
Introduction: The Tarda (C2-ungrouped) meteorite fell in Morocco in August 2020 and was swiftly collected within days of the fall [1]. Subsequent petrologic, chemical and isotopic analysis of bulk Tarda led to the conclusion that it is similar to the Tagish Lake meteorite (C2-ungrouped) and is representative of a D-type asteroid [2]. Insoluble organic matter (IOM) constitutes the major reservoir of carbon in type 1 and 2 carbonaceous chondrites and has been shown to vary considerably in both elemental and isotopic chemistry as well as in molecular structure in ways that appear to distinguish meteorite groups [3,4]. To the best of our knowledge, Tarda’s IOM has not yet been studied, and is presented here.

Methods: Isolation of Tarda’s IOM was performed using the CsF method [5], where ~55 mg of IOM was purified from ~2 gm of bulk Tarda. Elemental (H, C, and N) and isotopic analysis (δD, δ13C, and δ15N) were performed using a Thermo Delta V plus and a Delta Q Isotope Ratio Mass Spectrometers. Tarda’s IOM molecular structure was determined via 1H and 13C solid-state nuclear magnetic resonance (NMR) spectroscopy using a Chemagnetics Infinity 300 NMR with optimized experimental parameters [5].

Results: Elemental analysis (EA) reveals that Tarda’s IOM has a high H/C x 100 = 78.8 ± 1.6 and a N/C x 100 = 3.66 ± 0.002. Isotopically, Tarda’s IOM has a δD =1750 ± 1.6 ‰, δ13C = -18.2 ± 1.3 ‰, and the δ15N = 38.6 ±0.5 ‰.

The 13C solid-state NMR spectrum of Tarda’s IOM is presented in Fig. 1. Analysis of the spectrum exhibits clearly defined peaks and shoulders that correspond to the majority of the carbon functionality. Integration of the 13C solid-state NMR spectrum reveals that the fraction of aromatic/olefinic (sp2) carbon is 0.50, while the combined sp3 (aliphatic) carbon and carbonyl (C=O) carbon is 0.43 and 0.07, respectively.

The 1H solid state NMR spectrum of Tarda’s IOM is presented in Fig. 2. Three clearly defined regions of interest are identified: a sharp peak at 1.3 ppm corresponds to methyl H, the prominent shoulder at 3 ppm corresponds to methine and methylene H, and prominent shoulder at 7 ppm corresponds to aromatic/olefinic H. Integration of the 1H NMR spectrum reveals the fractions of aromatic and aliphatic H are 0.39 and 0.61, respectively.

Figure 1: 13C solid-state NMR spectrum of Tarda IOM. Carbonyl and carboxyl carbon (C=O), aromatic/olefinic carbon (C=C), alcohol/ether (CH2O), methine carbon (CH), methylene and methyl carbon (CH2,CH3), spinning side bands (SSB) are clearly indicated.

Figure 2: 1H solid-state NMR of Tarda IOM. Aromatic/olefinic H, CH and CH2 H, and methyl H are clearly indicated.
**Discussion:** Atomic H/C and the fraction of aromatic carbon (via $^{13}$C solid-state NMR) have been shown to vary considerably in IOM from type 1 and 2 carbonaceous chondrites [3,5] and even from a single meteorite (e.g., the Tagish Lake clasts [6]). Adding stable isotope abundances to these elemental and molecular parameters shows that IOM chemistry seems to vary with meteorite groups of type 1 and 2 chondrites.

Tarda is recognized as a C2-ungrouped and has been potentially connected to Tagish Lake (C2-ungrouped) [2]. It is, therefore, interesting to compare Tarda’s IOM isotopic and molecular characteristics with those of Tagish lake and other CC groups.

One of the striking aspects of Tarda’s IOM is the very high H/C x 100 and low FA indicating a very low degree of molecular evolution that has not been observed in any CI’s, CM’s or the Tagish Lake clasts [3,4,5,6] and has only been observed in via EA-IRMS in three CR’s and through $^{13}$C NMR in one CR2 (EET 92042 CR2) [5]. The large range of molecular evolution observed in the Tagish Lake (Fig. 3) clasts has been interpreted to arise from variation in degrees of hydrothermal alteration; Tarda, therefore, is inferred to have experienced minimal hydrothermal alteration.

The IOM of Tarda has a $\delta^{13}$C of $-18.2 \pm 1.3$ %o; this is in the range of CMs [3] of $-17$ % to $-19$ %o and CIs [3] $-17$ %o, but more $^{13}$C enriched than CRs [3] at $-21$ to $-27$ %o, and less $^{13}$C enriched than Tagish Lake Clasts at $-13$ %o to $-15$ %o. In this regard, Tarda’s IOM looks more like CM and CI IOM.

With regards to $\delta^{15}$N, Tarda’s IOM is 38.6 %o; whereas unheated CMs have values in the range of -8.5 to 18.0 %o [3]. IOM from two CIs tends to be heavier than CMs at 31 %o to 32 %o. IOM from CRs are much more enriched 153-309 %o. Tagish Lake clasts (C2-ungrouped) have $\delta^{15}$N spanning 53-73 %o. In this regard, Tarda IOM’s $\delta^{13}$N is closest to CI IOM.

IOM $\delta$D is expected to be the most variable isotopic parameter as D-H exchange is a distinct possibility during parent body processing. Tarda’s IOM has a $\delta$D=1750 %o, that is relatively enriched compared to CMs (639-1218 %o), and CIs (~975 %o), and depleted relative to CR’s (2620-3530 %o) [3]. Tagish Lake clasts reveal an additional complexity as the $\delta$D range from a high of 1484 %o down to 596 %o with increased molecular evolution [6]. Tarda IOM’s $\delta$D is slightly less than Tagish Lake Clast 5b’s high $\delta$D value, but Tarda’s IOM is significantly less molecularly evolved. Assuming that Tagish Lake’s IOM molecular and isotopic evolution is applicable to Tarda, projecting Tagish Lake’s isotopic trend to Tarda’s H/C x 100 value predicts a higher $\delta$D of 2060 %o. In this regard, Tarda IOM’s $\delta$D differs significantly from what would be expected for a Tagish Lake pairing, and differs significantly from CM, CI and CR IOM.

The molecular and isotopic state of IOM is not recognized as a criterion for establishing membership in a meteorite group, yet there is a connection between IOM and the bulk meteorite data that does define the meteorite groups at least amongst type 1 and 2 chondrites [3]; IOM is severely transformed in the radiogenically heated type 3+ chondrites so it is not clear that IOM molecular structure or stable isotopic abundance would have any connection to type 3 chondrite groups. Accepting this, based on its molecular and isotopic characteristics Tarda is not easily paired with CMs, CIs, CRs, or Tagish Lake (C2-ungrouped). Interestingly, the IOM from the ungrouped C2 meteorite, Essebi, with a H/C x 100 = 68.5 and isotope abundances of $\delta^{13}$C $= -17.97 \pm 0.03$ %o, a $\delta^{15}$N = 28.8 $\pm$ 0.6 %o and a $\delta$D = 1518.0 $\pm$ 20 %o [7] is relatively similar to Tarda’s IOM suggesting a possible pairing between these two falls.

**Acknowledgments:**