Tarda (C2-Ung): A New And Unusual Carbonaceous Chondrite Meteorite Fall From Morocco. H. Chennaoui Aoudjehane[1], C.B. Agee[2], K. Ziegler[2], L.A.J. Garvie[3], A. Irving[4], D. Sheikh[5], P.K. Carpenter[6], M. Zolensky[7], P. Schmitt-Kopplin[8] and L. Trif[9]. [1]Hassan II University of Casablanca, Faculty of Sciences Ain Chock, GAIA Lab, km 8 Route d'El Jadida 20150 Casablanca, Morocco (hassna.chennaoui@univh2c.ma), [2]Institute of Meteoritics, University of New Mexico,[3]Center for Meteorite Studies, Arizona State University, Tempe, AZ 85287-6004, [4]Dept. of Earth & Space Sciences University of Washington Seattle, WA, USA, [5]National High Magnetic Field Laboratory and Florida State University, Tallahassee, FL 32310, [6]Dept. of Earth & Planetary Sciences Washington University Saint Louis, MO, USA, [7]ARES, NASA Johnson Space Center, Houston, TX 77058 USA, [8]Technical University Munich, Freising, Germany, [9]Institute of Materials and Environmental Chemistry, Research Centre for Natural Sciences, 1117 Budapest, Magyar tudosok korutja, 2, Hungary.

Introduction: Morocco is known for its many meteorite finds on its land. In addition to the thousands of finds there are now 22 recovered falls. These numerous falls and finds reinforce Morocco's international position as a source of scientifically important extraterrestrial materials [1]. Among the falls are scientifically important and rare meteorites, such as the Tissint Martian shergottite [2] and the Tirhert eucrite-ubr [3]. Tarda is an unusual carbonaceous chondrite and is the latest Moroccan fall in 2020 making their total number 22, 18 of them during the last two decades. An international consortium of ten scientists forming the ACE (t**A**rda s**C**ience t**E**am) scientists undertook the initial classification and submission to the Nomenclature Committee. Tarda was subsequently accepted as an ungroup C2 meteorite [4].

Fireball and fall description: On the 25th of August 2020, around 2:30 pm Moroccan time (GMT+1), a fireball with a SW to NE trajectory was widely witnessed from the towns of Alnif, Zagora, Tazarine, and Rich in southern Morocco. As is usual when a fireball is seen in this area, hundreds of people immediately went to search for the likely fall between Goulmima and Errachidia. On the following day, the first piece was found close to the village of Tarda. The fall location is crossed by the national road linking Ouarzazate to Errachidia, making the area easily accessible to meteorite hunters. As a result, hundreds of meteorite hunters scoured the area.

Several eyewitnesses from areas up to 150 km away were interviewed during a field mission to the fall site on the 27th and 28th August 2020. They describe a yellow and bright, barrel-sized fireball with green edges lasting ~3s, and accompanied by a whistling sound, followed by multiple detonations. The meteor produced a thick trail of white smoke that remained suspended for several minutes. The fireball was reported to release little pieces around its edges.

Physical description of collected pieces: Thousands of small, mostly complete stones were collected ranging from only a few milligrams to 99 g (Fig 1), for a total mass around 4 kg. Most of the fusion-crusted stones are less than one gram. Some flight-oriented stones show a blue iridescence on their trailing edge, similar to that observed with Aguas Zarcas [5]. The stones have low density, are somewhat friable, and many stones shattered upon impact with the ground. They are particularly susceptible to moisture, and rapidly slake in contact with water or alcohol. Freshly picked up stones were said to have a charcoal-like odor. Small fragments crushed in water emit a powerful tar-like odor. The interiors of the stones are dull black with dispersed white or light-colored grains or clasts (up to ~1 mm in size). Many pieces were recovered by hunters using magnets.

Figure 1- In situ photograph of one of the largest Tarda stones, 86 g (© A. Aaranson)

Magnetic susceptibility: Measured by SM30 gives an average of log | values of 4.92±0.10, n=5.

Strewn field: The strewn field is about 3 km long and situated ~10 km west of Tarda village centered at 31.8265° N, 4.6794° W (Fig 2). The size and distribution of pieces on the field are compatible with the direction and information given by eyewitnesses.

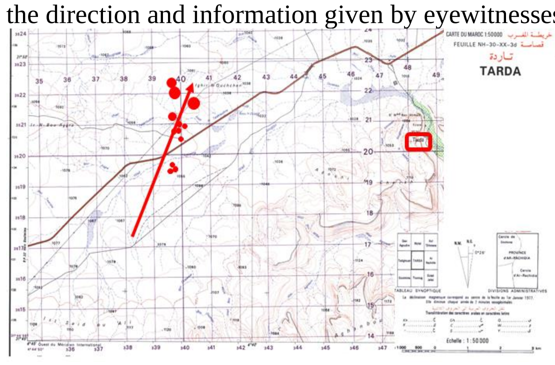

Figure 2 – Strewn field of the Tarda fall. Red dots show the location of individual stones.

