XENOLITHS AND STRANGE COGNATE LITHOLOGIES – OR WHAT THE HECK IS THAT?

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Introduction: Meteorites provide us with an unrepresentative sampling of the early solar system, but this problem can be partially remedied by exploiting the presence of small unusual pieces of cognate and foreign clasts found within meteorite regolith breccias (the latter being xenoliths). The xenoliths provide the opportunity to characterize a wide range of otherwise unsampled primitive small bodies. The cognate clasts (including the Dark Inclusions (DIs) found in CV and CR chondrites) reveal details of asteroidal evolution not recorded by the bulk of these meteorites.

The Samples: We have collected samples of clasts from 102 different meteorites, including HEDs, ordinary chondrites (OCs), carbonaceous chondrites (CCs), Aubrites, Ureilites and ungrouped meteorites. Some of these clasts have been known for decades but most have not been thoroughly investigated. In our previous work we recognized several distinct classes of clasts (in addition to many unique clasts), which we briefly describe here (see Figures 1-3). This abstract updates our reported work, bringing it up to date. In the Conference Poster for this abstract we will list the names of all meteorites involved, hoping to encourage detailed work on them by the community. Most of these clasts can be divided into three groups:

Type FGA (fine-grained anhydrous) clasts are widespread. These are fragmental breccias, sometimes with a bimodal size distribution. Coarse (1-100 µm), generally fragmented grains of olivine, low-Ca pyroxene, Fe-Ni sulfides are set within a fine-grained, anhydrous groundmass principally of ferromagnesian silicates. Some clasts have more unusual mineralogies (e.g. NWA 2364 and NWA 4723). Some have microchondrules, principally barred, microcrystalline or glassy. The majority of these clasts have received little detailed characterization. The fact that they are anhydrous leads us to believe that some may have the greatest potential to be Kuiper Belt Object (KBO) samples, as the Wild 2 samples provided by the Stardust Spacecraft are to date anhydrous [1]. FGA xenoliths include the well-known DIs in CVs and CRs which record regolith processes, hydration, and dehydration processes. Some DIs have sedimentary features (e.g. Vigarano and DAG 369).

Type FGH (fine-grained hydrous) clasts are perhaps the most widespread type and are often called "C1", "CR" or "CI" in past studies. These clasts tend to be rather small, probably reflecting low-strength. The ones that have been analyzed typically consist of 0.5-10 µm sized Fe-Ni sulfides and magnetite set within serpentine and saponite. Occasional fragmented grains of olivine or pyroxene are found in the larger clasts, which indicate that these are not petrologic type 1. Fe-Ca-Mg carbonates are sometimes present (e.g. Zag). Gounelle et al. [2&3] have pointed out that these clasts are mineralogically most similar to hydrous micrometeorites though some differences are apparent. One clast from Leighton contains abundant Ca-carbonate grains and Fe sulfides which synchrotron X-ray diffraction showed to be very poorly crystalline or amorphous – the probable result of shock. Several FGH have been found in the Zag and Almahata Sitta meteorites (subsamples 91A and 671, for example [4&5]) which have unique Cr isotopic compositions.

Type CGH (coarse-grained hydrous) clasts are almost as widespread as FGH and have frequently been called "C2"or "CM". These clasts tend to be significantly larger than the FGH. Those that have been analyzed typically consist of 0.5-10 µm sized Fe-Ni sulfides and partially-aqueously-altered chondrules, fragmented olivine and low-Ca pyroxene set within serpentine and (lesser) saponite. Some of these clasts have long been recognized as being very similar to CM2 [6-9], although a definite relationship has not been established. Other clasts are much more fine-grained than CMs (see Plainview), and some are downright strange.

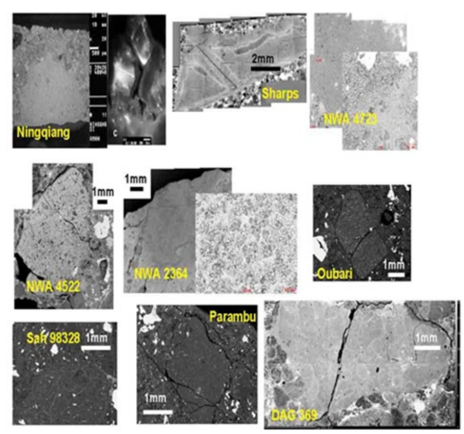

Figure 1. BSE images of FGA clasts. These are: Ningqiang, whose pea-sized clast consists of radiation-damaged anhydrous silicates [10]; Sharps whose cm-sized clasts consist mainly of metal, carbon and hydrocarbons [11]; NWA 4723, a fine-grained assemblage of olivine, pyroxene and plagioclase; NWA 4522, NWA 2364, Oubari, Sah 98328, Parambu, DAG 369.

