MOONMILK IN THE CARBONACEOUS CHONDRITES M. R. Lee[1], B. E. Cohen[1], A. J. King[2], R. C. Greenwood[3] and J. Gibson[3] [1]School of Geographical and Earth Sciences, University of Glasgow, G12 8QQ, U.K. (Martin.Lee@Glasgow.ac.uk). [2]Department of Earth Science, Natural History Museum (London), Cromwell Road, London SW7 5BD, U.K. [3]Planetary and Space Sciences, Open University, Walton Hall, Milton Keynes MK7 6AA, U.K.

Introduction: The CM carbonaceous chondrites typically contain a few per cent by volume of carbonates. These minerals have formed during aqueous alteration, and in spite of their low abundance are powerful tools for understanding parent body evolution. For example, they have been used for absolute dating of aqueous alteration [1], and for exploring parent body thermal evolution [2] and hydrology [3]. Almost all CMs contain calcite; those that have been mildly aqueously altered additionally have aragonite, and the heavily altered ones commonly host dolomite and occasionally also breunnerite [4]. These minerals typically occur as small equant grains in the matrix, but calcite can also replace chondrules and calcium- and aluminium-rich inclusions (CAIs) [4].

There is a considerable debate around the timing of carbonate crystal growth relative to aqueous alteration (e.g., formation only at an early stage, or sporadically during fluid/rock interaction), and the source(s) of oxygen and carbon [5]. In order to better understand the determinants of carbonate formation, we have studied Lewis Cliff (LEW) 85311. This is a very mildly aqueously altered CM and so has the potential to provide new insights into the early stages of fluid/rock interaction. We find that most of the carbonate in this meteorite is closely comparable to 'moonmilk', which is finely crystalline needle-fibre calcite that occurs in terrestrial caves and burial tombs [e.g., 6,7].

Materials and methods: LEW 85311 is an Antarctic find with a mass of 199.5 g and weathering grade of Be. Three polished thin sections were studied: LEW 85311,31, …39 and …90. Imaging and quantitative X-ray microanalysis used a Zeiss Sigma SEM at the University of Glasgow. Electron-transparent samples for TEM imaging and selected area electron diffraction were prepared using the focused ion beam technique. Subsamples of LEW 85311,85 were used to determine modal mineralogy (by PSD-XRD at the Natural History Museum (London)), and bulk oxygen isotopic composition (by laser fluorination at the Open University).

LEW 85311 petrography and mineralogy: This meteorite is comprised of chondrules (25.2 vol. %) and CAIs (0.2 vol. %), both of which have fine-grained rims (30.7 vol. %). These objects are embedded in a polymineralic matrix (43.9 vol. %). The bulk mineralogy of LEW 85311, and its chemical and isotopic composition, is consistent with mild aqueous alteration. Specifically, PSD-XRD shows that it has a phyllosilicate fraction of 0.67 (Table 1), corresponding to a subtype of 1.7 on the scale of Howard et al. [8]. LEW 85311 contains 0.80 wt. % H in water/OH, which equals a petrologic subtype of 1.9 on the scale of Alexander et al. [9], and it has also been provisionally classified CM2.6/2.7 relative to Rubin et al. [10].

Table 1. Modal mineralogy of LEW 85311 as determined by PSD-XRD (vol. %)

Phyllosilicate	64.8
Olivine	21.4
Enstatite	10.1
Magnetite	1.2
Sulphate	1.7
Fe-sulphide	0.5
Metal	0.3

The bulk oxygen isotopic composition of LEW 85311 is $\delta^{17}O$ -5.98 ‰, $\delta^{18}O$ -2.07 ‰, $\Delta^{17}O$ -4.90 ‰, which falls within the CV-CK-CO field. Although the CM classification is therefore questionable, it is retained here owing to the petrographic and mineralogical similarities of this meteorite to mildly altered CMs.

Carbonates: Carbonates are rare, and were not detected by PSD-XRD. Point counting of LEW 85311,39 found 0.2 vol. %, and [5] measured 0.03 wt. % of carbonate-hosted C in a bulk sample. SEM shows that scarce and small crystals of Ca-carbonate occur in the matrix, and Ca-carbonate is also present in a melilite-bearing CAI.

Moonmilk. The three studied thin sections all contain a variety of calcite that has not been previously described from a meteorite but is very similar in appearance to terrestrial moonmilk. The moonmilk in LEW 85311 comprises needle-fibre crystals of calcite that occur within objects that are typically more than 100 μm in size and have a fine-grained rim. A few of these objects are type I chondrules, and the moonmilk normally occurs in patches close to their edge (Fig. 1a). Moonmilk is the principal constituent of the other objects within which it is usually associated with kamacite (Fig. 1b), troilite and P-bearing sulphides.

