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# A nonmagnetic differentiated early planetary body

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## ABSTRACT

Paleomagnetic studies of meteorites have shown that the solar nebula was likely magnetized and that many early planetary bodies generated dynamo magnetic fields in their advecting metallic cores. The surface fields on these bodies were recorded by a diversity of chondrites and achondrites, ranging in intensity from several μT to several hundred μT. In fact, an achondrite parent body without evidence for paleomagnetic fields has yet to be confidently identified, hinting that early solar system field generation and the dynamo process in particular may have been common. Here we present paleomagnetic measurements of the ungrouped achondrite NWA 7325 indicating that it last cooled in a near-zero field ($<\sim1.7$ μT), estimated to have occurred at $4563.09 \pm 0.26$ million years ago (Ma) from Al–Mg chronometry. Because NWA 7325 is highly depleted in siderophile elements, its parent body nevertheless underwent large-scale metal-silicate differentiation and likely formed a metallic core. This makes NWA 7325 the first recognized example of an essentially unmagnetized igneous rock from a differentiated early solar system body. These results indicate that all magnetic fields, including those from any core dynamo on the NWA 7325 parent body, the solar nebula, young Sun, and solar wind, were $<1.7$ μT at the location of NWA 7325 at 4563 Ma. This supports a recent conclusion that the solar nebula had dissipated by ∼4 million years after solar system formation. NWA 7325 also serves as an experimental control that gives greater confidence in the positive identification of remanent magnetization in other achondrites.

## 1. Introduction

The existence of dozens of achondrite groups and ungrouped achondrites indicates that numerous planetesimals experienced large-scale melting and differentiation in the early solar system (Scheinberg et al., 2015b). Much of the energy for melting was likely supplied by the decay of the short-lived radionuclide $^{26}$Al, which should have substantially heated bodies that accreted a large fraction of their masses within 2 million years (My) after the formation of calcium aluminum-rich inclusions (CAIs) (Weisberg et al., 2006). Hf–W chronometry of iron meteorites confirms that many bodies experienced large-scale metal-silicate fractionation during this period (Kruijer et al., 2014). Thermal and compositional core convection (Nimmo, 2009), possibly combined with mechanical stirring from impacts, likely powered core advection for ten to perhaps a few hundred My (Bryson et al., 2015; Elkins-Tanton et al., 2011; Formisano et al., 2016; Scheinberg et al., 2015a; Sterenborg and Crowley, 2013).

Scaling relationships derived from magnetohydrodynamic simulations of convecting metallic cores indicate that many of these bodies should have been capable of generating dynamos (Weiss et al., 2010). Indeed, essentially every achondrite group that has yet been studied with modern paleomagnetic methods has been found to contain ancient natural remanent magnetization (NRM): evidence for past core dynamos has been identified in plutonic angrites (Wang et al., 2017), eucrites (Fu et al., 2012), and main

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group pallasites (Bryson et al., 2015; Tarduno et al., 2012). Remanent magnetization attributed to possible core dynamos has even been found in CV (Carporzen et al., 2011; Gattacceca et al., 2016) and CM chondrites (Cournède et al., 2015). Although a study of five eucrites including ALHA81001 and PCA 82502 concluded that they recorded low-field ($<10$ μT) conditions (Cisowski, 1991), this study lacked precise radiometric ages and thermochronometry, used only relatively low-field alternating field (AF) demagnetization, and was unable to prevent thermochemical alteration of the samples during thermal demagnetization; recent studies of ALHA81001 and PCA 82502 identified stable, unidirectional NRM of extraterrestrial origin acquired in fields of ~12 and ~70 μT, respectively (Fischer et al., 2013; Fu et al., 2012). All told, the available paleomagnetic data indicate that planetesimal dynamos were likely common, if not ubiquitous, in the early solar system.

Nevertheless, it is expected that not all differentiated bodies that underwent large-scale metal-silicate fractionation should have been capable of generating dynamos. There are numerous reasons a dynamo might be inhibited on a differentiated body. First, it is possible that a body underwent large-scale metal-silicate fractionation but formed localized, dispersed metal-rich regions rather than a large metallic core. The low gravity and possibility of incomplete melting on planetesimals means that even if temperatures exceeded that of the Fe–S solidus, metal percolation to the center of planetesimals was not guaranteed (Cerantola et al., 2015). Possible examples of such bodies include the winonaite-IAB iron meteorite parent body and the IIE iron meteorite parent body (Ruzicka, 2014). Second, even if a metallic core formed, it may have not advected. Thermal convection would be inhibited by sufficiently slow cooling rates, as might be expected if the overlying mantle was solid and sufficiently thick; such an outcome may be consistent with the proposal that planetesimals never formed silicate magma oceans but only melted episodically and in small quantities (Wilson and Keil, 2012). Compositional convection is a potent power source but is only expected for metallic cores containing a light alloying element (Nimmo, 2009). Furthermore, although both outward core crystallization and inward core crystallization in the iron snow regime (Rückriemen et al., 2015) provide a buoyancy flux for driving convection, inward dendritic core crystallization does not (Scheinberg et al., 2015a). Third, even if the metallic core advected, it still might not generate a dynamo. Fluid velocities may be too slow, as expected for core radii smaller than ~80–100 km (Elkins-Tanton et al., 2011; Nimmo, 2009; Weiss et al., 2010) or perhaps even ranging up to radii of 1000 km (Sterenborg and Crowley, 2013), or the velocity field may have an unsuitable geometry (e.g., not lead to a field-amplification instability) (Stevenson, 1983). One or more of these reasons can account for why, among all rocky and icy solar system bodies, only the Earth, Mercury, and Ganymede are known to have active dynamos today (Stevenson, 2010). Finally, even if a body generated a dynamo, meteorites from this body may not retain records of this field if the meteorites were last cooled or aqueously altered when the dynamo was not active. In particular, it has recently been argued that thermal blanketing of planetesimal cores by $^{26}$Al-enriched mantles should delay thermal convection dynamos until at least several million years after differentiation (Sterenborg and Crowley, 2013).

