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1	Paleomagnetism of Rumuruti chondrites suggests a partially differentiated
2	parent body
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14	Abstract: Different types of magnetic fields were at work in the early solar system: nebular
15	fields generated within the protoplanetary nebula, solar fields, and dynamo fields generated
16	within the solar system solid bodies. Paleomagnetic studies of extraterrestrial materials can
17	help unravel both the history of these magnetic fields, and the evolution of solar system solid
18	bodies. In this study we studied the paleomagnetism of two Rumuruti chondrites (PCA 91002
19	and LAP 03639). These chondrites could potentially bear the record of the different fields
20	(solar, nebular, dynamo fields) present during the early solar system. The magnetic
21	mineralogy consists of pseudo-single domain pyrrhotite in LAP 03639 and pyrrhotite plus
22	magnetite in PCA 91002. Paleomagnetic analyses using thermal and alternating field
23	demagnetization reveal a stable origin trending component of magnetization. Fields of 12 μT
24	or higher are required to account for the magnetization in PCA 91002, but the timing and
25	exact mechanism of the magnetization are unconstrained. In LAP 03639, considering various
26	chronological constraints on the parent body evolution and on the evolution of the different

sources of magnetic field in the early solar system, an internally-generated (dynamo) field of $\sim 5 \,\mu T$ recorded during retrograde metamorphism is the most likely explanation to account for the measured magnetization. This result indicates the existence of an advecting liquid core within the Rumuruti chondrite parent body, and implies that, as proposed for CV and H chondrites, this chondritic parent body is partially differentiated.

32 **1. Introduction**

The study of the natural remanent magnetization (NRM) of extraterrestrial materials gives clues as to the history of the primitive solar system and its evolution (Weiss et al., 2010). Indeed, paleomagnetic studies of meteorites provide a unique window into understanding early solar magnetic fields generated in the proto-planetary nebula (Cournède et al., 2015; Fu et al., 2014), as well as magnetic fields generated within the planetesimals through advection in a conducting liquid core by the dynamo effect (e.g., Weiss et al., 2008; Carporzen et al., 2011; Gattacceca et al., 2016).

Rumuruti (R) chondrites could potentially bear the record of different fields present 40 during the early solar system. They could have recorded a nebular field which would 41 constrain the intensity and lifetime of the solar nebula field (Weiss et al., 2017). On the other 42 hand, because the R chondrites have suffered thermal metamorphism, it is possible to test if, 43 like CV chondrites and H chondrites (Carporzen et al., 2011; Bryson et al., 2019a), R 44 chondrites recorded a magnetic field generated within the parent body by a dynamo powered 45 by advection in a liquid conducting core. Such a result would put strong constraint on the 46 parent body history and inner structure because it implies protracted accretion and partial 47 differentiation (Elkins-Tanton et al., 2011), and on its size (Bryson et al., 2019b). 48 In this study we test whether the paleomagnetic signals of R chondrites bear the record 49

50 of nebular or parent body magnetic fields. We performed a detailed paleomagnetic study of

two R chondrites collected in Antarctica: Pecora Escarpment (PCA) 91002 and LaPaz (LAP)
03639.

53 1.1 Rumuruti Chondrites

The Rumuruti chondrites are named after the Rumuruti meteorite that fell in Kenya in 54 1934, and have been recognized as a new chondrite group in 1994 (Schulze et al., 1994). They 55 are described in details in a review paper by Bischoff et al., (2011). Most R chondrites are 56 57 breccias of unequilibrated, petrologic type 3 fragments (Bischoff, 2000), and clasts metamorphosed to various degrees (e.g., Bischoff et al., 1994; Schulze et al., 1994; 58 59 Kallemeyn et al., 1996). They contain chondrules, with average apparent diameter ~350 µm, set in an abundant matrix, with a chondrule/matrix ratio of about 1. They are highly oxidized 60 meteorites, as reflected by the elevated favalite content of olivine (Fa₃₆₋₄₀ for equilibrated 61 lithologies) and by the rarity or absence of Fe,Ni metals (e.g., Rubin and Kallemeyn, 1994). 62 Iron is either oxidized or found in the form of iron sulfides (~6 vol% on average, mainly 63 pyrrhotite and pentlandite). Mineralogical features reflect variations in local conditions on the 64 R chondrite parent body such as inhomogeneous distribution of water (Isa et al., 2011). 65

The high oxidation state, high matrix/chondrules modal abundance ratio, relatively 66 low abundance of droplet chondrules, high Δ^{17} O (Rubin and Kallemeyn, 1994 and Bischoff et 67 al., 1994) suggest that the R chondrites parent body formed at heliocentric distance greater 68 than that of ordinary chondrites and lower than that of carbonaceous chondrites (Kallemeyn et 69 al., 1996; Khan et al., 2013). Accretion models (Desch et al., 2018) suggest that the parent 70 body of R chondrites accreted at 2.6 AU from the Sun. The accreting material, including 71 pyrrhotite, was likely oxidized before accretion (Bischoff, 2000; Gainsforth et al., 2017), 72 73 although a parent body origin for pyrrhotite has also been proposed (Schrader et al., 2016). The R chondrite parent body has suffered thermal metamorphism and hypervelocity impacts. 74 Thermal metamorphism led to an onion shell structure, as indicated by Ar-Ar and I-Xe dating 75

(Dixon et al., 2003; Claydon et al., 2013). The presence of type 5 and type 6 material suggests
metamorphic temperatures of up to at least 700 to 800°C (Dodd, 1981). The peak
metamorphic temperature in R5 chondrite LAP 04840 has been estimated to 670±60°C from
amphibole-plagioclase thermometry (Mc Canta et al., 2008). These temperature estimates are
coherent with olivine-chromite geothermometry on ordinary chondrites indicating
temperatures of 550-690°C for type 4/5 material and 880°C for type 6 material (Wlotzka,
2005).

