TRACING THE AQUEOUS ALTERATION OF CARBONACEOUS CHONDRITES USING MAGNETIC MINERALOGY. J. F. J. Bryson[1,2], S. Sridhar[2], R. J. Harrison[2], A. J. King[3] [1]Department of Earth Sciences, University of Oxford, Oxford, UK, [2]Department of Earth Sciences, University of Cambridge, Cambridge, UK, [3]The Open University, Milton Keynes, UK.

Introduction: A large number of carbonaceous chondrites were aqueous altered on their parent bodies. This was a key event during the history of these meteorites that affected their textures, compositions, mineralogies and isotopic signatures [1]. Previous studies have demonstrated that different chondrites were altered to different extents, ranging from remaining effectively pristine to essentially completely hydrated [2, 3, 4]. Despite the importance of this process, our understanding of aqueous alteration is currently limited. For example, it is unclear whether all chondrites followed the same pathway of alteration and whether different extents of alteration correspond to varying progression along this pathway.

One phase that was generated during parent body aqueous alteration is magnetite [5]. The abundance and morphology of magnetite vary among different chondrites [2, 6], suggesting that the properties of this mineral reflect the conditions and extent of aqueous alteration experienced by its host meteorite. As such, the bulk magnetic properties of aqueously altered chondrites are also expected to reflect their aqueous evolution and could provide novel insight into this process.

With this in mind, we measured first order reversal curve (FORC) diagrams of a number of carbonaceous chondrites. FORC diagrams provide the coercivity and interaction field distributions of the magnetic grains in a sample. These distributions can be used to recover the size, morphology and magnetic domain state of the magnetite grains in these meteorites. These properties depend on the process by which this magnetite formed, and, as such, can be used to constrain the primitive make up and alteration pathways of these meteorites.

Methods: We measured FORC diagrams of 28 CO, CM, CI and C2 chondrite powders that previously had their modal mineralogies determined using X-ray diffraction [7, 8]. The CO chondrites were petrologic type 3.0 - 3.1, while the CI and CM chondrites ranged from type 1.0 - 1.7 in the classification scheme proposed by [2]. FORC diagrams were measured using the alternating gradient magnetometer in the nanopaleomagnetism laboratory at the University of Cambridge. The FORC diagrams were processed using the VARIFORC approach [9] in the FORCinel software package [10].

Results: *CO chondrites*. The FORC diagrams of the CO3.0 - 3.1 chondrites are very similar to each other and consist of a three-lobed pattern. This pattern is characteristic of magnetic grains that have their spins organised into one or more vortices and are separated from each other such that they are weakly interacting [11]. The most abundant magnetic phase in CO3.0 - 3.1 chondrites is magnetite (~4 - 8 vol%) [12]. Magnetite typically adopts vortex states for grain sizes between ~0.1 - 1 µm, indicating that the predominate size of magnetite in the CO chondrites is ~0.1 - 1 µm.

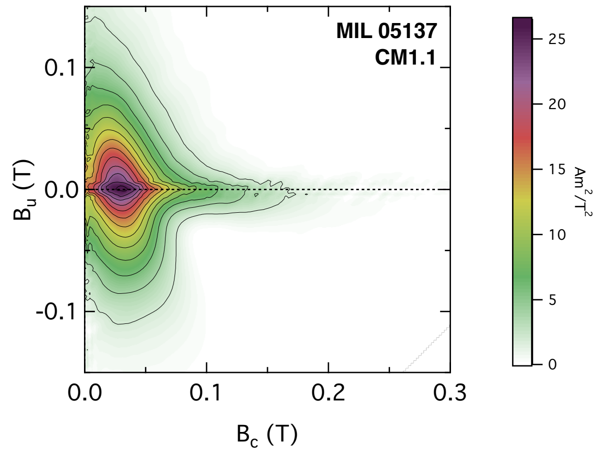

Fig. 1. FORC diagram of CM1.1 MIL 05137, which displays a lobed pattern that is typical of magnetic grains that have their spins organised into vortices (~0.1 - 1 µm large). B_u: interaction field, B_c: coercivity.

CM chondrites. The FORC diagrams of the CM chondrites vary with extent of aqueous alteration across this meteorite group. The FORC diagrams of the CM1.3 - 1.7 chondrites display a signal that extends along the horizontal axis and is minimally spread along the vertical axis. This pattern is characteristic of separated magnetic grains that have uniformly oriented magnetic spins. The most abundant magnetic phase in the CM chondrites is also magnetite (~1 - 4 vol%) [2, 8]. Equidimensional magnetite grains typically adopt this uniform state for sizes <0.1 µm.

The FORC diagrams of CM1.1 - 1.2 chondrites tend to display a lobed pattern that is similar to those of the CO chondrites (Fig. 1). Again, this pattern is characteristic of vortex-state magnetite grains (~0.1 - 1 µm in size). Together, the FORC diagrams of the CM chondrites indicate that the size of the predominant magnetite grains in this meteorite group is <0.1 - 1 µm.

