

**CHARACTERIZING TYPE 1 AQUEOUS ALTERATION IN CM CARBONACEOUS CHONDRITES WITH MODAL MINERAL ABUNDANCES.** A. J. King<sup>1</sup>, P. F. Schofield<sup>1</sup> and S. S. Russell<sup>1</sup>, <sup>1</sup>Department of Earth Sciences, Natural History Museum, Cromwell Road, London SW7 5BD, UK. E-mail: a.king@nhm.ac.uk

**Introduction:** The CM carbonaceous chondrites are the most abundant meteorite group to have experienced low temperature aqueous alteration on asteroid parent bodies. They contain >10 wt% extra-terrestrial water and provide insights into the distribution and transport of volatiles in the early Solar System.

Most CM chondrites are classified as type 2 meteorites, consisting of partially altered anhydrous silicate clasts set within a fine-grained (<1 µm) matrix of phyllosilicates, oxides, Fe-sulphides and carbonates. A small number of CM chondrites suffered near-complete alteration and are classified as type 1 meteorites. The original mineral assemblage of these rocks has been transformed into secondary phases and they represent some of the most hydrated extra-terrestrial materials available for study. The CM1s are also of interest as they have been linked to the C-type asteroid Bennu [1]. In the next decade the OSIRIS-REx mission will return samples from the surface of Bennu to Earth. It has therefore become increasingly important to characterize the CM1 chondrites in order to help selection of sampling sites and provide context for the returned materials.

Position sensitive detector X-ray diffraction (PSD-XRD) has previously been used to determine the modal mineralogy of >20 CM2 chondrites [2–4]. Modal mineral abundances can be used to understand the nature and extent of hydration and support isotopic and spectral analyses. Here, we have used PSD-XRD to determine the modal mineralogy of 6 CM1 and 5 intermediate CM1/2 chondrites. Our aim was to infer for the first time variations in the degree of aqueous alteration in CM1 chondrites, and examine their relationship to the CM2s.

**Experimental:** Approximately 50 mg interior chips of the CM1 chondrites Grosvenor Mountains (GRO) 95645, LaPaz Icefield (LAP) 02277, Miller Range (MIL) 05137, MIL 07689, Northwest Africa (NWA) 4765 and Moapa Valley, and the CM1/2s LAP 031166, LAP 031214, MIL 090288, MacKay Glacier (MCY) 05231 and NWA 8534, were powdered and packed into aluminium wells. Modal mineral abundances were obtained using an INEL X-ray diffractometer with a curved 120° PSD. Meteorites were analyzed for up to 16 hours, and mineral standards under the same analytical conditions for 30 minutes. Phase quantification was achieved using a profile-stripping method and abundances were determined for phases present at >1 vol% and with uncertainties <5 vol% [e.g. 5].

**Results:** Crystalline phases identified in the XRD patterns of the CM1 and CM1/2 chondrites include gypsum, olivine, enstatite, carbonates, magnetite and Fe-sulphides. Diffraction peaks at ~12° and ~25° (2θ Cu Kα<sub>1</sub>), and broad features at ~19° and ~61°, are attributed to “Fe-cronstedtite” and “Mg-rich serpentine” respectively [2–4].

The CM1 chondrites contain abundant (84 – 91 vol%) phyllosilicate (Fe-cronstedtite + Mg-rich serpentine) with minor amounts of carbonate (≤0.2%), magnetite (2 – 3%) and Fe-sulphide (≤0.5%). Olivine abundances are 4 – 8 vol% but significant enstatite (2%) was only detected in NWA 4765.

In the CM1/2s the phyllosilicate abundance is 85 – 88 vol%, except for LAP 031214 (72%) and MCY 05231 (74%). All of the CM1/2 chondrites contain olivine and enstatite, with total anhydrous silicate abundances of 7 – 24 vol%, plus carbonates (~1 %), magnetite (2 – 3%) and Fe-sulphides (1 – 2%).

**Discussion:** *Degree of Aqueous Alteration.* Aqueous alteration transformed anhydrous silicates into phyllosilicates. LAP 02277, MIL 05137, MIL 07689, NWA 4765 and Moapa Valley contain the highest abundances of phyllosilicate (88 – 91 vol%) and lowest abundances of anhydrous silicate (4 – 6 vol%) (Fig. 1), consistent with their classification as CM1 chondrites. The phyllosilicate abundance of GRO 95645 is lower (85 vol%), and in better agreement with the CM1/2 chondrites LAP 031166, MIL 090288 and NWA 8534 (85 – 88 vol% phyllosilicate, ~7 % silicate). Assuming that the starting mineralogy was similar, the phyllosilicate fraction (total phyllosilicate abundance / (total anhydrous silicate + total phyllosilicate abundance)) can be used to infer the degree of hydration [4]. The phyllosilicate fraction defines an alteration sequence for these meteorites of GRO 95645 < MIL 090288 < NWA 8534 < LAP 031166 < NWA 4765 < LAP 02277 < Moapa Valley < MIL 07689 < MIL 05137. We note that as alteration increases so does the Mg-rich component of the phyllosilicate.

The CM1/2s LAP 031214 and MCY 05231 contain significantly less phyllosilicate (72 – 74 vol%) and more silicate (23 – 24 vol%) than the CM1s. Tochilinite was also identified in the XRD patterns and we suggest that these meteorites are CM2 chondrites.