Evidence arises that R chondrite breccias were produced by impacts following 83 metamorphism (Scott et al., 1985). The mixing of fragments of equilibrated lithologies (type 5 84 and 6) from greater depth with clasts from near-surface lithologies (e.g., type 3 material) may 85 have occurred at ~4.47 Ga (Dixon et al., 2003). Impact heating is evidenced by the occurrence 86 of impact melt rocks (Bischoff et al., 2006), sulfide-rich shock veins and plagioclase-rich melt 87 pockets (Rubin and Kallemeyn, 1994). These impact-related lithologies cooled rapidly and 88 were incorporated into the surface breccias. In a later evolutionary phase, further impact 89 activity led to lithification of the loose regolith without significant reheating (Bischoff et al., 90 91 2011). Consolidated breccias can be produced even under shock pressures of 5-10 GPa (e.g. Bischoff et al., 1983). Indeed, most R chondrites are have shock stages S2 or S3, indicating 92 peak pressure of ~5 to 10-15 GPa (Stöffler et al., 1991). 93

Rumuruti is the only fall of the R chondrite group. Other R chondrites were found in hot and cold deserts and show various degrees of terrestrial weathering. With increasing weathering, S and Ni become increasingly depleted because of sulfide alteration. PCA 91002 has a weathering index wi=1 indicating no or minor alteration (Rubin and Huber, 2005). LAP 03639 has a weathering category A/B indicating only moderate weathering. Both meteorites have been little affected by terrestrial weathering. This is confirmed by our petrographic observations of polished sections that show no significant alteration of sulfides in both
meteorites.

102 *1.2 Rumuruti Chondrite magnetic properties and paleomagnetism: state of the art*

The major magnetic mineral in R chondrites is pyrrhotite, with an average abundance 103 of ~6 wt% (Schulze et al., 1994; Kallemeyn et al., 1996). The pyrrhotite analyses point 104 toward hexagonal pyrrhotite (Fe_{0.93-0.96}S). Hexagonal pyrrhotite is normally antiferromagnetic 105 106 (in contrast with the ferromagnetic monoclinic pyrrhotite $Fe_{0.87}S$), but in R chondrites it seems to be in a metastable ferromagnetic state (Rochette et al., 2008). Magnetite abundance 107 108 averages 0.35 wt% (Kallemeyn et al., 1996; Rubin and Kallemeyn, 1994), and a minority of R chondrites have magnetite as their main magnetic carrier (Rochette et al., 2008). Fe,Ni-metals 109 are extremely rare (below 0.1 wt%, Schulze et al., 1994). Other non-ferromagnetic opaque 110 111 minerals encountered in R chondrites are chromite and ilmenite with abundances of 0.45 wt% 112 and below 0.1 wt%, respectively. The paleomagnetism of five bulk samples of Rumuruti chondrites (all Antarctic finds including PCA 91002) was studied by Gattacceca and Rochette 113 (2004). A stable remanent magnetization was evidence in all five meteorites, mostly carried 114 by pyrrhotite with the exception of the magnetite bearing Asuka 881988 meteorite (Rochette 115 et al., 2008). Natural Remanent Magnetization (NRM) normalization techniques indicated 116 similar paleointensities around $\sim 5 \,\mu\text{T}$ for all five meteorites. In view of the pressure-induced 117 magnetic phase transition of pyrrhotite at 2.8 GPa (e.g., Rochette et al., 2003) and the typical 118 peak shock pressures of Rumuruti chondrites (shock stage S2, with peak pressures >5 GPa), 119 the NRM of these meteorites was interpreted as likely postdating the last major impact they 120 121 had suffered. The NRM was regarded either as a shock remanent magnetization (SRM) or, for highly-shocked samples a thermoremanence acquired during post-impact cooling. In either 122 case, the paleointensity estimates suggested the existence of a magnetic field of several µT 123

(possibly transient in the SRM hypothesis) at the surface of the Rumuruti parent body at thetime of the impact event.

126 **2. Samples and methods**

The two R chondrites studied here, PCA 91002 and LAP 03639, were collected during 127 the ANSMET Antarctic meteorite search expeditions in 1991 and 2003, respectively. PCA 128 91002 contains about 10-20 vol% of light colored type 5 and 6 clasts within a type 3.8/3.9 129 ground mass, and is accordingly classified as R3.8-6 (Rubin and Kallemeyn, 1994). It has 130 fragments that experienced different shock stages, the majority displaying shock stages S3 131 and S4 (Rubin and Kallemeyn, 1994), but the overall shock stage of the breccia is S2 132 (Kallemeyn et al., 1996). LAP 03639 was originally classified as R4, but has been reclassified 133 as R5 (Schrader et al., 2016). It is unbrecciated and we observed sharp optical extinction in 134 the 20 large (>50 μ m) olivine single crystals that we checked, indicating a shock stage S1 135 using the criteria of Stöffler et al., (1991). We were allocated in 2013 samples PCA 91002,57 136 137 (1.3 g) and LAP 03639,24 (1.2 g), both sampled > 5 mm away from fusion crust. Samples were stored in a magnetically shielded room (field < 400 nT) during several months to allow 138 partial decay of the viscous remanent magnetization potentially acquired during exposure of 139 the meteorites to the geomagnetic field since their fall. As the original orientation of samples 140 on the parent body is unknown, sample orientation was chosen arbitrarily. Samples were cut 141 in mutually-oriented sub-samples with a wire saw. All subsample mass averages 160 mg for a 142 typical size of 4x4x3 mm. 143

144 Cooling of room temperature saturation isothermal remanent magnetization (RT-SIRM), warming 145 of low temperature SIRM (LT-SIRM), and hysteresis loops versus temperature were investigated with 146 a Princeton Micromag Vibrating Sample Magnetometer (VSM), with a maximum applied field of 1 T 147 and a moment sensitivity of 10^{-9} Am². The hysteresis loops provided saturation remanent magnetization (M_{RS}) , saturation magnetization (M_S) and the coercive force (B_C) . The remanent coercive force (B_{CR}) was determined by back-field experiments performed with the VSM. Low temperature (10 to 300 K) experiments were also carried out using a Quantum Design Magnetic Properties Measurements System (MPMS).

The low field specific susceptibility (noted χ in m³ kg⁻¹) and its anisotropy were measured using the Agico MFK1 bridge (with sensitivity of 5 × 10⁻¹³ m³). The MFK1 was operated at 200 A.m⁻¹ peak field and at a frequency of 976 Hz. Anisotropy of magnetic susceptibility (AMS) was characterized by the shape parameter T, varying from -1 (prolate) to +1 (oblate), and the anisotropy degree P (ratio of maximum to minimum susceptibility). High field susceptibility (χ_{hf}) was determined by linear fitting of the 0.9-1 T field interval of the hysteresis loops.