We used principal component analysis (PCA) to quantify the variability and similarity among the CM FORC diagrams (Fig. 2) [13]. We find that the FORC diagrams of the CM1.3 - 1.7 chondrites and CM1.1 - 1.2 tend to fall into distinct clusters in the recovered principal components (PCs), suggesting that two types

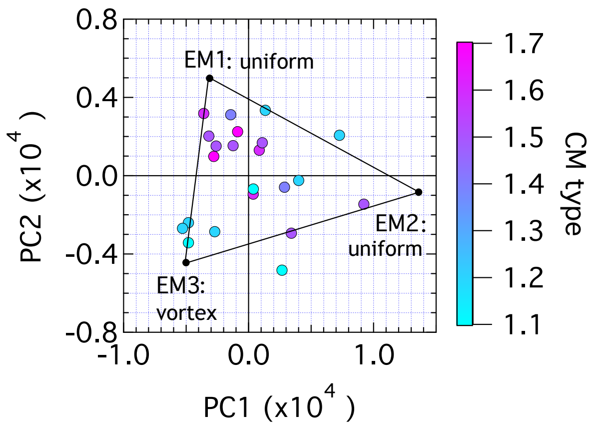

Fig. 2. PCA of the CM FORC diagrams. The CM1.3 - 1.7 chondrites contain higher abundances of end member 1 and 2 (EM1 and EM2), the FORC diagrams of which resemble uniformly magnetised grains. The CM1.1 - 1.2 chondrites tend to contain higher abundances of EM3, the FORC diagram of which resembles vortex-state magnetic grains (e.g., Fig. 1).

of FORC diagrams exist among the CM chondrites (those dominated by uniformly magnetised particles and those dominated by vortex-state particles).

Together, these observations suggest that the average size of the predominant magnetite grains in the CM chondrites increases with extent of aqueous alteration from <0.1 µm to ~0.1 - 1 µm.

CI and C2 chondrites. The FORC diagrams of the CI chondrites, Tagish Lake and WIS 91600 are similar to each other and are triangular in shape. This shape is distinct from the FORC diagrams measured from the CM and CO chondrites, suggesting that magnetite in the CI chondrites, Tagish Lake and WIS 91600 formed under different conditions or through a different process to that in the CO and CM chondrites. This triangular signal extends to higher values along the vertical axis than the signals measured from the CM and CO chondrites. This vertical extent indicates that magnetic grains in the CI chondrites, Tagish Lake and WIS 91600 are more strongly interacting than those in the CM and CO chondrites, suggesting that they are in closer proximity (i.e., more tightly packed). Again, these FORC diagrams indicate that the magnetic grains in the CI chondrites, Tagish Lake and WIS 91600 are predominately micron to sub-micron in size.

Discussion: The CO and CM chondrites both show petrographic evidence that magnetite formed in these meteorites through the reaction of FeNi metal with water [14, 15]. This process causes precursor metal grains to be replaced by magnetite grains. As such, our results suggest that a large number of micron- to sub-micron-scale metal grains originally existed in the primitive CO and CM chondrites prior to alteration.

On the other hand, the CI chondrites, Tagish Lake and WIS 91600 show petrographic evidence that magnetite formed from the reaction of pyrrhotite with water in these meteorites [16]. Instead of magnetite directly replacing pyrrhotite grains, this reaction generates a large number of small (<10 µm) magnetite grains that are found in framboid and platelet morphologies [16]. The magnetite crystals in these framboids are closely packed and, as such, are strongly magnetically interacting, explaining the measured FORC diagrams of these meteorites.

The FORC diagrams of the CO and CM chondrites do not display a clear signature of framboid magnetite (triangular pattern), suggesting that a minimal amount of magnetite formed from pyrrhotite in these meteorites. The FORC diagrams of the CI chondrites, Tagish Lake and WIS 91600 do not display a clear signature of isolated micron- to sub-micron-scale magnetite (lobed or horizontally extended patterns), suggesting that a minimal amount of magnetite formed from metal in these meteorites.

The CO3.0 chondrites do not contain phyllosilicates and the only evidence of aqueous alteration in these meteorites is magnetite replacing metal [14, 17]. This observation indicates that the reaction of metal to magnetite can be one of the first to occur during aqueous alteration and is clearly favourable. As such, the absence of a clear isolated micron- to sub-micron-scale magnetite signal in the FORC diagrams of the CI chondrites, Tagish Lake and WIS 91600 suggests that a minimal amount of metal was incorporated into these meteorites when their parent bodies accreted. This observation argues that these meteorites originate from a relatively metal-poor region of the solar system.

We are currently investigating the reason behind the minimal transformation of pyrrhotite to magnetite in the CM and CO chondrites.

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