IMPACTS ON THE LL-CHONDRITE ASTEROID(S) – NEW INSIGHTS FROM SHOCK-MELTED METEORITES.

Martin Schmieder[1,2] and David A. Kring[1,2], [1]Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston, TX 77058 USA, [2]NASA Solar System Exploration Research Virtual Institute.

Introduction: Petrologic analysis, in combination with geochronologic constraints, helps unravel the history of the ordinary chondrites (OC) and their parent bodies since the time of their accretion. The present study is focused on impact-modified LL-chondrites. The airburst of the Chelyabinsk meteoroid in Russia in 2013 [1–4] and the recent return of LL-type materials from asteroid 25143 Itokawa [5] have focused interest in the impact history of the LL-parent planetesimal(s), one or more bodies at least ~100 km in diameter [2,3].

Among the >49,000 OC currently known, ~15% are LL-chondrites, and less than 1% of these are partially to completely melted [6]. However, ~79% of the LL-chondrites are brecciated [7]. Although fewer LL-chondrite impact melt ages are known than among H- and L-chondrites [8–10], the collisional evolution of LL-chondrites is beginning to emerge. Phosphate U–Pb and whole-rock $^{40}Ar/^{39}Ar$ results indicate that evolution began ~4.52 Ga, immediately after accretion [1,10]. A series of collisions then occurred ~4.35 to ~4.20 Ga and circa 3.9 Ga. A ~2 Gyr gap in recorded impact ages occurs before events around ~1.9 Ga [10], ~1.7 Ga [14] ~1.3 to 1.2 Ga [5,15], 970±50 Ma (Northwest Africa 1701 [10]), ~600 Ma [16], ≤400 Ma [10], and ~30 Ma [13, 14]. One of the older impact ages may reflect a major disruption event that shattered the LL-chondrite parent planetesimal into a family of subkilometer-size LL-chondrite asteroids [17]. Cosmic ray exposure ages of ~5 to ~50 Myr recorded in the LL-chondrites [18,19] indicate one or more collisional events that affected the LL-chondritic asteroids. A young breakup event on one of the LL-asteroid fragments at ~1.2 Ma produced the brecciated Chelyabinsk meteoroid, which was later sent into an Earth-crossing orbit [2–4,20].

A petrologic investigation of additional impact-melted LL-chondrites (with recent results for Dominion Range 10092 [21,22] and Northwest Africa 6813 [23,24]) is underway at the LPI with the goal to further understand the collisional evolution of the LL-chondrite asteroids. The analysis of the cooling pattern of impact-melt breccias (IMB) provides information about the impact crater sizes and settings in which these asteroidal impactites were produced [25–28].

Samples and Analytical Methods: Polished thin sections of two Antarctic (ANSMET) LL-IMB, Dominion Range 08002 (DOM 08002; split ,9) [29] and Miller Range 090799 (MIL 090799; split ,4) [30], and one African LL-IMB, Northwest Africa 1701 (NWA 1701, LL5; sample LPL 1064) [31] were analyzed using optical microscopy at the LPI and an electron microprobe at the NASA Johnson Space Center.

Results: *Dominion Range 08002.* Sample DOM 08002,9 mainly consists of shocked LL-chondritic clasts ≤5 mm in size that feature poorly delineated chondrule rims (petrologic type 6). Olivine in the clast domain is $Fa_{29–31}$, Fe/Mn=61±3 (n=17). Low-Ca pyroxene is $Wo_{1–4}En_{71–74}Fs_{26–24}$, Fe/Mn=36±3 ($n$=18); high-Ca pyroxene is $Wo_{43}En_{46}Fs_{11–10}$, Fe/Mn=29±3 (n=13). Kamacite has 4.5 to 5.5 wt% Ni and 5.0 to 6.0 wt% Co (n=6); taenite has 37 to 47wt% Ni and 1.0 to 2.0 wt% Co (n=15). Troilite is abundant.

A clast ~2.2 mm in maximum length contains polyhedral and hopper-shaped crystals of olivine, $Fa_{29–30}$, Fe/Mn=58±4 (n=16), set in a microcrystalline, symplectic groundmass of pyroxene and feldspar with micrometer-sized particles of Fe-sulfide and Fe,Ni-metal. The texture and composition of this clast suggest it is an LL-chondritic melt clast that was subsequently shocked in another impact event. Additional mm-sized, microcrystalline impact melt pockets in the sample contain low-Ca and high-Ca pyroxene in feldspathic matrices.

