PALEOMAGNETISM OF IRON METEORITES: RECENT ADVANCES AND NEW QUESTIONS. C. Maurel[1], J. Gattacceca[2], J. F. J. Bryson[3], C. I. O. Nichols[3] and B. P. Weiss[1], [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [2]CNRS, Aix Marseille Univ, IRD, INRAE, CEREGE, Aix-en-Provence, France, [3]Department of Earth Sciences, University of Oxford, Oxford, UK.

Introduction: Most iron meteorites are thought to originate from the cores of differentiated planetesimals [1]. However, some iron meteorite groups experienced fast and non-isothermal cooling, unlike the expected thermal history of an insulated core [2]. This suggests that partial mantle stripping by impacts, and mantle-hosted metallic reservoirs resulting from incomplete differentiation or impacts, may have been somewhat common. Mantle stripping is also proposed to explain the metal-rich nature of the asteroid (16) Psyche [3].

Paleomagnetic studies of basaltic achondrites recognized that some planetesimals generated core dynamo magnetic fields. On the other hand, the study of iron meteorites has lagged that of other achondrites for two main reasons. First, their abundance of multidomain metal grains made it hard to relate their magnetization to properties of an ancient field [5]. Second, under the assumption that iron meteorites formed insulated deep inside their parent bodies, it was assumed that metal carriers in iron meteorites would only have acquired their magnetic records after the metallic core had solidified and dynamo activity had stopped [6].

Paleomagnetic investigations of iron meteorites were recently invigorated with the application of X-ray photoemission electron microscopy (XPEEM) [7], whose high spatial resolution enables measurements of the remanent magnetization of ensembles of nm-scale, single domain grains with optimal magnetic recording properties [8]. Furthermore, the increasing diversity of iron meteorites cooling histories has offered new perspectives on the venue for magnetization acquisition. Iron meteorite cooling in the mantle or outermost layers of a mantle-stripped planetesimal could have cooled fast enough to reach the low temperatures at which they recorded magnetization while their parent body was still generating a magnetic field via a core dynamo [4]. The forthcoming NASA Psyche mission, which will search for a remanent magnetization on (16) Psyche [9], will require an understanding of the connection between the nanopaleomagnetic record of iron meteorites and their larger scale magnetization.

Here, we review the findings enabled by our improved understanding of the nanopaleomagnetism of iron meteorites. We also present new paleomagnetic data acquired on increasingly larger iron meteorite samples from the mm^3 to the m^3. We briefly discuss the perspectives offered by both approaches.

Nanopaleomagnetic record of iron meteorites: XPEEM experiments have focused on cloudy zones, ensembles of Ni-rich, < 200-nm-size ferromagnetic grains [10]. Taking advantage of the preferential absorption of X-rays depending on a sample's local magnetization orientation [11], one can obtain a cloudy zone's average magnetization vector. With the current technique, we can determine whether a meteorite recorded an ancient planetary dynamo field. Under certain assumptions, an approximate estimate (uncertainty of about 2 orders of magnitude) of the paleointensity of this field can be obtained. XPEEM measurements have already been applied to a wide spectrum of iron meteorite parent bodies (Fig. 1):

Mantle-stripped differentiated body. The IVA iron Steinbach was found to carry a remanent magnetization indicating it recorded a >> 50-µT field [12]. Because metallographic data suggest the occurrence of a mantle-stripping event on the IVA parent body (e.g., [13]), this record was attributed to a short-lived dynamo activity during crystallization of the exposed core [12].

Non-mantle-stripped differentiated body. The main-group pallasites (MGP) likely cooled in their parent bodies' mantles [14]. Three MGP recorded a 2-200-µT likely later than ~100 Ma after CAIs, while two others do not carry a significant remanence [15-17]. The five MGP seemingly captured the onset of a dynamo activity, likely powered by core crystallization [16].

Incompletely differentiated bodies. The cloudy zones of three IAB irons (Odessa, Toluca, Tazewell) sampling at least two parent bodies were found not to carry a significant remanence [7,18]. This is consistent with the idea that those IAB parent bodies only contained metallic pools formed by local differentiation or impacts [19,20]. On the other hand, three IIE irons, which likely cooled in the mantle of a partially-differentiated parent body [21], recorded a 5-300-µT field between ~80 and ~160 Ma after CAIs. A dynamo powered by core crystallization was identified as the most likely source of the magnetizing field [22,23].

Bulk iron meteorites investigations: XPEEM investigations indicate that some iron meteorite parent bodies hosted active dynamos. Evidence for such activity will be investigated at (16) Psyche. To bridge the gap between nanoscale and spacecraft observations, we analyzed the magnetization (magnetic moment per unit mass) of pieces of iron meteorites ranging from mm^3 to ~m^3. Limited previous magnetic studies conducted on large meteorites concluded that magnetic vector randomness, or large-scale spontaneous magnetization, should yield the relationship $M \propto 1/\sqrt{V}$ for magnetization M and volume V (e.g., [24]).

We used a 2G superconducting rock magnetometer for mm^3 samples, spinner magnetometers (Molspin minispin and [25]) for cm^3 samples and a magnetometer array for m^3 meteorites [26]. Each instruments allowed us to isolate the remanent from the induced component of the magnetization. We discarded mm^3 and cm^3 samples that were obviously remagnetized by a magnet. The m^3 measurements were conducted *in situ* at the Museum Support Center of the Smithsonian Institution.

