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New constraints on the magnetic history of the CV parent body and the solar nebula from the Kaba meteorite

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ABSTRACT

Recent paleomagnetic studies of Allende CV chondrite as well as thermal modeling suggest the existence of partially differentiated asteroids with outer unmelted and variably metamorphosed crusts overlying differentiated interiors. To further constrain the magnetic history of the CV parent body, we report here paleomagnetic results on Kaba CV chondrite. This meteorite contains 11 wt% pseudo-single domain magnetite, making it a rock with an excellent paleomagnetic recording capacity. Kaba appears to carry a stable natural remanent magnetization acquired on its parent body upon cooling in an internally generated magnetic field of about 3 μT from temperatures below 150 °C during thermal metamorphism about 10 to several tens of Myr after solar system formation. This strengthens the case for the existence of a molten advecting core in the CV parent body. Furthermore, we show that no significant magnetic field (i.e. lower than ∼0.3 μT) was present when aqueous alteration took place on the Kaba parent body around 4 to 6 Myr after solar system formation, suggesting a delay in the onset of the dynamo in the CV parent body and confirming that nebular fields had already decayed at that time.

1. Introduction

Chondritic meteorites have long been regarded as samples from undifferentiated asteroids. However, recent paleomagnetic studies of the CV chondrite Allende have shown that its natural remanent magnetization (NRM) was acquired after accretion and after the likely lifetime of the solar nebula, suggesting that its parent body had generated a dynamo magnetic field and formed an advecting molten core (Carporzen et al., 2011). This implies that partially differentiated asteroids formed with outer unmelted and variably metamorphosed crusts overlying differentiated interiors (Carporzen et al., 2011; Elkins-Tanton et al., 2011; Weiss and Elkins-Tanton, 2013). This idea has important implications for our understanding of asteroid accretion, differentiation, and the links between spectroscopic properties of asteroid surfaces and their deep interior structures (Weiss and Elkins-Tanton, 2013). However, this paleomagnetic evidence was obtained from a single meteorite. To further test this hypothesis, we present a detailed paleomagnetic study of another CV chondrite: the Kaba meteorite.

Kaba is a fall and is classified as a CV3.0 in the Bali-type oxidized sub-group $CV3_{oxB}$ (Krot et al., 1995, 1998; Huss et al., 2006). Raman spectroscopy of its organic matter (Bonal et al., 2006) and the coexistence of almost pure forsterite and fayalite (Hua and Buseck, 1995) indicate that Kaba is the least metamorphosed and pristine sample available from the CV parent body. Peak metamorphism temperatures have been estimated to be in the <300–370 °C range based on X-ray absorption near edge structure and Raman spectroscopy of insoluble organic matter (Cody et al., 2008). Moreover, Kaba contains abundant magnetite (Watson et al., 1975) and shows no petrographic evidence for shock (Scott et al., 1992), making it prime material for recording the paleomagnetism of the CV parent body. The partial differentiation hypothesis predicts that like Allende, other CV chondrites including Kaba may also contain remanent magnetization acquired during thermal metamorphism and/or aqueous alteration on the parent body. Evidence for a core dynamo origin would be provided by substantial magnetization acquired after the dissipation of the solar nebula [∼3–5 My after the formation of calcium aluminum-rich inclusions (CAIs) (Wang et al., 2015)].

NRM in Allende attributed to a dynamo unblocks up to 290 °C. Estimates of Allende's peak metamorphic temperatures are uncertain, ranging from 250–600 °C (see refs. Carporzen et al., 2011). Therefore, the NRM in Allende could have been acquired either

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during continuous cooling in a field from a peak metamorphic temperature of 290 °C or alternatively during cooling from a higher temperature with the dynamo initiating only when temperatures reached 290 °C. Given Kaba's generally lower peak metamorphic temperature compared to Allende, the partial differentiation hypothesis predicts that Kaba may have an overprint blocked to a lower peak temperature than that of Allende (whose NRM unblocks up to 290 °C).

2. Material and methods

The Kaba meteorite fell in 1857 in Hungary and a single oriented stone of about 3 kg was recovered (Sztrokay et al., 1961). We obtained samples of Kaba from the Natural History Museum in London (two samples from BM.35794), Muséum National d'Histoire Naturelle in Paris (MNHN sample #88), the National History Museum in Vienna (sample #3352), and Arizona State University (ASU). For rock magnetism analyses, one sample from NHM was embedded in epoxy and cut into small pieces with masses of a few mg each using a wire saw cooled with ethanol, with some of these subsamples consisting exclusively of matrix material or chondrule material. The other samples were used for paleomagnetism.

