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1 **Geomagnetic field intensity variations during the second millennium BCE: new data**  
2 **from the Greek Middle and Late Bronze Age**

3

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15

16 **Abstract**

17 The archaeointensity records from Greece present several gaps in the prehistoric period  
18 among which the ones in the third and second millennia BCE (Early and Middle Bronze  
19 Age) are not justified by the abundance of relevant settlements in the broader Greek area.  
20 Their excavations yielded numerous collections of pottery and ceramics, well-studied to a  
21 big extent from archaeological and archaeometric point of view. We collected six groups  
22 of fragments dated from 2200 BCE to 1500 BCE which were subjected to a classical  
23 archaeomagnetic study. The material response to the experiments was mostly satisfactory,  
24 and the archaeointensity was calculated both with Thellier-Thellier and multispecimen  
25 protocols. These results, complemented by the ones recently published for the period 1500-  
26 900 BCE, and plotted versus the existing secular variation curves for Greece and relevant  
27 geomagnetic field models allow the recovery of a smooth V-shape already suggested for

28 the Middle East. Nevertheless, we only observed a slight intensity maximum around 1900-  
29 1800 BCE while the minimum suggested for the Near East around 1800 BCE is probably  
30 shifted to an earlier period.

31

## 32 **1. Introduction**

33 In the last two decades, a substantial progress in archaeomagnetic research has been  
34 achieved in Europe, Middle East and worldwide (for a review see Brown et al., 2021 and  
35 references therein). The acquisition of numerous, reliable, new data from well-dated,  
36 archaeological baked clays allowed to greatly improve our knowledge about the evolution  
37 of the Earth's magnetic field. Though this progress holds for both directions and intensities,  
38 the records of the latter are by far richer and more consistent leading to the improvement  
39 of regional and global geomagnetic models (Brown et al., 2021). Among the various  
40 recordings of the geomagnetic field (GMF) intensity, a feature which is being thoroughly  
41 studied are the "spikes" that is short-lived regional intensity maxima episodes whose  
42 spatial and temporal variation as well as their origin are nowadays better understood (e.g.,  
43 Shaar et al., 2011; de Groot et al., 2013; Genevey et al., 2016; Gómez-Paccard et al., 2012,  
44 2016; Livermore et al., 2021). One important handicap for the accurate description of the  
45 geomagnetic field strength evolution in the past is the rarity of continuous records, mostly  
46 during prehistoric times. This difficulty arises either from the limited availability of well-  
47 dated archaeological materials suitable for archaeointensity determinations or the  
48 difficulties in accessing the material.

49 The particularly solid Bulgarian database and deriving SVCs (Kovacheva et al., 2014;  
50 Kostadinova-Avramova et al., 2020, 2021) have partly accounted also for some Greek  
51 archaeomagnetic data, especially from N. Greece, allowing datings to be performed.  
52 Systematic archaeomagnetic investigations started in Greece, in the late nineties (see Tema  
53 & Kondopoulou, 2011 and De Marco et al., 2014 for a review) and are continuously  
54 increasing both in directional and intensity results (Kondopoulou et al., 2015, 2017; Aidona  
55 et al., 2018, 2021). Together with some results from Serbia and South Hungary, the  
56 Bulgarian and Greek data provide an almost continuous reconstruction of the full  
57 geomagnetic field vector variations in the Balkan area for the last 8000 years. However,  
58 the temporal distribution of the Balkan data is still uneven and several issues regarding the  
59 reliability of some of the published old Greek archaeointensity data have been outlined (De  
60 Marco et al., 2008; Tema & Kondopoulou, 2011; Tema et al., 2012; Genevey et al., 2018;  
61 Rivero-Montero et al., 2021). For instance, the scarcity of archaeomagnetic data from the  
62 4<sup>th</sup> millennium BCE, is due to several occupation gaps attested in many sites of N. Greece,  
63 as well as in Bulgaria (Maniatis, 2014 and references therein; Tsirtsoni, 2016). Two other  
64 important features may be observed for the Prehistoric period in the Balkans: the uneven  
65 temporal distribution of the data during the entire Bronze age (3<sup>rd</sup> and 2<sup>nd</sup> millennia BCE)  
66 and the systematically lower Greek archaeointensities, in comparison with the Bulgarian  
67 ones, for the late 6<sup>th</sup> to the late 3<sup>rd</sup> millennium BCE (Tema & Kondopoulou, 2011), but also  
68 for later periods, e.g Early Byzantine (Genevey et al., 2018). The considerable amount of  
69 Bulgarian prehistoric data was obtained only from “*in situ*” structures, providing thus full-  
70 vector values, while Greek data for this period are obtained, to a big extent, from ceramics  
71 and pottery. Prehistoric collections are abundant in Greece, very often well studied as far