Moonmilk calcite crystals are ~18 μm long by 2 μm wide. They may be straight or curved, and some crystals curve to such an extent that they are almost circular (Fig. 1c). The fibres are oriented randomly relative to each other to make a structureless meshwork (Fig. 1c). TEM shows that the fibres are calcite with a low density of defects and no inclusions.

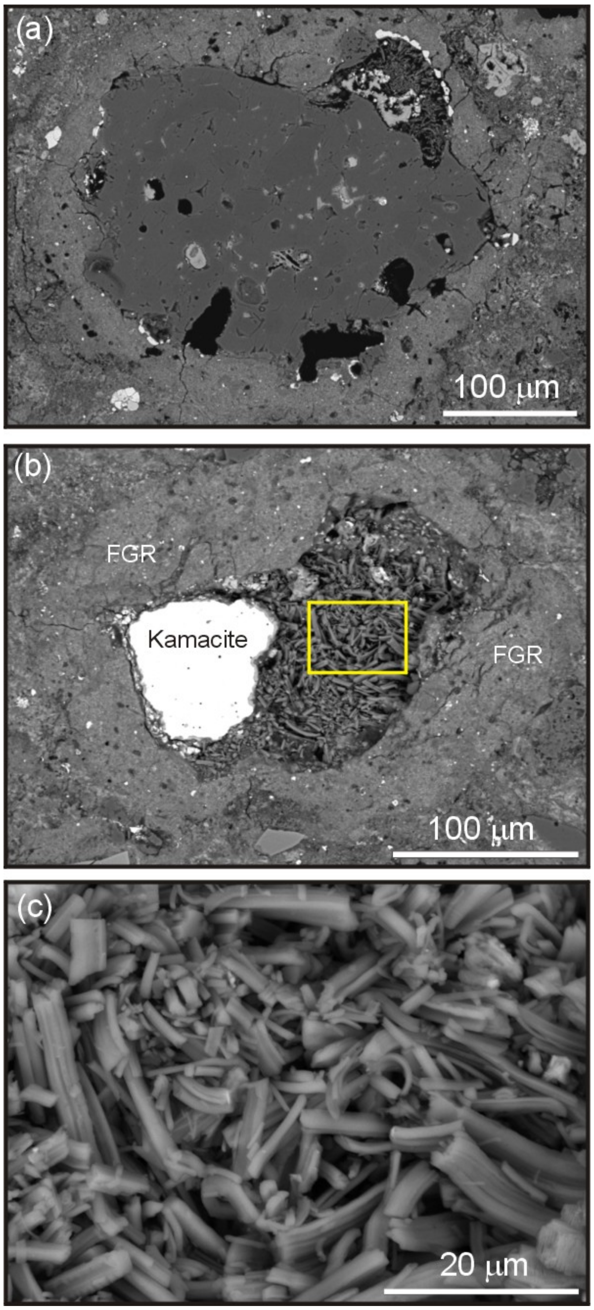

Fig. 1. Backscattered electron SEM images of moonmilk. (a) A type I chondrule in LEW 85311,31. A patch of moonmilk lined by troilite crystals (white) projects from its upper right hand edge. (b) An object in LEW 85311,90 that consists of kamacite and moonmilk calcite, and is enclosed by a fine-grained rim (FGR). (c) Detail of moonmilk fibres from the boxed area in (b). Many of these fibres are themselves made of stacked calcite needles.

Discussion: The moonmilk is a porous and fragile meshwork of calcite fibres, yet is the main constituent of objects that accreted fine grained rims in the solar nebular. The calcite fibres are therefore interpreted to have filled pore spaces that had formed after these objects had been incorporated into the parent body. As the calcite is always associated with kamacite or its alteration products (i.e., P-bearing sulphides), the pores are interpreted to have been created by dissolution of Fe,Ni metal. This metal is assumed to have been dissolved by reducing fluids in a parent body environment; the alternative of Antarctic weathering is unlikely because alteration of kamacite by oxidizing Antarctic meltwater forms Fe (oxy)hydroxides [11].

The pore spaces could have been filled by calcite fibres during parent body aqueous alteration or accompanying Antarctic weathering. There is currently no evidence to unambiguously distinguish between these two possibilities. Nonetheless, the size and shape of the fibres is indicative of rapid crystal growth from supersaturated solutions. Such conditions are consistent with an origin by evaporation during terrestrial weathering, and in this context it is notable that Lewis Cliff meteorites have an “above average” abundance of evaporate minerals [12], in agreement with the Be weathering classification of LEW 85311.

Conclusions: LEW 85311 is unique among the carbonaceous chondrites described to date in containing objects composed of needle-fibre calcite crystals that are very similar in appearance to terrestrial moonmilk. An origin by Antarctic weathering is more likely than parent body aqueous alteration, but this interpretation would be bolstered by further work including carbon and oxygen stable isotope analysis of the calcite.

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