Miller Range 090799. Sample MIL 090799,4 mainly consists of shocked LL-chondritic clasts, in which chondrules are poorly delineated (petrologic type 6), and minor portions of impact melt. Olivine in the clast domain is $Fa_{29–31}$, Fe/Mn=61±4 (n=36). Low-Ca pyroxene is $Wo_{1–2}En_{72–74}Fs_{26–25}$, Fe/Mn=36±2 ($n$=27); high-Ca pyroxene is $Wo_{43–45}En_{45–46}Fs_{12–9}$, Fe/Mn=28±3 ($n$=19). Fractures and open grain boundaries in the clast domain are commonly filled with troilite. The rock contains veins, networks, and mm-sized pockets of microcrystalline, symplectic impact melt with blebs of troilite and/or Fe,Ni-metal ≤25 µm in diameter. Relict olivine grains entrained in the melt domain have $Fa_{29–33}$, Fe/Mn=58±7 (n=6) cores and $Fa_{25–31}$, Fe/Mn=63±12 (n=5) rims. Taenite has ≤36 wt% Ni and ~1.0 to 1.7 wt% Co (n=7).

One clast ~0.8 mm in maximum length consists of subrounded olivine and pyroxene grains ≤30 µm in size and µm-sized, melted Fe,Ni-metal (~29 to 30 wt% Ni, ~1.4 wt% Co) and Fe-sulfide particles. Olivine in that clast is Fa_{27-31}, Fe/Mn=53±5 (n=6); low-Ca pyroxene is $Wo_{1–2}En_{73–74}Fs_{25}$, Fe/Mn=37±2 ($n$=6). This clast may represent a partially melted or cataclastic fragment of LL-chondrite derivation.

Northwest Africa 1701. Sample LPL 1064 consists of roughly equal proportions of shocked chondritic clasts (petrologic type 5) [31] and an igneous-textured impact melt domain composed of olivine, pyroxene, and feldspar with crystal sizes of ≤50 µm. Clasts are surrounded by quenched melt. Olivine and pyroxene in the clast domain are $Fa_{26–28}$, Fe/Mn=49±3 (*n*=24) and $Wo_{1–2}En_{74–76}Fs_{25–22}$, Fe/Mn=31±3 (*n*=15), respectively. Impact melt-grown olivine has $Fa_{22–29}$ cores and $Fa_{20–27}$ rims, Fe/Mn=50±4 (*n*=33). Low-Ca pyroxene in the melt domain is zoned from $Wo_{1–2}En_{74–81}Fs_{25–17}$ in cores to $Wo_{1–5}En_{73–76}Fs_{24–21}$ in more calcic rims, locally pigeonite [30], Fe/Mn=31±3 (*n*=30). Metal droplets in the melt domain (*n*=13), typically ≤30 µm in diameter, contain ~14 to 20 wt% Ni and ~1.0 to 1.2 wt% Co in their cores, up to ~28 wt% Ni in taenite rims, and are surrounded by Ni-bearing troilite. Grains of altered sulfide in the melt domain, ≤1 mm in size, seem to be pyrrhotite with ~4 to 10 wt% Ni and ≤0.5 wt% Co.

Cooling of Impact Melt: Impact melt breccias have a characteristic two-stage cooling profile. Stage I cooling of the superheated impact melt equilibrating with relatively cooler mineral and rock clasts is followed by subsolidus stage II cooling of the melt breccia body, usually through conductive heat transfer to the cooler surrounding rock [27,28]. The rate of stage I cooling can be calculated by the metallographic analysis of dendritic and/or cellular-textured sulfide–metal droplets in impact melt domains [26]. None of the LL-IMB samples analyzed contain Fe,Ni-metal with a dendritic or multi-cellular texture, but individual microscopic blebs of metal commonly surrounded by troilite. Metal cell widths of ≤20 µm suggest a tentative stage I cooling rate of ~80°C/sec or faster. Stage II cooling can be determined by the analysis of secondary kamacite surrounding Fe,Ni-metal and Ni rim gradients [25,27,28]. The lack of secondary kamacite and the high Ni concentrations (~28 to ~59 wt%) in the metal, typical for LL-chondrites, precluded the calculation of a meaningful stage II cooling rate [24,32]. However, the metal composition and the dispersed distribution of small metal-sulfide melt droplets in the IMB samples suggest cooling of these melt lithologies was rapid (perhaps on the order of ~100°C/day [25]), similar to other OC melt breccias, such as Gao-Guenie [28].