72 as their clay characteristics are concerned and accurately dated (e.g., Reingruber &  
73 Thyssen, 2009; Papadatos & Nodarou, 2018; Hein & Kilikoglou, 2012; Wardle et al., 2014;  
74 Gimatzidis & Weininger 2020, among others). Nevertheless, their access remains often  
75 difficult due to the long periods between excavations and publications which hampers their  
76 potential availability.

77 In our recent studies we provided an effort to fill these gaps, by focusing on this period -  
78 that is the Greek Bronze age- and extended our interest to the transition with the Early Iron  
79 Age.

80 Systematic research conducted in the last ten years in various sites of the Middle East has  
81 led to the elaboration of solid recordings of the GMF intensity during the Bronze age, a  
82 period considered as particularly interesting both from the geophysical and archaeological  
83 point of view (Gallet et al., 2014, 2020; Shaar et al., 2020). Unfortunately, this period has  
84 been poorly investigated in Greece but also in Bulgaria where data are scarce.

85 We present here the archaeomagnetic study of several ceramic fragments and baked clays  
86 collected from four archaeological sites located in Northern Greece, Euboea and Central  
87 Greece as well as in NE Crete (red stars in Fig. 1), corresponding to the Middle and Late  
88 Bronze Age: Archontiko (ARCII, III), Eretria (BOU), Kirrha (KIC) and the Cretan  
89 Phryktoariae (SKA and SX) respectively.

90 The new archaeointensity data obtained for the period between 2200 and 1500 BCE are  
91 compiled with previously published data from Greece, for the same time span, and provide  
92 a better coverage in the SVCs during prehistoric times. A further comparison with relevant  
93 compilations in the Eastern Mediterranean (Ertepinar et al., 2020) allows for the reliability  
94 of our new data to be attested at a larger scale.

95

96 2. **Description of the archeological sites**

97 The Bronze age of the southern Balkans in general and specifically the period from the late  
98 3<sup>rd</sup> to the late 2<sup>nd</sup> millennium BCE is increasingly studied from the archaeological but also  
99 environmental and social point of view. To an important extent this is related to a series of  
100 compiled and recent radiocarbon data, accurately treated for Bulgarian Thrace and Greek  
101 Eastern Macedonia (Tsirtsoni, 2021) but also, to a larger scale, to environmental data  
102 (Meller et al., 2015).

103 A detailed approach to the Greek Bronze age in the context of the Balkans and Eastern  
104 Mediterranean can be found in supplementary material.

105 By focusing to the Greek Macedonia and based on 77 <sup>14</sup>C dates, an apparent occupation  
106 break around 2000 BCE can be suggested but not ascertained (Tsirtsoni, 2021). This  
107 statement is important not only because our two sites (Archontiko II, III) are situated within  
108 this area, but also because our previous studies on Bronze Age materials referred to the  
109 broader area of N. Greece (Tema et al., 2012; Kondopoulou et al., 2017).

