PETROGENESIS OF MICROPORPHYRITIC IMPACT MELT CLASTS IN ORDINARY CHONDRITES.

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Introduction: In the course of continuing investigations of a lunar cataclysm [1-6] and small body scattering (thereby causing the late heavy bombardment [7-9]), we aim to expand on our understanding of early Solar System bombardment [10-14] by examining impact melts from ordinary chondrite (OC) breccias in the U.S. Antarctic Meteorite Collection at the Smithsonian Institution. As of the 2011 season, ~20,000 meteorites have been recovered by the U.S. Antarctic Program [15], ~90% of which are OCs. ~20% of OCs are brecciated [16,17]. With these ~3600 OC breccias, the U.S. collection provides a vast resource for looking at melted OC materials, underrepresented in terms of solar system ages [19].

Impact melt Clasts in Ordinary Chondrites: In OCs, impact melt clasts often have bulk compositions close to the meteorite/material from which they melted [19, 20]. Partial melts, which are more feldspathic in chondrites, have only been identified as small pockets [21]. Deviations in impact melt clasts from the bulk composition of their parent meteorites have been explained by processes that occurred after bulk melting, such as loss of volatiles or separation of immiscible sulfides/metals from silicate melts [19, 22].

While definitive identification of melt clasts is, in general, a complicated process [17], obvious microporphyritic impact melt clasts have been identified in at least 14 OCs [19, 22-28]. It is possible that this type of clast is the most often described because they are the most easily recognized, particularly as they are light-colored in handsample. The typical texture of these microporphyritic clasts is that of equant euhedral olivines in fine grained groundmass that includes a combination of euhedral-subhedral pyroxene, plagioclase, and interstitial glass, globules of Fe-Ni metal, troilite and schreibersite [23]. In some instances, olivine grains are poikilitically enclosed by pyroxene or plagioclase grains (e.g. [24]).

Samples: This work focuses on microporphyritic impact melt clasts found in three brecciated OC thin sections: PCA 02071,9 (L5), LEW 85397,2 (L6), and EET 87595,2 (L5). These are the largest impact melt clasts we have identified to date.

LEW 85397,2 and EET 87595,2. These sections are part of the Smithsonian library of U.S. Antarctic Meteorites. Both are brecciated OCs and each contains one relatively large microporphyritic clast. EET 87595,2 also contains 2-3 smaller melt clasts (Fig. 1).

The clast found in LEW 85397,2 is ~8 mm in the longest dimension, and contains equant olivine and pyroxene grains (~30-100 μm) set in interstitial glass. Globules of immiscible Fe-Ni metal and troilite are also present. Mafic silicates in this clast are reported to have Fa_{19-27} and Fs_{21-26} [28]. The clast found in EET 87595,2, (~9 mm in the longest dimension), contains euhedral-subhedral olvine grains (~100-300 μm) in a dark, devitrified matrix. Troilite is found in this clast, as well. Olivine composition in the clast is Fa_{25}.

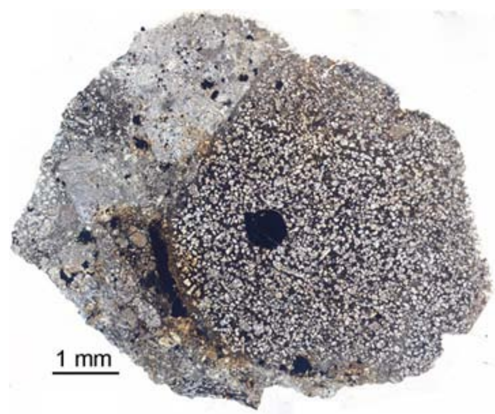

Figure 1. Plane polarized light image of thin section EET 87595,2, showing the large impact melt clast (right half of the section).

Olivine and pyroxene grains in the melt clasts in both LEW 85397,2 and EET 87595,2 exhibit undulose extinction, indicating that they were exposed to a later shock event, likely once these clasts had crystallized and were incorporated into their host breccias. This shock event may have been strong enough to affect the Ar system in these clasts, so dates obtained from them will be interpreted with caution.

PCA 02071,9: At least five thin/thick sections of this meteorite, an obvious breccia, have been made from slices of the main mass. The three thick sections have been examined in detail using the Smithsonian FEI Nova NanoSEM 600. A number of possible impact melt features have been identified in this meteorite, though only one microporphyritic impact melt clast has been found (in the ,9 section). This clast, (~3 mm in the longest dimension), contains olivine grains (~30-100 μm) set in a vitrophyric glass matrix. Bulk analyses of this clast have been conducted using both EDS element mapping and electron microprobe (Smithsonian JEOL 8900 Superprobe). Table 1 shows results from both methods of measuring bulk composition of the clasts as well as average L chondrites from Antarctica [29] (all in wt. %.). This clast differs from the L chondrite average composition probably owing to the exclusion of metal and sulfide in the impact melt clast.

Table 1	L ave [29]	SEM	EMPA
Al2O3	2.3	3.9	4.2
CaO	1.9	2.8	3.2
Cr2O3	0.5	0.8	0.7
FeO	15.9	14.2	13.7
K2O	0.1	0.4	0.3
MgO	24.7	27.2	25.6
MnO	0.31	0.4	0.4
Na2O	0.9	1.4	1.3
SiO2	39.6	48.7	50.9
TiO2	0.1	0.2	0.2

Discussion: The texture and mineral assemblages found in these clasts indicate that, after bulk melting, crystallization progressed rapidly [30]. These clasts were not super-heated, however, or the number of nucleation sites would have been significantly reduced, prohibiting a subsequent microporphyritic texture from forming. In the cases of the three clasts examined in this study, crystallization was obviously halted as the clasts quenched.