Here we focus on four meteorites measured at different size scales (Fig. 2). Interestingly, none follows a $M \propto 1/\sqrt{V}$ trend. Two even have magnetization that barely decreases with size. We examined three potential causes that could account for the departure of the data from the random magnetization model: exposure to hand magnets, heating from atmospheric entry, and viscous remanence (VRM) acquired in the Earth's field. The two former processes would affect too small of a region of the m^3 samples to explain the trends. We verified experimentally that a VRM would only make up for < 0.1% of the observed magnetization.

This appears to suggest that, even at meter scale, the meteorites' magnetizations exhibit a certain degree of directional uniformity that cannot be due to obvious contamination. Although the origin of this possible uniform component is unknown, could it reflect ancient magnetic fields on the parent bodies, analogous to those identified with XPEEM measurements? These results strengthen the idea that iron meteorites may retain meaningful records of past planetary magnetic fields.

Perspectives: A better understanding of the magnetization process of the cloudy zone is an area of active research, which could result in more accurate XPEEM paleointensity estimates. The IIIAB irons, which may also have experienced an early mantle-stripping event [27], could be interesting future targets. Using XPEEM to analyze other iron meteorite microstructures with potentially high-fidelity recording properties such as plessite is under consideration [28].

Our bulk sample measurements can provide insights for the Psyche mission. The fact that none of our meteorites follows a random vector trend hints at the possibility that some asteroids could have substantial magnetic moments. The remanent field of such bodies could potentially be characterized by spacecraft magnetometers. This would enable the magnetization to be measured in a geological context, placing further constraints on the origin of asteroids magnetization and the magnetic activity on small bodies.

References and acknowledgements: [1] Chabot and Haack (2006) in: *Meteorites and The Solar System II*, pp. 747-771. [2] Scott (2020) In: *Oxford Research Encyclopedia*, pp. 1-75. [3] Elkins-Tanton et al. (2020) *JGR* 125, e2019JE006296. [4] Harrison et al. (2016) in: *Planetesimals*, pp. 204-223. [5] Brecher and Albright (1977) *JGG* 29, 379-400. [6] Cikowski (1987) in: *Geomagnetism vol. 2*, pp. 525-560. [7] Bryson et al. (2014) *EPSL* 396, 125-133. [8] Bryson et al. (2019) *JGR* 124, 1-19. [9] Polanskey et al. (2018) *15th SpaceOps Conf.*, 1-14. [10] Uehara et al. (2011) *EPSL* 306, 241-252. [11] Stöhr et al. (1993) *Science* 259, 658-661. [12] Bryson et al. (2017) *EPSL* 472, 152-163. [13] Yang et al. (2008) *GCA 72*, 3043-3061. [14] Yang et al. (2010) *GCA* 74, 4471-4492. [15] Bryson et al. (2015) *Nature* 517, 472-475. [16] Nichols et al. (2016) *EPSL* 441, 103-112. [17] Nichols (2017) *PhD Thesis*, pp. 1-253. [18] Nichols et al. (2018) *GCA* 229, 1-19. [19] Worsham et al. (2017) *EPSL* 467, 157-166. [20] Hunt et al. (2018) *EPSL* 482, 490-500. [21] Ruzicka (2014) *Chemie der Erde* 74, 3-48. [22] Maurel et al. (2020) *Sci. Adv.* 6, eaba1303. [23] Maurel et al., *under review*. [24] Wasilewski et al. (2002) *MAPS* 37, 937-950. [25] Uehara et al. (2017) *Rev. Sci. Instr.* 88, 104502. [26] Clavé, Maurel et al. (2020) *G^3* 21, e2020GC009266. [27] Matthes et al. (2020) *GCA* 285, 193-206. [28] Mansbach et al. (2020) *AGU Fall Meeting*, GP001-05. We thank T. J. McCoy and J. Hoskin for granting us access to the Museum Support Center, and R. J. Harrison for invaluable discussions about XPEEM.

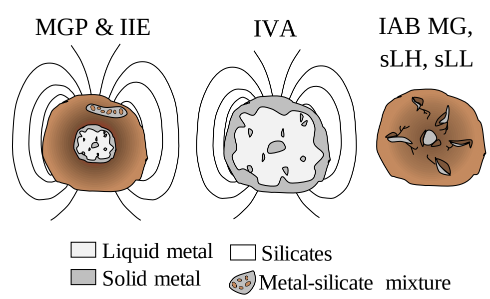

Fig. 1. Sketch of the internal structure and magnetic activity of iron meteorite parent bodies studied with XPEEM.

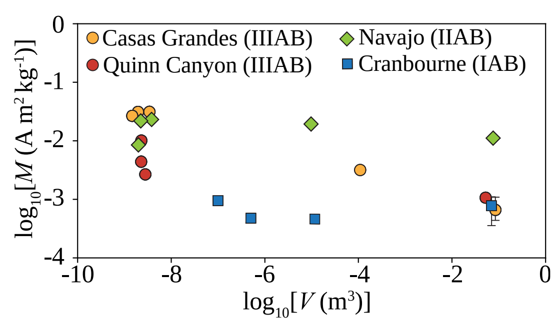

Fig. 2. Magnetization as a function of volume for four iron meteorites measured at different size scales.