THE OXYGEN ISOTOPIC COMPOSITION OF THE MOST AQUEOUSLY ALTERED CM CARBONACEOUS CHONDRITES.

A. J. King[1], R. C. Greenwood[2], J. M. Gibson[2], P. F. Schofield[1], I. A. Franchi[2] and S. S. Russell[1] [1]Department of Earth Science, Natural History Museum, London, UK, [2]Planetary & Space Sciences, The Open University, Milton Keynes, UK. E-mail: a.king@nhm.ac.uk

Introduction: The CM carbonaceous chondrites experienced low temperature (<100°C) aqueous alteration on a water-rich asteroid. Containing hydrated chondrules and calcium- and aluminium-rich inclusions (CAIs) set within a matrix of phyllosilicates, oxides, sulphides and carbonates, they provide a record of the nature and distribution of volatiles in the early solar system.

The CM chondrites span a petrologic range from partially altered type 2 meteorites to fully hydrated type 1 meteorites [e.g. 1]. Variations in the degree of aqueous alteration may be related to the duration of alteration, or differences in water/rock ratio and temperature. Oxygen isotopic compositions can be used to constrain the conditions of aqueous alteration on the CM parent body(ies). Clayton and Mayeda [2] proposed a model whereby isotopically "light" (low $\Delta^{17}O$) anhydrous silicates were altered by isotopically "heavy" (high $\Delta^{17}O$) fluids. In a closed system this should result in a correlation between bulk oxygen isotopic composition and degree of aqueous alteration, with the more altered meteorites having the heaviest compositions. However, several studies have argued that no such correlation exists [3–5], and the bulk oxygen isotopic compositions of the CM1 chondrites are typically lighter than those of the CM2s [2, 3, 6–9]. This lack of correlation implies that aqueous alteration of the CM chondrites may have occurred in an open system [e.g. 10], contradiciting evidence from relatively uniform elemental compositions [11].

To date bulk oxygen isotopic compositions have been reported for >30 CM2 chondrites but only five CM1 and four CM1/2 chondrites [2, 3, 6–9]. Here we present oxygen isotopic compositions for a further five CM1 and four CM1/2 chondrites previously characterized using X-ray diffraction (XRD) by [12]. Our aim is to better understand the relationship between bulk oxygen isotopic compositions and the degree of aqueous alteration, and infer the geochemical environment on the CM parent body(ies).

Experimental: King et al. [12] determined the bulk modal mineralogy of ~50 mg powders of the CM1 chondrites GRO 95645, LAP 02277, MIL 05137, MIL 07689, Moapa Valley and NWA 4765, and the CM1/2s LAP 031166, LAP 031214, MCY 05231, MIL 090288 and NWA 8534. The phyllosilicate abundances in these meteorites range from ~70 – 90 vol%.

Bulk oxygen isotope analysis of the CM1 and CM1/2 meteorites was performed by infrared laser-assisted fluorination in "single shot" mode at the Open University, UK [13, 14]. For each meteorite the reported oxygen isotopic composition is the average of two replicates each weighing ~2 mg. The precision of the system has been determined through analyses of an internal obsidian standard as ±0.053 ‰ for $\delta^{17}O$, ±0.095 ‰ for $\delta^{18}O$, and ±0.018 ‰ for $\Delta^{17}O$ (2σ) [15].

Results: The oxygen isotopic compositions of the CM1 and CM1/2 chondrites analysed in this study range in $\delta^{18}O$ by ~5 ‰ and $\delta^{17}O$ by ~3 ‰, and fall towards the isotopically light end of the CM2 mixing line (Fig. 1). The $\Delta^{17}O$ values of our samples range from −1.9 ‰ to −3.5 ‰. Previous analyses of CM1 and CM1/2 chondrites show a wider range of oxygen isotopic compositions ($\delta^{18}O$ by ~9 ‰ and $\delta^{17}O$ by ~6 ‰) that span the entire CM2 field [2, 3, 6–9]. We note that our values for Moapa Valley ($\delta^{17}O$ = 0.9 ‰, $\delta^{18}O$ = 6.4 ‰) are in good agreement with previous measurements ($\delta^{17}O$ = 0.8 ‰, $\delta^{18}O$ = 6.2 ‰, [7]), but that our results for NWA 8534 ($\delta^{17}O$ = 0.6 ‰, $\delta^{18}O$ = 5.9 ‰) differ from those reported by [8] ($\delta^{17}O$ = 4.4 ‰, $\delta^{18}O$ = 12.4 ‰). A linear least squares fit to our data gives $\delta^{17}O$ = −2.47 ± 0.44 + (0.53 ± 0.09) × $\delta^{18}O$ with R^2 = 0.79. However, excluding the data for LAP 031214 and MCY 05231, which [12] suggest are CM2 chondrites, the regression becomes $\delta^{17}O$ = −2.09 ± 0.21 + (0.48 ± 0.04) × $\delta^{18}O$ with R^2 = 0.94.

Discussion: Using the alteration scale of [16], which is based on the phyllosilicate fraction (PSF) (total phyllosilicate abundance / (total anhydrous silicate + total phyllosilicate abundance)) of a CM chondrite, we broadly find that bulk oxygen isotopic compositions get progressively heavier with hydration from petrologic sub-type 1.6 to 1.3 (i.e. the CM2s). The oxygen isotopic compositions of CM chondrites of petrologic sub-type 1.2 and 1.1 (i.e. the CM1s and CM1/2s) then move back towards lighter values. The same correlation is observed if we apply the the petrographic alteration scale of [1] and has also been reported in the CR chondrites [17].

