A PERVASIVE REDUCTION EVENT ON THE L-CHONDRITE PARENT ASTEROID.

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Introduction: A BSE survey of 154 L chondrites has revealed evidence in some samples for pervasive syn- or post-metamorphic reduction features in olivine, low-Ca pyroxene, sulfide and metallic Fe-Ni.

Results: Reduction features occur in 13 of 84 L6 chondrites (15%), but only one of 70 L chondrites of lower metamorphic grade (1.4%). Among L6 chondrites, samples exhibiting major reduction include Guangnan, Muroc Dry Lake, NWA 1857, Osceola and Thamaniyat Ajras; minor reduction is evident in Bluewing 035, NWA 184, NWA 428, NWA 429, NWA 988, NWA 6811, Pinto Mountains and Songyuan. Minor reduction also occurs in L4 NWA 8144.

The recent Osceola L6 fall (24 January 2016) has the most prominent reduction features:

Mafic silicates: There are 4-5-µm-thick reduction rims (dark bands in BSE images) on every olivine and orthopyroxene grain and along most of the fractures within each of these grains (Fig. 1). A typical large olivine grain in Osceola has a composition of Fa23.6±0.2 (n=10) in the center and Fa23.2±0.1 (n=2) in the reduction rim. The rims are so narrow that it is difficult to obtain quantitative EMP data. The rim Fa value is an upper limit due to the narrowness of the rim and the possibility of secondary fluorescence of Fe from outside the rim. The MnO/FeO ratio in the grain center and the reduction rim appear to be sub-identical (0.021, 0.020), but it seems likely that more-quantitative data would show the rims to have higher MnO/FeO ratios. The focused electron beam was still too wide to resolve differences in low-Ca pyroxene between grain centers (Fs19.9±0.2 Wo1.5±0.1, n=10) and reduction rims (Fs20.0 Wo1.6, n=1); both have MnO/FeO ratios of 0.035. Unlike the reduction rims on ureilite olivines [1], there are no small blebs of low-Ni metallic Fe at the mafic-silicate grain margins in Osceola or the other L chondrites.

Sulfides: Every grain margin and nearly every fracture in every troilite (FeS) grain in Osceola is lined by a 4-12-µm-thick band that is dark in BSE images (Fig. 2). This phase is presumably pyrrhotite ($Fe_{1-x}S$). The composition of troilite grain centers (n=10) is 62.7±0.2 wt.% Fe and 37.5±0.2 wt.% S (Fe/S = 1.67); BSE-dark rims (pyrrhotite) (n=8) contain 62.3±0.2 wt.% Fe and 37.7±0.1 wt.% S (Fe/S = 1.65). As with the silicates, the reported amount of Fe in the rim is an upper limit due to the narrowness of the rim and the possibility of secondary fluorescence of nearby Fe. Although pyrrhotite is typically found in oxidized chondrites wherein the Fe deficit was caused by oxidation of Fe from troilite during parent-body aqueous alteration [2,3], this is probably the first known instance where pyrrhotite formed from troilite by reduction of Fe^{+2} and removal of the resultant metallic Fe. (Sulfide grains appear unaffected in the nine L chondrites that exhibit only minor reduction.)

Metallic Fe-Ni: There are 2-5-µm-thick continuous or discontinuous BSE-dark rinds of low-Ni metallic Fe (kamacite) around taenite grains in Osceola (Fig. 3). The rinds apparently were derived from Fe^0 reduced from Fe^{+2} in silicate and sulfide that diffused into the metal.

Discussion: Because the reduction process affected type-6 L chondrites nearly exclusively, it seems clear that the reduction event was either syn- or post-metamorphic. The silicate and sulfide grains had coarsened to their present sizes and had been fractured prior to reduction. Because the organic matter that occurs in type-3 ordinary chondrites (OC) is unlikely to survive metamorphism to type-6 levels [4] and because graphite-bearing clasts in OC are rare, it seems likely that the reductant was introduced from outside the L-chondrite parent body, e.g., by a C-rich projectile. The reduction event was wide-spread, affecting 15% of L6 chondrites; it seems likely that the event was produced by a major impact. One possibility is that the projectile that caused the reduction event was the same one responsible for disrupting the L-chondrite parent asteroid ~470 Ma ago [5-8].

The pervasiveness of reduction in Osceola and related L6 chondrites (which is evident along every olivine, orthopyroxene and troilite grain boundary and along nearly every fracture in these grains) suggests that the reductant was a fluid, perhaps CO. Possible reduction reactions include: $Fe_2SiO_4 + 2CO = 2Fe + SiO_2 + 2CO_2$ and $FeSiO_3 + CO = Fe + SiO_2 + CO_2$. There is no evidence that the excess silica liberated from the reduction of ferroan olivine and orthopyroxene produced grains of free silica in these meteorites; the excess silica could have combined with olivine to make small amounts of additional low-Ca pyroxene.