The remanence measurements were performed with a SQUID cryogenic magnetometer (2G 158 Enterprises, model 755R, with noise level of 10^{-11} Am²) with an attached automatic alternating field 159 (AF) 3-axis demagnetization system (maximum peak field 170 mT) placed in a magnetically shielded 160 161 room. Thermal demagnetization was performed using an MMTD furnace, under argon atmosphere above 250 °C. For most samples, we measured the S₋₃₀₀ ratio that is the IRM obtained after applying a 162 163 3 T field and then a back field of -0.3 T normalized to the IRM acquired in 3 T. The NRM of all 164 samples and its stability against stepwise alternating field (AF) demagnetization up to 120 mT were measured. At each AF step the sample was demagnetized and measured at least three times in order to 165 166 reduce spurious anhysteretic effects and measurement noise. The directions of the components were computed using principal component analysis, without anchoring to the origin. After the study of 167 NRM all samples were given an anhysteretic remanent magnetization (ARM, peak AF field of 100 or 168 169 300 mT, and a 100 μ T bias field) that was subsequently stepwise AF demagnetized. Piezo-remanent 170 magnetization (PRM) acquisition through hydrostatic loading was realized on bulk rock samples using a non-magnetic pressure cell (Gattacceca et al., 2010). A "Thellier-Thellier" type paleointensity 171 experiment following the II method (Konigsberger, 1938) was conducted using the MMTD furnace 172 equipped with a coil connected to a stabilized DC power supply (applied field 10 µT). Thellier-173 174 Thellier paleointensity experiments were processed using Thellier Tool software (Leonhardt et al., 2004). SIRM, acquired in 3 T field with a pulse magnetizer, was also investigated on three subsamples 175

of each meteorite. The rate of acquisition of viscous remanent magnetization (VRM) of the samples was studied through measurement of the VRM decay rate, since both rates are similar (Enkin and Dunlop, 1988). VRM was acquired in a field of 100 μ T for 12 days and its decay was then measured versus time. All magnetic measurements were performed at CEREGE (Aix-en-Provence, France), with the exception of remanent measurements for one subsample of each meteorite at the paleomagnetic laboratory of the University of California Santa Cruz (USA) followed by the MPMS analysis at the Institute for Rock Magnetism at the University of Minnesota (USA).

⁴⁰Ar/³⁹Ar stepwise degassing was conducted at Berkeley Geochronology Center following the 183 analytical procedures described in Shuster et al., 2010 on a whole-rock aliquot of LAP 03639. The 184 sample was first irradiated within an aluminum disc alongside the Hb3gr fluence monitor [age = 1081185 186 Ma (Renne et al., 2011)] for 50 hours at the Oregon State University TRIGA reactor in the Cadmium-187 Lined In-Core Irradiation Tube (CLICIT) facility. Following irradiation, a small (~mg) aliquot of the 188 sample was placed into high-purity Pt-Ir tubes and incrementally degassed under ultra-high vacuum 189 using a 30W diode laser (810 nm wavelength), controlled to setpoint temperatures in feedback with a 190 coaxially aligned optical pyrometer. The extracted gas was then purified with one hot and one cold 191 SAES® GP-50 getter pump, each fitted with a C-50 cartridge. The isotopic composition of Ar was then measured at each degassing step using a Mass Analyzer Products 215c mass spectrometer. 192 Apparent ⁴⁰Ar/³⁹Ar ages for each degassing step were calculated relative to the Hb3gr fluence monitor 193 194 using the decay constants and standard calibration of Renne et al., (2011) and isotope abundances of Steiger and Jäger (1977). Due to uncertainty in the non-radiogenic ⁴⁰Ar component, we report ages 195 assuming a trapped (i.e., non-radiogenic) ${}^{40}Ar/{}^{36}Ar = 0$ and assuming the terrestrial atmospheric 196 ${}^{40}\text{Ar}/{}^{36}\text{Ar} = 298$ (Supplemental Table 1), which likely spans the complete range of plausibility for 197 198 any trapped, non-radiogenic Ar.

199

200 3. Rock magnetism results

201 *3.1. Magnetic mineralogy*

Hysteresis properties of these two meteorites have been previously published in Tikoo et al., 2015. S₋₃₀₀ are -0.79 and -0.61, and B_{CR} average 68 mT and 118 mT in PCA 91002 and LAP 204 03639, respectively (Table 1), indicating that the remanence is dominated by a high coercivity 205 mineral (pyrrhotite). M_{RS}/M_{S} and B_{CR}/B_{C} ratios are characteristic of pseudo-single domain 206 carriers (Supplemental Table 2 and Supplemental Fig. 1).

207 Low temperature remanence measurements are shown in Fig. 1. In PCA91002 a possible Verwey transition (characteristic of magnetite) near 125 K can be seen in the LT-SIRM 208 measurement, but not in the RT-SIRM curve, suggesting this may rather be a ferromagnetic to 209 210 paramagnetic transition, such as the Curie point of chromite (Gattacceca et al., 2011). MPMS measurements (Supplemental Fig. 2) indicate the presence of magnetite in PCA 91002 and 211 show a transition at ~ 15-20 K in both meteorites possibly interpreted as a spinel. The absence 212 213 of Besnus transition suggests the presence of hexagonal (Rochette et al., 2008; Horng and Roberts, 2018) rather than monoclinic pyrrhotite. 214

The variation of M_S with temperature allowed us to estimate the proportion of pyrrhotite ($M_S=24 \text{ Am}^2 \text{.kg}^{-1}$) and magnetite ($M_S=92 \text{ Am}^2 \text{.kg}^{-1}$) for the two meteorites (Supplemental Fig. 3). LAP 03639 and PCA 91002 contain 0.11 wt% and 0.16 wt% of pyrrhotite, and 0.02 wt% and 0.10 wt% of magnetite, respectively.

Magnetic susceptibility was measured on at least three sub-samples of each meteorite, giving an average log χ of 3.04±0.07 and 2.94±0.05 for PCA 91002 and LAP 03639, respectively, with χ in 10⁻⁹ m³/kg. (Table 1). The relatively small scatter in the susceptibility measurements, suggest that magnetic grains are homogeneously distributed at the scale of our samples (~ 0.14 g). Our results are also in agreement with values obtained previously on much larger samples (log $\chi = 3.11\pm0.05$ on 13 g and 45 g samples of PCA 91002 in Rochette et al., 2008), again indicating homogeneous dispersion of magnetic minerals at the scale of the meteorite. It is noteworthy that silicate paramagnetism (estimated from the hysteresis loops
shown in Supplemental Fig. 1) accounts for a significant part (50% in both studied samples)
of the total susceptibility.