110 The presently studied sites from older to younger (BCE) are as follows:

111 ***Archontiko (ARCH, III)***

112 The village of Archontiko hosts an archaeological settlement, between the regions of  
113 Ancient Pella and the city of Giannitsa (Central Macedonia). The settlement is built on a  
114 mound (Toumba), a characteristic feature for the Bronze Age, displaying two occupation  
115 phases: B (three horizons) spanning the end of the third to the beginning of the second  
116 millennium BC, that is the end of the Early Bronze Age, while phase A, covering the Late  
117 Bronze Age (~1500-1400 BCE), appears after 300 years of abandonment (Papaefthymiou-

118 Papanthimou & Papadopoulou, 2014; Bekiaris et al., 2021). The above dating given by the  
119 archaeologists was followed by the radiometric dating of 21 specimens which is displayed  
120 in Table 1 resulting in a narrower timespan (Maniatis, 2014). The main phase of the site  
121 dates from the end of the Early Bronze Age to the beginning of the Middle Bronze Age  
122 (Pilali-Papasteriou et al., 2001).

123 Additional palaeoenvironmental research was conducted by Syrides et al., (2009). This  
124 research dealt with the palaeogeography of the Giannitsa plain close to the site of  
125 Archontiko through sedimentological, palaeontological and stratigraphical techniques in  
126 order to trace the palaeoenvironments in connection to the sea. Additional  $^{14}\text{C}$  data from  
127 four boreholes indicate a rapid palaeoenvironmental change around 2000 BCE, converging  
128 with the possible abandonment suggested by Tsirtsoni (2021).

129 In an earlier archaeomagnetic investigation (Tema et al., 2012; Kondopoulou et al., 2017)  
130 ceramics belonging to the last horizon (I) were studied. In the present one we collected  
131 fragments from horizons II and III, aiming to trace GMF variations within almost a 500  
132 years period in total.

### 133 ***Bouratza-Eretria (BOU)***

134 The coastal settlement of Eretria, dated in the 3<sup>rd</sup> millennium BCE, was developed as a  
135 succession of a Final Neolithic and Early Helladic I (EH I) settlement. Its  
136 geomorphological context was thoroughly studied with the means of a deep-coring  
137 program (Ghilardi et al., 2014, 2016) which unraveled a series of loose marine and fluvial  
138 alluvia in coexistence with a zone of mica schists and phyllites.

139 One of the key excavations in the settlement took place in the Bouratzas plot between 1979-  
140 1981 where the pottery recovered was not well stratified and not in good condition due to

141 post-deposition factors and the presence of a high-water table (Muller-Celka et al., 2018).  
142 This pottery is attributed mostly to the EH III (2200-2000 BCE) and, to a smaller extent,  
143 to the previous phase EH II (c.2500-2300 BCE).  
144 All fragments selected for our study belong to the petrographic and chemical group FG8,  
145 that is the fine local pottery, according to Muller-Celka et al. (2018), which corresponds to  
146 the EH IIB slipped and burnished fine ware. The identification of all ware groups was  
147 accompanied by extensive investigations of local resources expanding to geological  
148 samples from other regions in Central Euboea as well. The predominant component of the  
149 locally available sediments are fine grained metamorphic rocks (Muller-Celka et al., 2018).  
150 This integrated study allowed us to select with certainty a group of certified local origin  
151 with fragments of various wares like handles, fragments of open or closed recipients, or  
152 jars and bowls of various colors ranging from brown-grey to red brown. Their fabrication  
153 was assigned to workshops in Central Euboea.

