

PRISTINE PRE-ACCRETIONARY SIGNATURES IN CM CHONDRITE SILICATES: A COMMON PARENT-BODY WITH THE CO CHONDRITES? D. L. Schrader¹ and J. Davidson². ¹Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, (schraderd@asu.edu), ²Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington DC 20015, USA.

Introduction: The Mighei-like carbonaceous (CM) chondrites are one of the most abundant and aqueously altered group of carbonaceous chondrites [1–4]. The organic molecules present and the effects of aqueous alteration have been extensively studied in the CM chondrites [e.g., 1,3,5]. As many CM chondrites are extensively aqueously altered, the compositions and formation histories of their anhydrous minerals are not well-constrained. However, since aqueous alteration occurred at temperatures below 230°C [6], perhaps between 20 and 71°C [7], pre-accretionary high-temperature anhydrous minerals (e.g., olivine) likely remain unaltered since accretion.

The CM and Ornans-like carbonaceous (CO) chondrites are recognized to exhibit mineralogical and chemical similarities and as such are considered to be a clan. The two groups either formed from similar precursor materials at a common heliocentric distance, or originate from a common parent asteroid [1,4]. This potential relationship is based on their similar chondrule sizes, anhydrous mineral compositions, and bulk elemental and O-isotope compositions [1,4,8,9]. While there are differences in the bulk compositions of CM and CO chondrites [10], analyses of matrix and chondrule olivine in CM and CO chondrites show they are compositionally similar [11]. While many CO chondrites are mildly thermally metamorphosed, Dominion Range (DOM) 08006 is potentially more pristine than the CO3.00 chondrite Allan Hills (ALH) A77307 [12]. This comparative study included mildly heated CO chondrites and defined the metamorphic trend for the CO chondrites [12]. We investigated anhydrous minerals in CM chondrite chondrules to critically evaluate: (1) if CM chondrites retain pre-accretionary formation signatures, and (2) if there is a cogenetic link with the CO chondrites.

Meteorite	Mean Cr ₂ O ₃	σ-Cr ₂ O ₃	SE mean Cr ₂ O ₃	# Grain Cores ^a	Subtype ^b	Phyllo./Anhyd. ^c
QUE 97990,4	0.30	0.12	0.02	49	2.6	2.19
Murchison USNM 5376-1	0.35	0.07	0.01	45	2.5	3.10
Murray USNM 1769-3a	0.32	0.07	0.01	22	2.4/2.5	3.24
Mighei USNM 3483-3	0.36	0.07	0.01	46	-	3.74
Cold Bokkeveld USNM 182-2	0.37	0.08	0.01	33	2.2	4.87
Sutter's Mill	0.38	0.08	0.03	7	-	-

(a) One analysis per grain core; (b) [3]; (c) [13] total phyllosilicate/total anhydrous mineral abundance.

Analytical: We studied six CM chondrites that cover a wide range of aqueous alteration [3,13]: Cold Bokkeveld, Murchison, Mighei, Murray, Queen Alexandra Range (QUE) 97990, and Sutter's Mill (Table 1). Thin sections were studied via optical microscopy, an FEI Nova NanoSEM 600 scanning electron micro-

scope, and a JEOL 8900 Superprobe electron probe microanalyzer at the Smithsonian Institution.

Results and Discussion: We obtained compositional data on olivine from 133 FeO-rich (type II) chondrules across the six different CM chondrites, including 585 analyses of olivine (Fa_{0.5-74.5}) in FeO-rich chondrules. Relict FeO-poor olivine within FeO-rich chondrules ranges Fa_{0.5-9.7}, with Fe/Mn ratios of 8 to 125 (22 analyses). FeO-rich olivine ranges from Fa_{11.0-74.5}, with Fe/Mn of 25 to 141 (563 analyses). Following the method of [14], we used FeO-rich olivine grain core analyses to calculate mean and standard deviation (σ) of Cr₂O₃ content; with only one analysis per grain to avoid bias (Table 1 and Fig. 1). The uncertainty in mean Cr₂O₃ was determined using standard error of the mean (SE). The thin section of Sutter's Mill studied consists of two clasts, and FeO-rich chondrules were only observed in the smaller clast.

