THE MILLER RANGE 090340 DUNITE: NOT A UNIQUELY FERROAN UREILITE, NOT EVEN A UREILITE. Paul H. Warren and Alan E. Rubin, Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA 90095, USA (pwarren@ucla.edu).

MIL 090340 (total mass, including its pair MIL 093056, 7.9 grams) is a dunite that has been preliminarily classified as a ureilite [1]. As a ureilite, MIL 090340 would be exceptionally ferroan. Among the >>100 previously known ureilites, the most ferroan have olivine (core) composition of $Fo_{74.7}$; this occurs in both LEW 88774 [unpublished UCLA data; cf. 2] and LAP 03587 [3]. MIL 090340 was described [1] as having "Fa_{27-30}" (i.e., Fo as low as 70) olivine cores.

Extension of the ureilite olivine range to Fo_{70} would arguably have significant implications for the important issue of the role of smelting (i.e., reduction of FeO through oxidation of C) during ureilite anatexis. A common assumption [e.g., 4, 5] is that the known spectrum of ureilites acquired its *mg* diversity (Fo_{75-95}) when an originally uniform starting material was subjected to anatectic smelting, with the extent of smelting controlled by lithostatic pressure (CO gas is formed in smelting, so the process is highly *P*-sensitive). The deepest materials, in this model, undergo the least smelting, and end up with the most FeO-rich compositions. As envisaged by its adherents [4], this model implies that the deep mantle of the (original) ureilite parent body would have sustained pressures too high for smelting, and thus would have remained far more ferroan than any of the previously known ureilites (Fo_{75}). The lack (hitherto) of the predicted hyperferroan ureilites represents one of numerous problems with the anatectic smelting hypothesis [6].

We have thus far studied this meteorite only through thin sections, one each from MIL 090340 and 090356. INAA bulk analyses will be done before the conference. However, the thin section evidence alone shows that the meteorite (hereafter MIL) is no ureilite.

Superficially, MIL looks like a dunitic (~2% pyroxene) ureilite. The pyroxene is mostly high-Ca ($En_{44.9}Wo_{44.6}$), but primary orthopyroxene ($En_{72.4}Wo_{2.3}$) is also present. Like ureilites, MIL is devoid of feldspar. MIL contains a large trace of Cr-spinel, but so do a few ureilites, mostly ferroan ones such as LEW 88774 [2; but cf. 7]. A few of MIL's largest, most elongate olivines (which display a weak foliation) are just under 2 mm long, but most of the silicates are only 0.2-0.5 mm in maximum dimension. In the sizes and generally equant shapes of its grains, MIL resembles a fine-grained ureilite. The resemblance carries over to presence of opaque rims on most of the silicates.

Detailed characteristics reveal a different story. Although the opaque-on-olivine rims were called "carbon-rich material" [1] (like the interstitial matter in ureilites), we find no carbon phase. Conceivably a former C phase has been totally oxidized, as suggested for the Hughes 009 ureilite by Goodrich et al. [8]. However, another characteristic feature of ureilites, rim-localized FeO reduction (possibly triggered by sudden *P* reduction and thus C oxidation linked with break-up of the original and still hot parent body; *not to be confused* with anatectic smelting; see e.g., [3, 9]), is weak or nonexistent in MIL.
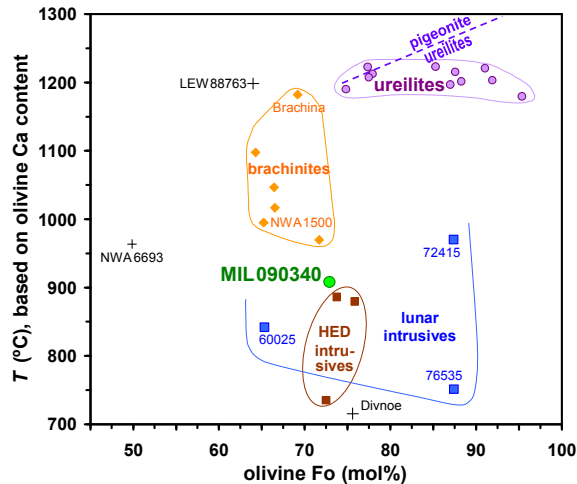
In MIL, the distinctive fine-grained opaque assemblage that occurs on most of the olivine rims closely resembles typical rim materials in brachinites [8] both mineralogically and texturally, and also by commonly extending as veins deep within olivine crystals. The rim assemblage is dominated by FeS and extreme-low-Ca ($En_{75.9}Wo_{1.3}$) pyroxene; following [8], we refer to this distinct, late-formed rim pyroxene as opx2. Fe-metal is rare (although weathering complicates this issue; and [1] reported macroscopically "high metal"). Compositionally (4.2 wt% Ni) and texturally it appears to have formed as primary igneous interstitial metal, not an ultra-fine-grained, Ni-poor reduction product. We analyzed many rim olivines, including positions that (in thin-section) appear isolated by opx2 from the interior olivine. Our least-ferroan olivine analyses ($Fo_{73.1-73.4}$) are from within or very near to rims, but so too are 4 of our 7 most ferroan analyses ($Fo_{71.5-71.9}$). In general, we find no clear pattern of reversed (reduction) zonation in MIL olivines.