#### 154 ***Cretan Phryktoariae (SX, SKA)***

155 During an extended archaeological survey in Crete, conducted by archaeologist N.  
156 Panagiotakis, within the area of Pediada (plain), NE Crete, between 1982-1989, an old,  
157 unique system of communications with the use of fire was discerned. It was not rare for  
158 fire to be used to exchange messages between two distant areas, since it had already been  
159 used in the region where Syria stands today (Mari, beginning of the 2<sup>nd</sup> millennium BCE).  
160 This system was initiated in ancient Greece during the Minoan times, especially from 1900  
161 to 1700 BCE (Protopalatial period). Pediada was a naturally wealthy area, feeding two of  
162 the most important Bronze Age Palatial domains, Knossos and Malia (Panagiotakis et al.,



163 2013). This network persisted during the Neo-Palatial period (1700-1400 BCE) but  
164 progressively declined afterwards.

165 The Pediada survey brought to light many peculiar sites, named Soroi, that is large  
166 constructions like piles, of truncated cone shape coated by large amounts of hard baked-  
167 clays and often surrounded by fortifications, not always conserved. The fire was lit on the  
168 manmade, tower-like structures, that also served as observatories and were later named  
169 “Phryctoriae (*Φρυκτορίες*)” from the ancient Greek word for torch (*φρύκτος*).

170 The number of structures, found in the area during the surface survey, is large, close to  
171 2000 and covered more than 800 square kilometers reaching the region of today’s  
172 Heraklion.

173 The abundant piles of hard baked clays on the top of the structures constitute a safe source  
174 of material ideal for archaeomagnetism. These red clays (Terra Rossa) are abundant in  
175 Central and Eastern Crete, directly connected to the large pottery production on the island  
176 from the antiquity till nowadays traditional workshops. Their geochemical and  
177 mineralogical properties were thoroughly studied by Hein et al., (2004) and point to  
178 authigenic and alluvial red clay deposits. We sampled two of them, Soros Hartis (SX) and  
179 Soros Kamberi (SKA), both close to the village Sambas.

180 The exact dating of the “Soroi” is problematic due to their aleatory distribution and the  
181 lack of excavations. Nevertheless, the presence of pottery within the constructions and the  
182 topographical connections with the Old Palaces settlements (Protopalatial, 1900-1700  
183 BCE) could suggest this period as their dating, at least for part of the sites. Given that these  
184 structures lasted until more recent times -see above- and in order to clarify this uncertainty,  
185 OSL experiments were performed on 5 samples in total (3 from SX and 2 from SKA). The

186 obtained results indicate younger ages than the archaeological estimation, being  $1521 \pm 40$   
187 BCE for SKA and  $1690 \pm 77$  BCE for SX. The description of the method and the detailed  
188 results are given in the supplementary material and Table 1s.

### 189 *Kirrha ceramics(KIC)*

190 The modern inhabited area of Kirrha is situated at the head of the Gulf of Itea and at the  
191 foot of the mountains forming the peninsula of Desphina, south of the famous site of  
192 Delphi. A characteristic of Kirrha is its long habitation, the oldest traces dating from the  
193 Early Helladic- essentially pre-Mycenaean period.

194 Rescue excavations conducted in 1984 and 1989 by the 10<sup>th</sup> Ephorate of Delphi at Kirrha  
195 brought to light domestic remains of four successive construction phases as well as three  
196 pottery kilns of the updraft double-chambered type, built entirely of mud bricks. Kilns 1  
197 and 2 are of small size, of horseshoe ground plan, and date to Middle Helladic (MH) III-  
198 Late Helladic (LH) I period. Kiln 3, of circular ground plan was excavated some 20m to  
199 the east. Nevertheless, its dating is strongly questioned in view of new archaeomagnetic  
200 and luminescence data (Aidona et al., 2015).

201 A ceramics ensemble unearthed during the 1989 excavation in the same parcel than the  
202 kiln 3, that is the western slope of the mound, dated at the end of the Mesohelladic period  
203 (ME III, 1700-1550 BCE) and in depths between 1.07 m to 2.30 m was sampled. Their  
204 typology attributes them to the wheel-made Minyan, pottery of red, well fired burnished  
205 type, characteristic of the MH period (Skorda, 2010). For a more precise dating, four  
206 samples were subjected to TL dating method and the results seems to be comparable with  
207 the archaeological age determining an age of  $1634 \pm 87$  BCE. The detailed results are given  
208 in the supplementary material and Table 1s.

