TARDA AND TAGISH LAKE: SAMPLES FROM THE SAME OUTER SOLAR SYSTEM ASTEROID?

D. L. Schrader[1], J. Davidson[1], D. Foustoukos[2], C. M. O'D. Alexander[2], Z. A. Torrano[2], E. A. Cloutis[3], D. M. Applin[3], T. J. Zega[4], T. Nakamura[5], and M. Matsuoka[6]. [1]Buseck Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA (devin.schrader@asu.edu), [2]Earth and Planetary Laboratory, Carnegie Institution for Science, Washington, DC 20015, USA. [3]Department of Geography, University of Winnipeg, Winnipeg, Manitoba R3B 2E9, Canada. [4]Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721, USA. [5]Department of Earth and Planetary Material Sciences, Faculty of Science, Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan. [6]Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris, 92195 Meudon, France.

Introduction: Tarda is an ungrouped type 2 carbonaceous (C2-ung) chondrite that fell in Morocco on August 25th, 2020 near the village of Tarda [1]. Tarda was found by [2] to: (1) be dominated by phyllosilicates, with minor amounts of olivine, magnetite, Fe-sulfides, and dolomite; (2) be distinct from CI and CY chondrites; and (3) display no evidence for heating. Based on bulk isotopic compositional similarities with Tagish Lake, [2–4] concluded that Tarda is similar to the C2-ung Tagish Lake and the Tagish Lake-like meteorites Meteorite Hills (MET) 00432 and Wisconsin Range (WIS) 91600 [5–8]. These Tagish Lake-like meteorites may be samples from D-type asteroid(s), which potentially formed in the outer Solar System between 8 and 13 AU [3,5,7,9]. These four similar carbonaceous chondrites are more numerous than the three samples required to define a grouplet, and only one meteorite shy of the five required to define a new meteorite group. To constrain the compositions and petrology of this rare material, here we discuss the petrography, bulk H-C-N isotopic compositions, and *in situ* chemical compositions of metals, sulfides, and chondrule silicates of Tarda and compare them to Tagish Lake.

Samples and Analytical Procedure: We analyzed two polished mounts of Tarda prepared from two separate stones (ASU2149_C1 and 2149_C2) that were collected within days of the fall. We also analyzed a polished mount of Tagish Lake (ASU1684_C1) for comparison. X-ray element maps, secondary and backscattered electron (BSE) images, and quantitative chemical compositions were obtained with the JEOL-8530F Hyperprobe electron microprobe analyzer (EPMA) at Arizona State University (Figs. 1 and 2) and the Cameca SX-100 EPMA at the University of Arizona, following the procedures described in [10,11]. Chondrule sizes were measured in full polished section BSE images and X-ray element maps using Adobe Photoshop®. Interior chips of Tarda (1.03 g, no fusion crust) were powdered and used to obtain: (1) visible near-infrared spectra (VIS-NIR) at the University of Winnipeg following the procedures of [12]; and (2) bulk H, C, and N abundances and isotopic compositions at Carnegie Institution for Science following the procedures of [13]. A comparison of spectra from Tarda to that of Tagish Lake, MET 00432, and WIS 91600 is discussed in [12].

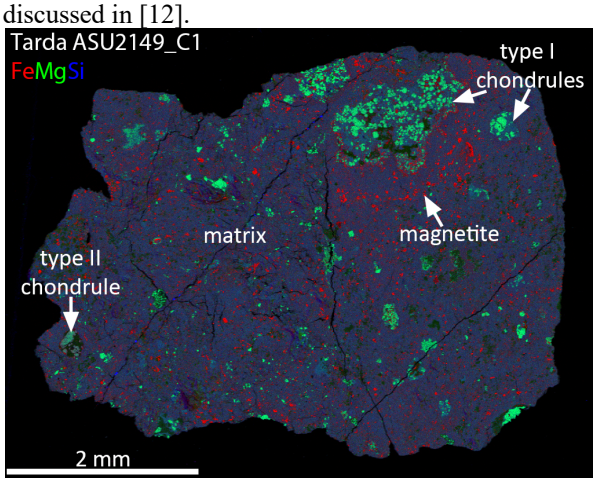

Figure 1. FeMgSi RGB X-ray element map of Tarda.

