PALEOMAGNETIC EVIDENCE FOR A PARTIALLY DIFFERENTIATED H CHONDRITE PARENT PLANETESIMAL. J. F. J. Bryson[1], B. P. Weiss[1], A. Scholl[2], A. T. Young[2] and F. Nimmo[3], [1] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA [2]Advanced Light Source, Berkeley, CA [3]Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA

Introduction: Chondritic meteorites are aggregates of the earliest known solar system solids. The textures and compositions of these meteorites indicate that they did not melt after accretion onto their parent asteroids, implying that these bodies did not undergo planetary differentiation (i.e., they did not separate into a rocky mantle and metallic core) [1]. Without a core, these asteroids could not have generated planetary magnetic fields [2], meaning that chondrites are not expected to have been magnetized by a planetary dynamo.

Because most chondrites are notoriously poor paleomagnetic recorders [3], a test of this model remained elusive for decades. Recent paleomagnetic measurements of the CV carbonaceous chondrites [4] provided the first tantalizing suggestion that chondritic parent bodies could have in fact generated dynamo fields. This observation challenges the above model by implying the existence of partially differentiated asteroids consisting of a molten, differentiated interior encased within a chondritic shell [5].

Here, we further test whether partially differentiated asteroids formed by examining the H chondrite parent body. We combine new paleomagnetic measurements of the metal in the metamorphosed H chondrite breccia Portales Valley with models of planetary accretion and heating to assess whether some ordinary chondrite bodies also generated a core dynamo.

Samples and methods: *Experimental Methods.* The Portales Valley H6 chondrite consists of approximately equal proportions of cm-scale chondritic material embedded within a matrix of bulk Fe-Ni metal. This metal underwent a series of low temperature phase transitions during slow planetary cooling [6], resulting in the Widmanstatten microstructure characteristic of meteoritic Fe-Ni. One of the components of this microstructure is the cloudy zone (CZ) – a nm-scale intergrowth of magnetically hard and soft phases – that has previously been shown to be an excellent paleomagnetic carrier, capable of recording a time-resolved record of the field present during its formation [7]. Using synchrotron X-ray magnetic microscopy (XPEEM) [8], we imaged the remanence of the CZ within Portales Valley (Figure 1A) and calculated a time-resolved record of the field generated by the H chondrite parent body from the individual images.

Modeling Methods. We also investigated the thermal history of the H chondrite parent body by modeling both instantaneous and incremental accretion (involving the gradual addition of cold chondritic material to the surface of an instantaneously accreted body) [5, 9]. Firstly, we calculated the initial heating due to the decay of ^{26}Al over the first ~5 Myr and used this parameter to estimate the depths and timing of internal melting within both types of body. We then modeled the subsequent cooling of these bodies over tens of millions of years [10], allowing us to predict the core mantle boundary heat flux and the magnetic Reynolds number in each case [11]. In incremental accretion, the initial radius of the body (i.e., the instantaneously accreted interior), the final radius of the body, the rate of addition of chondritic material, and the time after calcium aluminum-rich inclusion (CAI) formation of initial accretion were all varied. In the instantaneous case, only the radius of the body and time after CAI formation of accretion were varied.

Experimental Results: We find that Portales Valley experienced a strong paleomagnetic field during the ~6-12 Myr period over which the measured CZ acquired a remanence (Fig. 1). The calculated directions of this field are scattered over ~90°, and the calculated intensities vary between 40 – 330 μT; both properties are roughly constant over time. The permeability of the bulk metal in this meteorite should have concentrated any external field, altering its direction on length scales < 1 mm scale and amplifying its intensity by a factor of 3 – 200. The latter effect implies that the primary magnetizing field intensity was ≥ 1 μT and possibly tens of μT [10]. Hence, our observations are consistent with a long-lived, uniform field with an intensity similar to that of other asteroid dynamos [1, 3].

The CZ remanence is carried by islands of the magnetically hard phase tetrataenite (intrinsic coercivity >2 T [7]). This remanence is therefore extremely stable and hence likely represents a field generated by the parent asteroid. Also, both the Ar/Ar age of Portales Valley (4470 ± 11 Myr [12]) and its measured metallographic cooling rate (~10 K/Myr [13]), require that this meteorite cooled through the CZ formation temperature (593 K) tens of Myr after CAI formation. The slow cooling rate precludes the possibility that the paleomagnetic field was produced by short-lived impact-generated plasmas [14, 15], while the magnetization age precludes a nebular field source (present in the first ~<10 Myr of the solar system) [1].

Discussion and implications: The observed magnetic field properties (long-lived, stable, and late-stage) are consistent with those expected for a compositionally driven planetary field (very similar to that observed

