TWO RECENT CM FALLS: NEW EVIDENCE FOR A LITHOLOGICALLY AND ISOTOPICALLY HETEROGENEOUS CM PARENT BODY.

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Introduction: The CM carbonaceous chondrites (CCs) are a diverse group of meteorites which occupy a spectrum of mineralogical variation as a result of aqueous alteration and thermal metamorphism [1]. The degree of modification is expressed as a petrologic type, ranging from partially altered CM2s to fully altered CM1s [1, 2]. The nature, or even number, of CM parent bodies remains unclear, in part due to the large variation between CM specimens [1, 3]. However, it is apparent that individual samples also exhibit strong intra-sample variation [4]. Many CMs are complex breccias containing multiple lithologies (as clasts) that reflect varying degrees of alteration [4, 5, 6]. This mineralogical heterogeneity is reflected in large oxygen isotopic variations, as a result of the very different signatures of the original anhydrous precursor silicates and the water-ice that originally accreted into these parent bodies [1, 7].

Herein lies a considerable sampling problem, as bulk analyses of the same meteorites often yield isotopic compositions far apart on the slope ≈ 0.7 CM array [8]. A further challenge is the increased susceptibility of these very fine-grained samples to modification in the terrestrial environment, prior to collection and even subsequently once the material has been curated. Interaction with meteoric water and atmospheric oxygen have the potential to significantly impact the measured oxygen isotopic signature. CM2 falls are rather rare. However, two recent CM2 falls, Aguas Zarcas (AZ) and Mukundpura (MP), including a dark clast which bears similarities to a CM1-like lithology, offer a new opportunity to better understand the isotopic variation within these samples and implications for the nature and evolution of their parent body.

Materials and Methods: Two polished blocks of AZ and one polished block of MP were studied using a FEI Quanta 200 3D scanning electron microscope (SEM). Bulk mineralogy of the powders was determined using X-ray diffraction (XRD) at the Natural History Museum, London. Oxygen isotopic compositions were made using the "single shot" laser fluorination method, where only one sample and one standard are loaded per tray, thus reducing the effect of reaction with BrF_5 at room temperature [9]. Powdered and homogenized chips of AZ (500 mg) and MP (200 mg) were prepared, from which a few mg were used for analysis. Several mg was also sampled from a dark, lozenged-shaped clast found in the MP hand specimen by gently scraping with a stainless steel spatula.

Results and Discussion: AZ and MP are diverse regolith breccias [5]. MP appears more altered than AZ, owing to a greater abundance of phyllosilicate and poorly characterized phase (PCP) throughout its clasts [1]. Our sample contains chondrule-rich and chondrule-poor lithologies/clasts [8], exhibiting varying degrees of aqueous alteration. A large (cm-sized) clast of chondrule-free, dark, fine-grained material is also present. However, to-date only the chondrule-rich lithologies were examined by SEM.

XRD patterns indicate that the bulk mineralogy of both AZ and MP are typical of CM2s, with diffraction peaks for olivine, enstatite, phyllosilicates (including Mg serpentine and Fe cronstedtite), magnetite and carbonates present (Fig. 1) [10, 11]. Our measurements of AZ and MP are similar to other CM falls having been recovered before terrestrial alteration (Fig. 1). The pattern from the dark clast in MP indicates an absence of olivine, enstatite, tochilinite and high abundance of magnetite, consistent with the high degree of aqueous alteration seen in the CM1s (Fig. 1) [13, 14]. The clast may therefore be "CM1-like".

Our oxygen isotope analyses of bulk AZ plot within the CM2 field ($\delta^{17}O$ = 0.98, 0.76; $\delta^{18}O$ = 7.39, 7.06) but are ~ 4‰ lighter in $\delta^{18}O$ and span a smaller range than those published in the Meteoritical Bulletin [8] (Fig. 2). Further analyses of AZ on a third set of samples have intermediate compositions [12] highlighting the significant (~6‰) oxygen isotope heterogeneity in AZ specimens. This isotopic variation is likely also reflected in significant mineralogical differences, and

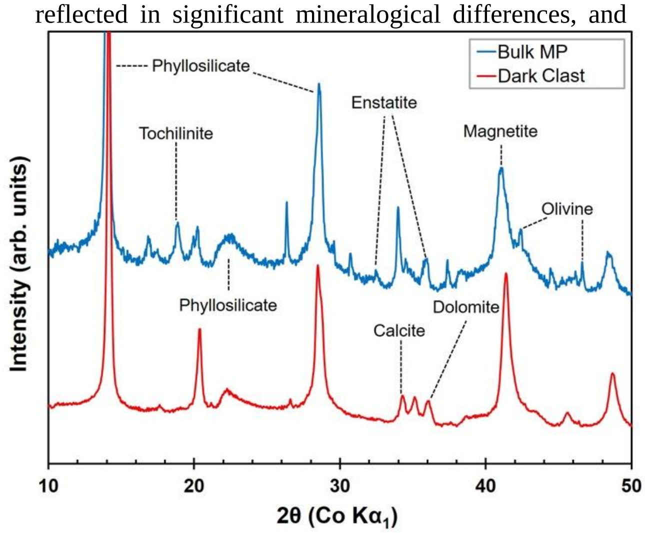

Fig. 1. *XRD patterns for bulk Mukundpura and the dark CM1–like clast.*

therefore caution is required integrating findings from different studies. Further study of AZ on the clast scale is therefore needed to better constrain the aqueous and thermal history of its parent body.