209 Clays suitable for potting were found close to Kirrha. They are predominantly highly  
210 calcareous clays, as one would expect in a region of limestone surface geology.  
211 An extended analysis of material unearthed in the site during an older excavation (1939)  
212 was conducted by Prof. T.Tartaron on 90 sherds including Gray Minyan (Middle Helladic  
213 II), and Yellow Minyan (MH III–LH I).Our fragments belongs to the Red Minyan group,  
214 but some properties of the above groups are providing useful information for our study.  
215 Additionally, 7 samples of clays from the vicinity of the Kirrha site were collected, formed  
216 into briquettes, fired at 600°, 800°, and 1000° C and thin sectioned. Optical microscopy  
217 suggests firing is pretty consistent around 800°C. The results of the firing of the clay  
218 samples show that almost all of the fragments refired red. The red color of the refiring  
219 indicated that the original clay color was reddish, perhaps iron-rich, even when calcareous.  
220 The most plausible explanation is found in the presence of bauxite, traced in the  
221 petrographic analysis (local bauxite seams and mines). Bauxite and fossiliferous  
222 mudstone/shale may be the most reliable indicators of local mineralogy and local  
223 manufacture. Since these were found previously in Early Helladic pottery from the site,  
224 continuity in local clay source exploitation is suggested (Tartaron, personal  
225 communication, 2022).

226

### 227 **3. 3. Experimental procedures**

228 Rock magnetic experiments have been conducted in order to determine the main magnetic  
229 carriers of the studied material. Isothermal remanent magnetization (IRM) was imparted  
230 with an impulse magnetizer (ASC IM10-30) at a maximum field of 1.2 T. Thermomagnetic  
231 analysis was performed with a Bartington MS2 meter (at AUTH, Greece) and a

232 Kappabridge KLY3 (at Montpellier), coupled with a MS2WF furnace and the Agico CS3  
233 furnace, respectively. The experiments were carried out in air at a heating rate of 1° C/min.  
234 Magnetic susceptibility changes were recorded continuously from room temperature up to  
235 600° C (heating curve) and down to room temperature (cooling curve).  
236 Hysteresis loops were recorded at room temperature with a P.A.R.155 Vibrating Sample  
237 Magnetometer (VSM) calibrated by means of a NIST certified Ni reference sample, in  
238 applied fields up to 2 T. We selected 11 representative samples from the six collections  
239 (two samples from ARC, SKA, SX, BOU and three from KIC). Each fragment was crushed  
240 gently in an agate mortar under the exact same procedure to produce similarly  
241 homogenized powders.

242 The classical Thellier – Thellier method (Thellier and Thellier, 1959) with pTRM checks  
243 and corrections for the TRM anisotropy and cooling rate was applied in the Geophysical  
244 Laboratory (AUTH, GR) for the determination of the archaeointensity in four collections  
245 (ceramics ARCII, III, baked clays SKA-SX). The remanent magnetization was measured  
246 with a Minispin spinner magnetometer (Molspin, Newcastle, UK) while the heating of the  
247 samples was performed in a thermal demagnetizer MMTD-80 (Magnetic Measurements,  
248 UK). The protocol used consists of double heating –cooling runs at each temperature step  
249 with a laboratory field (55  $\mu$ T in the present study) applied in both directions of a specimen  
250 axis (+z, -z). The temperature was progressively increased from 100° C with a 50° C step  
251 up to 400° C followed by smaller steps of 40-30° C up to 570° C. Partial thermoremanent  
252 magnetization (pTRM) checks have been performed every two steps to detect possible  
253 magnetic mineral alteration in the samples during the experiment. The TRM anisotropy  
254 tensor was determined by measuring in 6 positions (+x, -x, +y, -y, +z and -z axes)

255 followed by a stability check (Chauvin et al., 2000). The TRM anisotropy measurements  
256 were performed at different temperatures, when the NRM loss was around 70%. Finally,  
257 we applied the cooling rate correction following Gómez-Paccard et al., (2006) protocol,  
258 with a slow cooling over 24 h.

