

**DETERMINING PETROLOGIC TYPES OF CM CHONDRITES.** C.M.O'D. Alexander, DTM, Carnegie Institution of Washington, 5241 Broad Branch Road, Washington DC 20015, USA (calexander@carnegiescience.edu).

**Introduction:** The petrologic types of CM chondrites are intended to reflect the degree to which they have been aqueously altered. Traditionally, petrologic criteria have been used to determine the extent of aqueous alteration [1-4]. The reason for this is as much practical as it is scientific – optical and electron microscopes are more widely available than other techniques. Nevertheless, [3] showed that bulk H and noble gas contents also vary systematically with the extent of aqueous alteration. [3] also suggested that bulk O isotopes vary systematically with extent of aqueous alteration, although the case for this is less clear-cut [5].

That bulk H contents should correlate with extent of alteration is easily understood since it will reflect the abundance of phyllosilicates in the meteorites. Indeed, determining water/OH and/or phyllosilicate abundances in chondrites is the most direct measure of the extent of aqueous alteration that they have experienced. Recently, four non-petrologic techniques have been developed to measure either the abundance of water/OH associated with phyllosilicates [5, 6] or phyllosilicate abundances directly [7, 8]. A much larger number of unheated CMs have been measured with these techniques than have been classified petrologically - 54 vs. 14 [3, 4]. This difference poses both a potential problem and an opportunity. The relatively small number of CMs that have been studied by both petrologic and non-petrologic techniques means that there could be systematic differences in the classifications determined by the various techniques. Having greater overlap in the analyzed samples will not only enable better cross correlation between techniques, but if there are any inconsistencies this may reveal new information about alteration processes, shock histories, etc.

[4] used a number of petrologic criteria for classifying CMs, although none of them exhibited a continuous range over all types. Arguably the simplest of their petrologic criteria to measure is the “FeO”/SiO<sub>2</sub> ratio in ‘PCP’ (tochilinite and Fe-rich serpentine intergrowths), where the “FeO” includes Fe<sup>2+</sup> and Fe<sup>3+</sup> in silicates, tochilinite and sulfides. However, the S contents in ‘PCP’ can be very variable, even in a small region of matrix. An ideal mineralogical indicator would be relatively uniform within a meteorite but vary from meteorite to meteorite due to a thermodynamic control on its composition that is related to the degree of alteration.

[3] used matrix serpentine compositions alone to develop a mineralogical alteration index that was continuous across all analyzed samples. This involved

selecting only those matrix analyses with less than 2 wt.% S, and for those selected analyses subtracting the appropriate amounts of Fe and Ni assuming that all S was in Ni-bearing pyrrhotite. However, in most CMs there is a heterogeneous distribution of at least two populations of serpentines (higher and lower Fe), with the more Fe-rich serpentines tending to be more S-rich. Thus, it may be very difficult (or at least time consuming) to get a truly representative bulk matrix serpentine composition.

The original motivation for using serpentine compositions as indicators for the extent of alteration was the expectation that as more chondrules were altered so the bulk composition of the altered material should become more Mg-rich. However, the stabilities of tochilinite and magnetite relative to serpentines and sulfides may complicate the evolution of the serpentine compositions. Also, the fact that there are almost always at least two serpentine compositions present suggests that CM alteration conditions took place in a two serpentine phase stability field.

Here we report preliminary results of a survey to test whether there really are two serpentine phases in CMs, and if there are whether their compositions can be used as indicators of the extent of alteration.

**Technique:** This work was designed to take advantage of the Oxford X-Max 80 mm<sup>2</sup> Si drift detector (SDD) attached to Carnegie’s JSM 6500F SEM. Analyses were conducted at 1 nA and 15 kV with a 50 s analysis time. The sizes of the analyzed areas varied depending on the apparent uniformity of the regions of interest. The elements that were analyzed for were C, O, Na, Mg, Al, Si, S, Cl, P, K, Ca, Ti, Cr, Mn, Fe, Co and Ni. A series of mineral standards were used to calibrate the SDD for all elements. Typically  $\geq 25$  areas of both the higher and lower Fe phases were selected from BSE images of multiple regions that were distributed over an entire section, except close to fusion crust. For O, a correction must be made to account for absorption by the C coat and the buildup of contamination on the SDD window since the last calibration. This was done by analyzing olivine and pyroxene grains in a section and adjusting the assumed coat thickness to obtain stoichiometric O contents.

