PETROGRAPHY OF VERY PRIMITIVE CO3 CHONDRITES: DOMINION RANGE 08006, MILLER RANGE 07687, AND FOUR OTHERS. J. Davidson[1*], L. R. Nittler[1], C. M. O'D. Alexander[1], and R. M. Stroud[2]. Department of Terrestrial Magnetism, [1]Carnegie Institution of Washington, Washington, DC 20015, [2]Naval Research Laboratory Code 6366, 4555 Overlook Ave. SW, Washington, DC 20375. *E-mail: jdavidson@dtm.ciw.edu.

Introduction: After interplanetary dust particles, carbonaceous chondrites provide some of the most pristine extraterrestrial samples available for study. The least altered chondrites typically contain abundant presolar grains and other isotopically anomalous matter, which can provide valuable insight into the early Solar System and parent body processing [e.g., 1,2]. The CO3 chondrites exhibit the complete metamorphic sequence from type 3.0 to 3.9 [3]. For the least altered CO3s, it is possible to further subdivide them, from type 3.00 to 3.2, and identify the most pristine samples for additional study by determining the Cr content of ferroan olivine [4]. The same technique has been applied to the ordinary chondrites (OC), but they do not follow the same (poorly defined) trend as the CO3 chondrites. It was suggested that Dominion Range (DOM) 03238 represents a missing link in the CO3 chondrite metamorphic sequence [5]. However, here we report the results of a petrographic study of six other Antarctic CO3 chondrites that appear to define the CO trend and suggest that DOM 03238 is, in fact, an outlier. We also present detailed petrography for DOM 08006 that indicates it is the most primitive CO3.

Experimental: Thin sections of Miller Range (MIL) 05024, MIL 07687, MIL 090010, MIL 090470, DOM 08006, and DOM 10104 were imaged with a JEOL JSM-6500F field emission scanning electron microscope (FE-SEM) to locate FeO-rich olivine (both chondrules and chondrule fragments). Olivine grains (~50 per sample) were analyzed quantitatively with a JEOL 8900 electron microprobe analyzer with an accelerating voltage of 15 kV and a probe current of 30 nA. Standards used were forsterite for Mg and Si, cossyrite for Na and Ti, spessartine for Mn and Al, fayalite for Fe, Ni-olivine for Ni, chromite for Cr, and diopside for Ca. Matrix cross-sections were extracted from DOM 08006 by focused ion beam (FIB) lift-out with a FEI Nova 600 FIB-SEM at the Naval Research Laboratory (NRL). Analytical transmission electron microscopy studies were performed with a JEOL 2200FS field-emission scanning transmission electron microscope at NRL, equipped with a Noran System Six energy dispersive X-ray spectrometer. EDS spectra of individual grains were quantified with Cliff-Lorimer routines, with K factors calibrated from San Carlos olivine and Tanzanian hibonite standards [6].

Results and Discussion:

A CO metamorphic sequence. All COs analyzed here contain ferroan olivine in chondrules and as isolated grains in the matrix. The matrix grains may be chondrule fragments, but are generally more ferroan (up to Fa_{81}) than intact chondrules ($Fa_{<70}$). Following the procedures of [4], we analyzed the Cr_2O_3 content of the centers of ~50 different ferroan olivine grains within type-II chondrules and chondrule fragments from each of six CO chondrites in order determine their relative petrographic subtypes (Table 1).

Table 1. *Cr_2O_3 content of ferroan olivine.*

Chondrite	Number analyses	Mean Cr_2O_3 (wt.%)	σ-Cr_2O_3
DOM 08006	54	0.36	0.06
MIL 07687	52	0.35	0.11
DOM 10104	60	0.26	0.11
MIL 05024	51	0.23	0.10
MIL 090470	52	0.23	0.09
MIL 090010	57	0.21	0.09

Initially, the Cr content of olivine is high and relatively homogeneous [4]. As the earliest stages of metamorphism progress, chromite exsolves from olivine, lowering the Cr content of olivine and creating heterogeneity [4]. Further metamorphism ultimately results in homogeneously low Cr contents of olivine [4].

