THE ANOMALOUS ENSTATITE METEORITES - PART 2: THE RECRYSTALLIZED EL METEORITES. J. S. Boesenberg[1,2], M. K.Weisberg[2,3], R. C. Greenwood[4], J. M. Gibson[4] and I. A. Franchi[4]. [1]Dept of Geological Sciences, Brown University, 324 Brook Street, Providence, RI 02912. (joseph_boesenberg@brown.edu), [2]Dept. Earth & Planetary Sciences, American Museum of Natural History, New York, NY 10024, [3]Dept of Physical Sciences, Kingsborough College, 2001 Oriental Blvd, Brooklyn, NY 11235, [4]Dept of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK.

Introduction: Last year, we began a study of the anomalous enstatite meteorites [1], a group of extremely reduced rock types that lie beyond the "normal" textural (and sometimes mineralogical) boundaries of the enstatite chondrite subgroups (EH and EL) and the aubrites. Here, we continue that study by looking at those meteorites that have compositional similarities to the EL chondrites but have been metamorphically recrystallized. These meteorites include Happy Canyon, Miller Range (MIL) 090807, Zaklodzie, Northwest Africa (NWA) 4301 and Ilafegh 009.

The goals of this study are to 1) consider the petrologic, chemical and isotopic characteristics of these recrystallized rocks, and 2) briefly discuss the problem of interpreting their petrogenetic history.

Methods: Petrological and chemical analyses were performed by electron microprobe at Brown University. Oxygen isotope analysis was performed on MIL 090807 by infrared laser-assisted fluorination [2] at the Open University. Analyses were obtained on the whole-rock samples (0.5-2 mg) and were analyzed untreated. System precision (2σ) as determined on an internal obsidian standard is: ±0.05‰ for $\delta^{17}O$; ±0.09‰ for $\delta^{18}O$; ±0.024‰ for $\Delta^{17}O$. The $\Delta^{17}O$ value has been calculated using a linearized format [3].

Petrology: Zaklodzie, MIL 090807, Happy Canyon, and NWA 4301 dispaly a similar granular enstatite texture. Granular textures are indicative of recrystallization and commonly seen in metamorphic basalts, both terrestrial and extraterrestrial (i.e., eucrites, howardites) [4]. MIL 090807, Zaklodzie and NWA 4301 have fairly uniform enstatite grain sizes (~80 to 300 micron diameter), while Happy Canyon displays a complete range of sizes (~20 to ~350 micron diameter) that includes a much smaller size fraction than the others. All five meteorites studied contain interstitial feldspar, metal, sulfides and silica. No glass was found in any meteorite in this study though [5] reported a few small K-rich glass inclusions in enstatite in Ilafegh 009.

Ilafegh 009 is a much coarser-grained (up to 1 cm diameter) meteorite than the others and has a texture that initially looks quite similar to an igneous rock. In fact, on first investigation, it did not appear to be very closely related to the other four recrystallized EL rocks. However, upon subsequent observations using correlated backscattered electron and cross-polarized petrographic microscope images, the texture showed that it probably did not result from only primary crystallization from a melt as suggested by [5-7]. Instead, closer observation shows it contains smaller enstatite grains that have metamorphically welded themselves together into larger, blocky and irregularly-shaped grains. This is evidenced by 1) Ca/Al zoning across each of the smaller internal grains, and 2) sulfide, metal and feldspar grains which appear to be included in or cutting across many portions of the larger enstatite grain. These multiple small, welded enstatite grains give a slight irregular optical extinction to the larger grains in cross-polarized light.

The petrogenetic history of Ilafegh 009 seems to consist of an igneous rock that experienced at least two metamorphic events. Following the first event, Ilafegh 009 probably resembled the other "typical" recrystallized EL rocks and contained 20-300 micron diameter enstatites. However, following at least one subsequent metamorphic event, these smaller enstatites ripened and re-oriented around the intervening phases into the larger, centimeter-sized, crystallographically-contiguous grains now seen.