259 The other two collections (ceramics BOU and KIC) were studied with the multi-specimen  
260 method in Montpellier. The MSP-DSC protocol (Biggin & Poidras, 2006; Dekkers &  
261 Böhnel, 2006) comprises both normalization by the overprinted pTRM fraction  $f$  of the  
262 NRM and correction for multi-domain bias (Fabian & Leonhardt, 2010) (For more details  
263 on the method see Aidona et al., 2018). The experiment was carried out with a homemade  
264 furnace (FURÉMAG, patent #1256194) developed by the palaeomagnetic group at the  
265 University of Montpellier. This furnace heats standard palaeomagnetic samples as well as  
266 small chips quickly and uniformly. During heating and cooling the magnetic field is applied  
267 along the NRM direction with a precision of less than  $1^\circ$ . The chosen heating temperature  
268 should be high enough to contain a sufficient fraction of the TRM (at least 20%) and at the  
269 same time low enough to prevent chemical alteration. In the present study, following the  
270 thermal demagnetization results a dwell temperature of  $350^\circ\text{C}$  was chosen to impart the  
271 laboratory pTRM.

272 The data were processed with a linear regression analysis assuming a physical model  
273 compliant with the Fabian and Leonhardt's (2010) theoretical considerations that describe  
274 the relationship between the response variable and the explanatory variable. To this end,  
275 we anchored the fitting line to the point (0,-1). Prior the regression analysis, following the  
276 Fabian and Leonhardt's recommendations, we selected "a posteriori" the samples for  
277 which the ratio between the fraction of NRM overprinted by the laboratory pTRM and the

278 total NRM is between 0.2 and 0.8. In addition, only samples for which the angle between  
279 the NRM and the NRM remaining after the laboratory pTRM overprint is lower than a  
280 threshold angle here arbitrarily chosen to be  $15^\circ$ , have been selected. Moreover, because  
281 the MSP protocols involve for practical reasons to process with a regression analysis on a  
282 small number of data, it is obvious that MSP results are especially vulnerable to influential  
283 outliers. Thus, when influential outliers are clearly identified, here by means of the Cook's  
284 distance, we chose to discard them from the analysis.

285

#### 286 **4. Results**

287 IRM curves of representative samples from the six collections were performed and are  
288 shown in Figure 2.

289 ARC samples as well one sample for SKA (SKA2) indicate the presence of a low coercivity  
290 magnetic phase (likely magnetite or maghemite) as they seem to saturate at low fields.  
291 Most of the studied samples (SKA1, BOU1, 2, 3, 5, 10) show a mixture of low and high  
292 coercivity magnetic minerals, while the remaining two samples from KIC (2-7, 3-5)  
293 indicate the dominance of a harder component.

294 The thermomagnetic analyses display partially reversible curves (Fig. 3a). In the case of  
295 ARC and SX samples the heating curves are higher than the cooling ones and the calculated  
296 Curie temperatures, using the second derivative method, range from  $520-556^\circ\text{C}$ , indicating  
297 the presence of magnetite-like magnetic minerals. On the contrary, samples from BOU and  
298 KIC show a different behavior. Cooling curves are always higher than heating curves  
299 pointing to the creation of new magnetic phases during heating. The shape of the curves

300 shows a continuous decay of the magnetic susceptibility zeroing at the range of 550-600°  
301 C. However, due to this smooth decay the Curie points could not be derived.

302 The diagrams of the hysteresis loops provide information about the type of magnetic  
303 domain behavior the magnetic material has and therefore the grain size of the samples (Fig.  
304 3b).

