# METEORITIC EVIDENCE FOR INJECTION OF TRANS-NEPTUNIAN OBJECTS INTO THE INNER SOLAR SYSTEM.

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**Introduction**: There is excellent evidence that a dynamical instability in the early solar system led to gravitational interactions between the giant planets and trans-Neptunian planetesimals. Giant planetary migration triggered by the instability dispersed a disk of primordial trans-Neptunian object (TNOs) and created a number of small body reservoirs (e.g. the Kuiper Belt, scattered disk, irregular satellites, and the Jupiter/Neptune Trojan populations). It also injected numerous bodies into the main asteroid belt, where modeling shows they can successfully reproduce the observed P and D-type asteroid populations [e.g. 1].

The consequences of comet-like objects in the asteroid belt for at least 4 Gyr has not been sufficiently explored from a sample perspective. We postulate that during the injection era and after implantation, some of these "main belt TNOs" would have collided with S-class asteroids. A fraction of this material may have survived, leaving behind primitive debris that would have become a component of asteroid regolith breccias. Eventually, some of this material could have been delivered to Earth from the source asteroid(s) via cratering or disruption events, Yarkovsky drift, and resonances.

Thus, we have been searching for evidence of these impact events in the form of carbonaceous xenoliths in brecciated ordinary chondrites. These xenoliths would have experienced a wide range of impact velocities, and therefore we should expect to see everything between relatively unaltered material to completely shock-melted lithologies. This material might also be different from the carbonaceous chondrites that represent standard C-complex asteroids. A goal of this rsearch is to define useful criteria for distinguishing between these two classes of materials. Obvious possibilities include O, Cr, N and C isotopes, petrographic characteristics, and chronology.

**Experimental**: E-beam work was performed at the labs of ARES, NASA Johnson Space Center. New oxygen isotope analyses were performed at the Institute of Meteoritics, University of New Mexico, using a Finnigan 253 mass spectrometer. Previous oxygen isotope analyses of the two Zag clasts (A and B) were performed by Bob Clayton and Tosh Mayeda [2]

**Hydrated Lithologies**: Some H3-6 chondrite breccias contain C1 to C2 xenoliths, which have been variously called CI-, CM-, CR-, and micrometeorite-like [3]. These vary in detail, but are usually dominated by phyllosilicates, have abundant magnetite, carbonates, and pyrrhotite, and sometimes have minor olivine and low-Ca pyroxene (Fig. 1). They lack chondrules or CAI. Their olivine content, for example, is higher than observed in CI chondrites, but lower than that observed in CR or most CM chondrites. In terms of petrography they are clearly not CM material. The few that have been well characterized display a remarkable diversity of organics, but this aspect has been little explored. The best studied clasts are in Zag, Tsukuba, Plainview (1917), NWA 8369 and Carancas. The latter clast is the subject of another abstract at this meeting [4], while the Zag clast (clast A in this meteorite) is described in two recent publications [5,6]. Similar clasts are found in ureilites, HEDs and other meteorites. Studies of bulk O and Cr isotopes of these clasts are presently underway to better constrain their origin; whether their parent worlds were a TNO or asteroid 1/Ceres (as we have also proposed), or (very likely) both, remains to be settled. Zag clast A has a very heavy bulk O isotope composition: $\delta^{18}O=+23.68‰$, $\delta^{17}O=+13.71‰$, $\Delta^{17}O=+1.41‰$ [2,6], and has organics with correlated hotspots of $^{15}N$ and $^{2}H$ [6], all suggesting a very cold formation location - consistent with the outer solar system (Fig. 3). We will collect similar information on the other clasts where possible.

**Igneous Lithologies:** Zag Clast B appears to be an impact melt consisting of thin and skeletal laths of plagioclase, with thin rims of Ti-Fe oxides, floating in a mesostasis with a composition roughly similar to pyroxene (Fig. 2a). A few fine-grained aggregates float within this clast, and may be residual unmelted material. The oxygen isotopic composition of the clast is $\delta^{18}O=+5.90‰$, $\delta^{17}O=+2.74‰$, $\Delta^{17}O= -0.33‰$, near the terrestrial fractionation line (Fig. 3).

Semenenko et al. [7] have described graphite-bearing igneous clasts in the Krymka L3.2 chondrite. We have now located these in an additional four L3s: NWA 6169 (L3.15-2), NWA 8330 (L>3.5), NWA 7936 (L3.15), and NWA 5477 (L3 - no subtype reported) (Fig. 2b). Since these meteorites do not appear to be paired this clast type is relatively abundant in L3 chondrites. The modal composition of the clasts in 8330 and 6169 is as follows: 45% olivine ($Fa_{28-34}$), 30% low-Ca pyroxene ($Fs_{10-83}$), 13-15% troilite, 5-7% plagioclase ($Ab_{4-85}$), 5% graphite, <1% Fe-Ni metal. The graphite in the clasts ranges from subhedral to euhedral acicular crystals, which are frequently wet by troilite, metal and surrounded by plagioclase. The high carbon content is consistent with an origin as a melted carbonaceous lithology, and its continued presence in the clasts indicates crystallization under significant pressure (otherwise the carbon could have boiled away as CO). This clast bears similarities with a melted, graphite-bearing clast described in lunar material, for which an origin from impact by a carbon-rich body was suggested [8].