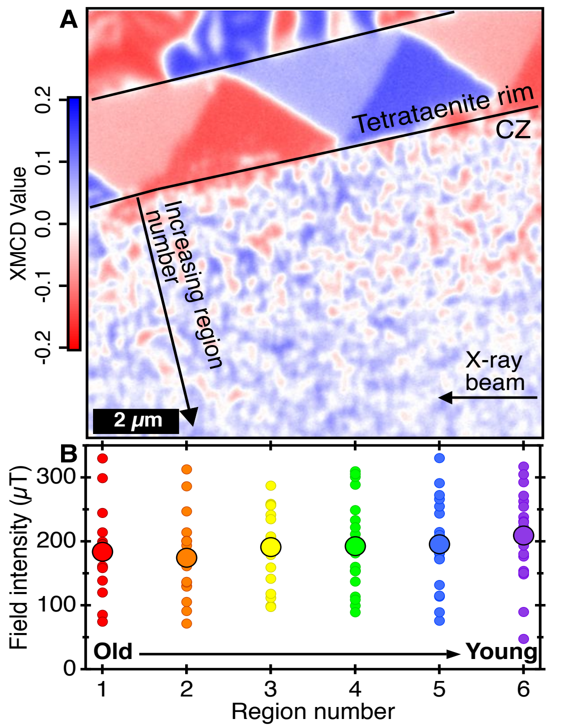

***Figure 1A** Representative X-ray magnetic circular dichroism (XMCD) image of the Portales Valley CZ. Blue and red correspond to positive and negative projections of the local magnetization onto the X-ray beam, respectively. **B** Evolution of the average field intensity (large points) calculated from each individual image (small points) along one interface. The age of the CZ decreases as region number increases (~1 – 2 Myr per region).*

previously for the Imilac pallasite [10]) or a crustal remanence (which requires earlier dynamo activity). This observation therefore indicates that the H chondrite parent body was partially differentiated, and further suggests that it may have generated a field through a similar mechanism to that acting within the Earth at the present day. A similar mechanism has also been suggested to have acted within other asteroids [10].

Our models of planetary heating demonstrate that partially differentiated asteroids can form readily through incremental accretion if the time period additional accretion is comparable to that of heating due to the decay of ^{26}Al (~5-10 Myr). Our models also demonstrate that for a partially differentiated asteroid with an initial and final radius of ~50 km and ~115 km, respectively, it is feasible that the deepest chondritic material cooled through 800 K at the experimentally measured rate for the Portales Valley and cooled through the CZ formation temperature while the asteroid core was solidifying and therefore capable of generating a field (Figure 1B). Models of instantaneous accretion only generate partial differentiation for an extremely narrow range of planetary radii and accre-

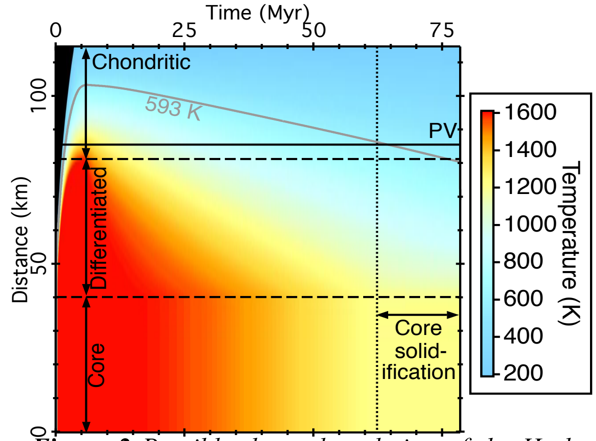

***Figure 2** Possible thermal evolution of the H chondrite parent body. The incremental addition of chondritic material allows for partial differentiation. The depth of the Portales Valley (PV, horizontal black line) meteorite was identified by comparing the experimental and predicted cooling rates. This depth reaches 593 K (CZ formation temperature, grey contour) during core solidification (dotted vertical line).*

tion time, implying that it is unlikely that the H chondrite parent body accreted instantly. This observation is also consistent with the several-Myr timescale recently inferred for planetesimal accretion from chondrule precursors [16].

An incrementally accreted partially differentiated asteroid is therefore consistent with the measured thermal history and magnetic properties of the Portales Valley meteorite, as well as independent petrographic and geochemical observations of partial melting on the H chondrite parent body [17]. These observations therefore further support the proposal that some chondrites represent the unaltered crusts of internally differentiated asteroids.

References: [1] Weiss B. P. and Elkins-Tanton L. T., (2013) *AREPS, 41,* 529–560. [2] Stevenson D. J. (2010) *Space Sci. Rev., 152,* 651–664. [3] Weiss B. P. *et al.*, (2010) *Space Sci, Rev., 152,* 341–390. [4] Carporzen L. *et al.,* (2011) *PNAS, 108*, 6386–6389. [5] Elkins-Tanton L. T. *et al.,* (2011) *EPSL, 305,* 1–11. [6] Goldstein J. I. *et al.*, (2009) *Chemie der Erde, 69*, 293–325. [7] Bryson J. F. J. *et al.*, (2014) *EPSL, 388,* 237–248. [8] Bryson J. F. J. *et al.*, (2014) *EPSL, 396,* 125–133. [9] Rubie D. C. *et al.*, (2015) *Treatise on Geophysics*, 43–74. [10] Bryson J. F. J. *et al.,* (2015) *Nature 517*, 472–475. [11] Olson P. & Christensen U. R. (2006) *EPSL, 250,* 561–571. [12] Bogard D. D. & Garrison D. H. (2009) GCA, 73, 6965–6983. [13] Scott E. R. D. *et al.* (2014) *GCA*, 136, 13–37. [14] Yang J. *et al.* (2007) *Nature*, 446, 888–891. [15] Hood L. L. & N. A. Artemieva (2008) *Icarus* 193, 485-502. [16] Johansen A. *et al.* (2015) *Sci. Adv.* 1 e1500109 [17] Ruzicka A. *et al.* (2005) *Meteorit. Planet. Sci.*, 40, 261-295.