

CHONDRULE-LIKE OBJECTS AND A REFRACTORY INCLUSION IN GEMS-BEARING ANTARCTIC MICROMETEORITES AND INTERPLANETARY DUST PARTICLES. T. Noguchi¹, N. Ohashi², J. P. Bradley³, D. Nakashima⁴, T. Nakamura⁴, M. Kimura⁵, T. Ushikubo⁶, N. T. Kita⁷, and N. Imae⁵, ¹Faculty of Arts and Science, Kyushu Univ., Fukuoka 819-0395, Japan, ²NEC Networks and System Integration Co., Tokyo 112-8560, Japan, ³Hawaii Institute of Geophysics and Planetology, Univ. of Hawaii at Manoa, HI 96822, USA, ⁴Department of Earth Science, Tohoku Univ., Miyagi 980-8578, Japan, ⁵National Institute of Polar Research, Tokyo 190-8518, Japan, ⁶Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology, Kochi 783-8502, Japan, ⁷WiscSIMS, Department of Geoscience, Univ. of Wisconsin-Madison, WI 53706, USA.

Introduction: Stardust samples returned from 81P/Wild 2 revealed that chondrules and refractory inclusions were transferred to the outer solar system [1, 2]. However, the majority of sub- μm -sized materials were modified during capture in aerogel. Therefore, it is not clear if glass with embedded metal and sulfide (GEMS) is present in the cometary material, while GEMS is the major component of chondritic porous interplanetary dust particles (CP IDPs) that have been regarded as cometary dust [3]. Moreover, mid-infrared (MIR) spectral studies show that cometary nuclei contain amorphous silicates [e. g. 4], suggesting that GEMS are abundant in comets. Therefore, GEMS-bearing Antarctic micrometeorites (AMMs) and IDPs containing chondrules and refractory inclusions are important to understand comets as well as icy small bodies such as P- and D-type asteroids. To date, only micro-chondrules have been found among GEMS-bearing AMMs and IDPs [5, 6]. Here we report chondrule-like objects and a refractory inclusion that are as large as those in the Stardust samples found in GEMS-bearing AMMs and IDP.

Samples and methods: AMMs were recovered from surface snow near the Dome Fuji station in 2003 and 2005. L2036 #20 was collected in 1997. They were embedded in epoxy and ultramicrotomed. The ultrathin sections were examined by transmission electron microscopes (TEM) at Ibaraki and Kyushu Universities and Lawrence Livermore National Laboratory. Potted butts were analyzed by field-emission scanning electron microscope (FE-SEM) at University of Tokyo, FE-electron microprobe analyzer at Kyushu University, and secondary ion mass spectrometry at University of Wisconsin-Madison.

Results: Backscattered electron (BSE) images of 3 chondrule-like objects and a refractory inclusion are shown in Fig. 1. All of them seems to be fragments of larger objects. D03IB64 contains an iron-rich (Fo_{73-71}) barred olivine (BO) chondrule fragment. Electron backscattered diffraction revealed that olivine bars have a coherent crystallographic orientation. D05IB66 contains a granular olivine pyroxene (GOP) chondrule fragment containing low-Ca pyroxene showing a wide compositional zoning (En_{98-83}) and homogeneous oli-

vine ($\sim\text{Fo}_{78}$). L2036 #20 contains a GO chondrule fragment containing Fe-rich (Fo_{86-71}) olivine and high-Ca pyroxene ($\text{Wo}_{42}\text{En}_{44}\text{Fs}_{14}$). All of them contain Fe-rich sulfide. D05IB84 contains a fragment of spinel-hibonite-perovskite (sp-hb-pv) inclusion.