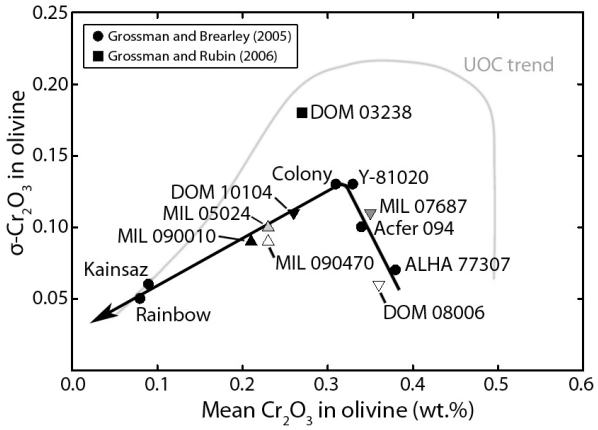

Fig. 1: *Plot of the standard deviation versus the mean of the Cr_2O_3 content of ferroan olivine in CO3 chondrites and ungrouped Acfer 094. A trend line for the CO3s is shown, along with the ordinary chondrite line from [4] for comparison. Additional data: [4,5].*

On the basis of mean content versus standard deviation of Cr_2O_3 in ferroan olivine (Fig. 1), DOM 08006

appears to be as primitive as, if not more primitive than, ALHA 77307 (CO3.00). MIL 07687 appears to be of similar petrographic grade to Acfer 094 (ungrouped C3.0). The four other CO3s analyzed here are of higher petrographic grade, lying along an apparent trend somewhere between Colony (CO3.05) and Kainsaz (CO3.2). This trend appears to define the CO3.00 to 3.2 metamorphic sequence and could be used to calibrate the CO3 scale to that used for the OCs [4]. On this basis, we consider DOM 08006 and MIL 07687 to be of metamorphic grade CO3.00, and DOM 10104, MIL 05024, MIL 090470, and MIL 090010 to all be CO3.1. DOM 03238, which is known to be unusually magnetite-rich (7.6 vol.%), appears to be an outlier [5]. The general trend of alteration shown by DOM 08006, DOM 10104, MIL 05024 and MIL 090010 is consistent with bulk C abundances [7].

MIL 07687 is unique in that it exhibits an unusual type of localized aqueous alteration and may be an ungrouped carbonaceous chondrite [8]. However, this alteration was likely at low temperatures as Cr in olivine appears to have experienced only mild mobilization. The inferred primitive natures of both DOM 08006 and MIL 07687 are in agreement with their presolar grain abundances [2,9] that are higher than or comparable to those from Acfer 094 and ALHA 77307 [e.g., 1]. DOM 08006 also has higher bulk D/H and $^{15}N/^{14}N$ ratios than ALHA 77307, suggesting that it preserves more primitive organics [2,7].

Petrography of DOM 08006. DOM 08006 contains abundant chondrules (<1 mm in diameter), chondrule fragments and mineral grains in an optically dark matrix [10]. Apparent chondrule diameters are 180±110 μm (n=317). FeO-poor type-I chondrules account for the majority (>95%) of chondrules and are predominantly forsterite ($Fa_{0–1}$). FeO-rich type-II chondrules are zoned (~Fa_{42} to Fa_{67}; core to rim) and contain relict grains ($Fa_{3–6}$). Aluminum-rich chondrules account for <1% of all chondrules. Both low-Ca (predominantly $En_{97–99}Fs_{1–3}Wo_1$; minor amounts of $En_{52–60}Fs_{39–46}Wo_1$) and high-Ca pyroxene ($Wo_{7–45}$) is seen within chondrules. Plagioclase within chondrules has compositions of $An_{68–99}$. Opaque mineral assemblages are found along chondrule exteriors and within the interiors, consisting of abundant magnetite, sulfide (pentlandite and pyrrhotite), and metal (kamacite and taenite). Carbide-inclusions were seen within metal grains – similar to those noted in ALHA 77307 [11].

