Impact fracturing and aqueous alteration of the CM carbonaceous chondrites. P. Lindgren, M. R. Lee and S. S. L. Simpson, School of Geographical and Earth Sciences, University of Glasgow, Glasgow G12 8QQ, U.K. Paula.Lindgren@Glasgow.ac.uk, Martin.Lee@Glasgow.ac.uk, S.Simpson1@research.gla.ac.uk

Introduction: Aqueous alteration of the CM carbonaceous chondrites has produced a suite of secondary minerals, and differences between meteorites in their abundance defines a progressive alteration sequence [e.g. 1, 2]. The means by which this water gained access to the original anhydrous constituents of the meteorites is the subject of considerable debate. Studies of rock texture, mineralogy and bulk chemical composition have concluded that solutions were generated by the melting of water ice *in situ*, and remained essentially static as a consequence very low intergranular permeabilities [e.g. 3, 4]. By contrast, results of oxygen isotope work and modelling have suggested that the fluids moved considerable distances within the parent body [5, 6]. Given the intergranular permeability of the CMs, an extensive fracture network would be required to support such flow.

Clues to how the two very different models for aqueous alteration of the CMs can be reconciled have been recently provided by Rubin [7]. He recognised a good correlation between the magnitude of impact-induced compaction of CM meteorites and their degree of aqueous processing, with the more highly deformed meteorites being more altered. Here we have asked whether compaction was accompanied by the development of fracture networks that could have provided the conduits for aqueous solutions that mediated all or some of the alteration.

Materials and methods: This study has used thin sections of five CM carbonaceous chondrites: Murchison (CM2.5), Murray (CM2.4-2.5), LON 94101 (CM2.3), QUE 93005 (CM2.1) and SCO 06043 (CM2.0). Backscattered electron (BSE) images were obtained from each sample with a FEI Quanta field-emission SEM. Using the BSE images, the degree of impact-related compaction of each meteorite was assessed by measuring: (i) the aspect ratios of chondrules, chondrule fragments and chondrule pseudomorphs (hereafter 'chondrules' for brevity), and (ii) the orientations of the chondrule long axes relative to a reference direction. The axes of any fractures or mineral veins were also recorded.

Evidence for dynamic compaction of CMs: In their study of the shock stages of CMs, [8] found that almost all are classified as S1 (i.e. they have not experienced a single impact of >~ 5 GPa). The shock stages of three of the meteorites studied here have been determined previously are they are essentially unshocked: Murchison (S1-S2 [8]; S1 [7, 9]), Murray (S1 [8]), QUE 93005 (S1 [7]). Despite this finding that most CMs are S1, [7] demonstrated that many have a petrofabric (defined by the preferred orientation of objects including chondrules, chondrule fragments and phyllosilicate aggregates), and attributed it to compaction during impacts. Here we have sought to obtain a semi-quantitative measure of shock pressure experienced by our sample set using chondrule aspect ratios together with the petrofabrics defined by common orientation of their long axes. Experiments on Murchison by [9] showed that chondrules are progressively flattened with increasing shock pressure, and flattening is in the plane of the shock wave. These data therefore provide an empirical calibration of flattening against shock pressure. The same experiments also demonstrated that fractures start to develop at ~20 GPa, and become wider and more abundant as pressures increase.

Results: The mean aspect ratios of chondrules in each of the studied thin sections are as follows: Murchison (1.67±0.51, n=20), Murray (1.28±0.27, n=23), LON 94101 (1.29±0.19, n=21), QUE 93005 (1.35±0.27, n=21), SCO 06043 (1.97±0.46, n=23). Following [7], the petrofabrics can be depicted in histograms showing the deviation of chondrule long axis from the median azimuth of the population. For example, SCO 06043 (CM2.0) has a strong petrofabric defined by chondrule pseudomorphs as indicated by a sharp peak near their median azimuth (Fig. 1). The petrofabric of each meteorite is expressed as the percentage of chondrules whose long axes lie within 10º of the median azimuth. Values are as follows: Murchison (50%), Murray (13%), LON 94101 (33%), QUE 93005 (43%), SCO 06043 (57%). Murchison and Murray lack fractures and veins, whereas LON 94101 contains a calcite vein [10] and QUE 93005 and SCO 06043 both have dolomite veins [11, 12].

