Oxygen isotope systematics of chondrules and olivine fragments from Tagish Lake C2 chondrite.

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Introduction:

Chondrules are igneous ferromagnesian silicate spherules that have experienced transient high temperature processes in the solar nebula and are a predominant component of chondrites (15-80 vol.%, Scott and Krot, 2013). They are also found on Comet Wild 2 (e.g., Nakamura et al., 2008), indicating that they are formed in large numbers and widely dispersed in the protoplanetary disk from the inner main belt to the Kuiper belt regions. Recent studies on oxygen isotope systematics of chondrules show that chondrules in in-dividual chondrite groups have characteristic distributions in their oxygen isotope ratios and Mg# (molar % of MgO/(MgO+FeO)) (e.g., Ushikubo et al., 2012; Nakashima et al., 2012; Tenner et al., 2018). The observed correlations between Mg# and Δ^{17}O values (= $\delta^{17}O_{VSMOW} - 0.52 \times \delta^{18}O_{VSMOW}$) of chondrules can be explained by mixing of ^{16}O-rich anhydrous dusts and an ^{16}O-poor oxidizing agent (most likely H_2O ice) in chondrule forming regions, suggesting existence of redox and oxygen isotopic heterogeneity in the protoplanetary disk. Although their formation process is still under debate (Scott and Krot, 2013), it is very likely that chondrules are formed from silicate dust precursors in the protoplanetary disk and they record isotopic composition and redox state of chondrule-forming environments.

In this study, we performed oxygen isotope analyses of chondrules and olivine fragments from Tagish Lake meteorite (ungrouped C2). Tagish Lake meteorite is a highly porous, carbon-rich, aqueously altered carbonaceous chondrite, and its ultraviolet–visible–near-infrared reflectance spectrum is close to those of D-type (or rare T-type) asteroids (Hiroi et al., 2001; Hiroi and Hasegawa, 2003). A recent study on carbonates in Tagish Lake meteorite suggested that its parent body contained CO_2 ice as well as H_2O ice when it accreted (Fujiya et al., 2019). All these observations suggest that the parent body of the Tagish Lake accreted further than any other chondrite parent bodies. The primary objectives of this study are to understand the Mg#-Δ^{17}O correlation of chondrules and olivine fragments from Tagish Lake meteorite and to investigate for cometary chondrule related signatures. Preliminary results have been reported at LPSC in 2019 (Ushikubo and Kimura, 2019).

Samples and Methods:

Two polished epoxy mounts of the Tagish Lake meteorite, TL-KC-1 (8mm × 5mm) and TL-KC-2 (4mm × 3mm), were prepared for this study. Frequent occurrence of magnetite in the matrix indicates that most of polished sections consist of the carbonate-poor lithology. Forty-nine samples (chondrules and olivine fragments) from two polished mounts were selected. Here, we classified samples as chondrule if we recognize apparent chondrule-like texture (such as porphyritic texture, aggregates of olivine grains and pseudomorphs, Fig. 1a). If individual olivine grain directly contacts with fine-grained matrix and no apparent layered structure is identified, we classified samples as olivine fragments (Fig. 1b). Twenty-two samples are classified as chondrules and 26 samples are classified as olivine fragments. One exception is an olivine aggregate, TL-KC-2-G16, which consists of a few small olivine grains without any apparent phyllosilicate structure around them (Fig. 1c). Thirty-five samples are type I (Mg#≥90) and 14 samples are type II (Mg#<90).

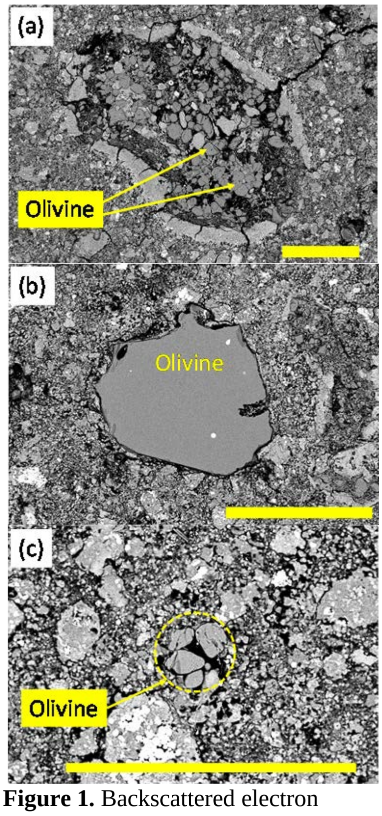

Figure 1. Backscattered electron (BSE) images of (a) a chondrule, 1-G5, (b) an olivine fragment, 1-G13, and (c) an olivine aggregate, 2-G16. Scale bars are 200μm.

