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CORRELATED MODAL MINERALOGY, AQUEOUS ALTERATION AND OXYGEN ISOTOPE COMPOSITION OF CM CHONDRITES. K. T. Howard¹, G. K. Benedix¹, P. A. Bland^{1,2}, R.C. Greenwood³, I.A. Franchi³ and G. Cressey¹. ¹Impacts and Astromaterials Research Centre (IARC), The Natural History Museum, Mineralogy Department, London, SW7 5BD, United Kingdom. ²IARC, Dept. of Earth Sci. & Eng., Imperial College, London, SW7 2AZ, United Kingdom. ³Planetary and Space Science Research Institute (PSSRI), Open University, Milton Keynes, MK7 6AA, United Kingdom. E-mail: kieren.howard@nhm.ac.uk

Introduction: CM carbonaceous chondrites represent incompletely serpentinized fragments of primitive asteroids. They preserve a record of nebular and parent body processes evident in the range of anhydrous and hydrous mineral components of which they are composed. The CM chondrites are all dominated by fine grained, low-temperature, phyllosilicate from the serpentine family of minerals. These complexly intergrown phyllosilicates form by hydration of high-temperature anhydrous phases in CMs, namely olivine and pyroxene. Partially hydrated olivines and pyroxenes, mostly in chondrules, dominate the remaining mineralogy of CM samples with minor magnetite, sulphide and carbonate [1]. While the origin of phyllosilicate is clearly hydration of anhydrous silicates, the relationship between the remaining volumetrically minor anhydrous components and the amount of aqueous alteration is not well understood. In studying these minor components to understand aqueous alteration, assumptions must be made. For this reason we define aqueous alteration by the ratio of phyllosilicate to anhydrous silicate – since one forms from the other this is unambiguous. Previously such a scheme was impossible because the modal mineralogy of CM samples had not been defined beyond matrix:chondrule volume. This was simply a reflection of the limitations in defining modal mineralogy in fine grained breccias by optical methods. By Position Sensitive Detector X-ray Diffraction (PSD-XRD) we have defined the modal mineralogy of CM chondrites spanning the entire petrographic range [1,2] and we add to this data set here. One of the advantages of a complete modal mineralogy for phases present in abundances >1wt% is that it allows for evaluation of the relationship between mineral phases at a much broader scale than is possible in petrographic studies. Modal data also allows for examination of potential mineralogical controls on chemical and isotopic compositions and the evolution of isotopic systems. In this study we attempt to move beyond defining alteration sequences towards understanding the relationship between CM mineralogy, aqueous alteration and O-isotope compositions.

Expected relationship between aqueous alteration and the O-isotope composition of CMs: It is generally accepted that O-isotope systematics in CM chondrites can be understood as reflecting interactions between isotopically “light” anhydrous silicate and isotopically “heavy” fluid reservoirs [3,4]. Therefore the expectation is that with increasing aqueous altera-

tion, the oxygen isotope compositions of CMs should evolve towards heavier values [3,4,5]. This reflects incorporation of “heavy” fluid in phyllosilicate at the expense of “light” anhydrous silicates. Here we integrate modal and O-isotope data to test this model.

Samples and methods: We have determined modal mineralogy by PSD-XRD and a pattern stripping technique using mineral standards [1,2,6,9]. Lack of a tochilinite standard prevents determination of its abundance. Every modal determination represents an analysis of 180mm³ (~0.2g). Here we present modal data for the following samples (values in parenthesis equal number of 0.2g samples analysed). CM2 falls: Mighei (3), Murray, Murchison, Nogoya (2), Cold Bokkeveld (2). CM2 finds: QUE97990; ALHA81002; Y791198; QUE93005 (2); CM1/2: ALH83100; CM1: MET01070 (2); SCO06043. C2/ung: Essebi.

We have determined the O-isotope compositions of the following samples that had not previously been analysed: ALHA81002; MET01070; QUE97990; Y79119. All analyses were performed by laser fluorination following the method and in the same lab as described in [7]. Remaining oxygen isotope values are taken from the literature [3,4,8]

Results: The maximum volume of anhydrous silicate (olivine+pyroxene) in CM chondrites is ~30%. In all CM samples Mg-rich olivine is the dominant anhydrous phase with pyroxenes always comprising <10%. This reflects the fact that, even though pyroxenes may be less reactive than olivine during aqueous alteration, the initial abundance of pyroxene was much less than olivine - as for all the carbonaceous chondrites. CM1 samples may contain as little as 6% olivine, approximately the same as for Orgueil (CI) [9]. Regarding this point, it is important to note that TEM and XRD studies show CI phyllosilicate is different to the CMs in containing saponite as well as serpentines [9,10]. Therefore it is difficult to define a mineralogic continuum between CM and CI chondrites, which relates only to the extent of aqueous alteration, because the process involved was fundamentally different on the two parent bodies.