305 For the hysteresis loops, eleven representative samples were examined. The magnetic field  
306 used was from -1.2T to 1.2T. All magnetic parameters, determined in room temperature,  
307 are displayed in Table 2s.

308 ARC1 and ARC6 samples, have generally a low mass magnetization, in the lower range of  
309 the samples presented in this study. The coercive force is estimated at 14 kA/m indicating  
310 a pseudo-single domain behavior.

311 For the SKAA and SKAC samples, a similar observation is evident in the loops although  
312 the coercive force  $H_c$  seems to have a small variability, indicating a multidomain character.

313 Nucleation type procedures of magnetic domains in titanomagnetites grains or the presence  
314 of other phases like hematite may serve as possible explanation for the widening of the  
315 loop in intermediate fields.

316 SX1 and SX2 samples are evidently different especially in the overall shape of the loop,  
317 although magnetization values are not very different. SX1 behavior is most probably multi-  
318 domain while for the SX2 sample a mixed behavior is proposed. The two samples present  
319 significant differences which could be attributed to a different starting material or different  
320 firing procedures; in the Phryctoriae the proximity to the large signaling fire was not the  
321 same through the whole structure and its lighting was aleatory. As in the previous cases a  
322 combination of magnetite and maghemite probably with additives like Ti is the most likely

323 cause of the magnetic properties while the presence of other iron oxides like hematite is  
324 possible.

325 Samples from Eretria (BOU3 and BOU6) present high coercivity but BOU6 also presents  
326 a considerably larger magnetization, probably related to differences in composition, e.g the  
327 density of the magnetic particles but also differences in oxides content. In both cases the  
328 behavior is probably single domain.

329 Kirrha ceramics (KIC) also present variations in their properties. Two of the samples  
330 (KIC3-3 and KIC2-5) are almost identical. Their behavior could be classified as mixed  
331 multi and pseudo-single domain; coercivity is relatively large but the loops are narrower in  
332 low fields, and this could be explained by grain boundary domains probably due to  
333 variations in stoichiometry. KIC3-4 sample presents notable lower values in all magnetic  
334 parameters, especially in magnetization; the latter is an indication of a mixed or multi-  
335 domain behavior. It can be concluded that the KIC3-4 sample is made of a different  
336 material.

337 During the Thellier-Thellier experiment (ARC, SKA, SX), forty-one specimens from  
338 twenty-one ceramic fragments were measured and 26 of them gave reliable results reaching  
339 ~61% mean success rate (Fig. 4a). Nine of the studied specimens failed during the  
340 experiment and the six were rejected during the analysis of the results as they did not meet  
341 the required criteria (Fig. 4b). The acceptance criteria used in the present study are as  
342 follows: The NRM fraction (f) should be more than 50% and the quality factor (q) more  
343 than 5 (Gómez-Paccard et al., 2006). Arai plots (NRM-TRM diagrams) must be linear and  
344 defined by at least 5 steps. Additionally, the maximum angular deviation (MAD) and the  
345 deviation angles (DANG) should be lower than 5° and 10° respectively. Finally,  $\beta$ , (the



346 ratio of the error in the slope to the slope of the linear best fit line) should not exceed 0.1  
347 (Shaar et al., 2016). The calculation of the above parameters was performed with  
348 ThellierTool (4.22) by Leonhardt et al., (2004). Our intensity results passing TTA and TTB  
349 criteria were classified as class A and B, respectively (Table 3s).

350 In our collections, all samples show MAD values lower than 5°, while there are only 4  
351 specimens with DANG values higher than 5°. In all cases the best fit line in Arai plots is  
352 calculated using more than 5 points (mean value 9.3) while the f, g, q, indicate mean values  
353 of 0.76, 0.83 and 21.6 respectively. All these calculated parameters at specimen level are  
354 displayed in Table 3s. For the ARC ceramic collection, the final archaeointensity value is  
355 determined at the sample level, that is the mean value of the specimens of the same sample  
356 is calculated and represents the archaeointensity estimation for the sample. For the SKA  
357 and SX collection we used the mean value of all studied samples as they come from baked  
358 clays and cannot be treated as individual fragments.