229 3.2. Remanent magnetizations

We have investigated the properties of the ARM and SIRM of both meteorites. Their 230 intensities are reported in Table 2. Median destructive field (MDF) is used to describe the 231 232 stability of SIRM and ARM against AF demagnetization. The two studied meteorites exhibit high MDF values both for ARM and SIRM. The ARM acquired in an alternating field of 233 100 mT exhibits similar range of stability with MDFs averaging ~48 mT in both meteorites. 234 The ARM acquired in an alternating field of 300 mT shows MDF of 65 mT for PCA 91002 235 and 95 mT for LAP 03639. It is noteworthy that in view of the dominance of a high coercivity 236 mineral, these ARM do not affect all ferromagnetic grains and this must be kept in mind when 237 interpreting its properties. The average saturation magnetization for PCA 91002, with a mean 238 log M_{RS} of 1.47 (with M_{RS} in 10^{-3} Am².kg⁻¹), is in agreement with the value of 1.61 reported 239 by Rochette et al., 2008. MDF of SIRM averages 60 mT and 110 mT in PCA 91002 and LAP 240 03639, respectively. 241

Because both studied meteorites remained in the geomagnetic field in Antarctica for typical 242 times of ~50 kyr (average terrestrial age of Antarctic meteorites, Welten et al., 2006), VRM 243 must be considered as a possible significant contribution to their NRM. In the worst case and 244 245 unlikely scenario where the meteorite remained in a fixed position with respect to the geomagnetic magnetic during 50 kyr in Antarctica and during the 10-20 years of curation, 246 followed by 6 months of VRM decay in our magnetically shielded room, we use the measured 247 VRM decay rate (equal to the acquisition rate, Supplemental Fig. 4) to estimate the maximum 248 VRM that may be present in our samples. The results indicate that VRM may account for 249 ~12% and ~30% at most of the measured NRM in PCA 91002 and LAP 03639, respectively 250

(Supplemental Table 3). Thermal demagnetization of the SIRM (Fig. 2) shows that both studied R chondrites are demagnetized at relatively low temperature with less than 10% and 30% of the magnetization remaining at 250 °C in LAP 03639 and PCA 91002, respectively. Together with the high coercivity and the low unblocking temperatures, this indicates that pyrrhotite dominates the remanence signal. It is noteworthy that PCA 91002 shows a second inflexion at ~580°C characteristic of magnetite.

257 *3.3 Magnetic anisotropy*

The degrees of anisotropy of magnetic susceptibility (AMS) degrees are weak (1.02 to 1.04, 258 Table 1) and fall in the range (1.016-1.065) previously estimated on larger samples 259 (Gattacceca et al., 2005). The anisotropy of ARM (AARM) has the same principal axes as the 260 AMS axes. AARM is moderate, and cannot account for deviations the paleomagnetic 261 directions of more than a few degrees. It is noteworthy that mutually oriented samples have 262 similar orientation of AMS and AARM axes (Supplemental Fig. 5), indicating a 263 264 homogeneous fabric at the scale of about 1 cm (initial size of the largest studied samples). The observed homogeneity of the fabric in our samples indicates that for the brecciated sample 265 (PCA 91002) the magnetic fabric, and hence the preferential orientation of pyrrhotite grains, 266 was acquired after brecciation. The most likely scenario is that the fabric was imparted by an 267 impact event (as already observed in ordinary chondrite breccias (e.g., Gattacceca et al., 268 2005)), possibly the impact that lithified the breccia. 269

270 **4. Paleomagnetism**

271 *4.1 Demagnetization behavior*

For each meteorite, AF and thermal demagnetizations were performed; four subsamples wereAF demagnetized, one thermally demagnetized after the removal of the low coercivity (LC)

component with AF, and one was demagnetized following the Thellier-Thellier II method
(Koenigsberger, 1938). The results are listed in Table 3, and displayed in Fig. 3 and 4.

For LAP 03639, NRM intensities are homogeneous and average 3.22±0.8 x 10⁻⁵Am².kg⁻¹. All 276 subsamples display a very similar demagnetization pattern during AF demagnetization with a 277 low coercivity (LC) component isolated below ~15 mT, and a high coercivity (HC) 278 component isolated between 19 and 145 mT on average. Above 145 mT, the demagnetization 279 path becomes erratic, as is often the case when demagnetizing pyrrhotite with AF. Thermal 280 demagnetization (after removal of the LC component with AF treatment), shows a HT 281 component isolated between 55 and 250°C (Fig 3) with the same direction as the HC 282 component (Fig 4a). HC/HT directions are well clustered among the different mutually-283 oriented subsamples with a Fisher precision parameters k = 163.7 (Fig 4a). 284

For PCA 91002, NRM intensity ranges from 1.64 to 9.84×10^{-5} Am².kg⁻¹, in agreement with 285 previously reported values $(2.98 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1} \text{ for a } 437 \text{ mg sample in Gattacceca and}$ 286 Rochette, 2004). AF demagnetization reveals a LC component isolated below 17 mT, and a 287 well-defined origin-trending high-coercivity (HC) component isolated between 20 and 138 288 mT on average. Above 138 mT, as observed in LAP 03639, the demagnetization path 289 290 becomes erratic. After removal of the LC component by AF, thermal demagnetization reveals a high-temperature (HT) component isolated between 160° and 520°C (Fig. 3). The directions 291 of the HT and HC component are relatively clustered with a Fisher precision parameter k=9.2 292 (Fig. 4b). 293

In order to check that the HC components are origin-trending, we compared the Maximum Angular Deviation (MAD) of these components with the angle (called α in the following, and given in Table 3) formed by the direction of the component and the direction of the first (i.e., lowest coercivity) NRM vector of the component (as described in e.g., Garrick-Bethell et al. 2009). Unlike the commonly used deviation angle (dANG), α has the advantage of using data further from the origin and therefore less noisy. Then, like the dANG, if α is smaller than the MAD, the component is considered origin-trending. In all samples but one α is lower or very close (within 2°) to the MAD suggesting that HC and HT directions trend toward the origin in both meteorites, and can be considered as Characteristic Remanent Magnetizations (ChRM). Only one subsample of PCA 91002 has α =14.2° compared to a MAD of 5.8°.