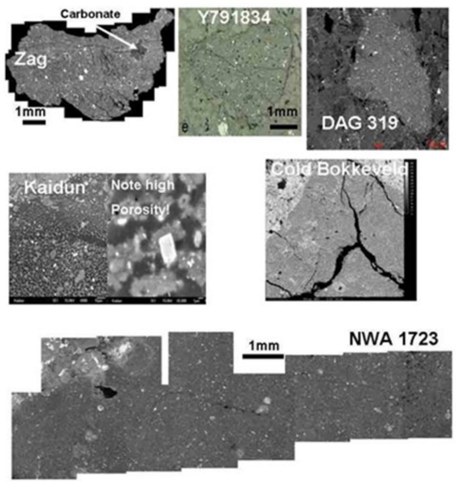

Figure 2. BSE images of FGH clasts. These meteorites are: Zag, this clast resembles CI1 material, and contains a Ca-Mn-Fe carbonate crystal (arrowed) [12]; Y791834, containing phyllosilicates, sulfides, magnetite and some anhydrous silicates; DAG 319, containing phyllosilicates, sulfides, magnetite and some anhydrous silicates; Kaidun, One highly-porous Kaidun lithology containing phyllosilicates, sulfides (the white trapezahedron in the close-up at right), magnetite and carbonates; Cold Bokkeveld, a dense clast consisting almost entirely of serpentine; NWA 1723, containing phyllosilicates, sulfides, magnetite and some anhydrous silicates.

References: [1] Brownlee et al. (2006) *Science* **314**, 1724-1726; [2] Gounelle et al. (2005) *Geochimica et Cosmochimica Acta*. **69**, 3431-3443; [3] Gounelle et al. (2003) *Geochimica et Cosmochimica Acta* **67**, 507-527; [4] Goodrich et al. (2019) *Meteoritics and Planetary Science* **54**, 2769-2813; [5] Hamilton et al. *Nature Astronomy Letters*, in press; [6] Zolensky et al. (1993) *Meteoritics* **27**, 596-604; [7] Zolensky et al. (1996) *LPSC XXVII*, pp. 1507- 1508; [8] Zolensky et al. (1996) *Meteoritics and Planetary Science* **31**, 518-537; [9] Buchanan et al. (1993) *Meteoritics* **28**, 659-682; [10] Zolensky et al. (2003) *Meteoritics and Planetary Science* **38**, 305-322; [11] Kebukawa et al. (2016) *Geochimica et Cosmochimica Acta* **196**, 74-101; [12] Rubin et al. (2002) *Meteoritics and Planetary Science* **37**, 125-142; [13] Rubin et al. (2005) *Geochimica et Cosmochimica Acta* **69**, 3419-3430; [14] Kallemeyn and Wasson (1979) *Lunar And Planetary Science X*, 644-646; [15] Krot et al. (1995) *Meteoritics* **30**, 748-775; [16] Zolensky et al. (2002) *Meteoritics & Planet. Sci.* **37***,* 737–762.

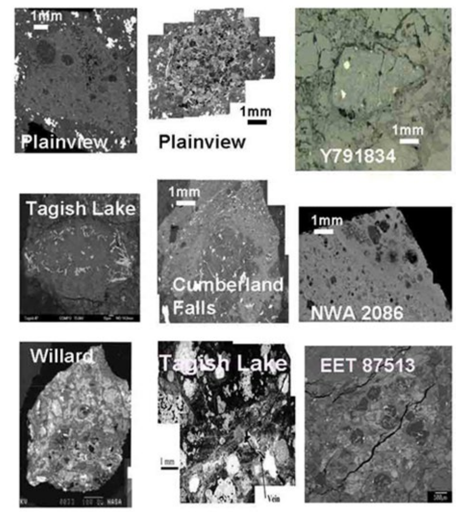

Figure 3. Several coarse-grained clasts we have identified in chondrites – all except Tagish Lake are BSE images, showing a fraction of the diversity of possible KBO chunks. These meteorites are: Plainview, Two clasts are shown, the one on the right resembles CM2 material in some respects, there are numerous clast types in Plainview, and Rubin et al. [13] have suggested some result from an impacting comet; Y791834, containing phyllosilicates, sulfides, magnetite and some anhydrous silicates; Tagish Lake, a clast containing phyllosilicates, and large sulfides; Cumberland Falls, well known clasts with unique characteristics [14]; NWA 2086, a typical coarse-grained dark inclusion in a CV3 chondrite, of unknown origin [15]; Willard, a clast mineralogically resembling CM2; Tagish Lake, this is the "CM1" lithology described by Zolensky et al. [16] containing phyllosilicates, and large sulfides, and pseudomorphed chondrules and CAI; EET 87513, containing phyllosilicates, sulfides, magnetite and abundant anhydrous silicates.