POROSITY VARIATIONS BETWEEN FINE GRAINED RIMS AND MATRIX IN A CM CHONDRITE BY 3D SERIAL SECTIONING.

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Introduction: The CM chondrite meteorites experienced substantial aqueous alteration on their parent body [1]. Despite this, their bulk chemistry is within 10 % of the bulk solar system as measured from the solar photosphere [2, 3]. The matrix of CM meteorites has a porosity ranging between 4-25 %, which may facilitate fluid flow, although higher values may reflect desiccation accompanying parent body heating, or sample curation [4]. Calculated permeabilities of CM meteorites, based on their average pore and grain size, indicate that fluid flow during aqueous alteration was limited to ~100 µm, so would only result in small length scale heterogeneities in soluble elements in CMs in agreement with petrographic descriptions [5]. This finding suggests that aqueous alteration on the CM parent body can be approximated to a closed system for bulk samples [5]. It has recently been suggested that this constraint on fluid flow could be reconciled with numerical models of asteroid evolution via whole body convection of the CM parent body prior to lithification [6]. However, localised heterogeneities in pore size, that may not be detectable by transmission electron microscopy or nuclear magnetic resonance cryoporometry studies, due to limits in sample size and spatial resolution respectively, may mean that fluid flow conduits are present in CMs that could extend the 100 µm limit for aqueous fluid flow.

Using plasma-focused ion beams (P-FIBs) it is now possible to extract large 1,000,000 µm^3 representative volumes of material from meteorites in a reasonable time frame (< 1 day). Here we use 3D serial sectioning to quantify the pore network and associated permeability of a 110×70×60 µm volume of EET 96029, an unusual CM2 chondrite that experienced mild aqueous alteration and thermal metamorphism [7].

Method: The EET 96029 thick section was polished using glycol suspensions. This minimises the risk of removing any water soluble minerals that may produce voids, and also minimise hydration and dehydration of the sample that may produce desiccation fractures. EET 96029 was initially mapped via back scattered electron (BSE) imaging and energy dispersive X-ray spectroscopy (EDS) on the Zeiss Sigma variable pressure field emission gun scanning electron microscope, at the Imaging Spectroscopy and Analysis Centre, University of Glasgow. A 110×70×60 µm volume region of interest, a matrix-FGR interface, was extracted using the Helios P-FIB at the Kelvin Nanocharacterisation Centre, University of Glasgow. A series of 163 sections 60 nm thick were cut using a P-FIB and rocking mill to minimise curtaining. Each slice was imaged using both BSE and secondary electrons (SE). The total measured volume was 45,000 µm^3. EDS maps were collected half way through the run, and at the end. EDS data were quantified using proprietary Bruker software. The 3D data were reconstructed using the Image J software package. A vertical FFT filter was applied to each image to remove curtaining effects. Pores were identified in SE imaging as regions of low brightness.

Results: EDS maps obtained at the middle and end of the run indicate that the matrix-FGR interface is Ca- and S-rich (Fig. 1). The matrix and FGR contain several large (1-20 µm) isolated pores. The porosity of the FGR is higher than the matrix (Fig. 2). The matrix-FGR interface is also porous; with continuous voids of interconnected pores ~1-2 µm across, along its length.

Discussion: The pores within the matrix and FGR of EET 96029 are larger than those reported for other CMs [5]. This is likely to be cause by dehydration during parent body heating and regolith processing of EET 96029 [7]. The pores are isolated from each other. Therefore, it is unlikely that this pore network could support significant fluid flow so that it would have lit-

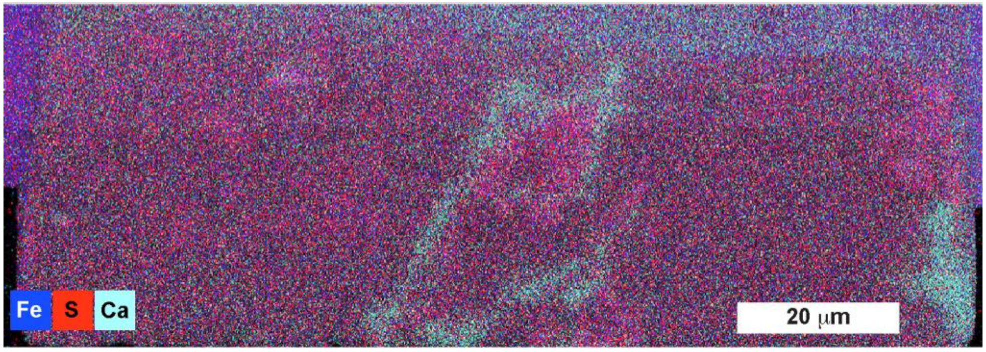

Figure 1: RGB EDS map obtained at the end of the 3D analyses (S - red, Ca - green, Fe - blue). The matrix-FGR interface is decorated with Ca.

tle impact on the overall permeability of the meteorite, consistent with previous studies [5]. However, the matrix-FGR interface is a continuous network of voids that would allow the transmission of fluids. Coupled with the enrichment in soluble elements including Ca and S within the interface, this void network provides some evidence of fluid flow along these interfaces.