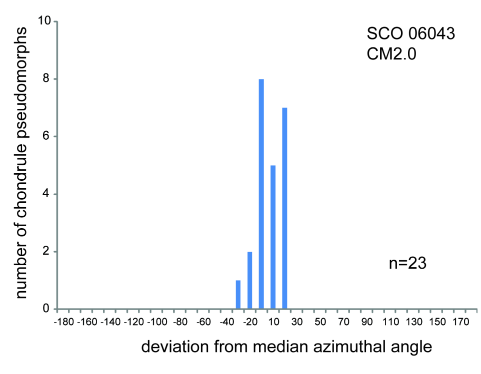

Fig.1. Histogram showing the deviation of chondrule pseudomorphs from their median azimuth in SCO 06043.

Discussion: As meteorites whose chondrules are flattened (i.e. high aspect ratios) also have a strong petrofabric, we conclude that chondrule flattening is due to parent body compaction accompanying impacts.

Murray chondrules have a low aspect ratio and the rock has a weak petrofabric, which is consistent with the Murray particles analysed by [7]. These results indicate that the meteorite has not been appreciably compacted. It is also free of fractures and mineral veins, thus further highlighting its low intensity stress history.

LON 94101 and QUE 93005 chondrules are flatter, and together define a stronger petrofabric; [7] likewise found a petrofabric in QUE 93005. These properties are consistent with compaction, and the presence within both meteorites of carbonate veins indicates that the parent body experienced tensional stresses greater than the yield strength of the rock to open fractures. This stress came prior to completion of parent body aqueous activity so that the fractures were cemented by carbonates.

All of the chondrules in SCO 06043 have been aqueously altered, and so the aspect ratios of chondrule pseudormorphs were measured. They have a high mean aspect ratio, and common orientation of the chondrule pseudomorphs defines a strong petrofabric (Fig. 1). This meteorite contains dolomite veins that lie sub-parallel to the foliation. Pre-terrestrial dolomite veins have been described from another CM2.0 meteorite, ALH 84051 [13], although their orientation relative to any petrofabric in the rock is unknown.

Murchison does not fit the pattern of the other samples in terms of the approximate correlation between degree of aqueous alteration and strength of petrofabric. It is the least altered meteorite of the sample set, lacks mineral veins and pre-terrestrial fractures, yet has a strong petrofabric that is defined by chondrules with high aspect ratios.

Impact fracturing and aqueous alteration: Results of this study are largely consistent with the findings of [7] that the more highly altered CMs have evidence for a greater degree of compaction. It is possible that this correlation is due to the more highly aqueously altered chondrules being less resistant to compaction owing to the presence within them of ductile phyllosilicates. However, the presence of mineral veins in three of the meteorites that have an impact-related petrofabric is consistent with them having been exposed to considerable stress. As the experiments of [9] generated fractures only at pressures of >~20 GPa, this suggests that LON 94101, QUE 93005 and SCO 06043 are likely to have been exposed to impacts of a corresponding magnitude.

With regards to Murchison, the high degree of chondrule flattening is likely to be the outcome of multiple impact events of a relatively low magnitude (i.e. below the threshold that generates fractures) rather than a single high intensity shock event. The effectiveness of this mechanism was demonstrated by [14], who showed that multiple low intensity impacts into Allende (CV3) will progressively flatten its chondrules.

Conclusion: The CM parent body/bodies experienced tensional stresses accompanying impacts that were of a sufficient intensity to open up fractures. Aqueous solutions subsequently entered the fractures to precipitate carbonates. These solutions may have been sourced by slow movement through the matrix of the enclosing meteorite, or originated from another parent body region that was ‘tapped’ by the propagating fracture network. We suggest that the latter possibility is more likely given the evidence from LON 94101 that the vein calcite is very different in oxygen isotope composition from calcite in the surrounding meteorite matrix [15]. This isotopic difference is consistent with crystallization of the vein calcite from solutions or a different temperature and/or oxygen isotope composition. This study supports the findings of [7] that many of the CMs have undergone compaction by impacts. Murchison records several low intensity impacts that progressively flattened its chondrules but did not exceed the yield strength of the meteorite matrix. LON 94101, QUE 93005 and SCO 06043 experienced shock pressures sufficient to open fractures that enabled the ingress of aqueous solutions. We conclude that the CM parent body/bodies had a low primary porosity and permeability, but where exposed to impacts a secondary (fracture) porosity was developed whose high permeability could have supported limited fluid flow.

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Acknowledgements: We are grateful to the Natural History Museum (London) and NASA for provision of the meteorite samples, and to the UK Science and Technology Funding Council for financial support.