LATE ORTHOPYROXENE+METAL ASSEMBLAGES IN UREILITES, BRACHINITES, AND OTHER OLIVINE-RICH ACHONDRITES. C.A. Goodrich, Planetary Science Institute, 1700 E. Ft. Lowell Dr., Tucson, AZ 85719 USA. (cgoodrich@psi.edu)

Introduction: Fine-grained assemblages consisting of orthopyroxene + Fe metal + Fe sulfide ± other phases occur in various textural settings suggesting late formation in ureilites, brachinites, and several ungrouped olivine-rich achondrites. I present new observations on these assemblages in brachinites Hughes 026, Reid 013 and NWA 5191, as well as ungrouped achondrites NWA 595 and NWA 1500. I evaluate their origin and whether they formed by redox processes similar to those inferred for ureilites.

Analytical: Back-scattered electron images (BEI), x-ray maps, and electron microprobe analyses were obtained using the Zeiss EVO50 XVP and Cameca SX-50 at U. Mass.

Brachinites: Hughes 026, Reid 013 and NWA 5191 contain 90-95% protogranular olivine, 2-7% augite, 0-4% plagioclase, and minor chromite and phosphate. Fine-grained assemblages of orthopyroxene (opx) plus opaque minerals are ubiquitous lining olivine-olivine, olivine-augite, and olivine-chromite grain boundaries, forming veins in olivine, and surrounding inclusions in olivine (Fig. 1). Within these assemblages, the opaques commonly show elongated, subhedral shapes and preferred alignment (Fig. 1b). Most of them are Fe-oxides, with variable Fe, O, Si, Mg and S. Textures and compositions suggest that they are alteration products (terrestrial) of metal and/or sulfide. Sulfides are not uncommon, but metal is very rare. Grains of augite (Fig. 1b) and rare chromite are also observed.

Compositions of olivine in Hughes 026, Reid 013 and NWA 5191 are similar – Fo 66.2, 66.8, and 66.4, respectively ([1] and Table 1). Opx in the grain boundary assemblages has *mg* ~70-72 and Wo ~2-3, with low but significant Al_2O_3 and Cr_2O_3 (Table 1).

Similar assemblages occur in brachinites NWA 4872/4874/4882/4969 [2]. However, from my observations they are absent in Brachina, and from published descriptions they are absent in brachinites ALH 84025, Eagle's Nest, and EET 99402/7 [3-5].

NWA 595: NWA 595 was originally classified as a brachinite [6], but [7] consider it ungrouped. Like typical brachinites [3,8] it is olivine-rich with 3-10% augite. However, it differs in containing 7-15% coarse-grained opx, having a more complex, poikilitic texture, and in being more magnesian (Fo 71.7) than most brachinites. Nevertheless, Fe-Mn-Mg relations of its olivine (Table 1) suggest an affinity to brachinites. Fine-grained opx–metal–sulfide assemblages very similar to those described above are pervasive in this rock. The coarse opx has *mg* 74.7±0.3 and Wo 2.2±0.05, with 0.40±0.02% Al_2O_3 and 0.22±0.02% Cr_2O_3 (Table 1). The fine-grained opx has similar *mg* (Table 1), but lower Wo (1.4), Al_2O_3 (0.04±0.01%) and Cr_2O_3 (0.07±0.02%).

Ureilites: Ureilites are characterized by "reduction" rims and veins on and within their olivine [8-10]. These generally consist of olivine that is more magnesian than the host (in the extreme, *mg* 99 rims on Fo 76) and is riddled with tiny grains of metal and FeS. In some cases, magnesian opx occurs instead of, or in addition, to reduced olivine [8]. No study has been made of how common such opx is, but my observations suggest that it is far less abundant than reduced olivine. These assemblages of reduced silicates + metal are interpreted as a product of late reduction of primary silicates by reaction with carbon on grain boundaries [8,9]. The Fe-S grains probably result from shock dispersion [11].