304

305 *4.2 Paleointensities and origin of the magnetizing field*

We first normalized the NRM by the SIRM (REM' method of Gattacceca and Rochette, 2004) 306 to estimate paleointensities with a non-destructive technique. For LAP 03639, the carrier of 307 308 the magnetization is pyrrhotite and we used the calibration constant a=3000 µT proposed by 309 Gattacceca and Rochette (2004) for the REM' method, very close to the average computed from the experimental calibration results for pyrrhotite compiled in Weiss and Tikoo (2014) 310 311 in their Table S4 (a=3089±1322 µT, N=15). For PCA 91002, the magnetization is carried by 312 both pyrrhotite and magnetite, and we used the average a=3000 µT proposed by Gattacceca and Rochette (2004). The ARM normalization method (e.g., Stephenson and Collinson, 313 1974), is not readily applicable to pyrrhotite-bearing rocks in view of the high coercivity of 314 315 pyrrhotite and the absence of specific calibration. The destructive Thellier-Thellier method 316 was used for one sample of each meteorite. It must be kept in mind that all these methods are designed and calibrated for the case where the NRM is a TRM. 317

REM' values are fairly constant over the HC component interval for both meteorites (Fig 5) averaging $(1.79\pm0.15)\times10^{-3}$ in LAP 03639 and $(9.87\pm3.07)\times10^{-4}$ in PCA 91002, corresponding to paleointensity of $2.96\pm0.75 \ \mu$ T in PCA 91002 and $5.38\pm0.36 \ \mu$ T in LAP 03639, with an uncertainty of a factor 2 (Table 3). We also used an alternative processing (as described in Garrick-Bethell et al., 2009) where we fit the NRM lost and SIRM lost over the HC interval with a linear regression, using the first vector of the HC component as the

reference vector (Fig 5), using the same calibration constant $a=3000 \mu$ T. The paleointensities 324 325 associated with the ChRM are consistent between both methods and average $2.3 \pm 0.4 \mu T$ and $5.1 \pm 0.9 \,\mu\text{T}$ for PCA 91002 and LAP 03639, respectively (Table 3). All the values mentioned 326 327 above are in agreement with the previous estimate of 5.3 \pm 3.3 μ T obtained for five R chondrites using the REM' normalization method (including PCA 91002, Gattacceca and 328 Rochette, 2004). It is noteworthy that for PCA 91002 these estimates must be regarded as 329 lower limits if the ChRM is interpreted as a SRM because this mechanism is less efficient 330 than TRM (e.g., Gattacceca et al., 2008; Tikoo et al., 2015). 331

The results of the Thellier-Thellier experiments are presented in Figure 6. For LAP 03639, 332 although the Arai plot shows good linearity (Sb/B=0.13), and satisfactory f and g factors (see 333 Leonhardt et al., 2004 for a definition of these parameters), the partial TRM (pTRM) checks 334 are unsatisfactory with a ∂ (CK) parameter of 41.1%, indicating alteration and destruction of 335 336 the pyrrhotite starting at temperatures as low as 150°C. As a consequence, the paleointensity of 42.0±5.4 µT that can be computed over the temperature interval 125-225°C strongly 337 overestimates the real paleointensity and in any case cannot be regarded as reliable. For PCA 338 339 91002, although the demagnetization plot shows a single component of magnetization over the whole 125-550°C interval, the Arai plot shows a peculiar strong slope break at ~350°C. 340 The presence of this kink exactly at the Curie temperature of pyrrhotite, combined with the 341 relatively poor pTRM checks on the lower temperature segment (50-350°C, with 342 ∂ (CK)=17.1%), and the alteration of pyrrhotite at such low temperatures in the LAP 03639, 343 suggest alteration of pyrrhotite (rather than magnetite) at low temperatures in PCA 91002 and 344 preclude robust interpretation of the lower temperature segment of the Arai plot in terms of 345 paleointensity. In the higher temperature interval (350-550°C), the pTRM checks are 346 satisfactory with ∂(CK)<3% (class A criteria of Calvo-Rathert et al., 2016) suggesting that the 347 magnetite in PCA 91002 is stable upon heating. Several other parameters (f, g and MAD) are 348

also satisfactory (class A) over this latter temperature interval. The paleointensity computed over the 350-550°C interval 12.1 \pm 2.2 μ T can therefore be considered as a reliable result.

351

352 **5. Discussion**

After removal of a LC component, the origin-trending magnetization directions isolated by AF and thermal demagnetization in mutually-oriented samples can be considered as the ChRM. The LC components of the NRM are likely terrestrial, either of viscous origin or the result of magnetic overprints during sample curation, handling, and/or preparation. These terrestrial components are not discussed in further detail.

The clustering of ChRM directions between mutually oriented sub-samples indicates a postaccretion magnetization for both meteorites and even post-brecciation and lithification for PCA 91002 at least at the original scale of the studied sample (1.2 g).

In view of the terrestrial residence time of the studied meteorites (50 kyr), the terrestrial VRM is expected to be stable up to 80-120°C upon laboratory thermal demagnetization whether it is carried by pyrrhotite (Pullaiha et al., 1975) or magnetite (Dunlop et al., 2000). The ChRM in both meteorites is unblocked up to significantly higher temperature (220°C for LAP 03639, 550° for PCA 91002), so that a VRM origin of the ChRM is ruled out.

In order to further constrain the nature of the ChRM, we compared the AF demagnetization behavior of ChRM, with that of SIRM, and PRM used as an analog for shock remanent magnetization (e.g., Tikoo et al., 2015) over the interval used to define the HC component for both meteorites (Fig 5, Supplemental Fig. 6). Similarly, we compared the ChRM and SIRM behaviors upon thermal demagnetization (Fig 2). It is noteworthy that in view of the high coercivity of pyrrhotite (only 40% of the SIRM is demagnetized at 100 mT AF) and the field used for ARM acquisition (100 mT AF), ARM cannot be considered as an analog for TRM as classically used for extraterrestrial rocks containing minerals with lower coercivity such as
 magnetite or kamacite (Stephenson and Collinson, 1974).

In LAP 03639, the main magnetic carrier, pyrrhotite is very sensitive to pressure 375 remagnetization and can be entirely reset by static stress of 2.8GPa. (Rochette et al., 2003). In 376 our hydrostatic pressure based experiments, we observe that the behavior of the PRM 377 (acquired at 2GPa) is different from that of the ChRM (Supplemental Fig. 6), indicating that 378 the ChRM is unlikely a SRM. Moreover, the low shock state (S1) and the unbrecciated nature 379 of LAP 03639 suggests that it is unlikely that this meteorite underwent an impact-induced 380 short thermal excursion that would have allowed the record of a transient shock-generated 381 field. Furthermore, a SRM nature of the ChRM would require a minimum ambient field of 382 $360 \mu T$ at the time of impact (Supplemental Table 4). This field was calculated by 383 extrapolating our experimental data at 2 GPa to 2.8 GPa using a linear fit. Above this 2.8 GPa 384 threshold additional PRM cannot be acquired, at least for monoclinic pyrrhotite that shows a 385 phase transition at this pressure. We acknowledge that this linear extrapolation and 2.8 GPa 386 387 threshold are debatable, especially when applied to the pyrrhotite in Rumuruti chondrites that may be in a more complex metastable hexagonal phase. Therefore, the required paleofield 388 value of 360 µT for a SRM remains a rough indication. However, such high values are 389 unreasonably high compared to magnetic fields intensities estimated to be present in the early 390 391 solar system history, likely disk-generated fields (maximum 100 µT in the midplane of the disk, e.g., Turner and Sano, 2008), solar wind fields (Oran et al., 2018), or shock-generated 392 fields (Crawford and Schultz, 1999) although the scaling laws for these shock-generated fields 393 are uncertain. A chemical remanent magnetization (CRM) origin for the ChRM would mean 394 that pyrrhotite was formed on the parent body by aqueous alteration following thermal 395 metamorphism, a sequence of events that is not expected on asteroidal bodies (Krot et al., 396 2006; Greshake, 2014). The low weathering grade of both studied meteorites, and the absence 397

