DETAILED COORDINATED ANALYSIS OF THE MINERALOGY, PETROGRAPHY AND ELEMENTAL COMPOSITION OF THE CARBONACEOUS CHONDRITE FALLS TARDA AND KOLANG.

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Introduction: In August of 2020, the observed fall and recovery of two carbonaceous chondrites (CCs) were reported within a single month. The first of these events occurred on August 1st in Indonesia leading to the recovery of Kolang (CM1/2). A second fireball observed over Morocco on August 25th lead to the recovery of the C2-ungrouped CC (C2-ung) Tarda.

Kolang is highly brecciated and contains at least three distinct lithologies characterized by the presence or absence of chondrules and fracture surfaces. The matrix primarily consists of serpentine with components of interstratified tochilinite, calcite, pyrrhotite, and pentlandite. Chondrules vary in degree of replacement of anhydrous silicates by hydrous phases. The official classification of Kolang as a petrologic type 1/2 CM chondrite is based on the bulk O-isotopes falling within the field of CM chondrites and the dominant lithology containing a mix of chondrules with partial and full replacement by hydrous phases [1].

Tarda is best described as a breccia predominantly consisting of an optically opaque fine-grained matrix (~80 vol.%) containing mineral clasts, chondrule fragments, and a few small chondrules. The bulk matrix consists primarily of phyllosilicates, with lesser components of magnetite, carbonates, olivine, troilite, pyrrhotite, and pentlandite. A unique feature of Tarda is an igneous achondrite clast containing anorthite, forsterite, enstatite, and diopside in the form of twinned laths [1]. The classification of Type 2-ungrouped is due to the distribution of the bulk O-isotopes falling mostly outside the range of CI chondrites, and aqueous alteration consistent with petrologic grade Type 2 [1].

A recent petrographic and isotopic study of Tarda found similarities with the D-type asteroid derived C2-ung Tagish Lake, suggesting Tarda may also be a sampling of a similar asteroid type [2]. Meanwhile, remote sensing of B-type asteroid (101955) Bennu by OSIRIS-REx suggests Bennu may be related to highly aqueously altered CM, CI, and C-ung chondrites such as Kolang and Tarda [3, 4]. The rapid recovery of Tarda and Kolang make them important samples to study the genetic relationships between meteorites and their suspected parent asteroids classes, particularly within the context of the imminent return of Bennu samples in 2023 by OSIRIS-REx.

We have conducted in-situ and bulk analyses to characterize the elemental composition, mineralogy, and petrology of Tarda and Kolang as part of a larger effort to study presolar grains and organics in meteorites analogous to asteroid Bennu.

Methods: We conducted in-situ analysis on polished thin sections and bulk analysis using dissolutions from 40 mg aliquots of Tarda and Kolang.

Electron Probe Micro-Analyzer (EPMA): We used the Cameca SX-100 Ultra EPMA in the Kuiper Materials Imaging and Characterization Facility (KMICF) at the University of Arizona for the initial mineral and chemical characterization. Whole sample and region-specific back-scattered electron (BSE) images and X-ray maps of major component elements (*e.g.,* Ca, Mg, Al, Fe) were acquired to understand the distribution of elements throughout each thin section (Fig. 1). Follow-up quantitative chemical analyses were then done using a focused beam on well-defined features and a de-focused (5 µm) beam for fine-grained material in locations of interest.

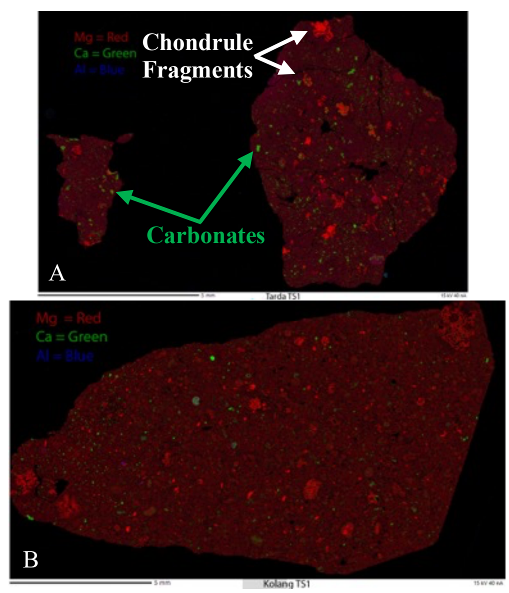

Fig. 1: Composite X-ray maps of Mg, Ca, and Al. **A.)** Tarda showing examples of chondrule fragments and carbonates. **B.)** Kolang, showing carbonates as green flecks.

Quadrupole-inductively coupled plasma mass spectrometry (q-ICP-MS): The bulk elemental composition of chips from Tarda and Kolang was measured using ICP-MS. Aliquots of ~40 mg were ground into powder and dissolved in a mixture of double-distilled HNO_3 and HF on a hot plate at ~130 °C for one week. The samples were then dried and redissolved in concentrated HNO_3 three times. Sample solutions were then prepared at dilution factors of ~50,000 for major elements and ~5,000 for minor and trace elements. Each sample solution was run multiple times in the Thermo Fisher Scientific iCAP Qc q-ICP-MS at WUSTL to determine the bulk chemical composition of Tarda and Kolang.