Two issues complicate the relationship between bulk oxygen isotopic compositions and the degree of aqueous alteration in CM chondrites. Firstly, many CM chondrites are regolith breccias and oxygen analyses of separate chips can yield very different compositions. An example of this intra-sample heterogeneity is seen

for NWA 8534, with a difference of ~4−6 ‰ between our measurements and [8]. Secondly, terrestrial weathering can significantly influence oxygen isotopic compositions. Most CM2 and all CM1 and CM1/2 chondrites are finds recovered from Antarctica or hot desert environments. Antarctic weathering moves oxygen isotopic compositions towards the terrestrial fractionation line (TFL) and lower δ^{18}O values, whereas hot desert weathering leads to higher δ^{18}O values [18, 19]. Fig. 2 shows that the Antarctic CM1 and CM1/2 chondrites analysed in this study have low δ^{18}O values and are shifted towards the TFL; however, our hot desert meteorites are not shifted to higher δ^{18}O values, in contrast to previous measurements [2, 8, 9]. Furthermore, the CM1 and CM1/2s in this study fall on a line of slope 0.48 ± 0.04, unresolvable from a mass fractionation line and also consistent with terrestrial weathering. The effects of weathering appear to be more severe for the most aqueously altered meteorites, probably because they contain a higher abundance of fine grained phyllosilicates, which have a larger surface area-to-volume ratio and are therefore more susceptible to exchange with terrestrial fluids [e.g. 17].

If we assume that prior to terrestrial weathering the bulk oxygen isotopic compositions of the CM1 and CM1/2 chondrites fell on the CM mixing line (slope ~0.7), then we can infer that the values were likely still lighter than many CM2s, contradicting the hydration model of [2]. Petrographic observations of CM1 and CM1/2 chondrites indicate that the last phases to be attacked by fluids were Mg-rich olivines and pyroxenes in chondrules with low Δ^{17}O values (−3 to −7 ‰) [20]. One explanation therefore is that the fluids from which the phyllosilicates formed during the last stages of alteration were isotopically ^{16}O-rich. Alternatively, the initial isotopic composition of the anhydrous components and altering fluids for the CM1 and CM1/2 chondrites differed from those of the CM2s, possibly because they are derived from a separate parent body. Pristine samples returned by the OSIRIS-REx mission from the surface of Bennu, which has affinities with the CM1 chondrites, will help shed light on the formation of the most aqueously altered meteorites.

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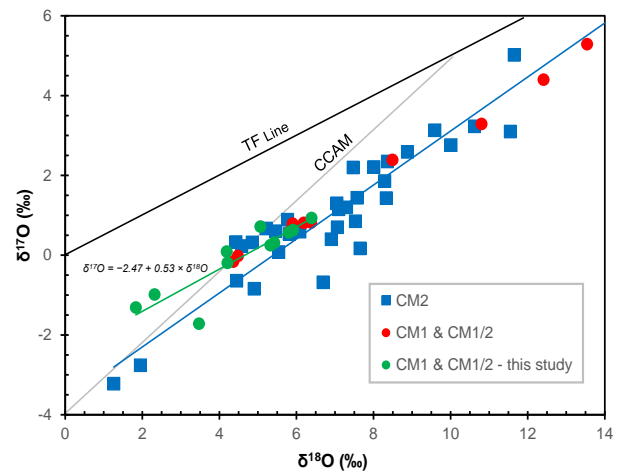

Figure 1. *Three-oxygen isotope plot for CM1, CM1/2 and CM2 chondrites analysed by [2, 3, 6–9] (including multiples of the same meteorite), and the CM1 and CM1/2s analysed in this study.*
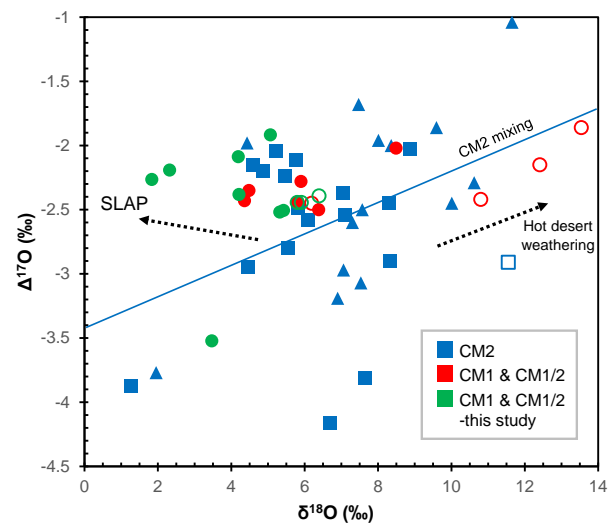

Figure 2. *$\delta 18O$ vs. $\Delta 17O$. Triangles represent falls, closed circles represent Antarctic finds, and open circles represent hot desert finds. Data are from this study and [2, 3, 6–9], and include multiples of the same meteorite. The arrows indicate the predicted shift in oxygen isotopic compositions caused by Standard Light Antarctic Precipitation (SLAP, $\delta^{18}O = -55.5$ ‰, $\Delta^{17}O = 0$ ‰), and hot desert weathering.*