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1 **Paleomagnetism of Rumuruti chondrites suggests a partially differentiated**
2 **parent body**

3

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13

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

27 sources of magnetic field in the early solar system, an internally-generated (dynamo) field of
28 $\sim 5 \mu\text{T}$ recorded during retrograde metamorphism is the most likely explanation to account for
29 the measured magnetization. This result indicates the existence of an advecting liquid core
30 within the Rumuruti chondrite parent body, and implies that, as proposed for CV and H
31 chondrites, this chondritic parent body is partially differentiated.

32 1. Introduction

33 The study of the natural remanent magnetization (NRM) of extraterrestrial materials
34 gives clues as to the history of the primitive solar system and its evolution (Weiss et al.,
35 2010). Indeed, paleomagnetic studies of meteorites provide a unique window into
36 understanding early solar magnetic fields generated in the proto-planetary nebula (Cournède
37 et al., 2015; Fu et al., 2014), as well as magnetic fields generated within the planetesimals
38 through advection in a conducting liquid core by the dynamo effect (e.g., Weiss et al., 2008;
39 Carporzen et al., 2011; Gattacceca et al., 2016).

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

49 In this study we test whether the paleomagnetic signals of R chondrites bear the record
50 of nebular or parent body magnetic fields. We performed a detailed paleomagnetic study of

51 two R chondrites collected in Antarctica: Pecora Escarpment (PCA) 91002 and LaPaz (LAP)
52 03639.

53 *1.1 Rumuruti Chondrites*

54 The Rumuruti chondrites are named after the Rumuruti meteorite that fell in Kenya in
55 1934, and have been recognized as a new chondrite group in 1994 (Schulze et al., 1994). They
56 are described in details in a review paper by Bischoff et al., (2011). Most R chondrites are
57 breccias of unequilibrated, petrologic type 3 fragments (Bischoff, 2000), and clasts
58 metamorphosed to various degrees (e.g., Bischoff et al., 1994; Schulze et al., 1994;
59 Kallemeyn et al., 1996). They contain chondrules, with average apparent diameter ~350 μm ,
60 set in an abundant matrix, with a chondrule/matrix ratio of about 1. They are highly oxidized
61 meteorites, as reflected by the elevated fayalite content of olivine (Fa_{36-40} for equilibrated
62 lithologies) and by the rarity or absence of Fe,Ni metals (e.g., Rubin and Kallemeyn, 1994).
63 Iron is either oxidized or found in the form of iron sulfides (~6 vol% on average, mainly
64 pyrrhotite and pentlandite). Mineralogical features reflect variations in local conditions on the
65 R chondrite parent body such as inhomogeneous distribution of water (Isa et al., 2011).

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

76 (Dixon et al., 2003; Claydon et al., 2013). The presence of type 5 and type 6 material suggests
77 metamorphic temperatures of up to at least 700 to 800°C (Dodd, 1981). The peak
78 metamorphic temperature in R5 chondrite LAP 04840 has been estimated to 670±60°C from
79 amphibole-plagioclase thermometry (Mc Canta et al., 2008). These temperature estimates are
80 coherent with olivine-chromite geothermometry on ordinary chondrites indicating
81 temperatures of 550-690°C for type 4/5 material and 880°C for type 6 material (Wlotzka,
82 2005).

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

94 Rumuruti is the only fall of the R chondrite group. Other R chondrites were found in
95 hot and cold deserts and show various degrees of terrestrial weathering. With increasing
96 weathering, S and Ni become increasingly depleted because of sulfide alteration. PCA 91002
97 has a weathering index $w_i=1$ indicating no or minor alteration (Rubin and Huber, 2005). LAP
98 03639 has a weathering category A/B indicating only moderate weathering. Both meteorites
99 have been little affected by terrestrial weathering. This is confirmed by our petrographic

100 observations of polished sections that show no significant alteration of sulfides in both
101 meteorites.

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

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

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

126 **2. Samples and methods**

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

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

148 magnetization (M_{RS}), saturation magnetization (M_S) and the coercive force (B_C). The remanent
149 coercive force (B_{CR}) was determined by back-field experiments performed with the VSM. Low
150 temperature (10 to 300 K) experiments were also carried out using a Quantum Design Magnetic
151 Properties Measurements System (MPMS).

152 The low field specific susceptibility (noted χ in $\text{m}^3 \text{kg}^{-1}$) and its anisotropy were measured using
153 the Agico MFK1 bridge (with sensitivity of $5 \times 10^{-13} \text{m}^3$). The MFK1 was operated at 200 A.m^{-1} peak
154 field and at a frequency of 976 Hz. Anisotropy of magnetic susceptibility (AMS) was characterized by
155 the shape parameter T, varying from -1 (prolate) to $+1$ (oblate), and the anisotropy degree P (ratio of
156 maximum to minimum susceptibility). High field susceptibility (χ_{hf}) was determined by linear fitting
157 of the 0.9-1 T field interval of the hysteresis loops.