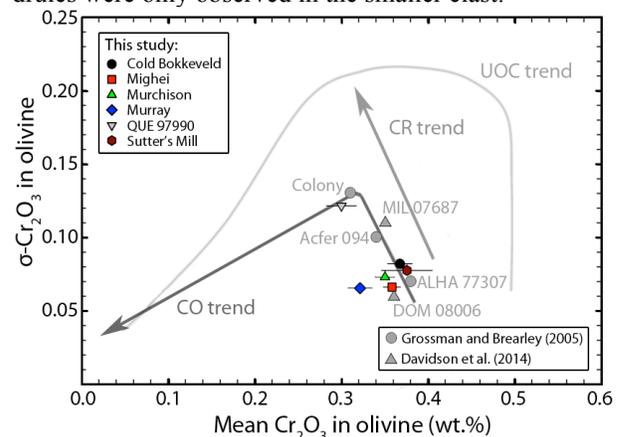


Figure 1. Mean Cr₂O₃ and σ-Cr₂O₃ in ferroan olivine for CM chondrites (Table 1), compared to CO chondrites ALH A77307 and Colony from [14], DOM 08006 and the general CO chondrite trend from [12], CR chondrite trend from [15,16], and ungrouped chondrites Acfer 094 [14] and Miller Range (MIL) 07687 [12]. The CM chondrites overlap with the CO chondrite metamorphic curve from [14]. Error bars are one SE.

Pre-accretionary Signatures. The distribution of Cr₂O₃ within FeO-rich chondrule olivine is related to the degree of thermal metamorphism. During metamorphism, the initial homogeneous distribution of Cr₂O₃ is modified by diffusion of Cr from the grain core to the rim [14]. Therefore, the variability of Cr₂O₃ in olivine grain cores can indicate the degree of thermal metamorphism experienced. While the metamor-

phic curves of UOC, CO, and CR chondrites differ from one another [12,14,15,16], the metamorphic curve for the CM chondrites appear to be identical to that of the CO chondrites (Fig. 1). The mean Cr_2O_3 and $\sigma\text{-Cr}_2\text{O}_3$ of CM chondrites shows that their high-temperature silicates mostly experienced little to no thermal metamorphism, comparable to DOM 08006 and ALH A77307 (Fig. 1). Unlike some Sutter's Mill clasts that have peak metamorphic temperatures of 150 to 500°C [17], the FeO-rich chondrule bearing clast studied here appears unaltered.

QUE 97990 is an exception; its olivine composition indicates mild thermal metamorphism, similar to the ~CO3.1 Colony (Fig. 1) [14]. This is curious as QUE 97990 has the lowest abundance of phyllosilicates of CM chondrites studied by [13], and has the most 'pristine' classification of CM2.6 according to [3] (Table 1). QUE 97990 does not show evidence for dehydration, suggesting that it was not aqueously altered and later heated. This may suggest that QUE 97990 was heated more, and had a lower abundance of water, than other CM chondrites (lower accreted abundance of ice). Alternatively, QUE 97990 may have had the same amount of fluid as other CM chondrites, which was driven away during heating before aqueous alteration could occur. This may suggest that aqueous alteration is not most pervasive in more-heated CM chondrites, as long as aqueous alteration occurs in an open system.