Petrography: Optical and electron microprobe observations of three fragments in polished thin sections reveal a matrix-rich breccia containing small chondrules (granular, BO) and chondrule fragments, fine-grained ameboid olivine aggregates AOA, forsterite grains (exhibiting slight undulose extinction) and other clasts set in a fine-grained matrix (~80 vol.%, opaque in thin section). Chondrule sizes measured in two thin sections: 310±150 μm, n=10; 450±200 μm, n=5. No CAIs were identified. The dominant chondrule phase is forsterite (but spinel is present in two examples), and some are mantled by forsterite dust or exhibit partial replacement by Fe-Mn-dolomite, siderite or phyllosilicate material. A single igneous achondrite clast with subophitic texture was observed and consists predominantly (~75 vol.%) of laths of twinned anorthite with subordinate forsterite, enstatite and minor diopside. Electron microprobe surveys of thin sections and powder X-ray diffraction studies of several ~20 mg fragments show that the matrix is dominated by phyllosilicates, with lesser magnetite, pyrrhotite, pentlandite, troilite, carbonates (Fe-Mn-dolomite, Mg-rich siderite and siderite), and olivine. The phyllosilicates show broad basal reflections at 14.7 Å and 7.4 Å, consistent with smectite and serpentine or interstratified serpentine/smectite, respectively. No reflections for sulfates were recognized. Magnetite (<20 μm) is scattered throughout the sample in the form of framboids, platelets, and individual spherules; other accessory phases identified in the matrix by EPMA are troilite, Ni-bearing pyrrhotite, chromite and very rare kamacite.

Geochemistry: EMPA of olivine gives the following values: Forsterite (Fa$_{1.0\pm0.6}$, range Fa$_{0.2-2.9}$; CaO wt% = 0.2±0.1, range 0.1-0.4; Cr_2O_3 wt% = 0.51±0.17, range 0.11-0.91; FeO/MnO =10±6, range 3-24; n=35), while ferroan olivine (Fa$_{26.5\pm1.6}$, range Fa$_{24.8-28.0}$; CaO wt% =0.2±0.1, range 0.2-0.3; Cr_2O_3 wt% = 0.44±0.06, range 0.40-0.51; FeO/MnO = 91±7, range 88-99; n=3). Achondrite clast EMPA gives anorthite (An$_{99.7\pm0.4}$, range An$_{99.4-99.9}$, n=2), forsterite (Fa$_{1.1}$, FeO/MnO = 7, n=1), enstatite (Fs$_{1.1\pm0.1}$ Wo$_{3.2\pm0.5}$, range Fs$_{1.0-1.2}$ Wo$_{2.7-3.7}$, FeO/MnO = 3, n=3), diopside (Fs$_{1.7}$ Wo$_{44.0}$, FeO/MnO = 3, n=1). Bulk composition of the matrix measured using 1-μm-sized beam (in wt%): SiO_2= 30.5±6.1, P_2O_5= 0.1±0.1, Cr_2O_3= 0.4±0.1, Na_2O= 1.0±0.2, TiO_2= 0.1±0.1, Al_2O_3= 2.1±0.5, FeO= 20.2±3.2, MnO= 0.3±0.3, MgO= 19.3±1.8, CaO= 0.5±0.5, K_2O= 0.1±0.1, NiO=2.0±1.0, S= 3.5±1.1, Sum 79.8±6.0, n=26.

Oxygen isotopes: (linearized, all per mil relative to V-SMOW, TFL slope=0.528): A total of seven untreated (i.e., not acid-washed) fragments were analyzed by laser fluorination. Sample weights for each measurement were between 2.0 and 4.7 mg. $\delta^{18}O$ = 21.971, 17.924, 15.943, 20.842, 16.434, 17.034, 20.607; $\delta^{17}O$ = 11.423, 9.124, 7.975, 10.613, 8.277, 8.859, 10.779; $\Delta^{17}O$ = -0.178, -0.340, -0.443, -0.391, -0.401, -0.135, -0.102. (Fig 3).

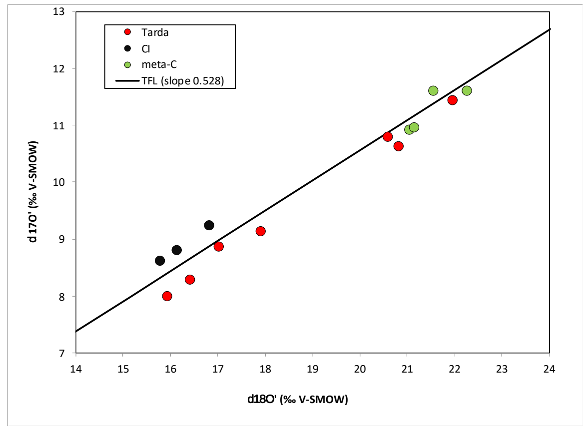

Figure 3 – Oxygen isotopes of Tarda (red crosses).

Discussion: Based on petrography and geochemistry Tarda is a carbonaceous chondrite. The bulk mineralogy is consistent with a petrologic grade 2, based on the predominance of smectite and serpentine together with the presence of anhydrous mafic silicates, AOA, and chondrules. The oxygen isotopes give a bi-modal distribution of the $\delta^{18}O$-values, with one group having values somewhat like those of the CI chondrites, and the other group like values for the Yamato-type (CY) carbonaceous chondrites [6]. However, $\Delta^{17}O$ are lower than for CI and CY chondrites, and plot below the TFL. These isotopic values do not overlap with those of any established carbonaceous chondrite group. These analyses allow a classification of Tarda as an ungrouped C2 not belonging to any known carbonaceous chondrite group.

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