CONSTRAINTS ON THE ICE COMPOSITION OF CARBONACEOUS CHONDRITES N. Sridhar[1], J. F. J. Bryson[1], A. J. King[2], R. J. Harrison[3], [1]Department of Earth Sciences, University of Oxford, [2]Natural History Museum, London, [3]Department of Earth Sciences, University of Cambridge.

Introduction: Carbonaceous chondrites experienced various extents of aqueous alteration on their parent asteroids [1-4]. This event was crucial in their history, affecting their textural, mineralogical, and isotopic signatures. Despite its importance, the mechanisms and conditions of chondrite aqueous alteration are not completely understood.

During aqueous alteration, a variety of secondary minerals were introduced to the carbonaceous chondrites, including phyllosilicates, carbonates, magnetite, and Fe-sulfides [1]. The abundance and morphology of magnetite differs among these meteorites, possibly reflecting changes in the chemistry and/or conditions of aqueous alteration experienced by their parent asteroids [5-7]. Variation in magnetite abundance and morphology can impact the bulk magnetic properties of these meteorites, such that magnetic measurements can provide a means of exploring their aqueous histories.

A novel and informative set of bulk magnetic measurements are first order reversal curve (FORC) diagrams. These diagrams can be used to recover the size, morphology and magnetic domain state of the magnetic grains present [8]. As these properties depend on the process by which magnetite formed, FORC diagrams provide a unique tool for investigating the different pathways of aqueous alteration experienced by carbonaceous chondrites.

Methods: We measured FORC diagrams of: 2 CO chondrite powders (petrological type 3.0 and 3.1 [7]); 2 CI chondrite powders (petrological type 1.0); 23 CM chondrite powders (petrological type 1.1-1.7 based on phyllosilicate fraction [4]), and two chips of the ungrouped C2 chondrite WIS 91600 (petrological type ~1.4). We also performed bulk magnetic measurements on ~20 mg powder samples of each chondrite to determine the modal volume percent of magnetite present. These measurements were conducted using an alternating gradient magnetometer at the University of Cambridge, and the FORC diagrams were processed using the VARIFORC approach in the FORCinel software package [9,10]. We also conducted principal component analysis (PCA) on the measured FORC diagrams to identify the proportions of ideal end-member (EM) magnetite morphologies present in the CI, CM and ungrouped C2 chondrites [11].

Results: *CI and C2 chondrites:* The FORC diagrams of the CI chondrites and WIS 91600 display a triangular signature that spreads vertically with a peak intensity off the origin, indicating the presence of strongly interacting magnetic grains (EM3 in Fig 1a).

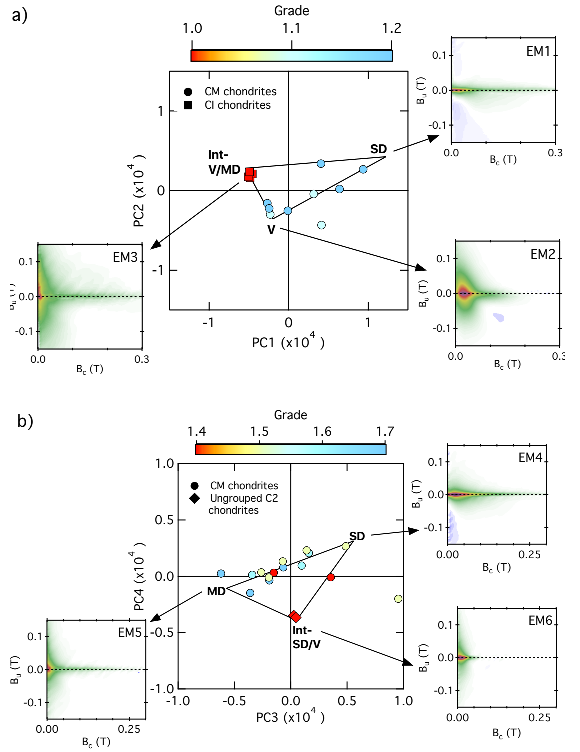

Fig 1a) Plot displaying proportions of PC1 and PC2 present in chondrites of grade 1.0-1.2, along with the positions of the end-members. EM1 is representative of a SD grain; EM2 is representative of a V grain; EM3 is representative of interacting V/MD grains. Fig 1b) Plot displaying proportions of PC3 and PC4 present in chondrites of grade 1.3-1.7, along with the positions of the end-members. EM4 is representative of a SD grain; EM5 is representative of MD grains; EM6 is representative of interacting V/SD grains.