398	of primary metal that under terrestrial conditions weather into magnetite, preclude the
399	possibility that the NRM can be a CRM acquired through crystallization of ferromagnetic
400	minerals during the Antarctic stay of the meteorites. Eventually, the most plausible possibility
401	is that the ChRM is a TRM, with the meteorite being magnetized over its full blocking
402	temperature spectrum (Fig 2) during cooling following peak thermal metamorphism or during
403	a later thermal event (shock heating). The ${}^{40}\text{Ar}/{}^{39}\text{Ar}$ age spectrum for LAP 03639 provides no
404	evidence of diffusive loss of 40 Ar, as we observed concordant step ages in the initial ~70% of
405	extracted Ar (Fig 7). The error-weighted mean of the first 14 degassing steps, calculated
406	assuming a trapped ${}^{40}\text{Ar}/{}^{36}\text{Ar} = 298$, is 4564 ± 17 Ma (Fig 7). As the K-Ar system is sensitive
407	to diffusive loss of radiogenic ⁴⁰ Ar at elevated temperatures, it may be reset due to impact
408	heating (Shuster et al., 2010). On the R parent body, the main impact events were dated to
409	start at 4.47Ga (Dixon et al., 2003). The old ⁴⁰ Ar- ³⁹ Ar age of LAP 03639 indicates that this
410	meteorite has not been affected by these impact events, although a mild post-shock
411	temperature sufficient to remagnetize the meteorite (≥250°C) may not be high enough or
412	sustained for a long enough period to reset or affect the Ar-Ar chronometer (Shuster et al.,
413	2010). Considering an initial temperature of the asteroid of -150°C, typical temperatures in
414	the asteroid belt, a temperature increase of 400°C would have been necessary to achieve the
415	250°C needed to magnetize the meteorite. A 400°C temperature increase would have required
416	shock pressures in excess of 35 GPa or multiple low pressure impacts (<5 GPa) (Bland et al.,
417	2014). In the former case, such pressures would correspond to a shock stage S4, generating
418	the presence of melt pockets that are not observed in LAP 03639 for which we have
419	determined a shock stage S1. In the latter case, the multiple low pressure necessary to reach
420	~400°C of bulk heating would have induced large temperature changes (up to localized
421	melting) in the matrix, which is not observed in LAP 03639. Therefore, a post-shock TRM is
422	unlikely for the origin of the ChRM of LAP 03639. The petrographic type (R5) of LAP 03639

suggests peak metamorphism temperatures of about 850°C (Schrader et al., 2016) which is 423 well above the maximum unblocking temperature of ~250 °C observed during thermal 424 demagnetization of NRM (Fig 2). As shown by the complete demagnetization of the SIRM at 425 250 °C (Figure 2), LAP 06639 has no paleomagnetic recording capacity above this 426 temperature. The high metamorphic grade and the unbrecciated and unshocked (S1) nature of 427 LAP 03639 indicate that most likely scenario is that the ChRM of LAP 06639 was acquired 428 during retrograde thermal metamorphism when the meteorite was cooling below 250°C in a 429 field of $\sim 5 \,\mu T$. 430

In PCA 91002, the ChRM is post-accretion as indicated by the similar ChRM directions in 431 mutually-oriented samples. No light-colored equilibrated clasts larger than 1 mm was 432 433 observed in our sample. In view of the typical size of our sub-samples, and homogeneous ChRM, the magnetization is clearly post-brecciation as any surviving magnetization in type 5 434 and type 6 clasts would have been randomized. The presence of unequilibrated type 3 material 435 436 in this meteorite indicates that post-lithification long-term temperatures were below ~500 °C to preserve this unequilibrated mineralogy. Like in LAP 03639, the NRM could be a CRM, a 437 TRM, or a SRM (Fig 2). A CRM is unlikely because it would require post brecciation 438 hydrothermalism, but aqueous alteration usually predates thermal metamorphism on 439 asteroidal bodies (e.g., Krot et al., 2006; Greshake, 2014). The shock level S2 of the meteorite 440 (Kallemeyen et al., 1996), indicates maximum shock pressure between 5 and 10 GPa. This is 441 above the magnetic transition of pyrrhotite at 2.8 GPa, but below that of magnetite at 12-16 442 GPa (Ding et al., 2008). If the ChRM was a SRM, it would require minimum ambient field in 443 444 the range 20-175µT at the time of impact (depending on the fit, linear or polynomial, used to extrapolate our PRM experiments) (Supplemental Table 4). Therefore, considering the lower 445 end (20 µT) of this rough estimate, a SRM nature of the ChRM for PCA 91002 remains 446 possible. This may also account for the strong kink of the Arai plot at 350°C that may indicate 447

that the NRM is indeed not a TRM. If the ChRM is a TRM preserved in magnetite, a stable 448 field of about 12 µT (as evaluated by the Thellier-Thellier method) had to be present during 449 cooling below ~550°C, regardless of the process that generated the temperature increase 450 (thermal metamorphism or shock). In the case of thermal metamorphism, this ~550°C 451 estimate is marginally consistent with the peak metamorphism temperature of ~500°C 452 suggested by the 3.8/3.9 metamorphic type of the groundmass of this meteorite. Although the 453 ChRM has to be older than 4.37±0.01 Ga. However, this ⁴⁰Ar-³⁹Ar age of PCA 91002 is ill-454 constrained (Dixon et al., 2003), and does not really bring decisive constraints on the nature 455 of the ChRM. Despite a more complex and less constrained scenario, the results for PCA 456 91002 indicate that a field of at several μ T (12 μ T if the ChRM is a TRM, >20 μ T if it is a 457 SRM) had to be present at some point in the history of this meteorite. 458

It is noteworthy that for both meteorites, the scenari discussed above hold whether the pyrrhotite is of nebular origin (Gainsforth et al., 2017), or formed during high temperature parent body processes at temperature of about 600°C (Schrader et al., 2016).