Results: *Tarda.* Tarda has a bulk isotopic and elemental composition of $\delta^{13}C$ = 8.0‰ (4.17 wt.% C), $\delta^{15}N$ = 62‰ (0.297 wt.% N), and δD = 608‰ (0.916 wt.% H), yielding a bulk C/H (wt.%) ratio of 4.55. The *in situ* mineral compositions and petrography of the two polished mounts are indistinguishable from one another. Therefore, mineral compositions and petrographic observations are presented together. We identified 21 whole chondrules, 18 FeO-poor (one dusty olivine and 17 type I) and three FeO-rich (type II) chondrules, all of which are porphyritic and highly aqueously altered (altered phenocrysts and no remaining unaltered glass). One type II chondrule is almost completely pseudomorphically replaced by phyllosilicates. FeO-rich chondrules are significantly less abundant than FeO-poor chondrules (e.g., Fig. 1). The range of diameters of the 21 chondrules is 0.07–1.30 mm (mean 0.26±0.12 mm; ±2SE). Many FeO-poor olivine fragments were observed in the matrix, which we conclude are fragments of type I chondrules, but their sizes were not measured. The range of chondrule olivine compositions is $Fa_{0.5–55.6}$, with Fe/Mn ratios in the range 4–134 (# analyses = n = 87). The Fe-sulfides observed include both Ni-poor (<1 wt.% Ni) Fe-depleted pyrrhotite (mean Fe/S at.% ratio = 0.87, n= 14) and

pentlandite (n = 22) (Fig. 2). Ni-rich pyrrhotite was also observed (n = 15), but may be due to EPMA beam overlaps with pentlandite. Rare Fe,Ni metal in a type I chondrule has Ni = 5.6–6.2 wt.% and Co = 0.20–0.24 wt.% (n = 2).

Tagish Lake. In a carbonate-rich sample [e.g., 14] we identified 58 whole chondrules to measure, 52 type I chondrules and six type II chondrules. The diameters of these 58 chondrules are in the range 0.05–1.37 mm (mean 0.28±0.06 mm; ±2SE). This range is similar to the size range from [14] (0.25–1 mm), although a mean diameter was not provided. The chondrules are heavily aqueously altered and the majority are porphyritic, only two barred olivine and one cryptocrystalline chondrule were observed. The range of chondrule olivine compositions is $Fa_{0.6–54.3}$, with Fe/Mn ratios in the range 5–142 (n = 97). The Fe-sulfides observed include Ni-rich Fe-depleted pyrrhotite (Ni is potentially from beam overlaps with pentlandite, n = 28) and pentlandite (n = 14). No Ni-poor pyrrhotite was analyzed that could be used to determine the at.% Fe/S ratio (e.g., [11]).

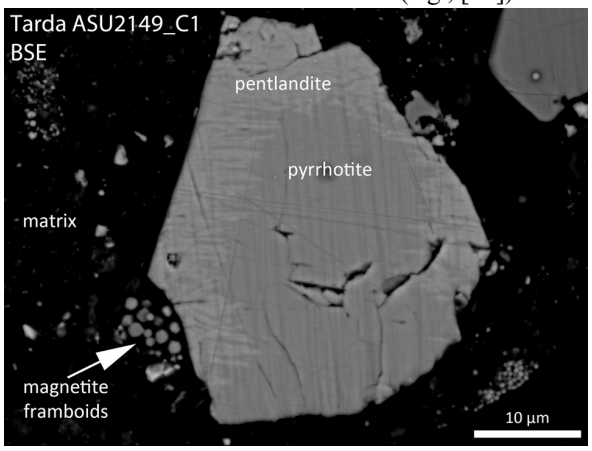

Figure 2. BSE of pyrrhotite-pentlandite intergrowth.