In these clasts, plagioclase did not crystallize before quenching was complete. In clasts identified in other studies, plagioclase occurs as a late stage crystallization phase. Experimental studies [31] have shown that once plagioclase is completely melted, significant undercooling is required for plagioclase nucleation to later take place. Therefore, large feldspars found poikilitically enclosing olivines in some of these clasts must have required this undercooling, and their large sizes were due to the limited availability of nucleation sites, as opposed to slow cooling.

The Fe-Ni metal found in these clasts may prove useful for measuring cooling rates of the impact melts. An initial attempt was made in the manner of [30] to apply cooling rates to these clasts [32, 33] by measuring the distance between globules of metal found enclosed in sulfide in LEW 85397,2 (Fig. 3), yielding a cooling rate of 3.7ºC/second. Verification of this rate and measurement of other sections will be completed. These clasts may, then, provide a method to examine the petrogenesis of microporphyritic impact melts as shock pressure relaxes; each individual clast akin to a natural experiment.

Age-dating: Ar-Ar dates of a number of clasts of this type show that they are too young to have formed in the protoplanetary disc [22, 24]. Identification of a possible late heavy bombardment signature in OC impact melt clasts relies on dating a statistically-significant number of clasts to eliminate both 4.5 Ga "clasts" that might not have an impact melt origin or clasts formed during postulated asteroid breakups, such as the 500 Ma heating event seen in L chondrites [34] (the type of each of these host meteorites). These clasts will be dated in search for impact events that occurred before this event, as well as before 3.9 Ga.

References: [1] Turner et al. 1973, *Proc. 4th LPSC*, 1889 [2] Tera et al. 1974, *EPSL* 1, 19 [3] Kring & Cohen 2001 *JGR* 107, doi: 10.1029/2001JE001529. [4] Cohen et al. 2005, *MAPS* 40, 755 [5] Ryder et al. 2002, *JGR* 107, 6-1 [6] Hartmann 2003, *MAPS* 38, 579 [7] Tsiganis et al. 2005, *Nature* 435, 459 [8] Morbidelli et al. 2005, *Nature* 435, 462 [9] Gomes et al. 2005, *Nature* 435, 466 [10] Kring & Cohen 2002, *JGR* 107, 4.1 [11] Bogard & Garrison 2003, *MAPS* 38, 669 [12] Swindle et al. 2008, *MAPS* 44, 762 [13] Wittmann 2010, *JGR* 115, doi: 10.1029/2009JE003433 [14] LaCrox & McCoy 2007, *LPSC XXVIII* #1601 [15] Righter et al. 2012, *AMN*. 35, 2 [16] Binns 1967, *EPSL* 2, 23 [17] Corrigan et al. 2012, *MAPS* #1577 [18] Bogard 2011, *Chem. de Erde* 71, 207 [19] Mittlefehldt & Lindstrom (2001) *MAPS* 36, 439 [20] Dodd et al. 1982, *EPSL* 59, 364 [21] Dodd & Jarosewich 1982, *EPSL* 59, 355 [22] Bogard et al. 1995, *GCA* 59, 1383 [23] Rubin et al. 1983, *Mets* 18, 179 [24] Keil 1980, *EPSL* 51, 235 [25] Metzler et al. 2011, *MAPS*, 46, 652 [26] Ehlman 1993, *LPSC XVIII*, 546 [27] Benedix et al. 1995, *Meteoritics* 30, 788. [28] Score et al. 1987, *AMN* 10, 2 [29] Jarosewich 1990, *Mets* 2, 323 [30] Semenenko & Perron 2005, *MAPS* 40, 173 [31] Lofgren 1983, *J. Pet*. 24, 229 [32] Scott et al. 1982, *GCA* 46, 813 [33] Keil et al. 2011, *MAPS* 46, 1719 [34] Turner 1979, *Met. Rsch*., 407.

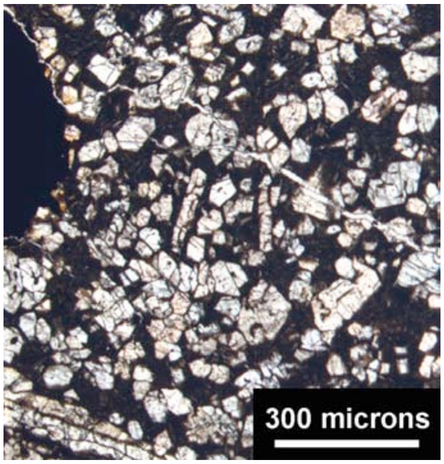

Figure 2. Cross polarized light image of olivine and pyroxene grains in the impact melt clast found in EET 87595,2.

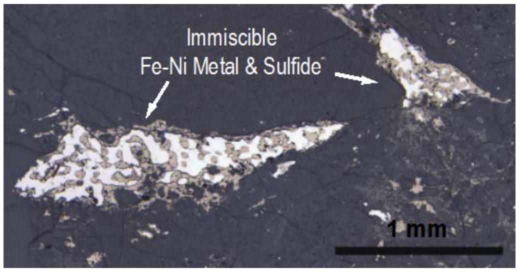

Figure 3. Reflected light image of globules of Fe-Ni metal and troilite in the impact melt clast found in LEW 85397,2.