiderites are known to have cooled very slowly at low temperatures based on Ni profiles in taenite. This is usually explained by deep burial in the mantle. But if induction heating was the heat source, slow decay of solar flare activities over billion years may explain such apparent slow cooling rates, if mesosiderites were located near the surface of the parent body.

Magnetic signature of the four paired Miller Range nakhlites MIL 03346, MIL 090030, MIL 090032 and MIL 090136.

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In a series of contributions we will focus on the magnetic signature, magnetic record, rock magnetic properties and phase composition of the four paired Miller Range nakhlites MIL 03346, MIL 090030, MIL 090032 and MIL 090136 [1-3]. A selected set of various other nakhlites have been included in our investigations for comparison and for deepening our knowledge concerning the source and geological setting of the nakhlite pile [4-6, 10]: the three paired Yamato 000593 / 000749 and 000802 meteorites from NIPR, and Nakhla, Lafayette, Governador Valdarez, NWA 817, NWA 998 and NWA 5790 (from various private collections) [1-3]. In this first contribution we will focus on the magnetic susceptibility, an independent parameter which is used for classification measures since many years [5].

MIL 03346 was discovered in the Miller Range (Transantarctic Mountains) by the ANSMET Team in 2003, while the other three paired stones were found by the 2009/10 ANSMET Team in the same area [1-3]. All four MIL stones are partly covered by fusion crust (FC) and are characterized by very low terrestrial alteration effects. We have received a set of samples for our projects by the the NASA/LPI team (K. Righter) consisting of two fragments of each paired stone and a PTS, of each meteorite, respectively: one near surface fragment without FC (called exterior sample, ext) and one central fragment (called interior sample, int). We could demonstrate that in this way it is possible to get certain indications for the likely presence and significance of terrestrial alteration effects [6-9].

The investigations presented in our report have been performed at the Laboratories of the National Polar Research Institute at Tachikawa /Tokyo (Japan) and at the Mineralogical State Collection, Munich (Germany). Magnetic susceptibility was studied with KLY3 (AGICO, CR) and digital optical microscopy (phase analyses) was performed at a Keyence VHX950F at MSM-SNSB, (magnifications up to 2500).



(a) MIL 03346



(c) MIL 0900032



(b) MIL 090030



(d) MIL 090136

Figure 1a-d: Digital microscopy view of the opaque and magnetic phases in the four paired MIL meteorites.

Table 1 provides a first overview of the magnetic susceptibility (MS) values of the four paired MIL nakhlites. Specific magnetic susceptibility (MS) in log $[10^{-9} \text{ m}^3 / \text{kg}]$.

	MS Int. Fragments	MS Ext. Fragments	Comments
MIL 03346	3,73	3,70	Ext: No FC
MIL 090030	3,83	3,80	Ext: No FC
MIL 090032	3,78	3,77	Ext: No FC
MIL 090136	3,84	3,80	Ext: No FC
Average	3,79(5)	3,76(8)	

MS in the MIL nakhlites shows quite a homogenous distribution which confirms our earlier results obtained on the three paired Yamato nakhlites. In all cases MS of the exterior fragments is slightly lower than in the interior fragments, an effect or trend which found already earlier in the Yamato nakhlites, and is most likely due to near surface terrestrial alteration effects [8-9].

Further details will be presented in our poster contribution.

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Limitations of the zircon dating in impact-shocked rocks from the terrestrial impact structures: A review.

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The different datings are widely used as excellent geochronometric determinations for the processes of planetary evolution and impact events on Earth and other planetary bodies (Kirkland et al. 2015). Zircon crystal can be enriched in excellent chronometers such as U,Pb,Th and the isotopes of several rare earth elements (REE) and it can efficiently expose the budget of isotopes on long geologic timescales. Therefore, zircon chronometry can provide reliable information from large-scale geologic processes and impact events occurred in the early crustal evolution of Earth. However, geological processes and impact events can cause microstructural changes in zircon, which can strongly affect the reliability of radiogenic dating (Reddy et al 2007). The purpose of the study is to present several examples how shock-metamorphism affects the reliability of zircon dating by reducing or losing the amount of radiogenic isotopes yielding different extents of radiation damage in the domains of the crystal structure.

Magmatic zircon is an abundant accessory mineral in igneous rocks, and its bulk crystals could survive more geological processes. Impact events commonly occur in igneous rocks, which constitute the deeper layers of the upper crust. The impact-shocked metamorphic alteration can occur on high-pressure levels (20-60 GPa), causing microstructural deformations with radiation damage on more grade depending on the shock deformation. Note that, the zircon can widely be used for dating reliable formation ages of terrestrial impact structures as based on the U-Pb analysis of recrystallized granular zircon grains derived from Lappajärvi impact structure (Kenny et al. 2019).