We see that there is every expectation that differentiated planetesimals should have formed in the early solar system that either never generated magnetic fields or at least produced fields not recorded by achondrites from these bodies. Searching for such examples would not only establish the frequency and diversity of planetesimal dynamo activity, but also test the methodologies that have been developed for identifying dynamos from the meteorite record. In short, demonstrating our ability to identify unmagnetized meteorites would build greater confidence in our identification of magnetized meteorites. Additionally, identification of unmagnetized meteorites would enable constraints on the intensity of magnetic fields generated external to their parent bodies like, those from the solar nebula and early solar wind.

Because arbitrarily weak paleofields will produce essentially no detectable NRM, it is not possible to demonstrate that an apparently unmagnetized rock formed in truly zero-field conditions but only to place an upper limit on the paleofield. Even so, meteorites with near-zero paleointensities are difficult to identify because they are unfamiliar: essentially all Earth rocks that have been studied with paleomagnetic methods formed in the geomagnetic field. Furthermore, numerous processes can impart secondary magnetization after the meteorites arrive at Earth and enter the geomagnetic field: surficial heating during atmospheric entry, weathering and associated crystallization of ferromagnetic grains, viscous remanence acquisition, and application of hand magnets by meteorite collectors (Weiss et al., 2010). Another major problem is the acquisition of spurious remanence during the laboratory demagnetization process. The ferromagnetism of the vast majority of basaltic achondrites is dominated by the iron–nickel minerals kamacite and martensite, which usually form low-coercivity, multidomain grains that readily acquire spurious remanence during alternating field (AF) demagnetization (Weiss et al., 2010). This spurious remanence could potentially be mistaken for NRM or, at the very least, limits out ability to put stringent upper limits on the paleointensities for these samples. Furthermore, thermal demagnetization of these samples typically leads to thermochemical alteration of these iron–nickel minerals (Suavet et al., 2014), which can render paleointensities measured using laboratory heating methods inaccurate. Finally, because individual ferromagnetic grains have spontaneous magnetization even when the bulk rock is not magnetized, paleomagnetic analysis of small samples (as is common in extraterrestrial paleomagnetic studies) is fundamentally limited by the statistics of small numbers of grains (Berndt et al., 2016; Lima and Weiss, 2016). As a result of these limitations, only recently have we been able to confidently identify largely unmagnetized rocks from the Moon that place meaningful upper limits ($<4$ μT) on the paleofield after 3.5 Ga (Tikoo et al., 2014).

Identification of null magnetic field conditions on an early planetesimal requires an ancient, well-preserved sample with high-fidelity magnetic recording properties. Here we present paleomagnetic, petrographic, and $^{40}$Ar/$^{39}$Ar analyses of the ungrouped basaltic achondrite Northwest Africa (NWA) 7325. Our measurements show that this meteorite was last cooled from above the peak magnetic disordering temperature (~780 °C) in a field of no greater than ~1.7 μT.

## 2. Petrology, thermal history, and age of NWA 7325

NWA 7325 is a dark green achondrite partially covered with a chartreuse-colored fusion crust found as 37 separate pieces in southern Morocco in 2012 (Barrat et al., 2015; Irving et al., 2013). It is an unbrecciated, fine- to medium-grained (typical grain size 0.5–1 mm) plutonic rock (probably a cumulate) composed of 56 vol.% calcic plagioclase, 27 vol.% diopside, 16 vol.% forsterite and accessory troilite containing Cr-rich lamellae, chromite, and FeNi metal.

NWA 7325 is thought to have been produced as a partial melt in the rocky exterior of a highly differentiated parent body (Barrat et al., 2015; Weber et al., 2016). Its abundances of highly siderophile elements are depleted by 3–4 orders of magnitude relative to CI chondrites, suggesting that its parent body underwent large-scale metal-silicate fraction (Archer et al., 2015). NWA 7325's distinctive elemental composition and unique combination of O and $^{54}$Cr isotopes (Barrat et al., 2015; Irving et al., 2013) indicate

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