NWA 1500: NWA 1500 is an augite-bearing (2-3%) olivine-rich achondrite (Fo ~66-71) that was originally classified as a ureilite [12] but is now considered ungrouped and possibly related to brachinites [13-16]. Goodrich et al. [14] described two types of opx in this rock (Fig. 1c): 1) opx1 (Wo 2.1, *mg* ~71, ~0.3% Al_2O_3) occurs as interstitial grains and overgrowths on olivine, and was interpreted as a product of the olivine + melt $\rightarrow$ opx reaction; 2) opx2 (Wo 0.9, *mg* 75-76, Al_2O_3 bdl) occurs in fine-grained assemblages with metal and sulfide along olivine grain boundaries, and was interpreted as a result of late reduction as in ureilites. New observations indicate that the opx2 assemblages are virtually identical to those described here in brachinites, and are distinct from narrow rims of reduced (but generally metal-free) olivine in this rock.

Discussion: Assuming that metal was the dominant pre-weathering opaque in these assemblages, I consider 3 possibilities for their origin. (1) Rumble et al. [2] suggested that these assemblages in NWA 4882 were similar to symplectic intergrowths of two pyroxenes + metal + spinel that occur as lamellae in olivine in a variety of rock types and are products of late oxidation [1,17]. However, since augite and chromite are rare, this origin is not likely. (2) The occurrence of these assemblages as rims and veins strictly on olivine suggests that they formed by the olivine + melt $\rightarrow$ opx reaction. However, in that case the presence of metal (and sulfide) would be fortuitous, which is inconsistent with the preferred alignment of metal grains within the opx (Fig. 1b). Furthermore, it is clear from NWA 1500 that opx formed by this normal fractionation reaction is distinct from the opx in the grain boundary assemblages (Fig. 1c). (3) Another possibility suggested by the association of these assemblages strictly with olivine is that they formed via the reduction reaction olivine + C → Fe + CO + enstatite, analogous to the reaction olivine + C → Fe + CO + silica that dominated in ureilites. This interpretation is supported by the preferred orientation of metal grains in the opx, which suggests that the two phases formed simultaneously (lack of orientation of metal in ureilites could be explained by lack of cleavage in olivine). Nevertheless, there are notable differences between the samples studied here and ureilites. First, the samples studied here do not contain significant carbon. Second, their grain boundary opx is not significantly more magnesian than what would be in equilibrium with coexisting olivine at typical brachinite equilibration temperatures of ~850-950°C (QUILF [18]). Third, their olivine does not itself show evidence of reduction. In all these respects, however, NWA 1500 may be the exception that proves the rule: it contains minute amounts of graphite, its grain boundary opx is slightly more magnesian than its primary opx, and its olivine grains show slight reverse zoning [14]. The interpretation that these assemblages formed by late reduction is currently the most reasonable hypothesis, and would be consistent with Fe-Mn-Mg relations suggesting a primary redox relationship among brachinites and the ungrouped achondrites studied here [1,3,16]. Finally, the absence of these assemblages in some brachinites supports the inference that not all brachinites come from a single parent body [2,3,15,16].

Table 1. Olivine and opx in NWA 595 and NWA 5191.

	NWA 595			NWA 5191	
	oliv (22)	coarse opx (12)	fine opx (5)	oliv (22)	fine opx (17)
SiO_2	37.4	54.4	54.0	36.8	54.2
TiO_2		0.07	0.02		0.02
Al_2O_3		0.40	0.04		0.11
Cr_2O_3	0.028	0.22	0.07	0.035	0.13
FeO	25.7	16.2	17.1	30.0	17.9
MgO	36.5	26.7	27.3	33.3	26.1
MnO	0.462	0.40	0.44	0.434	0.40
CaO	0.082	1.1	0.75	0.131	1.4
Na_2O		0.03	0.01		0.02
Total	100.2	99.5	99.8	100.7	100.3
mg	71.7	74.7	74.0	66.4	72.2
Wo		2.2	1.4		2.7