Ureilite Cr-spinels tend to feature high-*mg* (reduced) rims and low-*mg* cores [e.g., 7]. Rim zonation in the largest MIL Cr-spinels is *counter*-indicative of late reduction. The outer ~30 μm has a depleted *mg* (Fig. 1), as do the smallest Cr-spinels (inclusions within olivine), versus the cores of the large grains.

mg ratio in Cr-spinel (mol%)
- 25-26.1
- 24-25
- 23-24
- 22-23
- 21-22
- 20-21
- <20
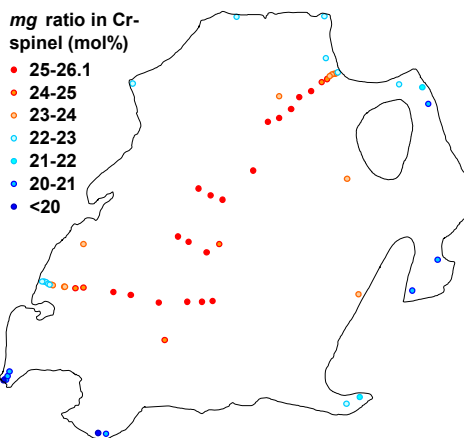
Temperatures of equilibration (T_{eq}) recorded by mineral compositions indicate that MIL is definitely not a ureilite. By a variety of measures [e.g., 5, 9-11], ureilites underwent extremely rapid cooling from a T_{eq} of ~1200-1300°C. Other non-basaltic achondrites (and intrusive igneous rocks in general) typically cooled slowly enough to record much lower T_{eq}.

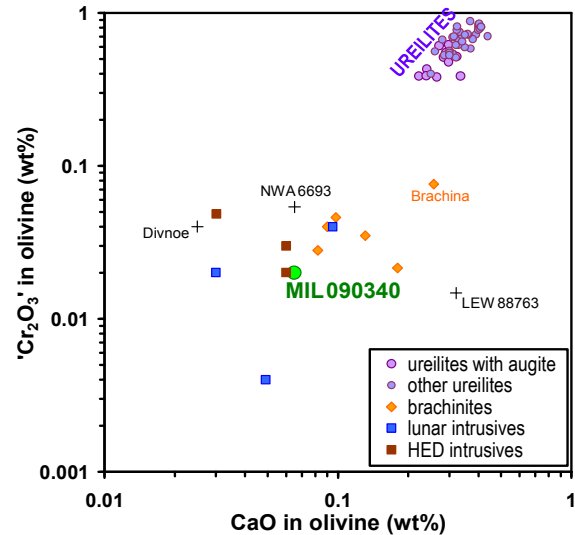Fig. 2 shows results based on Ca partitioning be-

tween olivine and clinopyroxene [12]. The augite-bearing ureilites for which this method is applicable tend to have uncommonly low CaO (0.22-0.35 wt%; vs. 0.34 wt% average for all other ureilites). Even so, T_{eq} is consistently ~1210°C. In contrast, MIL cooled slowly enough to reach an average olivine CaO content of 0.065 wt%, implying T_{eq} = 908°C.

The two-pyroxene technique [13] yields similar results: 880°C for MIL, vs. ~1200-1250°C for augite-bearing ureilites. A method developed specifically for pigeonite-bearing ureilites [5] implies the Fo – T_{eq} correlation shown by a dashed line in Fig. 2 [cf. 6].

A moderate T_{eq} is also implied by the MIL Cr-spinel compositions using the method of Wlotzka [14]. Cr/(Cr+Al) is nearly constant (84 mol%) in the spinels, and the range of mg variation (Fig. 1) implies a range in T_{eq} of ~790-920°C; for the low-mg smallest grains, and the high-mg large-grain cores, respectively.

Ureilite olivines are distinctively Cr-rich (Fig. 3). Even comparatively fast-cooled (impact melt?) rocks such as Brachina and LEW 88763 have far lower olivine Cr contents. On Fig. 3, MIL plots squarely within the "normal" intrusive rock range, and many sigmas (log-normal) outside the ureilite range.

Isotopic and trace bulk-compositional analyses will further constrain the classification of MIL, but based on petrology the most likely kinship is with brachinites, a class that includes, in our estimation, NWA 1500 [8, 15]. Brachinites generally consist of 80-90 vol% olivine, with augite as their second most abundant miner-

al, and with mg ratios, feldspar, FeS, spinel and metal contents, all similar to MIL [16]. In MIL's olivine, Fe/Mn (55, molar) is slightly low relative to Fe/Mg, by brachinite standards [cf. 8]. Another similarity to brachinites is the trace presence of Cl-rich (5.0 wt% Cl) apatite, found as a 6-µm inclusion within the same large Cr-spinel in Fig. 1. As noted by [15], this P_2O_5-rich phase suggests a distinctly moderate fO_2 relative to ureilites.

The origin of MIL's FeS+opx2 dominated rim material, and particularly the role of redox in this late-stage process, is enigmatic. In the case of NWA 1500, olivines are reverse-zoned (ureilite-style) [15], yet within other brachinites (as within MIL) the analogous rim materials are not accompanied by olivine zonation [8]. As discussed above, for MIL one line of evidence bearing on late reduction, rim-composition gradients in Cr-spinel, favors if anything late FeO oxidation. The mg of the rim pyroxene (opx2, 76.9 mol%) is higher than that of the primary orthopyroxene (74.1 mol%), but this disparity is not as great as in NWA 1500 (71.4-75.8 mol%) [15].

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