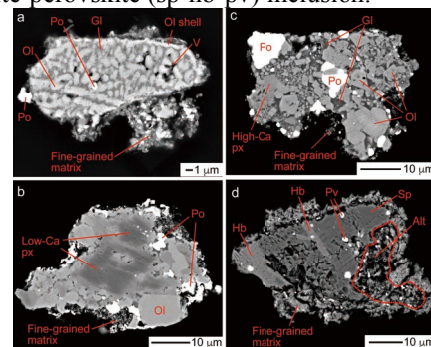


Fig. 1 BSE images of chondrule-like objects and a refractory inclusion in 3 AMMs and an IDP. A) D03IB64, B) D05IB66, C) L2036 #20, D) D05IB84. Ol: olivine, px: pyroxene, Po: pyrrhotite, Gl: glass, Sp: spinel, Hb: hibonite, Pv: perovskite, Alt: alteration product (enclosed by a dotted curve).

TEM observation revealed that fine-grained matrices of all the AMMs and IDP investigated are highly porous and contain GEMS (Fig. 2), olivine, low-Ca pyroxene, high-Ca pyroxene, pyrrhotite. Enstatite whiskers are also found in these matrices. These phases are connected by organic material. Although the fine-grained matrices of AMMs and IDP containing chondrule-like objects are completely indistinguishable from CP IDPs, fine-grained matrix of D05IB84 contains minor fibrous phyllosilicate showing $\sim 1\text{-nm}$ lattice fringes and aggregates of fine-grained Fe-Mg oxide, whose precursors are probably Fe-Mg carbonate before entering atmospheric entry [7]. These hydrated phases distribute heterogeneously in the matrix of D05IB84. This observation is consistent with FE-SEM observation, which shows that aqueous alteration products exist locally on the rim of the sp-hb-pv inclusion (Fig. 2D). We found that spinel contains tiny ($<100\text{ nm}$) Ti-bearing Zr oxides and Mo- and Ru-bearing Ir-Os alloy and that perovskite contains Y and Zr, suggestive of ultra-refractory nature.

Oxygen isotopic ratios of olivine and pyroxene in the chondrule fragments in D03IB64 and L2036 #20 are plotted 0.7‰ below and 2.7‰ above the terrestrial fractionation line on the three-oxygen isotope diagram, respectively. Figure 3 shows the relationship between Mg# ($100 \times \text{Mg}/(\text{Mg}+\text{Fe})$ atomic ratio) and $\Delta^{17}\text{O}$ of ferromagnesian silicates in the chondrule fragments.

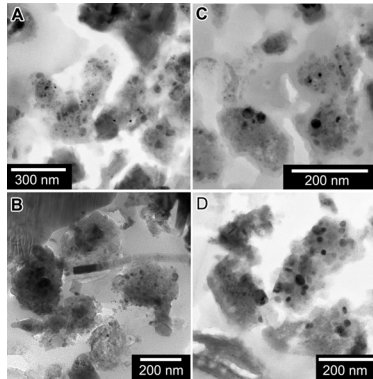


Fig. 2 BF TEM images of GEMS in fine-grained matrices of 3 AMMs and an IDP investigated in this study. A) D03IB64, B) D05IB66, C) L2036 #20, D) D05IB84.

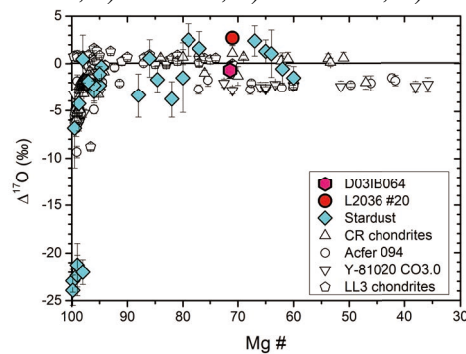


Fig. 3 Relationship between Mg# and $\Delta^{17}\text{O}$ of ferromagnesian silicates in chondrule-like objects (this study), Stardust samples, those in chondrules in CRs, Acfer 094, Y-81020, and LL3s [8, references therein].