At this stage we do not attempt to define polytypes in CM serpentines beyond a relatively crystalline component producing high-intensity peaks at 12° and 25° (2θ CuKα) and a much more fine grained component corresponding to broad *hk* reflections. TEM studies [11,12] show the crystalline phases to be Fe-rich ser-

pentines generally larger in grain size (up to 2500 nm) than the intergrown, more Mg-rich serpentines that may be cylindrical or fibrous and smaller than 20 nm. These Mg-rich serpentines correspond to the broad reflections in XRD patterns that are typical of fine grain size phyllosilicate present as platy crystals consisting of only a few structural layers along [001]. For this study, the distinction between polytypes is not significant as we define alteration simply by the ratio of total phyllosilicate to anhydrous phases. The modal abundance of phyllosilicate ranges up to 90% in CM1 samples and averages 75% in CM2 samples. The ratio of phyllosilicate/anhydrous silicate varies from 2-6 in CM2 samples and 9-13 in CM1/2 and CM1 samples.

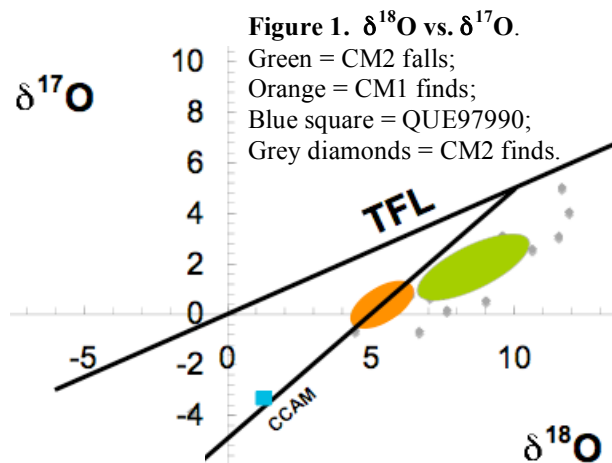
Oxygen isotope data from this and previous studies [3,4,8] are plotted in Fig. 1. In CM2 falls we observe a clear trend whereby as the phyllosilicate/anhydrous silicate ratio increases (increasing hydration), oxygen isotope compositions become steadily heavier. This is as predicted [3,4] and likely reflects equilibration of phyllosilicate with isotopically heavy fluid during hydration. The least altered CM2 sample QUE97990 plots in the CV/CK field. On petrographic grounds (e.g. chondrule size) the CVs and CKs are unlikely to be the anhydrous precursors of CMs, which are more often related to COs [3,4]. QUE97990 plots on the CM mixing line of [4], close to the COs and well away from other CM2 samples. It therefore appears to be an important link between these two groups. An unexpected finding is that more altered CM1/2 and CM1 samples are isotopically lighter than the CM2 falls and most Antarctic CM2 finds. This unexpected observation is apparent in our analyses but also in existing literature analyses of CM1/2 and CM1 samples [3,4,8]. O-isotopes in carbonates from CM2 samples also appear to become progressively lighter with increasing alteration [13]. The modal abundance of carbonate is very similar (<2vol%) in CM2 and CM1 samples and is not likely to be controlling O-isotope variations. Clearly these data require explanation, given that they appear to directly contradict existing models [3,4] for the evolution of O-isotope compositions in CMs during aqueous alteration.

Discussion: The paradoxical observation where more altered CM1 meteorites are isotopically lighter than CM2 meteorites is difficult to reconcile with these isotopic compositions having been inherited during alteration of CM2 and CM1 on a single parent body. This would require heterogeneous fluid compositions from the onset of alteration, or evolution of fluid compositions towards lighter values during late-stage alteration without this later fluid affecting CM2 samples. Models suggest variations in water:rock ratio should be reflected by variations in $\Delta^{17}\text{O}$ [3,4] but these values show no systematic differences between CM2 and CM1 samples, therefore differences in water:rock ratio

on the parent body also cannot explain these data. In the absence of a mechanism to create heterogeneous fluids on the CM parent body, or other independent non-isotopic evidence for separate parent bodies, an alternative explanation is required.

Exposure of meteorites to fluid during Antarctic weathering is well known to move O-isotope compositions toward lighter values [14]. This would be the simplest explanation for the lighter composition of CM1 samples relative to CM2 falls and most Antarctic CM2 finds. However, when Antarctic CM1 samples are compared to pristine CM2 falls in plots of $\delta^{18}\text{O}$ vs. $\Delta^{17}\text{O}$, there is little evidence for a significant isotopic shift in $\Delta^{17}\text{O}$ towards the TFL in the expected direction of Antarctic weathering [14].

We are currently undertaking additional O-isotope analyses to evaluate the extent of terrestrial contamination in CM1 meteorites. If CM1 isotope compositions indicate significant interaction with Antarctic precipitation, this raises the possibility that CM1 finds may actually be CM2 falls that were further hydrated on Earth.



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