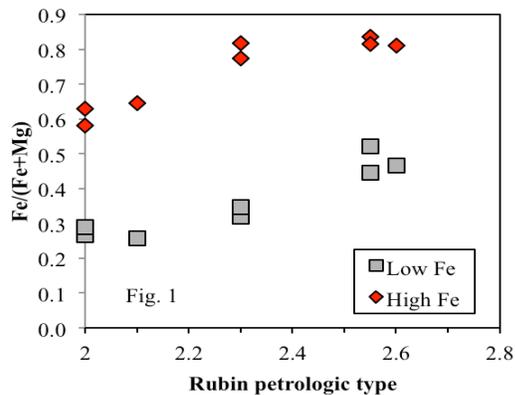
Similar to [3], analyses were rejected if totals <80 wt.%, or P>0.3 wt.%, Ca>0.5 wt.%, Cr>0.5 wt.% or S>3 wt.% to minimize the potential influences of phosphates, carbonates, chromites, sulfates, sulfides and tochilinite on the serpentine compositions. Ni/S ratios in most instances were higher than those seen in tochilinite in the same meteorites, suggesting that pent-

landite and Ni-bearing pyrrhotite are the main S-bearing components. Consequently, all S, Ni and Co were subtracted from the analyses along with the appropriate amount of Fe assuming that the sulfide is (Fe, Ni, Co)S. The average analyses were then converted to the stoichiometric serpentine formula  $(\text{Mg}, \text{Fe}^{2+}, \text{Fe}^{3+}, \text{Al})_6(\text{Si}, \text{Fe}^{3+}, \text{Al})_4$ , so that if the analyses were essentially pure serpentine their O abundances should be 18.

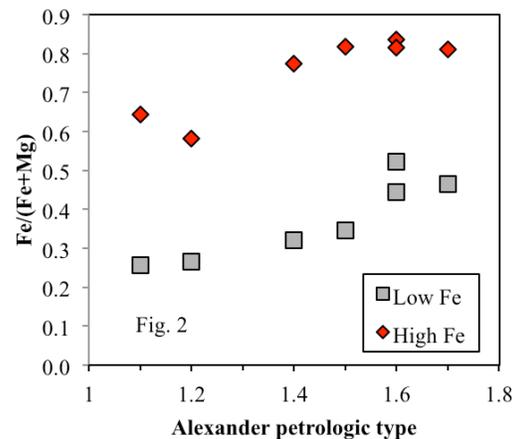
**Results and discussion:** Generally, for a single meteorite section the higher and lower Fe phases seem to be quite uniform. The higher Fe phase tends to give higher totals than the lower Fe phase, and totals in both phases tend to increase with increasing degree of alteration. This may in part reflect less porosity in the higher Fe phase, and crystal growth of both phases with increasing alteration. However, at least in the less altered meteorites C contents (not yet quantified) appear to be significantly higher in the lower Fe phase, suggesting that formation of the higher Fe phase led to the concentration of organic matter in regions dominated by the lower Fe phase.

Excluding O, both the higher and lower Fe phases have compositions that are consistent with stoichiometric serpentines. The higher Fe phase is dominated by a cronstedtite component, but it is by no means pure cronstedtite. On the other hand, the lower Fe phase is dominated by serpentine and greenalite components, although there is a significant cronstedtite content in the least altered samples.

The O contents of the two phases in the most altered samples scatter (17.88-18.39) about the stoichiometric value (18). This scatter probably largely reflects the accuracy of the technique. However, in the less altered samples the O contents are more varied (16.33-20.85). Whether this enhanced variability is because the phases in the less altered samples are more poorly crystalline, include non-serpentine minerals, or is an artifact associated with higher porosities, etc. is unclear at the moment.



The Fe/(Fe+Mg) ratios of the two phases both clearly correlate with degree of alteration, whether on the Rubin et al. scale (Fig. 1) or the Alexander et al. scale (Fig. 2). As noted by [4], the Fe content of the higher Fe phase is fairly constant in the less altered CMs, whereas the opposite behavior is seen in the lower Fe phase. Clearly, if the serpentine dominated phases are to be used for classification purposes, both the higher and lower Fe phases will have to be used together. However, a larger number of meteorites will need to be analyzed to determine just how well correlated the serpentine phase compositions are with other indicators of the degree of alteration.



Finally, a heated CM, EET 87522 [5], was also analyzed. The Fe/(Fe+Mg) ratios of both its serpentine phases are consistent with it being amongst the least altered samples studied here. On the reasonable assumption that provided that the impact heating does not cause recrystallization their bulk chemistries remain unaltered, it may be possible to use the serpentine phases to determine the pre-impact petrologic types. On the other hand, the O contents of both the higher and lower Fe phases (14.88 and 16.10, respectively) are less than the stoichiometric value. If analyses of more samples shows that this O deficiency is a consistent feature of heated CMs, the O contents of the phases may be another way to identify them and perhaps even to determine the relative intensities of the heating.

**References:** [1] McSween H.Y., Jr. (1979) *GCA*, 43, 1761-1770. [2] Van Schmus W.R. and Wood J.A. (1967) *GCA*, 31, 747-765. [3] Browning L.B. et al. (1996) *GCA*, 60, 2621-2633. [4] Rubin A.E. et al. (2007) *GCA*, 71, 2361-2382. [5] Alexander C.M.O'D. et al. (2013) *GCA*, 123, 244-260. [6] Garenne A. et al. (2014) *GCA*, 137, 93-112. [7] Howard K.T. et al. (2015) *GCA*, 149, 206-222. [8] Beck P. et al. (2014), *Icarus*, 229, 263-277.