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

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

183 $^{40}\text{Ar}/^{39}\text{Ar}$ stepwise degassing was conducted at Berkeley Geochronology Center following the
184 analytical procedures described in Shuster et al., 2010 on a whole-rock aliquot of LAP 03639. The
185 sample was first irradiated within an aluminum disc alongside the Hb3gr fluence monitor [age = 1081
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
192 then measured at each degassing step using a Mass Analyzer Products 215c mass spectrometer.
193 Apparent $^{40}\text{Ar}/^{39}\text{Ar}$ ages for each degassing step were calculated relative to the Hb3gr fluence monitor
194 using the decay constants and standard calibration of Renne et al., (2011) and isotope abundances of
195 Steiger and Jäger (1977). Due to uncertainty in the non-radiogenic ^{40}Ar component, we report ages
196 assuming a trapped (i.e., non-radiogenic) $^{40}\text{Ar}/^{36}\text{Ar} = 0$ and assuming the terrestrial atmospheric
197 $^{40}\text{Ar}/^{36}\text{Ar} = 298$ (Supplemental Table 1), which likely spans the complete range of plausibility for
198 any trapped, non-radiogenic Ar.

199

200 **3. Rock magnetism results**

201 *3.1. Magnetic mineralogy*

202 Hysteresis properties of these two meteorites have been previously published in [Tikoo et al.,](#)
203 [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
208 Verwey transition (characteristic of magnetite) near 125 K can be seen in the LT-SIRM
209 measurement, but not in the RT-SIRM curve, suggesting this may rather be a ferromagnetic to
210 paramagnetic transition, such as the Curie point of chromite ([Gattacceca et al., 2011](#)). MPMS
211 measurements ([Supplemental Fig. 2](#)) indicate the presence of magnetite in PCA 91002 and
212 show a transition at ~ 15-20 K in both meteorites possibly interpreted as a spinel. The absence
213 of Besnus transition suggests the presence of hexagonal ([Rochette et al., 2008; Horng and](#)
214 [Roberts, 2018](#)) rather than monoclinic pyrrhotite.

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

219 Magnetic susceptibility was measured on at least three sub-samples of each meteorite, giving
220 an average $\log \chi$ of 3.04 ± 0.07 and 2.94 ± 0.05 for PCA 91002 and LAP 03639, respectively,
221 with χ in $10^{-9} \text{ m}^3/\text{kg}$. ([Table 1](#)). The relatively small scatter in the susceptibility
222 measurements, suggest that magnetic grains are homogeneously distributed at the scale of our
223 samples (~ 0.14 g). Our results are also in agreement with values obtained previously on
224 much larger samples ($\log \chi = 3.11\pm 0.05$ on 13 g and 45 g samples of PCA 91002 in [Rochette](#)
225 [et al., 2008](#)), again indicating homogeneous dispersion of magnetic minerals at the scale of the

226 meteorite. It is noteworthy that silicate paramagnetism (estimated from the hysteresis loops
227 shown in [Supplemental Fig. 1](#)) accounts for a significant part (50% in both studied samples)
228 of the total susceptibility.

229 *3.2. Remanent magnetizations*

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

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

251 (Supplemental Table 3). Thermal demagnetization of the SIRM (Fig. 2) shows that both
252 studied R chondrites are demagnetized at relatively low temperature with less than 10% and
253 30% of the magnetization remaining at 250 °C in LAP 03639 and PCA 91002, respectively.
254 Together with the high coercivity and the low unblocking temperatures, this indicates that
255 pyrrhotite dominates the remanence signal. It is noteworthy that PCA 91002 shows a second
256 inflexion at ~580°C characteristic of magnetite.

257 *3.3 Magnetic anisotropy*

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

270 **4. Paleomagnetism**

271 *4.1 Demagnetization behavior*

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

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

276 For LAP 03639, NRM intensities are homogeneous and average $3.22 \pm 0.8 \times 10^{-5} \text{Am}^2.\text{kg}^{-1}$. All
277 subsamples display a very similar demagnetization pattern during AF demagnetization with a
278 low coercivity (LC) component isolated below ~ 15 mT, and a high coercivity (HC)
279 component isolated between 19 and 145 mT on average. Above 145 mT, the demagnetization
280 path becomes erratic, as is often the case when demagnetizing pyrrhotite with AF. Thermal
281 demagnetization (after removal of the LC component with AF treatment), shows a HT
282 component isolated between 55 and 250°C (Fig 3) with the same direction as the HC
283 component (Fig 4a). HC/HT directions are well clustered among the different mutually-
284 oriented subsamples with a Fisher precision parameters $k= 163.7$ (Fig 4a).