Mineral Chemistry: *Zaklodzie and NWA 4301:* Nearly every mineral composition that could be measured in both Zaklodzie and NWA 4301 overlap. Zaklodzie contains $En_{98.9\text{-}99.4}$, with 0.1-0.6 wt% CaO and 0.1-0.4 wt% Al_2O_3, while NWA 4301 has $En_{98.8\text{-}99.2}$, with 0.22-0.45 wt% CaO and 0.1-0.2 wt% Al_2O_3. Interstitial feldspar compositions are $An_3Ab_{89}Or_8$ to $An_{38}Ab_{61}Or_1$ for Zaklodzie, while NWA 4301 feldspars are slightly more calcic ($An_{11}Ab_{85}Or_4$ to $An_{41}Ab_{57}Or_2$). NWA 4301 also has rare feldspar inclusions within enstatite, but these are compositionally indistinguishable from the interstitial ones. Metal compositions in Zaklodzie (5.6-6.1 wt% Ni and 1.46-1.59 wt% Si) and NWA 4301 (5.4-6.1 wt% Ni and 1.4-1.6 wt% Si) are in the typical range for EL chondrites. Occasional intact troilites (0.33-0.43 wt% Ti, 3.1-3.6 wt% Cr, and 1.0-1.7 wt% Mn) and schreibersites (10.5-11.0 wt% Ni and 0.17-0.31 wt% Co) can be found in NWA 4301 despite bad weathering. These vary slightly from those in fresher Zaklodzie (troilite: 0.75-0.86 wt% Ti, 4.1-4.7 wt% Cr and 0.95-2.05 wt% Mn; schreibersite: 9.9-13.25 wt% Ni and 0.1-0.29 wt% Co). Alabandite was only found in Zaklodzie (0.17-0.25 wt% Na, 4.8-5.1 wt% Mg, 0.74-0.85 wt% Ca, 1.85-2.09 wt% Cr). Daubreelite was not found in either meteorite. Traces of oldhamite were found in both meteorites, but no useful analyses could be obtained.

Happy Canyon: There are two pyroxenes, instead of just one, in Happy Canyon, enstatite ($En_{98.-99.3}$, 0.29-0.43 wt% CaO and 0.05-0.4 wt% Al_2O_3) and diopside ($Wo_{45}En_{55}$, 0.07-0.08 wt% TiO_2, 0.55-1.0 wt% Al_2O_3, and 0.17-0.25 wt% Na_2O). Feldspar compositions (An_{14}-$Ab_{83}Or_3$ to $An_{31}Ab_{67}Or_2$) lie in the same range as the other recrystallized EL rocks. Very severe weathering allows only silicate analyses to be quantitatively useful.

MIL 090807: This meteorite is also unusual among the recrystallized ELs as it bears rare olivine grains ($Fo_{99.9}$, 0.03 wt% CaO). Enstatite and feldspar compositions are typical ($En_{98.8-99.2}$, 0.25-0.50 wt% CaO and An_5-$Ab_{90}Or_5$ to $An_{40}Ab_{59}Or_1$, respectively). Metal (5.6-6.6 wt% Ni and 0.67-0.84 wt% Si) and sulfide (troilite: 0.7-1.11 wt% Ti,0.8-1.8 wt% Cr and 0.04-0.22 wt% Mn; daubreelite 0.07-0.37 wt% Ti and 1.94-2.95 wt% Mn; alabandite 0.02-0.05 wt% Na, 3.7-3.9 wt% Mg, 0.27-0.35 wt% Ca and 1.5-1.8 wt% Cr) are similar to the other recrystallized ELs, though schreibersite (21.0-29.9 wt% Ni and 0.05-0.25 wt% Co) in MIL is more Ni-rich.

