PALEOMAGNETIC EVIDENCE FOR A LAYERED PARTIALLY DIFFERENTIATED IRON-METEORITE PARENT BODY. C. Maurel[1], J. F.J. Bryson[2], B. P. Weiss[1] and A. Scholl[3], [1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [2] Department of Earth Sciences, University of Cambridge, Cambridge, UK, [3] Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Introduction: The identification of dozens of petrologically diverse chondritic and achondritic meteorite parent bodies indicates that a diversity of planetesimals formed in the early solar system [1]. It is commonly thought that planetesimals formed as either unmelted or else fully differentiated bodies, implying that chondrites and achondrites cannot have originated on a single body. However, it has been suggested that partially melted bodies with chondritic crusts and achondritic interiors may also have formed [2]. This alternative proposal is supported by the recent identification of post-accretional remanent magnetization in CV and H chondrites, which was interpreted as possible evidence for a core dynamo on their parent bodies [3, 4].

A key challenge facing the partial differentiation hypothesis is to identify meteoritic breccias containing samples of all the layers with various degree of differentiation expected in such body. Although certain achondrites are compositionally and isotopically affiliated with the forementioned chondrite groups [2], no meteorites containing both achondritic and chondritic fragments have yet been unambiguously identified.

An important exception may be the silicate-bearing IIE iron meteorites. The IIEs are composed of a Fe-Ni alloy matrix containing achondritic, primitive achondritic, and chondritic silicate inclusions that likely formed on a single parent body isotopically indistinguishable from H chondrites [5]. The different types of IIEs silicates may therefore sample all putative silicate layers of a partially differentiated body. Although, the origin of the matrix metal continues to be debated, its siderophile element composition demonstrates that it is not the product of fractional crystallization of a single molten core [6]. Instead, the matrix metal could have formed in isolated reservoirs of metal in the mantle and/or crust. However, it remains unknown whether a large-scale metallic core, not represented by known IIE samples, also formed on the same parent planetesimal.

Here, we search for evidence of a molten, advecting metallic core by assessing whether IIE irons contain natural remanent magnetization (NRM) produced by a core dynamo.

Experimental method: We studied the Fe-Ni matrix of the meteorite Colomera, a IIE iron containing achondritic silicates. We measured the paleomagnetism of four cloudy zones (CZs) separated by 0.5 to 5 mm on our sample. CZs are the result of a spontaneous phase separation that occurs in a Fe-Ni alloy as it cools through a characteristic, Ni-content dependent temperature. They consist of nanoscale intergrowths of Ni-rich, ferromagnetic tetrataenite islands embedded in a Ni-poor matrix. Because of their small size (61.5 ± 1 nm in radius for Colomera [7]), and characteristic high magnetic coercivity (~ 2 T [8]), CZ islands are very robust magnetic recorders capable of preserving an imprint of fields present when they cooled through the 320°C tetrataenite formation temperature on their parent planetesimal. We measured the surface magnetizations of the CZs using X-ray photoemission electron microscopy (XPEEM) [9]. This technique enables recovery of the three components of the paleodirection and intensity of the paleofield.

CZ islands growth model: To accurately interpret the XPEEM data, it is necessary to understand how the nanometer-scale CZ islands carrying the magnetic record formed and evolved to their present-day size. The size of the islands at the tetrataenite ordering temperature plays a crucial role. In particular, because the island size dictates the number of existing magnetic recorders at the time of magnetization acquisition, it controls the accuracy with which the intensity of the ancient field is recorded. However, this island size has been poorly constrained. To address this uncertainty, we developed a numerical model of CZ formation by diffusion (spinodal decomposition) based on the free energy equations for Fe-Ni alloys [10] and the diffusivity of Ni in these alloys [11]. Given a Ni content and a cooling rate, the model provides the average size of CZ islands at any temperature.