References: [1] Goodrich C.A., Righter K. (2000) MAPS 35, 521. [2] Rumble D. et al. (2007) LPS 39, #1974. [3] Mittlefehldt D.W. et al. (2003) MAPS 38, 1601. [4] Warren P.H., Kallemeyn G.W. (1989) Proc. 19th LPSC, 475. [5] Swindle T.D. et al. (1998) MAPS 33, 31. [6] Connolly H.C. et al. (2006) Met. Bull. 90, MAPS 41, 1383. [7] Irving A.J. et al. (2005) MAPS 40, #5213. [8] Mittlefehldt D.W. et al. (1998) In Planetary Materials, RIM 36. [9] Wlotzka F. (1972) *Meteoritics* **7**, 591. [10] Berkley J.L. et al. (1976) GCA 40, 1429. [11] Rubin A.E. (2006) MAPS 41, 125. [12] Bartoschewitz et al. (2003) MAPS 38, A64. [13] Mittlefehldt D.W., Hudon P. (2004) MAPS 39, A69. [14] Goodrich C.A. et al. (2006) MAPS 41, 925. [15] Greenwood R.C. et al. (2007) LPS 38, #2163. [16] Kita N.T. et al. (2009) LPS 40, #1393. [17] Irving A.J. et al. (2007) MAPS 42, 5129. [18] Anderson D.J. et al. (1993) Computers and Geosciences 19, 1333.

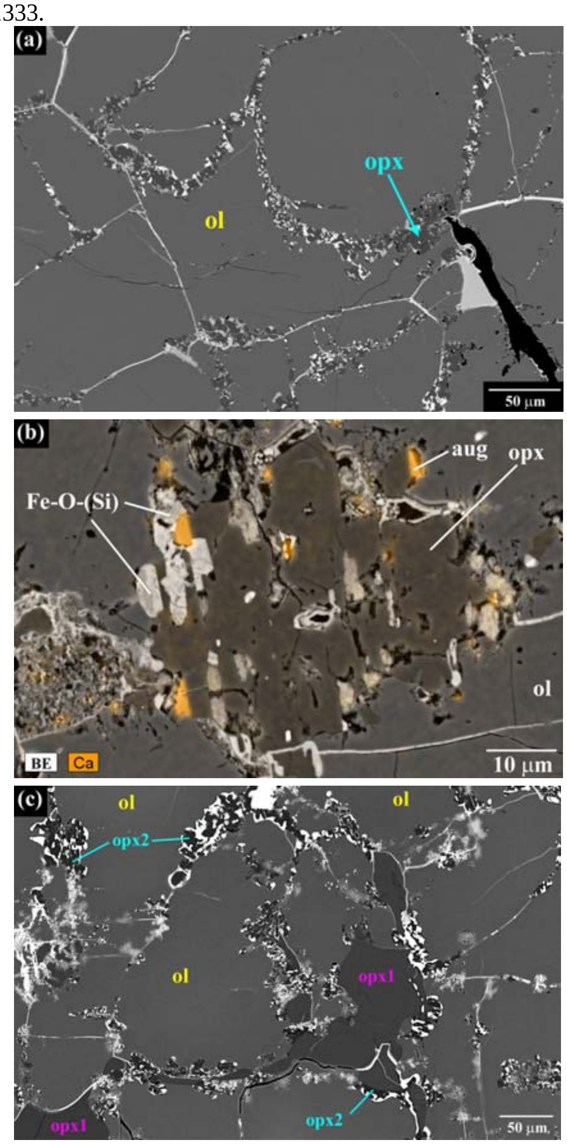

Fig. 1. BEI of fine-grained opx-metal assemblages. (a) Hughes 026; (b) Reid 013 (combined with Ca x-ray map). (c) NWA 1500.