This is characteristic of tightly packed, <1μm magnetite grains [12], consistent with SEM observations of of framboids and plaquettes of magnetite in these chondrites [1,5]. Magnetite modal abundances in WIS 91600 and the CI chondrites range between 2-7 vol%.

CM chondrites: The FORC diagrams of the CM chondrites display a range of patterns. The CM1.3-1.7 chondrites are broadly dominated by a signal that extends along the horizontal axis and displays minimal vertical spreading along the vertical axis (similar to EM1 in Fig 1a and EM4 Fig 1b). This is characteristic of <0.1μm isolated, non-interacting magnetite grains, with uniformly orientated magnetic spins [9]. The FORC diagrams of the CM1.1-1.2 chondrites tend to display a tri-lobe signature similar to EM2 in Fig 1a. This is characteristic of <0.1–5μm magnetite grains that have their magnetic spins orientated into one or more vortices [13]. Magnetite comprises ~0.2-3.5 vol% of the CM chondrite samples.

CO chondrites: The FORC diagrams of the CO chondrites show a tri-lobe pattern, characteristic of <0.1–5μm, vortex state (V) magnetite grains. The FORC diagrams also display slight spreading along the vertical axis, indicative of weak magnetic interaction between the grains. Magnetite makes up ~6-11 vol% of the CO chondrites measured.

PCA: We conducted two sets of PCA: one on chondrites with grades 1.0-1.2, and one on chondrites with grades 1.3-1.7. Splitting the chondrites into two groups based on their extent of aqueous alteration allowed for trends between the groups to be easily identified. The PCA shows that FORC diagrams of CI and C2 chondrites plot in distinct principal component space compared to the CM chondrites (Fig1a and Fig1b). This difference indicates that magnetite formed in WIS 91600 and the CI chondrites through a distinctly different process to that in CM and CO chondrites, and could be the product of aqueous alteration under different conditions or via different mechanisms.

Discussion: FORC diagrams, PCA, and SEM images indicate that the CI and C2 chondrites exhibit magnetite with different morphologies to the CM and CO chondrites, arguing for at least two pathways of aqueous alteration among these two families of meteorite groups. Previous studies have shown that the ungrouped C2 chondrite Tagish Lake shows a similar FORC diagram to the CI chondrites [14], and contains plaquettes and framboids of magnetite [15]. Both of these morphologies of magnetite are also present in CR chondrites [16]. The presence of framboids and plaquettes is not due to preservation bias as there is no correlation between their occurrence and the weathering grade of the chondrites examined. Ruling out terrestrial processes, the presence of these unusual forms of magnetite must be related to their conditions of formation during aqueous alteration on their parent bodies.

A number of factors could have played a role in the aqueous alteration pathway experienced by an individual chondrite, including: the extent of aqueous alteration [2,16]; the primitive water:rock ratio of the meteorite [1,17]; the degree of metamorphism [7,18]; the primitive composition of metal and sulfides [7,15,16]; and/or the presence of organics [6]. By reviewing published data, we have ruled out systematic variation in these factors as controls on the pathway of aqueous alteration.

The composition of the hydrous fluid in chondrite parent bodies could also have affected their pathways of aqueous alteration. This composition will have evolved as different phases reacted, however the initial fluid composition will have been controlled by the makeup of the ice accreted into the different parent asteroids. As magnetite appears to have been one of the very first phases to form during aqueous alteration [7,19,20], the properties of this mineral are more dependent on the composition of the initial ice accreted rather than the evolved fluid composition. As we can rule out other factors, we argue that the ice accreted into CO and CM chondrites differed in its composition compared to CI, C2, and CR chondrites.

As temperatures decreased in the nebula, a number of molecules are expected to have condensed onto water ice grains [21]. The first molecule that condenses onto water ice at geochemically relevant quantities, is ammonia [22]. We speculate that the presence of ammoniated ice could have affected the pathways of aqueous alteration due to an initial change in alkalinity. This could imply that the CI chondrites, Tagish Lake, WIS 91600 and the CR chondrites accreted in a colder region of the solar system, past the ammonia ice line. This is supported by recent work that links framboid formation to alkaline conditions [23], and petrographic and chemical studies that indicate similar formation conditions for the CM and CO chondrites [24]. Given constraints on parent body accretion ages, this argues that the CI chondrites, Tagish Lake and WIS 91600 originate from a more distal region, and that the ammonia ice line had migrated inwards by the time of accretion of the CR chondrite parent body.

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