Ilafegh 009: Perhaps the most interesting of the 5 meteorites, Ilafegh 009 has enstatite with a CaO content slightly higher than the others ($En_{99.4-99.8}$, CaO 0.5-1.05 wt% CaO, 0.12-0.28 wt% Al_2O_3). The large enstatites are also zoned in Ca/Al and appear to be composed of smaller enstatites that have been welded (and/or ripened) together. The feldspar composition (An_{11}-$Ab_{84}Or_5$ to $An_{31}Ab_{67}Or_2$) overlaps the other meteorites in this study. Metal (6.1-6.8 wt% Ni and 1.03-1.15 wt% Si), troilite (0.87-1.24 wt% Ti, 1.1-1.6 wt% Cr, and 0.05-0.1 wt% Mn) and schreibersite (6.0-14.8 wt% Ni and 0.18-0.41 wt% Co) are all consistent with an EL origin. Alabandite and oldhamite were found, but are too badly weathered to yield useful data. No daubreelite was found.

Oxygen Isotopes*:* The oxygen isotopic results for MIL 090807, as well as previously published data for Happy Canyon and Ilafegh 009 [8] and Zaklodzie [9] are plotted in Fig. 1 relative to the fields generated from the data of [8]. NWA 4301 has not yet been analyzed for oxygen and is severely weathered.

The four meteorites analyzed plot inside the EH chondrite region of oxygen isotope space, but all are very close to the EL chondrite region as well. No systematic oxygen isotopic versus chemical or petrological differences were found.

Origins: One of the controversial aspects of many of the anomalous E meteorites, in general, and these five meteorites specifically, is whether their petrogenetic origin results from either external (impact melting) or internal (igneous melting) parent body processes. Texturally, the recrystallized EL rocks described here resemble many primitive achondrites, such as the lodranites, acapulcoites and winonaites. All of these rocks have "presumably" been melted and subsequently metamorphically recrystallized. Petrologically, however, there has still been no definitive means shown to determine the source of the heat which either initially formed or subsequently metamorphosed them. The only differences between these groups is their initial bulk compositions (controlled by temperature and oxygen fugacity) and their direct link, if any, to a known chondrite group. The recrystallized E rocks can easily make a compositional and oxygen isotopic connection to the EL chondrites, however the lodranites, acapulcoites and winonaites can't make a direct connection to any known chondritic parent.

All of the EL rocks studied here are quite homogeneous with only metal and feldspar showing chemical evidence of small fractionation trends. Happy Canyon is probably the least metamorphosed of the five, since it still contains its smallest size fraction of enstatites and has a size distribution similar to a primary igneous rock. The others, however, have more uniformly ripened enstatites, possibly having their growth aided by being surrounded by a low temperature, metamorphically-generated sulfide melt [10].

References: [1] Boesenberg J. S. et al. (2013) *Lunar Planet. Sci. XLIV*, abstract #2320. [2] Miller M. F. et al. (1999). *Rapid Commun. Mass Spectrom.* 13, 1211-1217. [3] Miller M. F. (2002) *GCA 66,* 1881-1889. [4] Duke M. B. and Silver L. T. (1967) *Geochim. Cosmo. Acta* 31, 1637-1665.[5] Bischoff A. et al. (1992) *Lunar Planet. Sci.* XXIII, 105-106. [6] McCoy T. J. et al. (1992) *Lunar Planet. Sci. XXIII*, 869-870. [7] McCoy T. J. et al (1995) *Geochim. Cosmo. Acta* 59, 161-175. [8] Newton J. et al. (2000) *Meteorit. Planet. Sci.* 35, 689-698. [9] Stepniewski M. et al. (2000) *Meteorit. Planet. Sci. 35, A152.* [10] Cabane et al. (2005) *Contrib. Mineral. Petrol.* 150, 37–53.

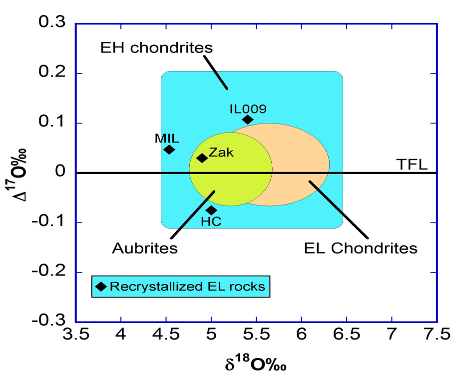

Figure 1. Oxygen isotope plot showing the recrystallized EL meteorites relative to the EL, EH and aubrite fields.