*Magnetite.* Abundances increase from <1 vol% in the least altered CM chondrites to ~3 vol% in the CM1s (Fig. 2). Initially magnetite formed through the oxidation of Fe-metal [e.g. 6]. As alteration proceeded

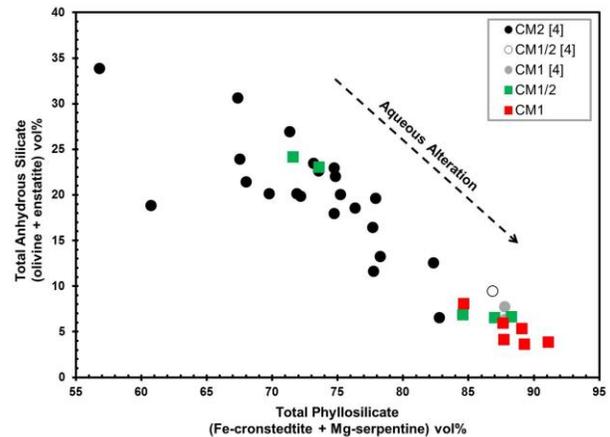
and the abundance of Fe-metal declined, the oxidation of Fe released from Fe-cronstedtite, and replacement of Fe-sulphides, were probably the dominant sources of magnetite [4, 7].

**Fe-sulphides.** The breakdown of tochilinite supplied S for the formation of Fe-sulphides [8]. However, there is only a weak correlation between the degree of aqueous alteration and the abundance of Fe-sulphides in CM chondrites. In contrast to [8], we do not observe a hiatus between the abundance of Fe-sulphide in CM1s and highly altered CM2s. The large scatter in the Fe-sulphide abundances could reflect local variations in the alteration conditions, post hydration brecciation or terrestrial weathering.

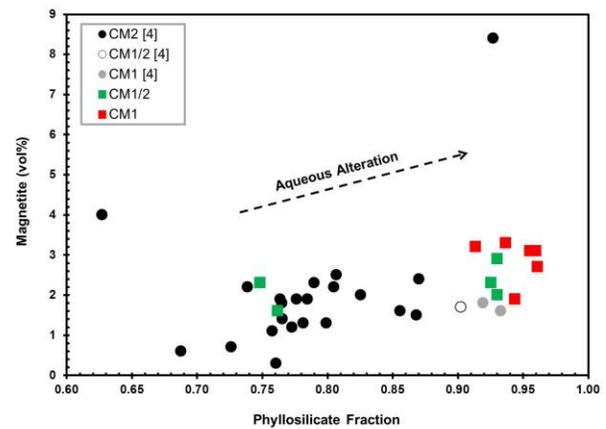
**Carbonates.** Previous studies have failed to recognize a correlation with the degree of alteration [9, 10]. Fig. 3 confirms that carbonate abundances are highly variable (<0.5 – 4.2 vol%) in the CM chondrites but, in agreement with [7], we observe that many CM1s and CM1/2s are depleted relative to CM2s. After initial formation, carbonate abundances likely declined during replacement by phyllosilicates and Fe-sulphides [10]. This process appears to have been more extensive in the CM1s, possibly because the duration of alteration was longer or the temperature was higher. The presence of dolomite and absence of tochilinite, which breaks down >120°C, in the CM1 chondrites favors the latter explanation [7, 10].

**Asteroid sample return.** C-type asteroid surfaces likely consist of materials that suffered varying degrees of aqueous alteration. Trends in the abundance and chemistry of phases within the CM chondrites can therefore be used to interpret returned samples. For example, if Bennu is “CM1”-like, we predict that samples will have a high abundance of Mg-rich phyllosilicates, oxides and Fe-sulphides but possibly be depleted in carbonates. Similarly, if they are more “CM2”-like, Fe-rich phyllosilicates will be common, whilst oxides, Fe-sulphides and carbonates will only be a small component.

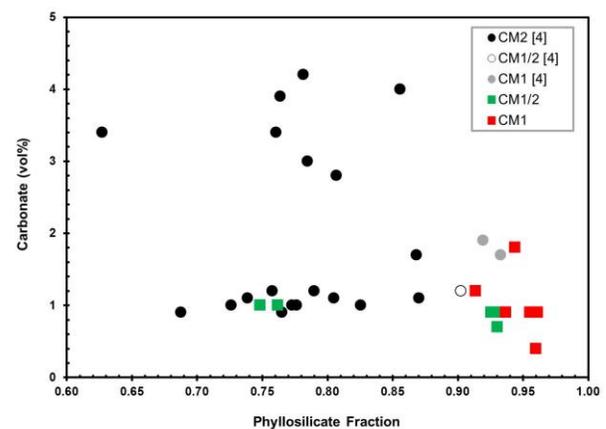
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**Figure 1.** The abundance of phyllosilicates and anhydrous silicate in CM chondrites can be used to infer the relative degree of aqueous alteration (e.g. [4]).



**Figure 2.** The abundance of magnetite increases with aqueous alteration in CM chondrites.



**Figure 3.** Many CM1 chondrites are depleted in carbonate relative to the less altered CM2s. This likely reflects aqueous alteration under higher temperatures.