There are two reported instances of impact-induced reduction of H-chondrite materials: (1) One 15×15-mm impact-melt-rock clast in the Nulles H6 regolith breccia contains olivine grains averaging Fa13 [9], appreciably more magnesian than those typical of equilibrated H chondrites (Fa17.3-20.2) [10]. (2) In the center of a 12×24-mm impact-melt-rock clast in the Dimmitt H4

regolith breccia there is a 1.4-mm-diameter metallic-Fe-Ni-rich nodule containing schreibersite with 41 wt.% Ni [11]. Because schreibersite is essentially absent in OC, the P component of this phase was presumably derived by reduction of P_2O_5 in phosphate (which has a modal abundance in OC of $\lesssim$0.6 wt.% [12]). It appears that impact heating of OC materials occurred occasionally in the presence of a reductant.

Conclusions: The pervasive reduction features in Osceola and related L6 chondrites appear to reflect a major impact event on the L-chondrite parent asteroid that occurred during or after peak metamorphic temperatures were reached. The projectile probably introduced the reductant and may have been ultimately responsible for metamorphic heating of the target to type-6 levels [13]. It is possible that the projectile that caused the pervasive reduction event on the L-chondrite parent asteroid was the same one that disrupted the body ~470 Ma ago.

References: [1] Goodrich C. A. (1992) *Meteoritics, 27,* 327-352. [2] Kerridge J. F. et al. (1979) *EPSL, 43,* 359-367. [3] Bullock E. S. et al. (2005) *GCA, 69,* 2687-2700. [4] Quirico E. et al. (2003) *MPS, 38,* 795-811. [5] Heymann D. (1967) *Icarus, 6,* 189-221. [6] Turner G. (1988) In *Meteorites and the Early Solar System,* 276-288. [7] Korochantseva E. V. et al. (2007) *MPS, 42,* 113-130. [8] Swindle T. D. et al. (2013) *Geol. Soc. London Sp. Pub., 378,* 333-347. [9] Williams C. V. et al. (1985) *Meteoritics, 20,* 331-345. [10] Rubin A. E. (1990) *GCA, 54,* 1217-1232. [11] Rubin A. E. et al. (1983) *PLPSC, 13,* A741-A754. [12] Van Schmus W. R. and Ribbe P. H. (1969) *GCA, 33,* 637-640. [13] Rubin A. E. (2004) *GCA, 68,* 673-689.

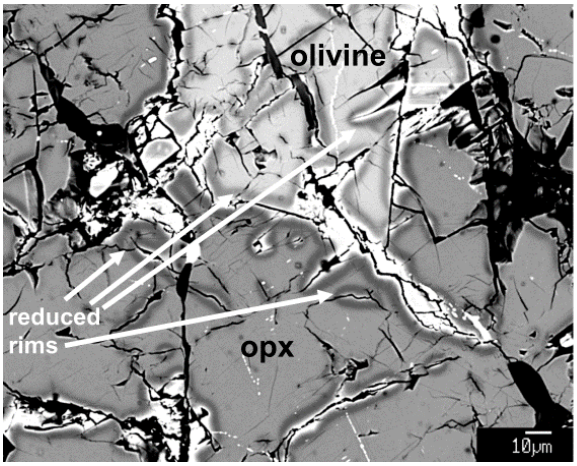

Fig. 1. Olivine (light gray) and orthopyroxene (opx) (medium gray) grains with reduction rims (dark gray) in the Osceola L6 chondrite. BSE image.

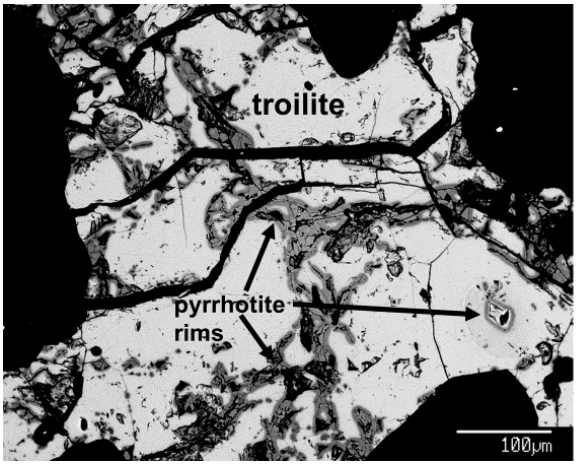

Fig. 2. Portion of a large troilite grain (light gray) and pyrrhotite rim (dark gray) in L6 Osceola. The black areas surrounding the troilite grain are silicates. BSE image.

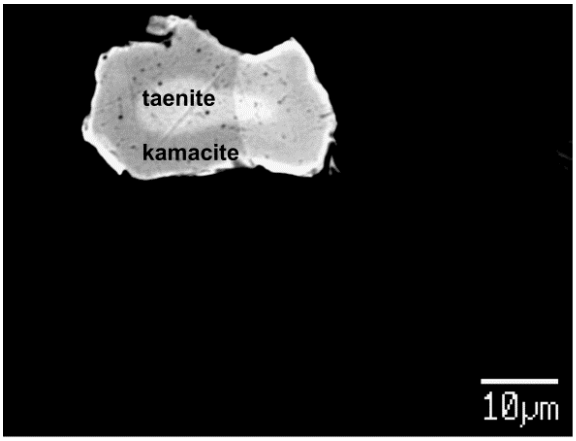

Fig. 3. Metallic Fe-Ni grain in L6 Osceola consisting of a taenite core (light gray) with a 5-μm-thick rim of kamacite (dark gray). The kamacite probably formed from reduced Fe liberated during the reduction of mafic silicates and sulfide. The black areas outside the metal grain are silicates. BSE image.