A CARBON-RICH REGION IN UREILITE MILLER RANGE 091004. C.A. Corder[1], J.M.D. Day[1], D. Rumble III[2], N. Assayag[3], P. Cartigny[3], L.A. Taylor[4]. [1]Scripps Institution of Oceanography, La Jolla, CA 92093-0244 (ccorder@ucsd.edu); [2]Carnegie Institution of Washington, Washington, DC 20015; [3]IPG-Paris, UMR 7154 CNRS, Univ-Paris Diderot, PRES Sorbonne Paris Cité, France; [4]PGI, University of Tennessee, Knoxville, TN 37996.

Introduction: Ureilite meteorites are ultramafic rocks formed during partial melting of chondritic pre-cursor materials [1-4]. They are the most numerous partially melted achondrites known (>340 ureilites in the Meteoritical Database as of 18 Nov 2013). Ureilites are primarily composed of olivine and low- and high-Ca pyroxenes with minor sulfide, FeNi metal, and elemental carbon [1-4]. Carbon is present in significant amounts as graphite, lonsdaleite, and diamond [4], and the existence of these minerals discriminates ureilite samples from other meteorite groups. Here, we report detailed petrology and chemistry for Miller Range (MIL) 091004. The meteorite had an initial mass of 32.5 g and was originally described as a lodranite [5], but is, in fact, a ureilite. The existence of a carbon-rich region (Figure 1) makes MIL 091004 a unique addition to the ureilite collection. It has important implications regarding ureilite petrogenesis and for reduction processes during planetesimal differentiation.

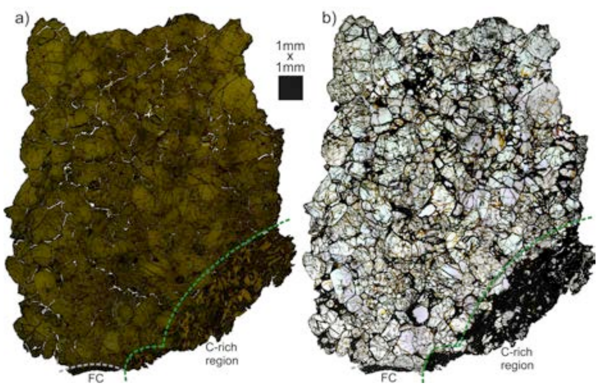

Figure 1. *Composite photomicrograph maps of MIL 091004, 7 in (a) reflected light and (b) plane-polarized light. The carbon-rich (C-rich) region is highlighted by green dotted lines. FC = fusion crust.*

Sample and Analytical Methods: Detailed petrology was performed on a polished thick-section (sample area = 1.35 cm^2) of MIL 091004 (,7). Major- and minor-element mineral compositions were obtained using a *Cameca* SX-100 electron micro-probe (EMP) at the University of Tennessee. A 1.04 g bulk rock sample (,4) was also obtained from the Meteorite Working Group for bulk-rock analyses. Whole-rock trace-element abundances were determined at SIO using standard procedures [6] with a *Thermo Scientific* iCAP Q ICP-MS. Oxygen isotope data was obtained at the IPG-Paris by laser fluorination.

Results: *Petrography and petrology* – The polished section that we studied contains two discrete regions visible to the naked eye. A main granoblastic region makes up 90% of the section and is composed mainly of olivine, pigeonite, and augite (90 modal %) with a texture similar to ureilites described previously (e.g., [1-3]). Also present in this region are FeNi metal, FeS, and schreibersite (2 modal %). The FeNi metal in the main region contains an appreciable amount of Si (~1.5 wt.%). The second distinct region, making up 10% of the section, has an intergranular texture of lath-like carbon grains (34 modal %) in association with olivine (64 modal %; 21 modal % reduced olivine + 43 modal % non-reduced olivine) and minor FeNi metal (2 modal %). We term this region the 'C-rich region'. In this region, FeNi grains can contain up to 11 wt.% Si. The contact between the two regions is quite sharp, indicating that one of the regions intruded into the other (see below). For the entire section, silicates account for 87 modal %, FeNi, FeS, and schreibersite account for 2 modal %, and carbon accounts for 3 modal %. The remainder of the section (8 modal %) is terrestrial weathering products found along grain boundaries and fractures, and a small amount of fusion crust.

