ALLENDE METEORITE REMANENCE: EVIDENCE FOR MAGNETIC INTERACTIONS. T. M. O'Brien[1] and J. A. Tarduno[1,2], [1]Department of Earth & Environmental Science, University of Rochester, Rochester, NY 14627 (tobri15@ur.rochester.edu), [2]Department of Physics & Astronomy, University of Rochester, Rochester, NY 14627.

Introduction: The Allende meteorite (CV_{OxA}) represents an important source of information regarding formation of the early solar system as well as the primordial planetesimals that populated it. Additionally, Allende, and meteorites in general, provide details of the processes operating in their parent bodies (e.g. presence of a magnetic field) [1, 2].

Previous paleomagnetic work on the Allende meteorite has suggested preservation of a parent body dynamo [3, 4]. The magnetic mineralogy of Allende consists of a complex assemblage that includes pyrrhotite ($Fe_{x-1}S_x$), pentlandite [$(Fe, Ni)_9S_8$], magnetite (Fe_3O_4), and awaruite (Ni_3Fe) [5]. The primary remanence of the parent body dynamo was reported as being preserved by the sulfide carriers, with no significant remanence being carried by the higher Curie temperature (T_c) magnetite and awaruite grains [3].

Sulfides (i.e. pyrrhotite) are a challenge for any paleomagnetic study due to the complex relationship between magnetization and temperature. This includes the formation of non-magnetic "anomalous" pyrrhotite from ferrimagnetic monoclinic pyrrhotite, and the change of antiferromagnetic hexagonal pyrrhotite to ferromagnetic pyrrhotite when heated through its λ-transition between ~200 and 210 °C [6, 7]. A fast cooling rate can quench ferromagnetic hexagonal pyrrhotite, with it only being reversible through its λ-transition temperature range at a cooling rate of 0.5 °C min^{-1} [7].

Given the complex nature of sulfide magnetic behavior, the present work aims to further evaluate the viability of sulfides in Allende as effective long-term carriers of a stable remanence. This includes improving our understanding of the importance grain interactions can have on directional and intensity records obtained from sulfide carriers.

Methods: We report magnetic data from samples of the Allende meteorite fall (Fig. 1). Specimens for measurement consisted of bulk unoriented pieces extracted from the interior, away from the altered fusion crust exterior. Specimens typically ranged in size from 1-2 mm in diameter.

All magnetic data was collected at the University of Rochester Paleomagnetic Research Group. Magnetic hysteresis data were collected using a Princeton Measurement Corporation Alternating Gradient Force Magnetometer (AGFM) and remanence measurements were performed with a 3-component high-sensitivity DC SQUID magnetometer in a magnetically shielded room (ambient field <200 nT). Heating and cooling experiments (in air) were conducted using a CO_2 laser [8]. AGFM first order reversal curves (FORCs) were processed using FORCinel v2.05 and smoothed using VARIFORC [9, 10].

Scanning electron microscope (SEM) images were collected using an SEM/FIB Zeiss-Auriga Microscope outfitted with an EDAX X-ray spectrometer system at the University of Rochester's Integrated Nanosystems Center.

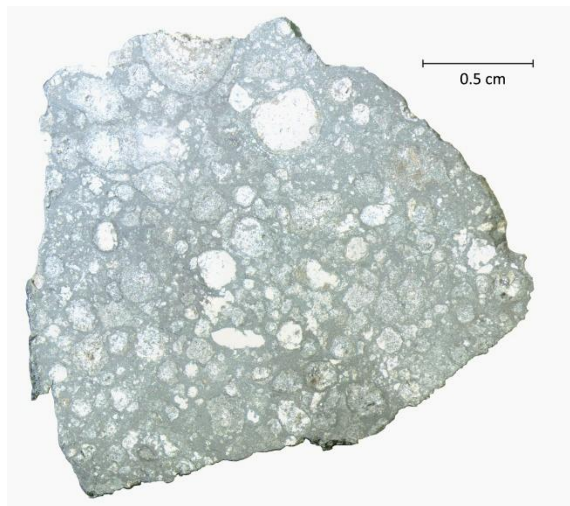

Figure 1. Allende meteorite with visible chondrules.