A variety of magnetic properties were measured: NRM and artificial remanence and their behavior upon thermal pressure and alternating field demagnetization, hysteresis parameters, anisotropy of magnetic susceptibility, and magnetic susceptibility as a function of temperature. All magnetic measurements were performed at CEREGE (Aix-en-Provence, France) and in the Massachusetts Institute of Technology (MIT) Paleomagnetism Laboratory (Cambridge, USA). Hysteresis measurements were performed with a Princeton® Micromag Vibrating Sample Magnetometer (VSM) with a maximum applied field of 1 T and a sensitivity of 5×10^{-9} Am^2. The analysis of hysteresis loops provided saturation remanent magnetization (M_{RS}), saturation magnetization (M_S) and the coercive force (B_C). High field susceptibility (χ_{HF}) was determined by a linear fit for applied fields > 0.9 T of the hysteresis loops. The remanent coercive force (B_{CR}) was determined by DC back field experiments performed with the VSM. The low field specific susceptibility (χ in m^3/kg), its variation at low and high temperatures, and its anisotropy were measured using Agico MFK1 apparatus with a sensitivity of 5×10^{-13} m^3 and operating at 200 A/m and a frequency of 976 Hz. The anisotropy of magnetic susceptibility (AMS) was characterized by the shape parameter T (Jelinek, 1981), and the anisotropy degree P (ratio of maximum to minimum susceptibility). All remanence measurements were performed with a SQUID cryogenic magnetometer (2G Enterprises, model 755R, with noise level of 5×10^{-12} Am^2), with an attached automatic alternating field (AF) 3-axis degausser system (maximum peak field 250 mT) placed in a magnetically shielded room with a residual field of ~500 nT. Thermal demagnetization was performed using a MMTD furnace using argon atmosphere above 250 °C (at CEREGE) or an ASC furnace (at MIT). Isothermal remanent magnetization (IRM) was imparted using a pulse magnetizer from Magnetic Measurements. We used this to determine the $S_{-300\,\mathrm{mT}}$ ratio, defined as the IRM obtained after applying a 3 T field and then a back-field of 300 mT normalized to the IRM acquired in 3 T. Remagnetization under pressure was studied using a nonmagnetic pressure cell and experimental settings described in Gattacceca et al. (2010). We also experimentally estimated the viscous remanent magnetization (VRM) acquisition and decay rates. Acquisition was monitored over a period of one month by periodic measurements of the VRM gained in the terrestrial field. The decay rate was then measured by periodic measurements with the sample kept in a sub-null (~50 nT) ambient field. VRM acquisition and decay were best fitted using a linear fit with log time to compute the acquisition and decay rates noted rates (denoted S_a and S_d).

Table 1
Magnetic properties.

	Unit	Average ± s.d.	N
Hysteresis properties			
M_{RS}	Am^2/kg	1.69 ± 0.25	8
M_S	Am^2/kg	10.41 ± 2.60	5
B_{CR}	mT	34.6 ± 2.9	21
B_C	mT	14.5 ± 1.8	21
B_{CR}/B_C		2.41 ± 0.24	21
M_{RS}/M_S		0.15 ± 0.0	21
Magnetic susceptibility and its anisotropy			
χ	m^3/kg	$6.64 \pm 1.1 \times 10^{-5}$	7
P_{AMS} [a]		1.065	3
T_{AMS} [a]		0.13	3
Remanence			
S_a	Am^2/kg µT logs	$1.63 \pm 0.61 \times 10^{-6}$	6
S_d	Am^2/kg µT logs	$4.91 \pm 2.08 \times 10^{-7}$	5
TRM 590 °C	Am^2/kg µT	3.40×10^{-4}	
pTRM 250 °C	Am^2/kg µT	5.48×10^{-6}	
ARM 100 mT	Am^2/kg µT	1.18×10^{-4}	
PRM 2 GPa	Am^2/kg µT	1.52×10^{-5}	

All abbreviations are defined in the text. TRM, ARM, and PRM intensities are normalized to the ambient field.
[a] Tensorial average value.

3. Intrinsic magnetic properties

The magnetic properties of Kaba are summarized in Table 1. Its intrinsic magnetic properties are remarkably homogeneous down to very small scales: χ, M_{RS}, and M_S do not depart by more than 10% away from their mean values for masses ranging from 40 mg (for hysteresis properties) and several grams (for susceptibility) down to ~1 mg. The susceptibility measured for an 8 g sample by Rochette et al. (2008) is remarkably similar to the values measured here on ~mg samples. This indicates that ferromagnetic minerals are homogeneously dispersed throughout the meteorite at fine scales. Only one large porphyritic chondrule (1.5 mm in diameter), which showed abundant opaque grains (100–200 µm in size) in reflected light microscopy, was found to have χ and M_S significantly higher than the mean (by a factor of two).

Kaba's hysteresis properties are typical of magnetite (Fig. 1a). The ratios $B_{CR}/B_C = 2.39$ and $M_{RS}/M_S = 0.17$ indicate a pseudo-single domain behavior (Fig. 1b). Matrix samples and chondrule samples are subtly different, with the latter being slightly closer to multidomain behavior (Fig. 1b). This indicates a larger ferromagnetic grain size or a different magnetic mineralogy in the chondrules compared to the matrix.

The evolution of magnetic susceptibility at low temperature exhibits a clear Verwey transition at 120 K, indicating the presence of stoichiometric magnetite (Fig. 2). Thermal demagnetization of saturation isothermal remanent magnetization (SIRM) and thermoremanent magnetization (TRM) show major inflexions at 580 °C, indicating that magnetite is the dominant remanence carrier (Fig. 3). This is consistent with measurements of the temperature-dependence of M_S (Watson et al., 1975). The dominance of magnetite is confirmed by an $S_{-300\,\mathrm{mT}}$ ratio of 1.00 that exclude the significant presence of high coercivity minerals like pyrrhotite. Petrographic observations also indicate that metal and pyrrhotite, common in other CV chondrites (Rochette et al., 2008) are insignificant in Kaba (Sztrokay et al., 1961). The sulfides described in Kaba (Sztrokay et al., 1961; Rubin and Grossman, 1985; Keller and Buseck, 1990) are mostly pentlandite (paramagnetic) and minor troilite (antiferromagnetic at room temperature). Although troilite may be able to carry a remanent magnetization at room temperature, its low modal abundance (a minor fraction of the total sulfide abundance of about 2 vol%) and weak saturation magnetization (tentatively estimated at about 3.7×10^{-3} Am^2/kg