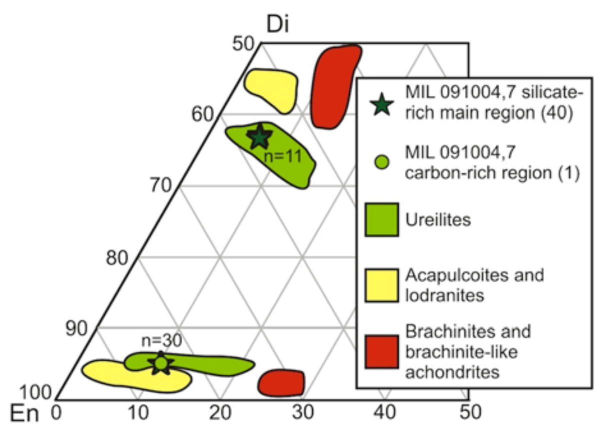

Figure 2. *Pyroxene compositions for MIL 091004, 7 along with fields for ureilites, acapulcoite-lodranites, and brachinite and brachinite-like achondrites [6].*

Mineral chemistry – The main granoblastic region in MIL 091004 contains olivine with Fo_{88-89} cores, pigeonite ($Fs_{10}Wo_5$), and augite (Fs_6Wo_{37}) (Figure 2). The small amount of FeNi metal in the region contains ~95 wt.% Fe, ~2 wt.% Ni, and ~1.5 wt.% Si. Accessory troilite grains have ~56 wt.% Fe, ~37 wt.% S, and

~6 wt.% Cr. Minor schreibersite grains have ~82 wt.% Fe, ~15 wt.% P, and ~2 wt.% Ni.

The carbon-rich region contains olivines with cores of Fo_{88} and reduced rims with up to Fo_{99}. A single pigeonite ($Fs_{10}Wo_5$) grain was observed poikilitically enclosed within an olivine grain. FeNi metal grains within the C-rich region but near the boundary between the silicate-rich main region have FeNi compositions with high Si content; ~93 wt.% Fe, ~4 wt.% Si, and ~2 wt.% Ni. One 50×50 µm anhedral FeNi grain has a composition of ~85% wt.% Fe, ~11 wt. % Si, and ~ 2 wt. % Ni.

Oxygen isotopes - Analysis of oxygen isotopes from non-magnetic minerals separated from the bulk rock gave a $\Delta^{17}O$ value of -0.727 per mil (Figure 3). The O-isotope systematics of MIL 091004 are consistent with it being a ureilite.

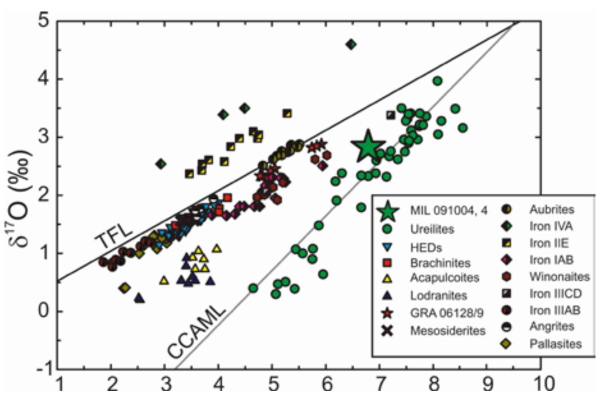

Figure 3. *Oxygen isotope systematics of MIL 091004 versus other planetary samples (from [6, 7]).*

Trace-element abundances – Absolute and relative abundances of trace elements in MIL 091004 are consistent with those reported for ureilites previously (e.g., [8]). As with other ureilites, the rare earth element (REE) pattern of MIL 091004 is consistent with it representing a residue after partial melting (Figure 4). Some ureilites have elevated light REE suggesting later melt infiltration (c.f., auto-fertilization).