Findings: Magnetic hysteresis and FORC data were collected on bulk samples to evaluate the potential for grain interactions. FORCs plot a measure of grain interaction (H_u) (y-axis) against microcoercivity (H_c) (x-axis). Generally, the greater the spread in the ±y-axial direction, the more magnetic grains are interacting. The FORC data suggest interaction amongst grains across the observed range of microcoercivities (Fig. 2). The lack of saturation is probably the result of sulfides within the sample, which can have very high coercivities.

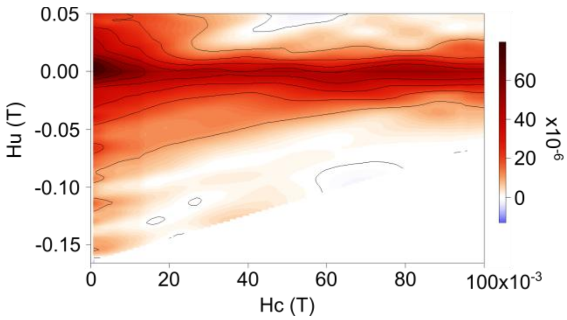

Figure 2. FORC diagram of bulk Allende sample. VARIFORC settings for smoothing: Sc0, Sb0, Sc1, Sb1 = 8; Lambda = 0.1.

SEM-Backscatter (BSD) images coupled with X-ray spectral data revealed a wide distribution of Ni-sulfide and awaruite grains. The close association of magnetic grains (Fig. 3) further highlights the potential importance of grain interaction. A large number of Ni-sulfide grains within the single domain (SD)/pseudosingle domain (PSD) range, (< 2μm), were observed throughout the samples. This widespread occurrence of SD/PSD magnetic grains observed in Allende would tend to suggest higher unblocking temperature magnetizations, particularly with respect to pyrrhotite (T_c = 325 °C), which is not observed in the thermal demagnetization results (maximum unblocking of ~290 °C). Instead remanence appears to be carried by an anomalous pentlandite or Ni-sulfide phase as suggested by Funaki and Wasilewski [4].

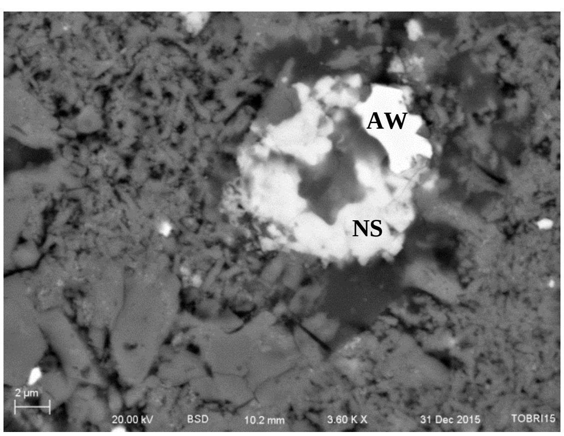

Figure 3. SEM-BSD image of Allende showing a cluster of Awaruite (AW) and Ni-Sulfide (NS).

Experiments investigating the thermal acquisition of remanence further indicate magnetic interactions [11]. Additional experiments evaluated the "softness" of the magnetic carriers within Allende, including subjecting a sample to a 60 μT field at room temperature for 5 minutes. This isothermal remanent magnetization (IRM) aimed to test the potential for viscous thermal magnetization (VRM) overprinting on Allende magnetic grains. The experiment resulted in a small but measurable increase in sample moment, supporting the presence of soft magnetic carriers within Allende.

SEM images of the Allende matrix also reveal a complex assemblage of elongate grains that suggest the potential for anisotropy. A sample was given a partial thermal remanent magnetization (pTRM) in a 60 μT field along the +Z- and –Z-axes at 290 °C displayed a ~30 % difference in moment as a result of the direction of field application. This suggests a strong anisotropy for Allende that would impact any paleomagnetic directional and intensity data collected.

Discussion: The magnetization of the Allende meteorite has been interpreted as a signal of a core dynamo, which in turn requires parent body differentiation. The analyses presented here, however, indicate that these conclusions are premature. Sulfides, the predominant magnetic carrier in Allende, are not generally considered as reliable paleointensity recorders because of their non-uniform behavior with respect to temperature. Our rock magnetic, SEM and paleomagnetic data indicate a role for magnetic interactions among the complex mineral phases within the Allende meteorite. Because at least some of these mineral phases formed during parent body metamorphism it is likely that the Allende meteorite records magnetization related to the interaction of magnetic phases. Further magnetic analyses are needed to define the history and nature of these interactions.

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