TRACKING THE EARLIEST STAGES OF AQUEOUS ALTERATION IN THE MILDLY ALTERED CM CHONDRITE EET 96029. P. Lindgren and M. R. Lee, School of Geographical and Earth Sciences, University of Glasgow, Gregory Building, Lilybank Gardens, G12 8QQ Glasgow, UK. Paula.lindgren@glasgow.ac.uk

Introduction: The earliest stages of CM carbonaceous chondrite aqueous alteration are very poorly understood as mildly altered CMs are extremely rare. The Paris meteorite (CM2.7) [1-3] and QUE 97990 (CM2.6) [4,5] are among the least aqueously altered CMs described to date. However, neither of them contain the pristine attribute of chondrule mesostasis glass. Glass is highly reactive and so among the very first phases to undergo aqueous alteration [6]. Therefore, the CM carbonaceous chondrite EET 96029 is very unusual as it has been shown to have retained mesostasis glass in at least one chondrule [7]. According to the new CM classification scheme of [8], which is based on H content, EET 96029 has an index of 2.0 (data in [9]), meaning that it is less altered than all but one of the fifty CMs analysed by [8]. A caveat is that a low H content could be due to mild heating as well as a low degree of aqueous processing [9]. However, the bulk O oxygen isotope composition of EET 96029 (as determined by [10]) is consistent with a low degree of alteration as it is slightly closer to that of the CO3 falls (possible representatives of the anhydrous progenitors of the CMs) than even the least altered lithology of Paris (Fig. 1).

To better understand the earliest stages of CM aqueous alteration and its impact on mesostasis glass, we have undertaken a detailed study of chondrule mesostasis textures and compositions in the mildly aqueously altered CM chondrite EET 96029.

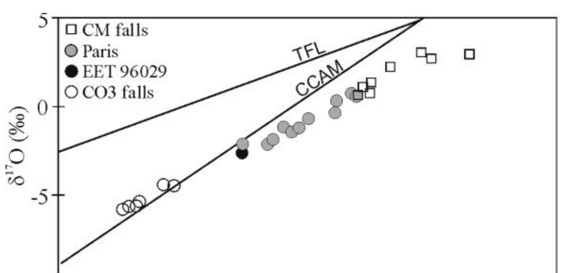

Fig. 1. The oxygen isotope composition of EET 96029 [10] compared with CM and CO3 falls [11], and multiple subsamples of Paris [2].

Methods: One polished thin section, EET 96029,9, was coated with carbon prior to BSE imaging and quantitative elemental ED X-ray analyses using a field emission Zeiss Sigma SEM operated at 20 kV. We selected well-defined chondrule types (porphyritic IA, IB and IIA) for analyses of their mesostasis and primary mafic silicates. TEM work was performed on FIB liftouts from mesostasis and the meteorite matrix. The foils were cut using a FEI Nova 200 Dualbeam FIB instrument and welded on to a Cu support. Diffraction contrast images, selected area diffraction patterns and X-ray chemical analyses were acquired using a FEI T20 TEM and a JEOL ARM200F, both operated at 200 kV. Mineral identification via Raman spectroscopy used a Renishaw inVia Raman microscope with a 514 nm laser.

Results and discussion: EET 96029,9 contains ~62 vol% matrix, ~18 vol% chondrules, ~8 vol% mafic silicate fragments, ~7 vol% fine-grained rims, ~2 vol% Fe,Ni-sulphide grains, ~1 vol% calcium- and aluminium-rich inclusions (CAIs), ~1 vol% metal, ~1 vol% calcite and <1 vol% Fe-(hydr)oxide as determined by point-counting. Twelve out of twenty chondrules that we studied in detail are porphyritic type IA chondrules (Fe-poor with >80% olivine [12]) and they are abundant throughout the section. They range in size from ~100-800 μm, excluding their fine-grained rims. The Fo-rich olivine is well preserved, and where En-rich pyroxene is present it ranges from being well-preserved to containing micrometer sized voids that are sometimes connected by thin cracks (Fig. 2a). These chondrules contain widespread micrometer sized droplets of unaltered Fe,Ni-metal, and sometimes also larger irregular metal blebs that are up to 20 μm in diameter; in one instance up to 200 μm. The larger metal grains are partially altered to Fe-(hydr)oxide displaying an onion ring texture, where metal is preserved within the core. The mesostasis of all type IA chondrules has been altered to secondary phases, but in seven out of the twelve chondrules the original igneous texture of Di-rich pyroxene quench crystallites has been preserved. The texture ranges from dense arrays of lath-shaped crystallites (Fig. 2a) to well-defined needle-shaped crystallites (Fig. 2b) and voids with the shapes of former crystallites (Fig. 2c).

Two out of twenty studied chondrules are porphyritic type IB (Fe-poor >80% pyroxene [12]). They are ~200 and ~300 μm in diameter respectively, excluding fine-grained rims, and both have a larger proportion of mesostasis in comparison to mafic silicate phenocrysts. The mafic silicates are En-rich pyroxene. Both chondrules have preserved a texture of quench crystallites within their mesostasis.