Discussion: The C-rich region of MIL 091004 is one of the most remarkable lithologies reported from any meteorite. This feature is seen in more than one section of the meteorite (MIL 091004, 7 and 2) and is most likely an intrusive C-rich vein. Petrographic evidence for this relationship includes side-wall orientation of carbon grains, inheritance of the texture of the main granulitic region in silicates within the C-rich region, and lack of enhanced reduction at the interface between the main granoblastic and C-rich regions. Combined with evidence for light REE enrichment in some ureilites and variable degrees of melt-depletion (Figure 4), we propose a similar auto-fertilization mechanism to that observed in some terrestrial mantle peridotites (e.g., [9]). After initial melt depletion, some ureilites acted as conduits to melt migration from low degree partial melts from within the parent body.

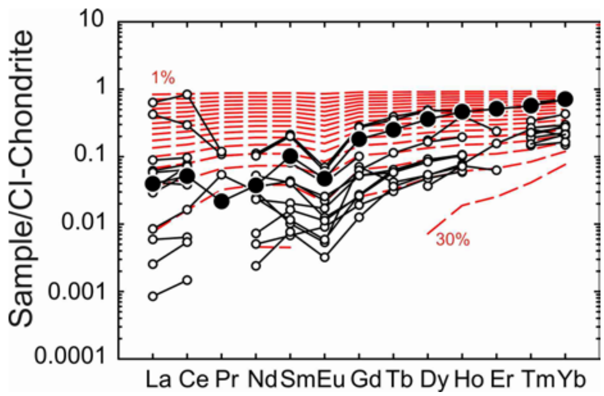

Figure 4. *CI-normalized REE patterns for MIL 091004, 4 (filled circles) versus published ureilite data (unfilled circles) [8] showing a residue depletion model (dashed lines) assuming 70% olivine, 25% opx, 5% cpx and melting proportions 0.2/0.3/0.5. Residues after 1-30% partial melting are shown.*

An auto-fertilization model has important implications for smelting [10], since it would allow coexistence of high Fe/Mg olivines with C due to a combination of melt depletion at a range of pressures, followed by C-rich melt-infiltration. It would also be a more reduced analog to terrestrial peridotite environments where low-degree C-rich partial melts are increasingly cited for explaining features of melt processes. In the case of low degree partial melts in a reduced ureilite parent body, they would likely need to be CH_4-rich to explain the mineralogy of MIL 091004.

There are two possible mechanisms by which C-rich melt-infiltration could have occurred in ureilites. The first is during primary differentiation. The second is through impact-processes. It has previously been noted that only the lowest-shock ureilites have significant carbon [11]. That the granoblastic region of MIL 091004 is infiltrated by the C-rich region but is also shocked (undulose extinction and shock-discoloration of olivine) suggests impact-related melting as a possible mechanism for auto-fertilization of ureilites.

References: [1] Goodrich (1992) *Meteoritics*, **27**, 327. [2] Goodrich (2004) *Chemie Erde*, **64**, 283. [3] Berkley et al. (1980) *GCA*, **44**, 1579. [4] Mittlefehldt et a. (1998) *RIM*, **36**. [5] Satterwhite & Righter (2012) *AMN*, **35**. [6] Day et al. (2012) *GCA*, **81**, 94. [7] Clayton & Mayeda (1996) *GCA*, **60**, 1999. [8] Spitz & Boynton (1991) *GCA*, **55**, 3417. [9] Niu (2004) *J. Petrol*, **45**, 2423 [10] Walker & Grove (1993) *Meteoritics*, **28**, 629. [11] Warren & Rubin (2010) *GCA*, **74**, 5109.