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Solar field have been shown to be much weaker than the paleointensity of several µT 463 evidenced in both meteorites (Oran et al., 2018). Therefore, they cannot account for the 464 measured magnetization. A recent compilation of several studies on four different meteorite 465 groups provided consistent constraints on the nebular magnetic field lifetime (Weiss et al., 466 2017). In detail, a nebular field of 5-50 μ T was estimated in LL chondrites chondrules, ~1-3 467 Ma after CAIs (Fu et al., 2014); a time-average field of ~2 µT was determined for CM 468 chondrites, 3.20 ± 0.66 Ma after CAIs (Cournede et al., 2015); an instantaneous field < 0.6 μ T 469 at 3.8 Ma after CAIs was determined from angrites analysis (Wang et al., 2017); and the Kaba 470 CV chondrite showed that the time averaged field was <0.3 µT at 4.50±1.66 Ma after CAIs 471 (Gattacceca et al., 2016). Therefore, the nebular field likely persisted until sometimes between 472

4564.3 and 4563.5 Ma using an age of the 4567.30±0.16 Ma for the crystallization of CAI 473 (Connelly et al., 2012). The Ar-Ar age of 4563±17 Ma measured for LAP 03639 in this study 474 cannot discriminate between a nebular and an internal origin of the magnetizing field. 475 However, the accretion age of the Rumuruti parent body is estimated at 2.1±0.1 Myr after 476 solar system formation (Sugiura and Fujiya, 2014), i.e. at 4565.2 Ga. All parent body thermal 477 models show that the peak of thermal metamorphism is reached shortly after accretion but 478 that cooling below the temperatures relevant for paleomagnetism (550°C and below here) 479 occurs several Myr after accretion (e.g., Golabek et al., 2014), so most probably after 4563 480 Myr. Therefore, a retrograde metamorphic cooling below ~250°C in LAP 03639 would be too 481 482 young to record time-averaged or instantaneous nebular magnetic fields that should have decayed to at most 0.5 µT by 4563.5 Ma at such heliocentric distances. The most likely 483 hypothesis for a late (at least 4 Myr after solar system formation) stable field of several µT is 484 485 a dynamo field, generated within the parent body, as proposed for angrites (Weiss et al., 2008), CV chondrites (Carporzen et al., 2011; Gattacceca et al., 2016), and H chondrites 486 (Bryson et al., 2019a). This would imply that like that proposed for the CV chondrites 487 (Carporzen et al., 2011), and H chondrites (Bryson et al., 2019a), the R chondrite parent body 488 may have had a molten advecting liquid core, and that R chondrites originate from an 489 490 undifferentiated shell overlying a partially differentiated interior.

491

492 6. Conclusion

The R chondrites LAP 03639 and PCA 91002 both carry a stable remanent magnetization acquired in a field of several μ T. The magnetization scenario for PCA 91002 is not well constrained because of the complex geochronology data and shock effects, but a field of at least 12 μ T is necessary to account for the observed magnetization whatever the nature of the ChRM. For LAP 03639, the most plausible scenario is that the remanent magnetization is the 498 result of cooling below 250°C during retrograde metamorphism in the presence of an 499 internally generated (dynamo) magnetic field of ~ 5 μ T. This result implies the existence of 500 an advecting conductive liquid core within a partially differentiated Rumuruti chondrite 501 parent body. Together with H and CV chondrite parent bodies, this is the third example of a 502 partially differentiated chondritic parent body.

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 1673-1702. DOI: 10.1111/j.1945-5100.2005.tb00138.x
- 705
- 706 Captions
- 707 Figures
- 708 <u>Fig. 1:</u> Measurements of low temperature (LT) and room temperature (RT) SIRM for samples
- studied here. In the LT-SIRM measurement of PCA91002, the vertical arrow near 125 K
- 710 possibly indicates a Verwey transition (characteristic of magnetite).
- 711
- <u>Fig. 2:</u> Normalized intensities of NRM (black line) and SIRM (gray line) versus thermal
 demagnetization for the studied R chondrites.
- 714

Fig. 3: Orthogonal projections of AF and AF + Thermal demagnetization data for the two studied R chondrites. All the orthogonal projections are represented in the same referential (W, Up). The solid and open circles represent vector end points projected onto horizontal and vertical planes, respectively. The blue and red arrows highlight the interpreted low and high coercivity components, respectively. For sample E1 of both meteorites, AF steps above 130 (in PCA 91002) and 180 mT (in LAP 03639) are not shown because of their erratic behavior.

Fig. 4: Stereographic projection of the stable component of magnetization and their 95%
confidence interval (black circles) for LAP 03639 (a) and for PCA 91002 (b). Boxes: LC
components, Circles: HC/HT components (ChRM). Star and their 95% confidence interval
(grey circles) represent the mean direction of the LC and/or HC component(s). Open and solid
symbols are projection in the upper and low hemisphere, respectively.

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Fig. 5: Normalized intensities of NRM (black line), ARM (dashed line) and of IRM (gray 728 729 line) versus demagnetizing field (left) and REM' values versus alternating field demagnetization (middle) for three subsamples of each of the two studied R chondrites. On 730 the REM' plots, the LC (light grey) and HC (black) portions are represented. The horizontal 731 line indicates the integrated REM' value and the range of integration of the HC component. 732 733 NRM lost vs IRM lost plots (right) over the LC (open circles), HC (black circles) are shown. The equation of the linear regression fit and the associated R^2 are indicated on the graph for 734 each portion. 735

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Fig. 6: Arai plots of the normalized NRM remaining versus the normalized pTRM gained
 during Thellier–Thellier II method experiment (left) and the corresponding orthogonal
 projections (right). All the orthogonal projections are represented in the same referential (W,

- Up, same as Figure 3). The solid and open circles represent vector end points projected onto
 horizontal and vertical planes, respectively. The blue and red arrows highlight the interpreted
 low and high coercivity components, respectively.
- 743

Fig. 7: Apparent ⁴⁰Ar/³⁹Ar age (A), Ca/K (B) spectra for LAP 03639. Each spectrum is plotted against the cumulative release fraction of ³⁹Ar. Dimensions of boxes indicate ±1 standard deviation (vertical) and the fraction of ³⁹Ar released (horizontal). Ca/K ratios were calculated from the ³⁷Ar_{Ca}/³⁹Ar_K ratio assuming the relative production ratio for Ca to K is 1:1.96. In panel (A), the green boxes were calculated assuming a trapped ⁴⁰Ar/³⁶Ar = 0, and red boxes were calculated assuming a trapped ⁴⁰Ar/³⁶Ar = 298.

