UNRAVELLING THE THERMAL AND AQUEOUS ALTERATION HISTORIES OF CARBONACEOUS CHONDRITES USING MAGNETIC MINERALOGY

S. Sridhar[1], J. Ryan[1], A. J. King[2], H. C. Bates[2], C. I. O. Nichols[1], R. J. Harrison[3], and J. F. J. Bryson[1], [1]Department of Earth Sciences, University of Oxford, Oxford, OX1 3AN, UK, [2]Planetary Materials Group, Natural History Museum, London, SW7 5BD, UK, [3]Department of Earth Sciences, University of Cambridge, Cambridge, CB2 3EQ, UK [james.bryson@earth.ox.ac.uk]

Introduction: Thermal and aqueous alteration are common occurrences in the lifetime of carbonaceous chondrites. These alteration processes must be well understood in order to unravel the history of these meteorites. Alteration leads to the breakdown, formation, and modification of several magnetic minerals, i.e., Fe-Ni metal, magnetite, and pyrrhotite [1-4]. Crucially, the bulk magnetic properties of carbonaceous chondrites are governed by the abundance, morphology, size, and chemistry of these phases. As such, their bulk magnetic properties can be used to recover novel information regarding their thermal and aqueous history. A particularly informative set of bulk magnetic measurements that can provide such insights are first order reversal curve (FORC) diagrams [5]. Here, we utilize this approach to investigate the parent body histories of a suite of CO, CI and CM chondrites.

Methods: We measured FORC diagrams of: 2 CO chondrite powders (petrologic type 3.0 and 3.1); 2 CI chondrite powders (petrologic type 1.0); 2 chips of the ungrouped C2 chondrite WIS 91600 (petrologic type ~1.4); and 46 CM chondrite powders including 25 that experienced some degree of transient metamorphism (petrologic type 1.1 – 2.4; ranging from unheated to stage IV, <300 - >750 °C). These measurements were conducted using an alternating gradient magnetometer (AGM), and the FORC diagrams were processed using the VARIFORC approach in the FORCinel software package [6]. Principal component analysis (PCA) was used to identify variations in magnetic mineralogy in these carbonaceous chondrites [7].

Results: PCA of the FORC diagrams indicates that there are distinct and systematic variations in magnetic mineralogy with increasing aqueous alteration, and/or metamorphism of CM chondrites. These differences are reflected in the morphology of magnetite and the abundance of metal.

Aqueous alteration: FORC-PCA of CI and ungrouped C2 chondrites plot in distinct principal component space compared to 'unheated' CM chondrites. FORC diagrams of CI and ungrouped C2 chondrites (petrologic types 1.0 – 1.4) indicate the presence of framboids and plaquettes of magnetite formed during alteration, while CM and CO chondrites of similar aqueous alteration extents contain isolated <0.1–5μm magnetite grains.

Thermal alteration: FORC-PCA is able to distinguish 3 different stages of heating (I/II, III, IV) from 'unheated' CM chondrites. FORC diagrams reveal populations of magnetically interacting, < 0.1μm magnetite grains upon heating to stage I/II (150 – 500 °C, likely due to the thermal breakdown of tochilinite on heating), and the formation of metal from magnetite and Fe-sulfides upon heating to stage III & IV (>500 °C).

Discussion: Differences in the morphology of the magnetite formed during aqueous alteration between carbonaceous chondrite groups is most readily attributed to changes in the chemistry of the ice accreted into the CM parent body compared to CI & C2-ung parent bodies. This could then feasibly facilitate the formation of magnetite framboids and plaquettes in the CI and C2-ung chondrites [8]. FORC-PCA also provides a unique perspective on the systematic changes in mineralogy associated with the formation and destruction of metal and magnetite during increased thermal alteration of the carbonaceous chondrites.

This extensive bulk magnetism study demonstrates that FORC-PCA is a powerful tool for the analysis of carbonaceous chondrites. It is a quick, non-destructive technique which requires little to no sample preparation, making it ideal for the study of meteoritic material. FORC-PCA can classify the extent of heating among CM chondrites and can help identify the mineralogical and morphological changes that magnetic minerals experience during aqueous alteration. Crucially, this approach targets the magnetic mineralogy of a sample, so provides complementary information to that gleaned from other indicators of aqueous and thermal history, e.g., X-ray diffraction and spectroscopy (which target Si-O bonding) [2], thermogravimetric analysis (which targets H_2O abundance) [9] , and chemical composition [10]. As such, FORC diagrams can serve as a novel tool, which in combination with a suite of other techniques, will unlock a comprehensive understanding of the processes that modify chondritic asteroids.

References: [1] Brearley A. J. (2006) *Meteorites and the Early Solar System II* 584–624. [2] King A. J. et al. (2015) *Geochimica et Cosmochimica Acta* 165:148–160. [3] Nakamura T. (2005) *Journal of Mineralogical and Petrological Sciences*, 100:260-272. [4] Quirico E. et al. (2018) *Geochimica et Cosmochimica Acta* 241:17-37. [5] Roberts A. P. et al. (2014) *Reviews of Geophysics* 52:557–602. [6] Egli R. (2013) *Global and Planetary Change* 110:302–320. [7] Harrison R. J. et al. (2018) *Geochemistry Geophysics Geosystems* 19:1595–1610. [8] Sridhar, S. et al. (2021) *Earth and Planetary Science Letters* 576:117243. [9] Gilmour C. M. et al. (2019) *Meteoritics & Planetary Science* 54:951–1972. [10] Van Schmus W. R. & Wood J. A. (1967) *Geochimica et Cosmochimica Acta* 81:747–765.