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

294 In order to check that the HC components are origin-trending, we compared the Maximum
295 Angular Deviation (MAD) of these components with the angle (called α in the following, and
296 given in Table 3) formed by the direction of the component and the direction of the first (i.e.,
297 lowest coercivity) NRM vector of the component (as described in e.g., Garrick-Bethell et al.,
298 2009). Unlike the commonly used deviation angle (dANG), α has the advantage of using data

299 further from the origin and therefore less noisy. Then, like the dANG, if α is smaller than the
300 MAD, the component is considered origin-trending. In all samples but one α is lower or very
301 close (within 2°) to the MAD suggesting that HC and HT directions trend toward the origin in
302 both meteorites, and can be considered as Characteristic Remanent Magnetizations (ChRM).
303 Only one subsample of PCA 91002 has $\alpha=14.2^\circ$ compared to a MAD of 5.8° .

304

305 *4.2 Paleointensities and origin of the magnetizing field*

306 We first normalized the NRM by the SIRM (REM' method of Gattacceca and Rochette, 2004)
307 to estimate paleointensities with a non-destructive technique. For LAP 03639, the carrier of
308 the magnetization is pyrrhotite and we used the calibration constant $a=3000 \mu\text{T}$ proposed by
309 Gattacceca and Rochette (2004) for the REM' method, very close to the average computed
310 from the experimental calibration results for pyrrhotite compiled in Weiss and Tikoo (2014)
311 in their Table S4 ($a=3089\pm1322 \mu\text{T}$, $N=15$). For PCA 91002, the magnetization is carried by
312 both pyrrhotite and magnetite, and we used the average $a=3000 \mu\text{T}$ proposed by Gattacceca
313 and Rochette (2004). The ARM normalization method (e.g., Stephenson and Collinson,
314 1974), is not readily applicable to pyrrhotite-bearing rocks in view of the high coercivity of
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
317 designed and calibrated for the case where the NRM is a TRM.

318 REM' values are fairly constant over the HC component interval for both meteorites (Fig 5)
319 averaging $(1.79\pm0.15)\times 10^{-3}$ in LAP 03639 and $(9.87\pm3.07)\times 10^{-4}$ in PCA 91002,
320 corresponding to paleointensity of $2.96\pm0.75 \mu\text{T}$ in PCA 91002 and $5.38\pm0.36 \mu\text{T}$ in LAP
321 03639, with an uncertainty of a factor 2 (Table 3). We also used an alternative processing (as
322 described in Garrick-Bethell et al., 2009) where we fit the NRM lost and SIRM lost over the
323 HC interval with a linear regression, using the first vector of the HC component as the

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

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

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

351

352 **5. Discussion**

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

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

361 In view of the terrestrial residence time of the studied meteorites (50 kyr), the terrestrial VRM
362 is expected to be stable up to 80-120°C upon laboratory thermal demagnetization whether it is
363 carried by pyrrhotite ([Pullaiha et al., 1975](#)) or magnetite ([Dunlop et al., 2000](#)). The ChRM in
364 both meteorites is unblocked up to significantly higher temperature (220°C for LAP 03639,
365 550° for PCA 91002), so that a VRM origin of the ChRM is ruled out.

366 In order to further constrain the nature of the ChRM, we compared the AF demagnetization
367 behavior of ChRM, with that of SIRM, and PRM used as an analog for shock remanent
368 magnetization (e.g., [Tikoo et al., 2015](#)) over the interval used to define the HC component for
369 both meteorites ([Fig 5, Supplemental Fig. 6](#)). Similarly, we compared the ChRM and SIRM
370 behaviors upon thermal demagnetization ([Fig 2](#)). **It is noteworthy that in view of the high**
371 **coercivity of pyrrhotite (only 40% of the SIRM is demagnetized at 100 mT AF) and the field**
372 **used for ARM acquisition (100 mT AF), ARM cannot be considered as an analog for TRM as**

373 classically used for extraterrestrial rocks containing minerals with lower coercivity such as
374 magnetite or kamacite (Stephenson and Collinson, 1974).