We suggest that some of these clasts formed during the impact of a “main belt TNO” directly or indirectly onto one or more S class asteroids, with the resultant melt being buried to a significant degree during cooling. It is interesting that O isotope compositions of the three clasts we have measured lie near or along the terrestrial fractionation line. We will measure O and Cr isotope data for additional clasts. Formation dates for these samples might help constrain the timing of giant planet migration, which is poorly known and highly debated. Thus, we are searching through the samples for glass that could be used for dating, for example.

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**References**: [1] Vokrouhlický et al. (2016) *The Astronomical Journal* **152:39**, 1-20; [2] Zolensky et al. (2003) *Meteoritics and Planetary Science* **38**, abstract 5216; [3] Briani et al. (2012) *Meteoritics and Planetary Science* **47**, 880–902, [4] Chan et al. (2018) *LPSC 2018 Abstracts*; [5] Chan et al. (2018) *Science Advances*, 4, eaao3521; [6] Kebukawa et al. *Nature Astronomy*, submitted; [7] Semenenko et al., (2004) GCA 68, 455-475; [8] Steele et al. (2010) *Science* **329**, pp.51-51.

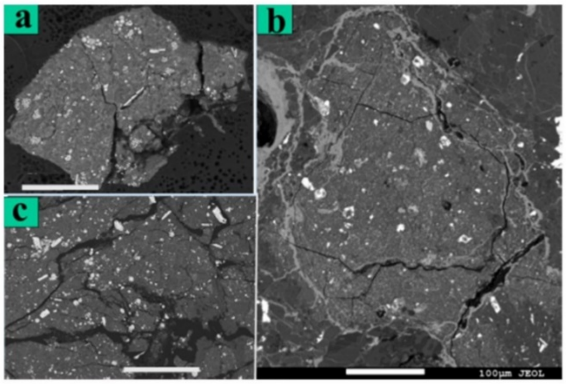

Figure 1. BSE images of three carbonaceous chondrites clasts in H chondrites. At this scale all that can be discerned is phyllosilicate (dark grey) and magnetite and pyrrhotite (white). (a) Clast in Tsukuba, (b) Clast in NWA 8369, (c) Clast in Carancas. Scale bars are 100 µm.

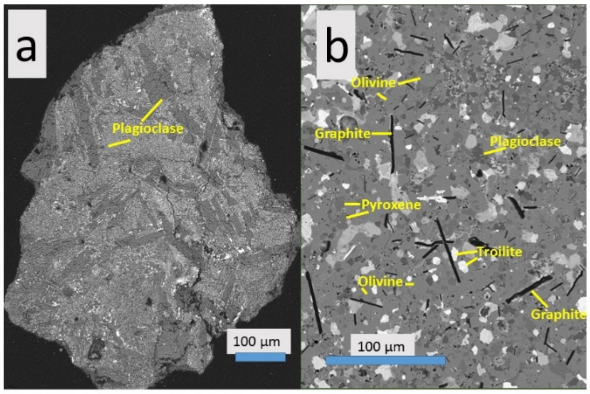

Figure 2. Melt clasts from two ordinary chondrites. (a) Melt clast in Zag. (b) Graphite- (black) bearing melt clast in NWA 6169. Scale bars are 100 µm.

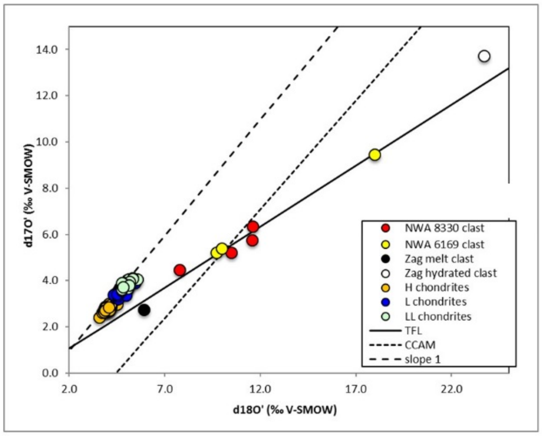

Figure 3. Oxygen 3 isotope plot of hydrated (CC) clast in Zag and melted clasts in H and L chondrites. Positions of ordinary chondrites are shown for comparison.