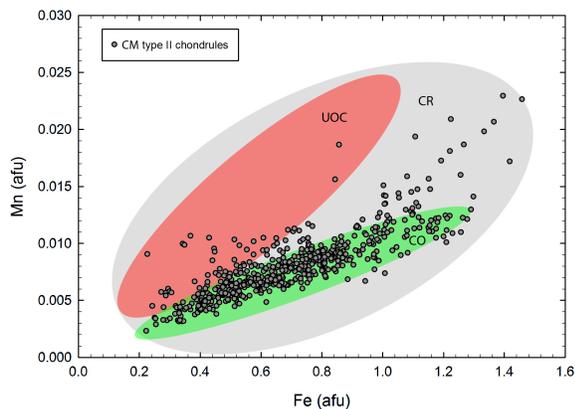


Figure 2. Fe vs. Mn (afu) of FeO-rich olivine from CM chondrite type II chondrules; overlap with CO chondrites. UOC and CO field from [18]; CR field from [16].

Relationship to CO chondrites. The relationship between Fe and Mn in CM chondrite chondrules is similar to that seen in CO chondrite chondrules (Fig. 2). A linear regression of all FeO-rich olivine data from CM chondrite chondrules studied here, anchored at the origin, gives $\text{Mn [afu]} = 0.010 \pm 0.001 (2\sigma) * \text{Fe [afu]}$ ($R^2 = 0.70$); a relatively low correlation coefficient. Berlin et al. (2011) found that CO chondrites yield a

slope of 0.010 with an R^2 of 0.89, whereas the UOCs yield 0.023 with an R^2 of 0.78. In contrast, there is no overall group trend for the CR chondrites [16,18]. There are differences in the Fe vs. Mn relationship between chondrules within the UOCs [18], which were attributed to differences in cooling rates [18,19]. Within the CR chondrites the relationship between Fe and Mn in chondrules often have regressions with R^2 of ~1, although the relationship between Fe and Mn varies widely between chondrules [16]. This is because chondrules behave as individual igneous systems, potentially with distinct precursor compositions, redox conditions, and cooling rates [16]. The range in slopes for CM chondrules ranges from $0.007 \pm 0.001 (2\sigma)$ ($R^2 = 0.99$) to $0.020 \pm 0.002 (2\sigma)$ ($R^2 = 0.99$); these resolvable differences in the Fe/Mn relationship explain why the overall group correlation is relatively low. However, the nearly identical overall slope for CM chondrites compared to CO chondrites may suggest a petrogenetic relationship between the two, or at least similar formation conditions.

Conclusions: The majority of CM chondrites contain high-temperature anhydrous minerals that are among the least thermally metamorphosed in chondrites, comparable to the CO3.00s DOM 08006 and ALH A77307. QUE 97990 is the least aqueously altered and the most thermally metamorphosed CM chondrite studied here. In agreement with [11], pre-accretionary high-temperature anhydrous silicates from CM chondrites show many similarities to those in the CO chondrites.

References: [1] Kallemeyn and Wasson (1981) *GCA* 45, 1217–1230. [2] Zolensky et al. (1993) *GCA* 57, 3123–3148. [3] Rubin et al. (2007) *GCA* 71, 2361–2382. [4] Greenwood et al. (2014) *45th LPSC*, #2610. [5] Pizzarello et al. (1991) *GCA* 55, 905–910. [6] Busemann et al. (2007) *MAPS* 42, 1387–1416. [7] Guo and Eiler (2007) *GCA* 71, 5565–5575. [8] Clayton and Mayeda (1999) *GCA* 63, 2089–2104. [9] Weisberg et al. (2006) *MESS II*, Univ. Arizona Press. [10] Rubin and Wasson (1986) *GCA* 50, 307–315. [11] Frank et al. (2014) *GCA* 142, 240–259. [12] Davidson et al. (2014) *45th LPSC*, #1384. [13] Howard et al. (2011) *GCA* 75, 2735–2751. [14] Grossman and Brearley (2005) *MAPS* 40, 87–122. [15] Davidson et al. (2015) *46th LPSC*, #1603. [16] Schrader et al. (2015) *MAPS* 50, 15–50. [17] Jenniskens et al. (2012) *Science* 338, 1583–1587. [18] Berlin et al. (2011) *MAPS* 46, 513–533. [19] Jones and Lofgren (1993) *Meteoritics* 28, 213–221.