Oxygen isotope ratios of spinel in the sp-hb-pv inclusion are $\delta^{18}\text{O}$ of -43.8‰ to -45.1‰ and $\delta^{17}\text{O}$ of -44.8‰ to -46.8‰, respectively. These values are common to spinel in refractory inclusions (RIs) in C chondrites [9]. Resolvable ^{26}Mg excesses ($\delta^{26}\text{Mg}^* \sim 13 \pm 2\%$ and $14 \pm 3\%$) are observed in hibonite with $^{27}\text{Al}/^{24}\text{Mg}$ ratios of 35 – 43, while spinel show marginal excess ($\sim 1\%$). The inferred initial ($^{26}\text{Al}/^{27}\text{Al}$)₀ ratio is $(5.0 \pm 0.7) \times 10^{-5}$ (2σ) based on the slope of the internal Al-Mg isochron, which is consistent with the canonical ^{26}Al abundance of RIs in CV chondrites [10].

Discussion: Recent spectral studies of asteroids and comets suggested that pyroxene-rich CP IDPs were derived from B-, G-, and C-type asteroids based on olivine/(olivine + low-Ca pyroxene) ratios deduced from MIR spectra [11]. These ratios of B-, G-, and C-type asteroids, P- and D-type asteroids, and comets

were deduced to be <12%, 36-52%, and >50%, respectively [11]. The ratios of the matrices in D03IB64, D05IB66, L2036 #20, and unaltered areas of D05IB84 are 0.48 (N=27), 0.61 (N=18), 0.41 (N=29), and 0.59 (N=22), respectively. These ratios are well above the values of B-, G-, and C-type asteroids and comparable with those of P- and D-type asteroids and comets. Therefore, P- and D-type asteroids and comets seem to be more plausible as parent bodies of these chondrule-like objects and refractory inclusion than B-, G-, and C-type asteroids. If that is the case, P- and D-type asteroids and comets contain abundant GEMS as an amorphous silicate phase.

Although the numbers of the chondrule-like objects are very scarce, all of them belong to type II (Mg# <90). Similarly, the proportion of ferromagnesian silicates with Mg# <90 is 78% in the Stardust samples returned from 81P/Wild 2 [12]. Ferromagnesian silicates with Mg# <90 in both of them distribute around $\Delta^{17}\text{O} \sim 0\%$ in the Mg# vs $\Delta^{17}\text{O}$ diagram (Fig. 3) [8], suggestive of a similar origin. This seems to be consistent with the hypothesis that P- and D-type asteroids were migrated from the outer solar system [13]. Both of them were formed in more oxidizing conditions than ferromagnesian chondrules in CR chondrites that are also plotted along with these objects because type II chondrules occupy only $\sim 1\%$ of in CR chondrites [14]. All the chondrule-like objects investigated contain Fe-rich sulfide instead of Fe-Ni metal (Fig. 1). To preserve S in the objects, pulse heating and subsequent rapid cooling as well as moderate peak temperatures under oxidizing conditions may have occurred during formation of chondrule-like objects existing in P- and D-type asteroids and possibly in some comets.

The formation age of the sp-hb-pv inclusion is comparable with the oldest RIs [15]. Because this AMM experienced aqueous alteration, its parent body was formed when ^{26}Al existed in the accreted material.

References: [1] Zolensky M. E. et al. (2006) *Science*, 314, 1735-1739. [2] Nakamura T. et al. (2008) *Science*, 321, 1664-1667. [3] Ishii H. A. (2008) *Science*, 319, 447-450. [4] Colangeli L. et al. (2006) in *Comets II*, 695-717. [5] Wozniakiewicz et al. (2012) *ApJ*, 760:L23 (6pp). [6] Noguchi T. et al. (2017) *GCA*, 208, 119-144. [7] Nozaki W. et al. (2006) *MAPS*, 41, 1095-1114. [8] Defouilly C. et al. (2017) *EPSL*, 465, 145-154. [9] MacPherson G. J. et al. (2012) *EPSL*, 331-332, 43-54. [10] Larsen et al. (2011) *ApJ*, 735:L37 (7pp). [11] Vernazza P. et al. (2015) *ApJ*, 806:204 (10pp). [12] Frank D. R. et al. (2014) *GCA*, 142, 240-259. [13] Levison H. et al. (2009) *Nature*, 460, 364-366. [14] Weisberg M. K. et al. (1993) *GCA*, 57, 1567-1586. [15] Bouvier A. and Wadhwa M. (2002) *Nat. Geosci.*, 3, 637-641.