Implications for the Impact Record on the LL–Chondrite Asteroids: The fast cooling of the IMB analyzed here suggests some of these impact melt lithologies may have formed within the breccia lenses of simple impact craters (with little overburden [25,27]); as ejected melt particles; or possibly as breccias with thin pockets and networks of melt (DOM 08002 and MIL 090799) and/or thin (a few cm- to ~1 m-wide) veins or dikes of impact melt (NWA 1701, produced at ~1 Ga [10]) within the basement of simple impact craters [28] on the LL-chondrite asteroid(s). No noble gas data are currently available for DOM 08002, MIL 090799, and NWA 1701 that could constrain the asteroidal setting for the formation and emplacement of the IMB further. Our findings, in combination with recent results for NWA 6813 [24] and DOM 10092 [22], suggest these rapidly cooled LL-impact melt lithologies record relatively minor impact events – or did not sample larger, coherent impact melt bodies – in contrast to some of the slowly cooled impact melt rocks and breccias known from the H- and L-chondrite [25,33,34] asteroids.

Although geochronologic constraints on the impact history of the LL-chondrites are somewhat limited, the $^{40}Ar/^{39}Ar$ [10] and cosmic ray exposure age distribution [18,19] suggests the collisional and/or dynamical evolution of the LL-chondrite parent asteroid(s) may differ from that of the other OC [8,27]. The prevalence of brecciated LL-chondrites [7], and of clast-rich and rapidly cooled impact melt volumes seen in most LL-IMB, possibly indicates different types of impact events or a different location within the asteroid belt for the LL-chondrite planetesimal when it was impacted to produce the material that then migrated into a resonance for transport to Earth.

References: [1] Popova O. P. et al. (2013) *Science, 342*, 1069–1073. [2] Kring D. A. (2013) *Lunar Planet. Inf. Bull., 133,* 2–5. [3] Kring D. A. and Boslough M. (2014) *Phys. Today, 09*, 32–37. [4] Righter K. et al. (2015) *MAPS, 50*, 1790–1819. [5] Park J. et al. (2015) *MAPS, 50*, 2087–2098. [6] *Met. Bull. Database* (2018), https://www.lpi.usra.edu/meteor/metbull.php. [7] Schleiting M. and Bischoff A. (2017) 80th MetSoc, #6085. [8] Wittmann A. et al. (2010) *JGR*, *115*, E07009, 22 p. [9] Swindle T. D. et al. (2009) *MAPS*, *44*, 747–762. [10] Swindle T. D. et al. (2014) *Geol. Soc. Spec. Pub., 378*, 333–347. [11] Dixon E. T. et al. (2004) *GCA*, *68*, 3779–3790. [12] Lapen T. J. et al. (2014) LPS XLV, #1777. [13] Beard S. P. et al. (2014) LPS XLV, #1807. [14] Trieloff M. et al. 2017. MAPS (in press). [15] Okano O. et al. (1990) *GCA, 54*, 3509–3523. [16] Jourdan F. et al. (2010) *GCA*, *74*, 1734–1747. [17] Rubin A. and Moore W. B. (2011) *MAPS*, *46*, 737–747. [18] Graf T. and Marti K. (1994) *Meteoritics, 29*, 643–648. [19] Scherer P. et al. (1998) *MAPS, 33*, 259–265. [20] Nishiizumi K. et al. (2013) 76th MetSoc, #5260. [21] Satterwhite C. and Righter K. (2014) *AMN*, *37(1)*, 21. [22] Phelps P. R. et al. (2016) Lunar Planet. Sci. Conf. XLVII, #1698. [23] Garvie L. A. J. (2012) *Met. Bull., 99*, p. E38. [24] Hoare L. et al. (2017) Lunar Planet. Sci. Conf. XLVIII, #1337. [25] Smith B. A. and Goldstein J. I. (1977) *GCA, 41*, 1061–1072. [26] Scott E. R. D. (1982) *GCA*, *46*, 813–823. [27] Kring D. A. et al. (1996) *JGR, 101*, E12, 29,353–29,371. [28] Schmieder M. et al. (2016) *MAPS, 51*, 1022–1045. [29] Satterwhite C. and Righter K. (2010) *AMN, 33(1),* 21. [30] Satterwhite C. and Righter K. (2012) *AMN*, *35(2)*, 21. [31] Russell et al. (2003) MB87, *MAPS, 38*, p. A207. [32] Farsang S. et al. (2015) LPS XLVI, #1832. [33] Weirich, J. R. et al. (2010) *MAPS, 45*, 1868–1888. [34] Kring, D. A. et al. (1999) *MAPS, 34*, 663–669.