Backscattered electron (BSE) and secondary electron images of the samples were obtained using the Hitachi SU-1510 SEM at Kochi Institute, JAMSTEC. Major element oxide analyses of olivine and some pyroxene grains were conducted at 15 kV and a sample current of 30 nA with JEOL JXA8200 EPMA at NIPR. Cathodo-luminescence (CL) images of olivine grains were observed using JEOL JSM-7100F FE-SEM equipped with ChromaCL2 detector at NIPR. Oxygen three-isotope ratios of olivine grains were measured with CAMECA IMS 1280-HR, an ion microprobe at Kochi Institute, JAMSTEC. Because of small grain size of olivine grains, we employed a small primary beam (~3 μm in diameter) to obtain data, instead of using a normal primary beam (~15 μm in diameter). The analytical condition was same as that of the 3 μm beam condition in Ushikubo et al. (2012). Typical 2-SD of $\delta^{18}O_{VSMOW}$ and Δ^{17}O values were ±0.74‰ and ±0.87‰, respectively.

Results and Discussion:

High concentration of Cr_2O_3 abundances of olivine grains with >2wt% FeO (0.37±0.17 wt%, 1 SD) is consistent with the least metamorphosed carbonaceous chondrites. Tagish Lake olivine datapoints in the FeO-MnO plot (Fig. 2) are distributed along the CO-CM chondrule trend, or slightly above that trend like CR chondrite chondrules (e.g., Berlin et al., 2011; Frank et al., 2014).

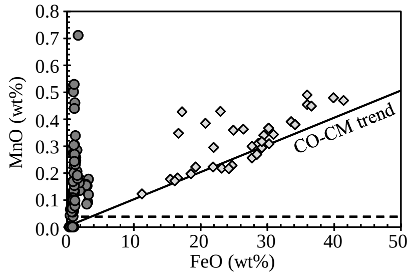

Figure 2. FeO vs. MnO plot of studied olivine grains. The CO-CM trend is also shown.

Oxygen three-isotope ratios of the samples from Tagish Lake are distributed along the PCM (primitive chondrule minerals) line (Ushikubo et al., 2012). The olivine aggregate, 2-G16, has a very ^{16}O-rich signature (Δ^{17}O=−24.0 ±0.6‰) like CAIs and AOAs. Others are within a typical range of chondrules from carbonaceous chondrites (Δ^{17}O=−7.7±1.1 to −0.1±0.9‰, Fig. 3a). Most type I chondrules and olivine fragments are relatively ^{16}O-rich (Δ^{17}O=−7.7 to −3.9‰ with uncertainty of ~±1‰). In contrast, type II chondrules and olivine fragments are rela-tively ^{16}O-poor (−3.1 to −0.1‰) with a large gap in the Mg# between type I and type II samples (Fig. 3a). Similar trend has been observed in ferromagnesian silicates from a Tagish Lake like (TL-like) chondrite, WIS 91600 (Yamanobe et al., 2018). When we compile the Mg#-Δ^{17}O data of Tagish Lake and TL-like meteorites (This study; Russell et al., 2010; Yamanobe et al., 2018), type II samples have variable Δ^{17}O values, which is similar to those of CR chondrites but distinct from those of CM, CO, and Acfer 094 chondrites (Fig. 3b, Tenner et al., 2018 and references therein). Type II chondrules/olivine fragments with Δ^{17}O≥0‰ are commonly found from chondrules/silicate grains from the Comet Wild 2 samples (e.g., Defouilloy et al., 2017).

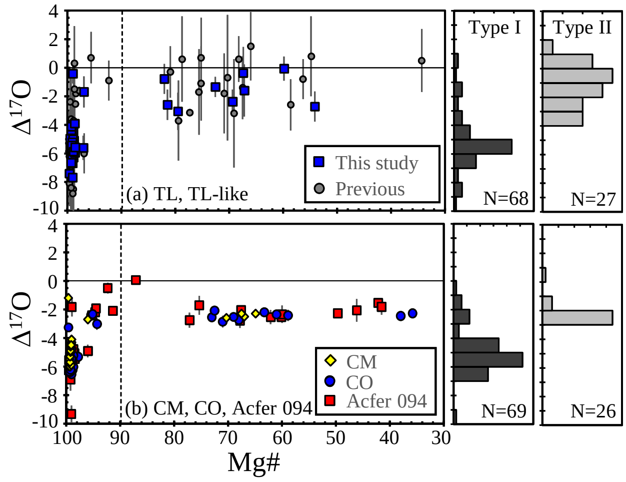

Figure 3. The Mg#-Δ^{17}O plot and histograms of Δ^{17}O values of chondrules and olivine grains: (a) Tagish Lake and TL-like meteorites, (b) CM, CO, and Acfer 094 chondrites.

Assuming that CM chondrites, Tagish Lake and TL-like meteorites, and comet Wild 2 represent C-type asteroids, D-type asteroids, and Kuiper belt objects, respectively, we can broadly determine the spatial distribution of chondrule-forming environments in the protoplanetary disk. The ^{16}O-rich type I chondrules likely formed in the middle to outer main belt regions because this chondrule group is the major component of CM chondrite chondrules. The type II chondrules with Δ^{17}O≥0‰, which are abundant in comet Wild 2 silicates, must have formed in the outermost parts of the chondrule-forming region. Because of the rare occurrence of type II chondrules with Δ^{17}O≥0‰ in Tagish Lake and TL-like meteorites, this type of chondrules must have formed much farther than the region where Tagish Lake meteorite parent body (probably one of D-type asteroids) accreted.

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