Results:

Island size: Using the free energy equations for a Fe-Ni alloy, we first derived the boundaries of the spinodal region on the Fe-Ni phase diagram and found that for a large range of Ni contents (35–41 wt.%), the alloy crosses the spinodal (i.e., decomposes into islands and matrix) at least 20°C above the blocking temperature of tetrataenite. Consequently, given the slow cooling rate of Colomera below 800°C (5 K Myr^{-1} [7]), the CZ had already evolved for tens of million years before recording a putative field. Moreover, the formation mechanism by spinodal decomposition differs from the intuitive mechanism of nucleation and growth. In the CZ, proto-islands form with a infinitely large radius and shrink before coarsening again. For Ni contents from 38 to 41 wt.% (typical for the region of the CZs we studied) and cooling rates slower than

~1000 K Myr^{-1}, our model shows that islands 1) do not shrink below the superparamagnetic size (where they would lose their ability to record an ambient field) and 2) are much larger at 320°C than previously assumed. In particular, we find that the mean island size at 320°C was on average only ~6% smaller than the present-day size (Fig. 1). Combining the size range found for a cooling rate of 5 K Myr^{-1} with statistics given in ref. [12], we calculated that fewer than 7,000 islands are necessary to obtain a directional error less than 5° and paleointensity error of 5 %. In comparison, we estimate that the number of islands sampled by our XPEEM measurements between 9,000 and 19,000. Therefore, CZs are indeed very efficiently magnetized, meaning that XPEEM studies of CZs can yield statistically robust measurements of ancient field properties.

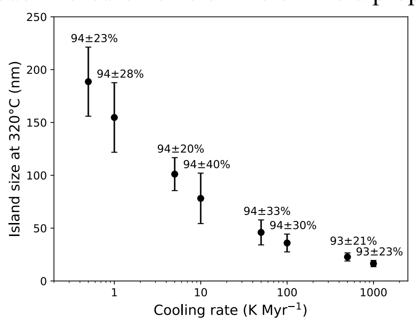

Fig. 1. Mean CZ island size at 320°C as a function of the cooling rate for 39 wt.%Ni alloys. Error bars show the 1σ uncertainty. Percentage of present-day size is indicated.

Paleomagnetism: We processed the XPEEM data to recover the direction (Fig. 2a) and intensity (Fig. 2b) of the field present when each of the four measured CZs formed. The magnetization directions share a common direction. Our demonstration of coherently-oriented NRM across 5 mm of the meteorite strongly argues against the remanence being a rock magnetic artifact. Moreover, the paleointensities recovered from the four CZs are within error of one another with an average value of 10 µT. These results, bolstered by our new model of CZ formation (see above), indicate that Colomera cooled in a field of ~10 µT.

Source of the magnetizing field: Colomera should have acquired its magnetization near the time of its 4.448 ± 0.1 Ga Ar/Ar age [13]. This late age excludes the solar nebula field, which had dissipated by 4.563 Ga [14]. Furthermore, neither impact-generated transient plasma fields (which should last < 1 day [15]) nor the early solar wind field (which is estimated to have a mean value of several nT [16]) can reasonably explain how a meteorite that cooled as slow as 5 K Myr^{-1} was coherently magnetized by a 10-µT field. However, our results are well explained by a magnetic field generated by a dynamo powered by the advection of the IIE parent body's metallic core. The intensity of the field generated by an active dynamo can reach up to 100–1000 µT at the surface of a <500-km asteroid [17].

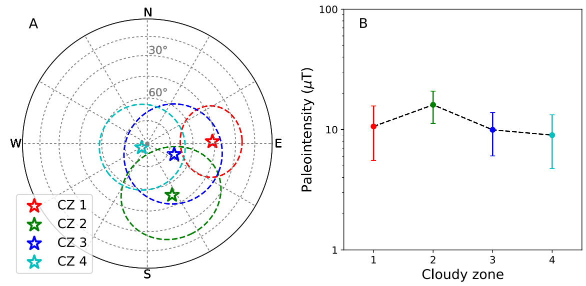

Fig. 2. A) Equal area projection showing the average, mutually oriented, paleofield directions recovered from the four CZs (1 to 4). Ellipses represent the 95% confidence interval accounting for the scatter in the recovered directions. Open (closed) symbols denote upper (lower) hemisphere. B) Paleofield intensities for each CZ with the 1σ uncertainty due to post-processing of XPEEM data.

This implies that the parent body of Colomera likely had a metallic core. Even so, large metal pools must have also remained unsegregated to allow the IIEs metal and silicate to mix and to account for the siderophile elemental patterns. Combined with the presence of chondritic and achondritic silicate inclusions in the meteorites, this supports the idea of partial differentiation for the IIE parent planetesimal. Therefore, IIE irons are apparently the first meteorite group from a single parent body containing records of the full range of planetary differentiation states: a metallic core, fully melted mantle, partially-melted mantle, and unmelted silicate crust. This implies that some achondrites, primitive achondrites, and chondrites could have originated from a single parent body.

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