If the matrix-FGR interface acts as a vector for fluids, the length scale of heterogeneous alteration may increase in proximity to the interface. The pore size and porosity along the matrix-FGR interface results in a localised permeability spike of ~10^{-15} m^2, two orders of magnitude higher than the typical chondritic range [5]. If these interfaces were interconnected throughout the rock, they would enable fluid flow on the mm-cm length scale [5]. However, as the majority of CM meteorites are comprised of ~70% matrix [8], this would result in a matrix supported medium. Therefore, it is unlikely that these interfaces would connect to produce a continuous network that would allow cm-scale fluid transport, consistent with petrographic observations of aqueous alteration in CM/CI chondrites, which are limited to 100 µm length scales [9].

These observations can be used as a ground truth to compare whole body convection to fluid flow through a lithified rock. If these materials are in a fixed location, we would expect a spheroid, proximal to matrix-FGR interface, to exhibit a slightly more expansive aqueous alteration zone, facilitated by these localised spikes in permeability. Previous studies have shown a chemical variation up to 25 µm in the FGR-chondrule interface of CM chondrites due to mobilisation of soluble elements [10]. Here we only observe a Ca and S enrichment in the vicinity of the matrix-FGR interface. This finding would suggest that aqueous alteration initially occurred in a dynamic environment, and the matrix-FGR interface, at least in its current configuration, formed late. These results are therefore consistent with the whole body convection model of Bland & Travis [6]. However, the enrichment of soluble elements such as Ca and S across the interface suggest that a later generation of fluids may have been active post lithification and convection during parent body thermal heating of EET 96029 [7]. Clast supported CM chondrites may provide constraints as to the extent of post lithification alteration, as fluids here would readily migrate through such a meteorite, resulting in deviations in soluble element abundances from the solar photosphere.

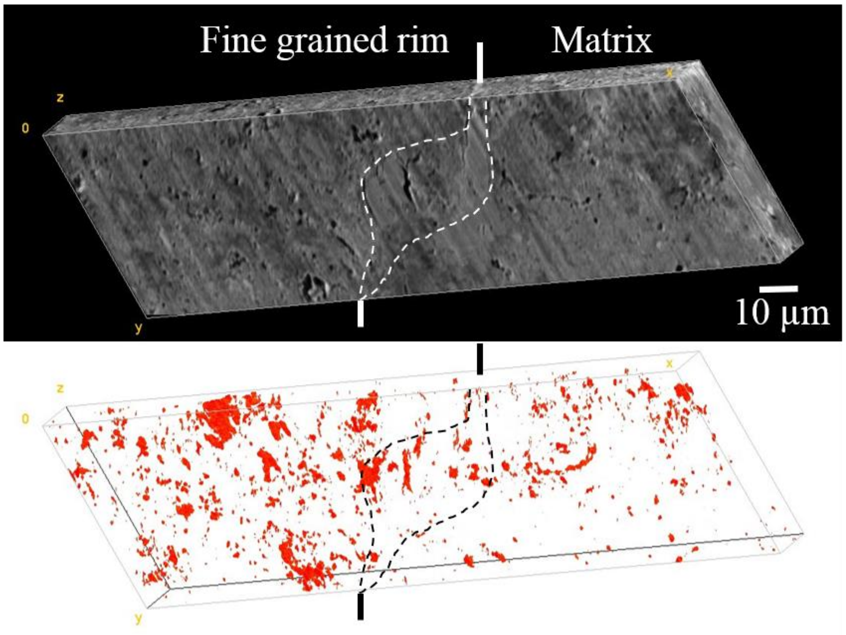

Figure 2: 3D slice and view data across a matrix-FGR interface (dashed lines). A stack of SE images where dark regions are voids (upper image) and the location of pores within the volume (lower image).

Conclusion: 3D serial sectioning of the matrix-FGR interface in a CM chondrite suggest that, despite the presence of large pores within the matrix and FGR, they are insufficiently interconnected to transmit fluids over significant distances (> 100 µm). However, the matrix-FGR interface could act as vector for fluid flow at the cm scale. In a lithified body, these spikes in permeability should result in increased aqueous alteration proximal to the matrix-FGR interface, while whole body convection would not produce this, as the region of matrix and FGR would not be linked in time and space. The alteration observed here suggest that whole body convection is plausible, but that fluids were also active post lithification.

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