Bulk MP plots in the CM2 field close to AZ ($\delta^{17}O$ = 1.55, 1.42; $\delta^{18}O$ = 7.87, 7.52). The oxygen isotopic composition is slightly heavier than that of AZ, consistent with the less altered nature of this sample. However, the oxygen isotopic composition of the dark clast in MP is ~1.5‰ lighter in $\delta^{18}O$ than the bulk ($\delta^{17}O$ = 0.769; $\delta^{18}O$ = 6.08) and lies within a cluster of CM2 finds and CM1 and CM1/2 samples (Fig. 2).

Previous CM1 and CM1/2 oxygen isotope measurements define a slope of 0.48 in three isotope space [13, 14, 15, 16] (Fig. 2), and appear isotopically lighter compared to CM2s. As many CM1s are Antarctic finds, this slope was attributed to possible terrestrial weathering as a result of interaction with isotopically light Antarctic precipitation [11, 17]. The MP chip and associated dark clast was from a stone recovered shortly after falling, prior to exposure to any rainfall and therefore with minimal exposure to terrestrial weathering, and therefore, uniquely, the oxygen isotopic composition of this CM1-like material cannot be attributed readily to terrestrial effects. While many CM1s have certainly been extensively weathered to lighter values, this result from CM1-like fall material indicates that CM1s may indeed be isotopically lighter than CM2s [13, 14, 18]. Owing to the fact that MP is a regolith breccia [5], there is a good probability that the clast is derived from the same parent body as the CM2 host, demonstrating that a considerable range of aqueous alteration phenomena can be produced on a single parent body. The observed isotopic evolution from isotopically heavy, less altered CM2s to isotopically less heavy, more altered CM1s is difficult to accommodate within a closed system type of alteration [e.g. 3], and may require a complex evolution of an open system model of aqueous alteration such as proposed by [7]. However , some caution may be required as CM-like material is found in a range of solar system materials such as HEDs, lunar rocks, and ordinary chondrites [18, 19], and therefore the possibility of the clast being sourced from a different parent body cannot be excluded. Improved understanding of the provenance of CM1-like material to determine its relationships to CM2 material is required to understand the full implications of the observed complex oxygen isotope relationships between these two meteorite types.

The nature of CM breccias and implications for sample return: Conservative (and justified) selective sampling of precious meteorite material has resulted in an oxygen isotope heterogeneity problem. Oxygen isotopic measurements of regolith breccias, including

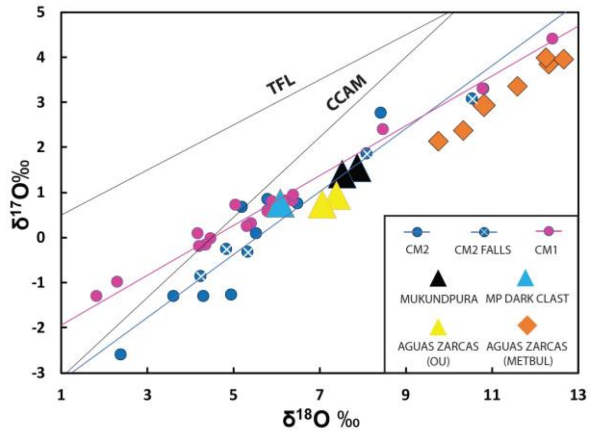

Fig. 2. *Oxygen isotopic composition of CM2 (slope 0.7) [18] and CM1 – CM1/2 chondrites (slope 0.48) [13, 14, 15, 16]. Coloured triangles are the CM and CM1- like lithologies measured in this study.*

CM2s can display large variations in oxygen isotopes (Fig. 2). This study has further emphasised that these variations are tied to mineralogical differences and different alteration/thermal histories. Consequently, great care is required in interpreting results acquired from different portions of the same sample, or even sampled at different scales. Examples of where such concerns may be important is in interpreting spectroscopic imaging of Bennu and Ryugu with the samples returned by OSIRIS-Rex and Hayabusa2 respectively. Furthermore, the results of this study highlight the challenge presented by complex breccia/regolith samples and the importance of understanding the provenance of individual clasts in order to develop an understanding of the alteration history of the parent asteroid.

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