LITHOLOGICAL DIVERSITY OF A C-COMPLEX ASTEROID RECORDED IN LON 94101 R. Findlay[1,2], I. A. Franchi[1], M. E. Zolensky[3], R. C. Greenwood[1], M. Anand[1,4], A. J. King[4], M. D. Suttle[1] and J. Malley[1]. [1]*Planetary and Space Sciences, School of Physical Sciences, Open University, Milton Keynes, MK7 6AA.* [2]*Department of Earth Sciences, University of Cambridge, Downing site, Cambridge, CB2 3EQ (arwf2@cam.ac.uk).* [3]*ARES, NASA Johnson Space Center, Houston, TX, USA.* [4]*Planetary Materials Group, NHM, London, SW7 5BD.*

Introduction: CMs are the most common carbonaceous chondrite type, providing a wealth of information about the formation and aqueous alteration of primitive asteroids. Owing to their brecciated nature and possible rubble pile heritage, CMs host many lithologies [1]. Indeed, recent results from Hayabusa2 and OSIRIS-REx have revealed a plethora of boulder types on the surface of C-complex asteroids [2], from which most carbonaceous chondrites are likely derived, attesting to the complex history individual asteroids have experienced. Deciphering the relationships between lithologies, particularly when drawing upon multiple meteorites remains challenging, as C-complex asteroids are very common, and multiple asteroids could be providing similar materials.

The aqueously altered clasts in CMs are expressed as a 'petrologic range' from fully altered CM1s to partially altered CM2s [3, 4]. This is reflected in large bulk O-isotope variations, within and between meteorites, along a slope ~0.7 array in 3-isotope space (e.g., Fig. 2 and [5]). In large part, the observed O-isotope variation is likely driven by variable quantities of anhydrous precursor silicates that have very different isotopic signatures to the water ice that contributed to the formation of the secondary minerals.

Lonewolf Nunataks 94101 (hereafter 'LON') is a minimally weathered, Antarctic CM find [6]. While all CM2s have clasts [3, 4], LON is exceptional [7, 8], with every section appearing different [7]. This offers an opportunity to study CM parent body heterogeneity in detail, as it can be argued that the clasts have a high probability of being derived from the same asteroid [9]. Furthermore, the diversity of materials in LON provides a means to investigate the formation of secondary rubble piles and the alteration history of the primary parent asteroid(s), exploring aspects such as whether the alteration occurred in closed systems [5] or more complex open system scenarios [10, 11].

Materials and method: A single 42 g piece of LON 94101-4 was mounted as a large epoxy block, scanned by X-ray CT at UT High-Resolution X-ray CT Facility, and then cut in half. One half was investigated by SEM and the cosmic ray exposure ages were determined for individual clasts [6,7]. The mirror half is described here. To aid SEM investigation the block was lapped at the NHM, London, and then back scattered electron SEM images were acquired using a Zeiss Crossbeam 550 FEGSEM at The Open University. Samples of the

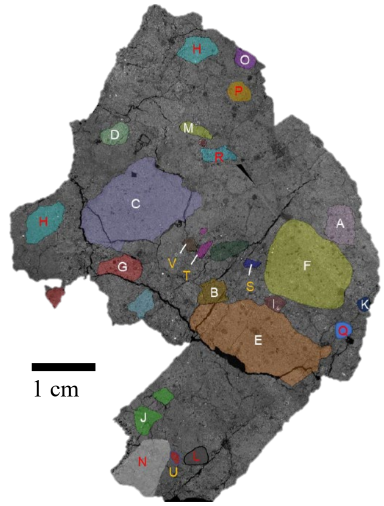

Figure 1 – *Large BSE montage of LON 94101-4. Each colour represents an individual CM lithology type ranging from CM2.0 (CM1) – CM2.8.*

matrix (~200 µg) within each distinct lithology were then extracted using a New Wave MicroMill and a 500 µm, tungsten carbide ball point bit, drilling dry at low speed. O-isotope analysis of the matrix was undertaken via laser-assisted fluorination using our modified 'single shot' mode [12]. Small sample 2σ precision is ±0.11 ‰ for δ^{17}O-, ±0.20 ‰ for δ^{18}O and ±0.04 ‰ for Δ^{17}O (n=23).

Petrography: LON displays examples of all CM petrologic grades from CM2.0 (CM1) – CM2.8 (Fig. 1). At least 72 individual clasts were observed, from which 19 lithologies, each representing a unique clast, were selected for further research.

CM2 lithologies: Ten CM lithologies spanning CM2.1-2.8 were investigated (e.g., Fig. 1). Tochilinite-Cronstedtite morphology and chemistry (e.g., 'FeO'/SiO_2); phyllosilicate, carbonate, sulphide composition; and chondrule alteration extent were used to define petrologic subtypes [4, 13]. LON also contains weakly altered lithologies, such as a large, ~1 cm^2 CM2.8 clast akin to the recently identified Asuka CM chondrites [14], as well as diverse, matrix-rich clasts of variable alteration and petrologic grade.