Results: Whole sample X-ray maps of Tarda show that chondrule fragments and carbonates are abundantly dispersed throughout the matrix (Fig.1A).

Closer inspection of the matrix reveals numerous magnetite framboids, often in clusters, that range in size from ~ 1 to 15 µm. Defocused electron probe analyses in the matrix give average measurement totals of 81.4 ± 2.6 wt.% (SE, n=7), which suggests the presents of hydrated phases and is consistent with expectations of type 2 CCs. The dominant matrix component (excluding SiO_2) is MgO ranging from 15.8 to 23.7 wt.%, and the average matrix content of FeO = 16.8 wt.%.

The bulk composition of Tarda from q-ICP-MS finds MgO = 18.0 wt.% and FeO = 24.6%. In comparison with the EPMA data, the matrix MgO content is representative of the bulk material. However, the matrix is comparatively Fe-poor, with a significant amount of the Fe-content being contained within the abundant magnetite framboids.

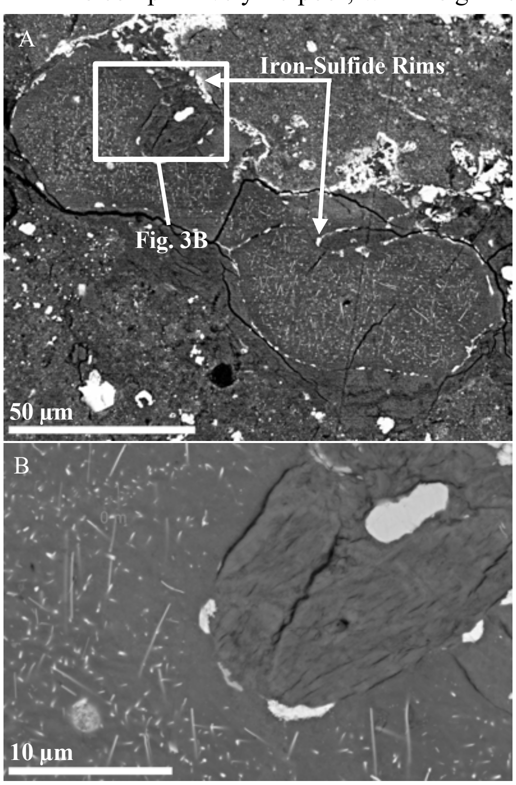

Fig. 3: BSE micrograph of: **A.)** The igneous clast in Tarda showing the laths of anorthite and rim iron-sulfide rims. **B.)** Close up view of the anorthite laths in the boxed region of Fig. 3A.

We identified a clast in our thin section (Fig. 2) with twinned laths of anorthite that appear to be similar to the igneous achondrite clast described by [1]. The laths are enriched in Cr and P compared to the rest of the sample, while the clast is rimmed by a mixture of iron-sulfides and P-bearing phases.

Our thin section of Kolang was dominated by the chondrule-poor lithology (Fig. 1B), with an average defocused probe total of 75.7 ± 2.8 wt.% (SE, n=14) indicating the matrix is consistent with petrologic type 1/2. The matrix components appear to be more heterogeneously distributed than Tarda, with FeO being most abundant in all 14 measurements at an average of 24.4 wt.% but varying between 16.6 and 36.2 wt.%. The second most abundant component is MgO with a narrow range of only 6 wt.% with an average composition of 15.8 wt.%. Additionally, the matrix contains numerous carbonate grains, with the largest being ~180 µm in diameter.

Kolang's matrix is mostly representative of the bulk composition with FeO = 26.7wt.% and MgO = 18.9 wt.%. Both components are ~3 wt.% lower in the matrix than in the bulk sample, which is consistent with a hydrated matrix and anhydrous silicates in chondrules.

Summary: Through our EPMA and q-ICP-MS analyses, we have begun to constrain the mineralogy and petrography of Tarda and Kolang. The matrix of Tarda is representative of the bulk MgO content but is highly FeO poor in this respect, owing to the high abundance of magnetite framboids. Kolang's matrix is nearly representative of the bulk material but slightly poorer in both FeO and MgO by ~ 3 wt.%, which is consistent with a highly abundant hydrated matrix and the presence of some anhydrous silicates.

We identified the igneous clast in Tarda described in [1], finding the twinned laths of primarily anorthite to be slightly enriched in Cr and P. This clast is surrounded by a rim of iron-sulfides and P-rich phases.

Ongoing work includes searching for isotopically anomalous organics and presolar grains using NanoSIMS, and TEM analyses of two electron transparent sections of Tarda's igneous clast.

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References: [1] Gattacceca J., et al. (2021) *MAPS* 56,8,1626-1630. [2] Marrocchi, Y., et al. (2021) *ApJL* 913:L9 [3] Kaplan, H.H., et al., (2020) 51st LPSC #1050 [4] Merlin, F., et al. (2021), *A&A* 468,A88