Based on the Raman and Scanning Electron Microscope-Cathodoluminescence properties of the shocked zircon samples in nature and experiment (Gucsik et al. 2002, 2004a and b), it was shown that there is a systematic spectral change of the shocked zircon as a function of increasing shock pressure. In general, the studies above determined that every 10 GPa shock-peak pressure gives approximately 10 nm wavelength change (as peak shifts, peak broadening, peak appearance or disappearance, for instance) in the electromagnetic spectrum (so-called Gucsik-index). Therefore, the shock stage of the zircon samples can be determined by that index. This information can also aid in understanding how the shock metamorphism affects the U-Pb systematics of zircon for age-determining processes.

Consequently, zircon, a resilient and ubiquitous mineral, has the remarkable ability to preserve its crystalline structure even in the face of extreme conditions, such as those encountered during meteorite impacts or other high-energy events. As these experimental studies above continue to advance, they will undoubtedly contribute to our understanding of the structure, dynamics, and evolution of planetary interiors, where zircon and other geological materials are subjected to extreme conditions.

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Recovering true size distribution of the chondrules from two-dimensional plane sections close to each other

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Introduction: Chondrules are most commonly examined by using thin sections (Vogel 2003, Weisberg et al. 2006) (Fig 1). Studying thin sections can provide us with direct information on the geometric properties of chondrules. However, the apparent, two-dimensional (2D) particle size distributions obtained directly by the previous studies above do not correspond to the true size distributions. The scientific problem of how to calculate the true size distribution from the two-dimensional one has been a matter of discussion for a long time. In a pioneering study (Cuzzi and Olson 2017) made a good summary of the results and methods of the above-mentioned problem. The approach to the problem in this study is different from the previous ones, using the tools of probability theory. We have succeeded in derivating a formula to calculate the true size distribution from the two-dimensional one (Fig 2).



Figure 1. An optical microscope image of Kaba CV3 carbonaceous chondrite illustrating the size distribution as well as spacing of the chondrules. The photo was taken by Prof. Márta Polgáry and Dr Ildikó Gyollai at HUN-REN (Budapest, Hungary).



Figure 2. Schematic figure of the geometrical model.

Results and Discussion: We have calculated the formulae describing the relationship between these last three size distributions and the true size distribution of the chondrules. In the course of the work, Monte-Carlo simulations were used to verify the correctness of the relationships. If these formulas are used alongside those for the "traditional" first and second distributions, the true 3D size distribution can be more accurately determined.

The first step is to introduce four random variables as follows: X shows the radius of a randomly selected circle from the section plane. Y shows the radius of an intersected, randomly selected sphere. Z shows the distance between the section plane and the center of an intersected, randomly selected sphere. W shows the radius of a randomly selected sphere from the whole region (Fig 3.).



Figure 2: Illustration of the random variables X, Y, and Z in the case of a randomly selected sphere.

The two-dimensional size distributions measured by thin sections correspond to that of the random variable X. The one of main goals of this study is to provide the analytical formulas that can be used to calculate the X and W distributions from each other.

In this case, the selected sphere can be either intersected or not intersected. It is important to note that the random variables W and Y are different. Both of them are connected to the sizes (the radii) of the spheres but their random events are different. The random event of X is that we choose an intersected sphere, in the case of random variable W the chosen sphere can also be a non-intersected sphere. The random events of the random variables X, Y, and Z are equivalent. Pythagorean theorem gives the simple connection between the random variables X, Y, and Z.

$$Y^2 = X^2 + Z^2.$$
 (1)

Calculating the conditional cumulative distribution function (CDF) of Y under the same condition is possible. We can get

$$X = \sqrt{Y^2 - Z^2},\tag{2}$$

which is under the condition Y = R is

$$X = \sqrt{R^2 - Z^2},\tag{3}$$

The CDF of distribution of W is

$$F_W(y) = 1 - \frac{2}{\pi} \frac{1}{\lambda} \int_y^\infty \frac{f_X(x)}{\sqrt{x^2 - y^2}} dx.$$
(4)

Since FW (0) = 0, the constant λ can be calculated from the equation

$$\lambda = \frac{2}{\pi} \int_{0}^{\infty} \frac{f_X(x)}{x} dx.$$
⁽⁵⁾

By using (3) and (4) the three-dimensional distribution of W can be calculated from the two-dimensional distribution of X.

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