Discussion: The bulk isotopic and elemental compositions of H, C, and N indicate that Tarda is very similar to Tagish Lake compositions from [3,15]. The mean at.% Fe/S ratio of Ni-poor (<1 wt.% Ni) pyrrhotite in Tarda is 0.87, which indicates a high degree of aqueous alteration consistent with that seen in CM1/2 and CI chondrites by [11]. Pyrrhotite-pentlandite geothermometry via phase diagram analysis (e.g., [16]) shows Tarda sulfide equilibration temperatures of approximately 100–135°C, which is also consistent with formation of the sulfides during low-temperature aqueous alteration, and provides an estimate for the minimum parent asteroid alteration temperature of Tarda. This is consistent with the observation of [2] that Tarda has not been heated. Following the work of [17], the low Co content of Ni-poor Fe,Ni metal also indicates that Tarda has not been noticeably heated. Our pyrrhotite-pentlandite geothermometry of Tagish Lake also shows sulfide equilibration temperatures of approximately 100–135°C. Tarda's mean chondrule size of 0.26±0.12 mm is most similar to that of Tagish Lake (0.28±0.06 mm, this study) and that of CMs (i.e., 0.27 mm; [18]).

The Fe-Mn systematics of chondrule olivines can help identify genetic relationships between groups (e.g., [19,20]). The Fe-Mn compositions of chondrule olivines in Tarda are most similar to those of Tagish Lake (this study), and CO and CM chondrites [19,20]. While the distinct bulk O-isotope compositions [1] and H-C-N compositions ([3]; this study) excludes the possibility that Tarda is a CM or CO chondrite, Tarda's chondrules may have formed under similar conditions and from similar precursor materials, potentially in a similar formation region.

We conclude that Tarda shares a genetic relationship to Tagish Lake and likely originated from the same outer Solar System asteroid. Relationship(s) to the Tagish Lake-like meteorites MET 00432 and WIS 91600 will be investigated to determine if a new grouplet (potentially the CT chondrites, or Tagish Lake-like carbonaceous chondrites) is justified. Tarda is a highly hydrated carbonaceous chondrite that will likely provide an informative comparison to the hydrated samples returned by Hayabusa2 and OSIRIS-REx, the spectra of D-type asteroids to be surveyed by Lucy (e.g., [21]), and spectra/samples from Phobos by MMX [22].

Acknowledgments: We thank the ASU BCMS for the samples used in this study, Laurence Garvie for sample preparation, and NASA grants NNX17AE53G (DLS PI, TJZ Co-I) and 80NSSC19K0559 (DF, CA) for funding a portion of this research.

References: [1] Gattacceca J. et al. (2021) *MAPS*, 56, 1626–1630. [2] King A. J. et al. (2021) *LPSC* LII, #1909 (abst.). [3] Marrocchi Y. et al. (2021) *ApJ Letters*, 913, L9. [4] Dey S. et al. (2021) *LPSC* LII, #2517 (abst.). [5] Hiroi T. et al. (2005) *LPSC* XXXVI, #1564 (abst.). [6] Nakamura T. et al. (2013) *MAPS*, 48, #5122 (abst.). [7] Yamanobe M. et al. (2018) *Polar Sci.*, 15, 29–38. [8] Ushikubo T. and Kimura M. (2019) *GCA*, 293, 328–343. [9] Bryson J. F. J. et al. (2020) *ApJ*, 892, 126. [10] Donaldson Hanna K. L. et al. (2019) *Icarus*, 319, 701–723. [11] Schrader D. L. et al. (2021) *GCA*, 303, 66–91. [12] Applin D. M. et al. (2022) *LPSC* LIII, this meeting (abst.). [13] Alexander C. M. O'D. et al. (2007) *GCA*, 71, 4380–4403. [14] Zolensky M. E. et al. (2002) *MAPS*, 37, 737–761. [15] Alexander C. M. O'D. et al. (2012) *Science*, 337, 721–723. [16] Schrader D. L. et al. (2016) *GCA*, 189, 359–376. [17] Kimura K. et al. (2008) *MAPS*, 43, 1161–1177. [18] Rubin A. E. and Wasson J. T. (1986) *GCA,* 50, 307–315. [19] Berlin J. et al. (2011) *MAPS*, 46, 513–533. [20] Schrader D. L. et al. (2020) *GCA*, 282, 133–155. [21] Levison H. F. et al. (2021) *PsJ*, 2, 171. [22] Nakamura T. et al. (2021) *EPS*, 73, 227.