750

751 **Tables:**

752 <u>Table 1:</u>

753 *Title:* Intrinsic magnetic properties of studied Rumuruti chondrites.

Samples studied in this work with their intrinsic magnetic properties. M_{RS} : saturation remanence, S_{-300} (=(IRM-0.3T)/(IRM3T)), χ : magnetic susceptibility, χ_p : paramagnetic susceptibility, χ_f : ferromagnetic susceptibility. All susceptibilities are in 10⁻⁹ m³ kg⁻¹, χ_f : susceptibility variation corrected for paramagnetic susceptibility, P, T: anisotropy degree and shape parameter for magnetic susceptibility, P_{rem} , T_{rem} : anisotropy degree and shape parameter of remanence.

760

761 <u>Table 2:</u>

762 *Title:* Artificial remanent magnetizations of studied Rumuruti chondrites.

Remanent magnetizations with the corresponding median destructive field (MDF) results obtained for the studied samples. M_{RS} : saturation remanence (SIRM, acquired in 3 T or 1 T (*) field), ARM: anhysteretic remanent magnetization was acquired in an AF of 100 mT, or of 300 mT (*), and a 100 μ T steady field. PRM: piezo-remanent magnetization was acquired in 2GPa in a field of 751.4 μ T.

768

769 <u>Table 3:</u>

770 *Title:* Paleomagnetic results.

NRM components identification and interpretation for the studied samples. REM': REM' integrated over the given alternating demagnetization field range with associated paleofield estimate (μ T). Directional information of the identified components are reported. LC = low coercivity component, HC=high coercivity component HT= high temperature component. α is also given to check the origin trending tendency of the HC/HT (see text). The paleofield (μ T) using linear regression with IRM method is also given (see text).

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778 Supplemental material: Figures

<u>Supplemental Fig. 1:</u> Hysteresis loops for LAP 03639 sample D4 (m=149 mg, dashed line)
and PCA 91002 sample D4 (m=178 mg, full line) raw and corrected for the paramagnetic and
diamagnetic contribution using the slope over the 0.9-1 T field range.

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<u>Supplemental Fig. 2:</u> MPMS data; Zero field cooling (ZFC) curves for the two studied
meteorites.

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Supplemental Fig. 3: Hysteresis loop versus temperature (not corrected), zoom of the low applied magnetic field region, back field curves versus temperature, B_{CR} , M_S and M_{RS} and B_C versus temperature for the two studied meteorites.

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790 <u>Supplemental Fig. 4:</u> VRM decay curves for both meteorites (see text).

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<u>Supplemental Fig. 5:</u> Magnetic anisotropy: maximum (squares) and minimum (circles) axes
of magnetic susceptibility and ARM (indicated by the letter R) for the two studied R
chondrites (equal area stereographic projection on lower hemisphere).

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<u>Supplemental Fig. 6:</u> Left: NRM (plain line) and PRM (dashed line) (acquired at 2GPa)
behavior upon AF demagnetization. Right: PRM acquisition curve and extrapolation up to
5GPa using a linear or a logarithmic fit.

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800 Supplemental material: Tables

801 <u>Supplemental Table 1:</u>

802 *Title:* Complete 40 Ar/ 39 Ar incremental heating results for LAP 03639.

Isotope abundances given in 10^{-15} mol (spectrometer sensivity is ~1.12 x 10^{-14} mols/nA), and 803 corrected for ³⁷Ar and ³⁹Ar decay, half-lives of 35.2 days and 269 years, respectively, and for 804 805 spectrometer discrimination per atomic mass unit of 1.004535 ± 0.002968 . Isotope sources calculated using the reactor constants in Renne et al. (1998), assuming $({}^{38}\text{Ar}/{}^{36}\text{Ar})\cos = 1.54$. 806 $({}^{38}\text{Ar}/{}^{36}\text{Ar})$ trap = 0.188, and $({}^{40}\text{Ar}/{}^{36}\text{Ar})$ trap = 0. No corrections were made for cosmogenic 807 808 ⁴⁰Ar. Ages calculated using the decay constants and standard calibration of Renne et al. (2011) and isotope abundance of Steiger and Jäger (1977) and calculated relative to Hb3gr 809 fluence monitor (1081 Ma). Corrections were made for reactor produced ³⁸Ar and ³⁶Ar in age 810 calculations. J-Value is 0.013048 \pm 0.000260. Average analytical blanks are: ⁴⁰Ar = 0.015; 811 39 Ar = 0.0001; 38 Ar = 0.00002; 37 Ar = 0.0001; 36 Ar = 0.00007 (nanoamps). Temperature was 812 controlled with approximately \pm 10 °C precision and \pm 10 °C accuracy; each heating duration 813

814 was 600 seconds. ¹Calculated assuming (${}^{40}\text{Ar}/{}^{36}\text{Ar}$)trap = 0. ²Calculated assuming 815 (${}^{40}\text{Ar}/{}^{36}\text{Ar}$)trap = 298. n.d. is not determined.

816

- 817 <u>Supplemental Table 2:</u>
- 818 *Title:* Samples studied in this work with their intrinsic magnetic properties.
- 819 M_{RS} : saturation remanence, M_{S} : saturation magnetization, B_{C} : coercivity, B_{CR} : coercivity of
- remanence. Some of the data have already been published in Tikoo et al., 2015.

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- 822 <u>Supplemental Table 3:</u>
- 823 *Title:* VRM properties for the studied Rumuruti chondrites.

824 Estimated residential time on Earth, Sd: VRM decay rate obtained using a linear fit (SP Fig.

4), VRM_{max} calculated for the estimated time spend on Earth since their fall (residential time

on Earth), and maximum percentage of VRM regarding NRM intensity for the two studied

- 827 meteorites.
- 828
- 829 <u>Supplemental Table 4:</u>
- 830 *Title:* PRM properties for the studied Rumuruti chondrites.

PRM intensity value extrapolated at 2.8, 5, 10, 20 and 35GPa using a linear or a logarithmic

fit (cf SP Fig. 6), and corresponding minimum paleointensity value required at the time of

833 impact to impart it.