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

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 $^{40}\text{Ar}-^{39}\text{Ar}$ 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 ($\geq 250^\circ\text{C}$) 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 $\sim 400^\circ\text{C}$ 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

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

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

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

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

462
463 Solar field have been shown to be much weaker than the paleointensity of several μT
464 evidenced in both meteorites (Oran et al., 2018). Therefore, they cannot account for the
465 measured magnetization. A recent compilation of several studies on four different meteorite
466 groups provided consistent constraints on the nebular magnetic field lifetime (Weiss et al.,
467 2017). In detail, a nebular field of 5-50 μT was estimated in LL chondrites chondrules, ~ 1 -3
468 Ma after CAIs (Fu et al., 2014) ; a time-average field of ~ 2 μT was determined for CM
469 chondrites, 3.20 ± 0.66 Ma after CAIs (Cournede et al., 2015); an instantaneous field < 0.6 μT
470 at 3.8 Ma after CAIs was determined from angrites analysis (Wang et al., 2017); and the Kaba
471 CV chondrite showed that the time averaged field was < 0.3 μT at 4.50 ± 1.66 Ma after CAIs
472 (Gattacceca et al., 2016). Therefore, the nebular field likely persisted until sometimes between

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

491

492 6. Conclusion

493 The R chondrites LAP 03639 and PCA 91002 both carry a stable remanent magnetization
494 acquired in a field of several μT . The magnetization scenario for PCA 91002 is not well
495 constrained because of the complex geochronology data and shock effects, but a field of at
496 least $12 \mu\text{T}$ is necessary to account for the observed magnetization whatever the nature of the
497 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 μT. 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
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503

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514

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705

706 **Captions**

707 **Figures**

708 Fig. 1: Measurements of low temperature (LT) and room temperature (RT) SIRM for samples
709 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

712 Fig. 2: Normalized intensities of NRM (black line) and SIRM (gray line) versus thermal
713 demagnetization for the studied R chondrites.

714

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

721

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

727

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

736

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

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

743

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

750

751 **Tables:**

752 Table 1:

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

754 Samples studied in this work with their intrinsic magnetic properties. M_{RS} : saturation
755 remanence, $S_{.300}$ ($=(\text{IRM}-0.3\text{T})/(\text{IRM}3\text{T})$), χ : magnetic susceptibility, χ_{p} : paramagnetic
756 susceptibility, χ_{f} : ferromagnetic susceptibility. All susceptibilities are in $10^{-9} \text{ m}^3 \text{ kg}^{-1}$, χ_{f} :
757 susceptibility variation corrected for paramagnetic susceptibility, P, T: anisotropy degree and
758 shape parameter for magnetic susceptibility, P_{rem} , T_{rem} : anisotropy degree and shape
759 parameter of remanence.

760

761 Table 2:

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

763 Remanent magnetizations with the corresponding median destructive field (MDF) results
764 obtained for the studied samples. M_{RS} : saturation remanence (SIRM, acquired in 3 T or 1 T

765 (*) field), ARM: anhysteretic remanent magnetization was acquired in an AF of 100 mT, or of
766 300 mT (*), and a 100 μ T steady field. PRM: piezo-remanent magnetization was acquired in
767 2GPa in a field of 751.4 μ T.

768

769 Table 3:

770 *Title:* Paleomagnetic results.

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

777

778 **Supplemental material: Figures**

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

782

783 Supplemental Fig. 2: MPMS data; Zero field cooling (ZFC) curves for the two studied
784 meteorites.

785

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

789

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

791

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

795

796 Supplemental Fig. 6: Left: NRM (plain line) and PRM (dashed line) (acquired at 2GPa)
797 behavior upon AF demagnetization. Right: PRM acquisition curve and extrapolation up to
798 5GPa using a linear or a logarithmic fit.

799

800 **Supplemental material: Tables**

801 Supplemental Table 1:

802 *Title:* Complete $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating results for LAP 03639.

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

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

816

817 Supplemental Table 2:

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
820 remanence. Some of the data have already been published in [Tikoo et al., 2015](#).

821

822 Supplemental Table 3:

823 *Title:* VRM properties for the studied Rumuruti chondrites.

824 Estimated residential time on Earth, S_d : VRM decay rate obtained using a linear fit ([SP Fig.](#)
825 [4](#)), VRM_{max} calculated for the estimated time spend on Earth since their fall (residential time
826 on Earth), and maximum percentage of VRM regarding NRM intensity for the two studied
827 meteorites.

828

829 Supplemental Table 4:

830 *Title:* PRM properties for the studied Rumuruti chondrites.

831 PRM intensity value extrapolated at 2.8, 5, 10, 20 and 35GPa using a linear or a logarithmic
832 fit (cf [SP Fig. 6](#)), and corresponding minimum paleointensity value required at the time of
833 impact to impart it.