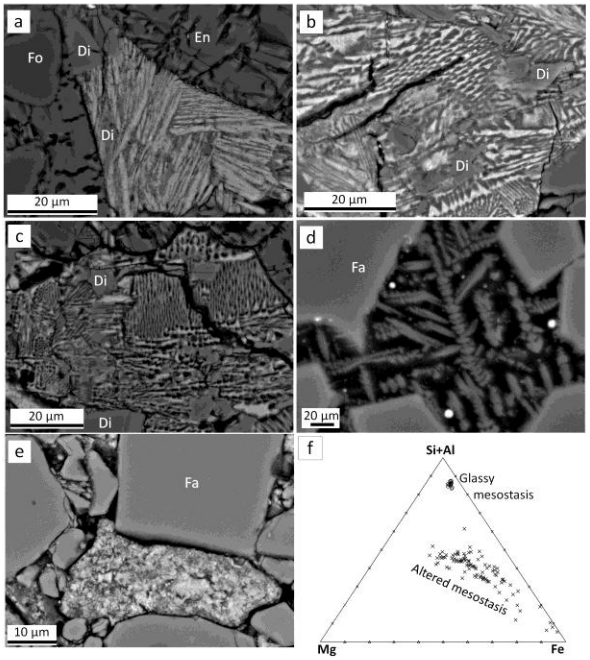

Fig. 2 (a-e) SEM-BSE micrographs of chondrule mesostasis textures in EET 96029: **(a)** Lath-shaped crystallites (grey) in altered mesostasis (bright). Note voids in En-rich pyroxene (En), well-preserved Fo-rich olivine (Fo) and Di-rich pyroxene crystals (Di). **(b)** Altered mesostasis (bright) with preservation of needle-shaped quench crystallites (grey). **(c)** Dark voids of remnant crystallites in altered mesostasis (bright). **(d)** Glassy mesostasis (black) with quench crystallites (grey needles) and Fe,Ni-metal droplets (white). Note well-preserved Fa-enriched olivine (Fa) **(e)** Altered mesostasis with microgranular texture. **(f)** Ternary diagram showing compositions (at.%) of glassy mesostasis (circles) depleted in Fe and Mg, enriched in Si+Al, compared to altered mesostasis (crosses).

Six out of twenty chondrules belong to type IIA (Fe-rich with >80% olivine [12]). They range in size from ~140-1000 μm, excluding their fine-grained rims. Fa-rich olivine in four of the chondrules is well-preserved and has no or very minor evidence of dissolution. However, olivine in the other two type IIA chondrules has started to alter around crystal edges and contains fractures with serrated margins that are filled with fine-grained alteration products. As previously noted [7], one of the type IIA chondrules contains a mesostasis that has retained glass in addition to well-defined quench crystallites (Fig. 2d). In two of the chondrules the glass has been altered but the crystallite texture remains, and in three chondrules the glass has been altered with no crystallite texture being preserved. The fine-grained alteration phase of the mesostasis from one of the type IIA chondrules with no preserved crystallites is shown by electron diffraction to be cronstedtite with a high density of stacking faults. However, this mesostasis has a microgranular texture and Fe-enrichment suggesting that it also contains grains of Fe-oxide (Fig. 2e). Chemical analysis (Fig. 2f) shows that aqueous alteration of chondrule mesostases is accompanied by export of Si+Al, and import of Fe and Mg.

TEM imaging of the meteorite matrix has revealed the presence of a compact amorphous material, fine-grained phyllosilicates and organic nanoglobules. As an amorphous groundmass also occurs in the matrix of Paris [1] and Y-791198 [13], it would appear to be a characteristic of mildly altered CMs.

CAIs are relatively abundant in the thin section (0.2 CAI/mm^2) and at least one of them contains gehlenite as confirmed by X-ray microanalysis and Raman spectroscopy. Melilite (solid solution between åkermanite and gehlenite) is thought to have been a common constituent of CAIs that were accreted by the CM parent body(ies), but has been lost owing to its susceptibility to aqueous alteration [14]. Melilite is extremely rare in CMs and have only been reported in mildly altered CMs including Paris [1], Murchison [15,16] and LEW 85311 [17].

Conclusions: EET 96029 may be the least altered CM yet described. Indicators of its near-pristine nature include (i) chondrule mesostasis glass; (ii) gehlenite-bearing CAI; (iii) an amorphous groundmass to the matrix. The mesostases of most chondrules have been altered, although twelve out of twenty chondrules have preserved a quench crystallite texture in their mesostasis phyllosilicates (ranging from well-defined needles to lath-shaped crystals and voids of remnant crystallites), indicating a very early state of aqueous alteration [5]. EET 96029 provides another rare example of a mildly aqueously altered CM, recording the earliest stages of CM alteration.

References: [1] Marrocchi et al. (2014) *MAPS* 49, 1232-1249 [2] Hewins et al. (2014) *GCA* 124, 190-222 [3] Rubin (2014) *LPS XLV* Abstract #1130 [4] Rubin et al. (2007) *GCA* 71, 2361-2382 [5] Maeda et al. (2009) *J. Min. Pet. Sci.* 104, 92-96 [6] Burger & Brearley (2004) *LPS XXXV* Abstract #1966 [7] Lindgren & Lee (2014) *MetSoc LXXVII* Abstract#5276 [8] Alexander et al. (2013) *GCA* 123, 244-260 [9] Alexander et al. (2012) *Science* 337, 721-723 [10] Tyra et al. (2007) *GCA* 71, 782-795 [11] Clayton & Mayeda (1999) *GCA* 63, 2089-2104 [12] Lauretta et al. (2006) *MESSII*, 431-459 [13] Chizmadia & Brearley (1998) *GCA* 72, 602-625 [14] Rubin et al. (2007) *MAPS* 42, 1711-1726 [15] MacPherson et al. (1983) *GCA* 47, 823-839 [16] Simon et al. (2006) *Am. Min*. 91, 1675-1687 [17] Simon et al. (2005) *MAPS* 40: A141. **Acknowledgements:** NASA Antarctic meteorite collection and UK-STFC.