The DOM 08006 matrix mineralogy is very similar to those of ALHA 77307 [12,13] and Acfer 094 [14]; all three are comprised of similar sized, unequilibrated mixtures of amorphous silicate, olivine, pyroxene, metal and sulfides (Fig. 2a) [6]. There is some evidence for mobilization of Cr (chromite sub-grains in pyroxene), but no Fe-rich rims were observed indicating that thermal metamorphism was very limited [6]. The presence of Fe oxy-hydride needles suggests that there may have been some terrestrial weathering (Fig. 2b). Although it cannot be ruled out that some hydroxides may have formed on the parent body.

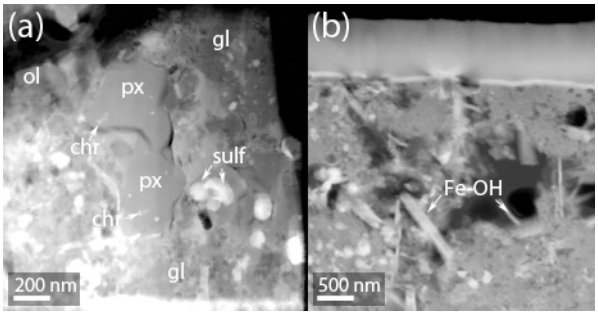

Fig. 2: *DF-STEM images of matrix, where px = pyroxene, ol = olivine, chr = chromite, sulf = sulfide, gl = amorphous silicate (glass), and Fe-OH = Fe oxy-hydrides.*

Summary: The six CO3 chondrites analyzed here appear to complete the CO3.00–3.2 metamorphic trend initially defined by [4], whilst magnetite-rich DOM 03238 [5] may be an outlier. Although MIL 07687 has undergone significant terrestrial weathering, it experienced low degrees of parent body alteration as evidenced by data presented here and high presolar grain abundances [9]. DOM 08006, like ALHA 77307, shows evidence for very limited thermal metamorphism and appears to be a CO3.00.

Acknowledgements: We thank J. N. Grossman for initially bringing the MIL 07687 sample to our attention and J. T. Armstrong for assistance with the electron microprobe. This work was funded by NASA grants NNX10AI63G and NNX11AB40G (PI: LRN), NNX11AG67G (PI: CMODA), and NNH09AL20I (PI: RMS).

References: [1] Nguyen, A. N. et al. (2007) *Astrophys. J., 656,* 1223–1240. [2] Nittler, L. R. et al. (2013) *LPSC XLIV*, #2367. [3] Sears, D. W. et al. (1980) *Nature, 287*, 791–795. [4] Grossman, J. N. and Brearley, A. J. (2005) *MAPS, 40,* 87–122. [5] Grossman, J. N. and Rubin, A. E. (2006) *LPSC XXXVII*, #1383. [6] Stroud, R. M. et al. (2013) *LPSC XLIV*, #2315. [7] Alexander, C. M. O'D. et al. (2014) *LPSC XLV*, this volume. [8] Brearley, A. J. (2012) *LPSC XLIII*, #1233. [9] Davidson, J. et al. (2014) *LPSC XLV*, this volume. [10] Weisberg, M. K. et al. (2010) *MAPS, 45*, 1530. [11] Scott, E. R. D. and Jones, R. H. (1990) *GCA, 54*, 2485–2502. [12] Brearley, A. J. (1993) *GCA, 57*, 1521–1550. [13] Brunner, C. E. and Brearley, A. J. (2011) *MAPS,* #5403. [14] Greshake, A. (1997) *GCA, 61*, 437–452.