CM2.0/CM1 lithologies: CM2.0 / CM1 (hereafter, CM1) lithologies are common throughout the sample, dominated by chondrule pseudomorphs, Mg-rich phyllosilicates, Mg-carbonate and typically an absence of tochilinite. Three instances of a CM1 lithology with a high concentration of pyrrhotite laths surrounding chondrules resemble the recent C1 fall, Flensburg [15].

CMm material lacking coarse grained objects: The large surface area of the sample revealed many unusual, 3-4 mm^2, matrix-rich clasts dubbed 'CMm'. This clast subset is dominated by those showing pervasive, near complete alteration (CM1m), though less altered examples also exist. These clasts have low BSE contrast and no chondrule pseudomorphs, with the mineralogy governed by Mg-rich matrix, Mg-rich carbonate, and abundant magnetite framboids that sometimes form veins. They could be 'CM-like Dark Inclusions' (DIs), although they are highly altered, in contrast to the partially altered DIs found in CV3s [16].

Oxygen isotopes: Fig. 2 shows the spatially resolved, triple O-isotope composition of the phyllosilicate matrix in 19 lithologies. Collectively, LON matrix displays a 12 ‰ range in $\delta^{18}O$ spanning much of the known CM array. The ^{16}O-rich material is derived from the least altered clasts that sample anhydrous minerals which are enriched in ^{16}O and fall near to CCAM line or the ^{16}O-rich portion of the slope ~0.7 CM array. The remaining matrix samples, which include little or no anhydrous precursors, display little variation in $\Delta^{17}O$. Within this dataset, the CM2s broadly define a pattern of increasing $\delta^{18}O$ with increasing degree of alteration. Paradoxically, CM1 clasts in LON have lower $\delta^{18}O$ values than the CM2s, in line with the majority of published CM1 datasets [17]. CM1m clasts display a wide range of $\delta^{18}O$ values.

Discussion: A linear regression through all matrix phyllosilicate points (excluding the anhydrous clasts) defines a slope of 0.55, indistinguishable within error from a mass-dependent fractionation line (Fig. 2). The scatter is large, greater than analytical certainty, but some of this may reflect weathering or traces of anhydrous precursor. Overall, this limited range in $\Delta^{17}O$ is a result of our sampling method which seeks to exclude chondrules, CAIs and other large grains that may contain ^{16}O-rich anhydrous phases. The apparent mass-dependence is poorly explained by a two-component closed system mixing model, as proposed by [5], which predicts variable $\Delta^{17}O$ values for phyllosilicates derived from different lithologies with variable starting materials and water-rock (WR) ratios. Instead, the opposite is observed, suggesting a single dominating process is linking the phyllosilicates in all aqueously altered clasts, possibly a similar range of WR ratios encompassing one large alteration event, at least when considering the volume of material altered. This characteristic thereby causes near invariant $\Delta^{17}O$ (Fig. 2), while variable alteration conditions (e.g., temperature and mineralogical controls) impart different $\delta^{18}O$ values. The exact mechanism behind the O-isotope data is challenging to decipher, but an open system contained within an asteroid could be one possibility, where fluid was well mixed throughout a network of cracks. Such cracks are poorly represented in the meteorite record, but large carbonate veins in boulders on Bennu suggest they exist on C-complex asteroids [19]. We cautiously postulate such a network may have produced all of LON's clasts through an asteroid-wide or locality-wide alteration event encompassing a range of accreted textures — at a later stage to the event recorded by T1 carbonate data, but possibly congruent with T2 carbonate data [e.g., 20]—wherein a relatively consistent WR ratio was facilitated. The narrow range in $\Delta^{17}O$ is distinctive and provides grounds for arguing these samples originate from a heterogeneously accreted and altered parent body.

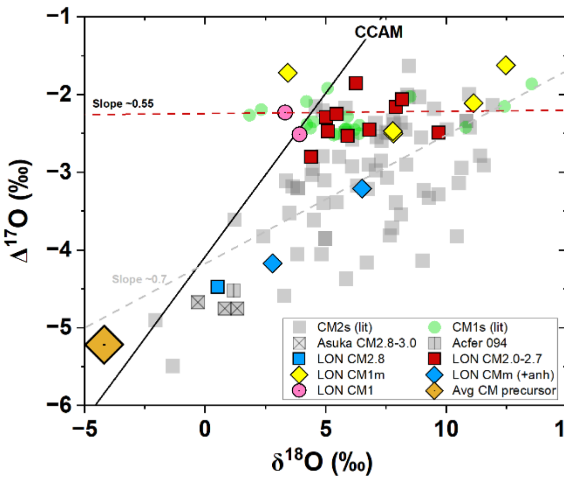

Figure 2 – *LON 94101 O-isotope data. CM2 data [5, 12] and references therein. Asuka CM2 data [14]. CM1 data [17] and references therein. Acfer 094 data [18]. CM precursor data is from [5]. 2σ uncertainty is within symbols.*

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