359 MSP-DSC results are illustrated on Figure 5 where data not included in the analysis are  
360 represented either by open circle or slashed open circle symbols for influential outliers and  
361 poor-quality measurements, respectively. These later are in most of the case due to a  
362 significant spurious secondary component of remanence overprinted to the primary TRM.  
363 95% confidence interval is assessed by bootstrapping the archaeointensity estimates. Note  
364 that this bootstrapped approach allows, at a glance, an ‘a posteriori’ validation of the  
365 robustness of the regression analysis by checking if the bootstrapped PI values display a  
366 normal distribution as illustrated on Figure 5. The final mean values of all six collections  
367 are shown in Table 2.

368

369 **5. Discussion**

370 *Implications of the rock-magnetic properties for the samples' suitability.*

371 We will present below an overall view of the samples composition as it arises from the  
372 performed magnetic experiments (hysteresis loops, thermomagnetic curves, isothermal  
373 remanent magnetization) in combination with other information when available e.g  
374 chemical analyses, XRPD, etc.

375 We first deal with the 4 collections studied with the classical Thellier protocol (ARCII, III,  
376 SKA, SX) and following this, with the ones studied with the multispecimen protocol (BOU,  
377 KIC).

378 Archontiko-ARC

379 The hysteresis loops display a pseudo-single domain behavior and indicate magnetite or  
380 titanomagnetite with low-Ti content. This converges with the thermomagnetic analysis  
381 where the T<sub>c</sub> varies from 520-556°C and the IRM one which features the dominance of  
382 low-coercivity minerals. Despite this promising pattern, the Thellier experiment was only  
383 45% successful (10 successful specimens out of 22). In order to find a possible explanation,  
384 we used information published in our previous publication (Kondopoulou et al., 2017) on  
385 another group from the same settlement but of younger age, the final horizon I (1516-1414  
386 BCE). In this study, a detailed XRPD analysis on 8 fragments suggested two groups of  
387 firing temperatures (550-600° C and 750-800° C). Layered magnetization measurements  
388 through hysteresis loops exhibit inhomogeneous compositional contents ref. to magnetic  
389 minerals. The success rate in the Thellier experiment was comparable to the present one.  
390 Despite the 300 years gap between this later material and the one studied here, there is  
391 evidence of continuity in clay selection for ceramics though the production of the EBA

392 horizons seems to have taken place in open fires or pits (Deliopoulos et al., 2014). This is  
393 ascertained by the existence of color- layered surfaces related to inhomogeneous firing  
394 conditions, characteristic of open firing (Rice,1987).

#### 395 Cretan Phryktoariae- SKA-SX

396 The SKA material is dominated by multi-domain magnetic minerals as derived by the  
397 hysteresis measurements. The thermomagnetic analyses point to Tc of 510-560° C, while  
398 the IRM curves indicate the presence of both low and high coercivity phases.

399 The SX material suggests probably multi-domain magnetite and maghemite through the  
400 hysteresis loops and the same Tc as above, 520-556° C.

401 An additional input is found in a detailed study on the chemical and mineralogical  
402 properties of the Cretan Red Clays (Hein et al., 2004) which include the broader area of  
403 provenance for our samples (Thrapsano). The analyses on representative samples from this  
404 area gives a concentration of Fe<sub>2</sub>O<sub>3</sub> at 8.43-8.60 wt% with a much lower TiO<sub>2</sub> of 1.09-1.14  
405 wt%. Additionally, four samples from the same Phryktoariae formations (two from SKA  
406 and two from SX) were subjected to XRPD analyses in order to estimate their firing  
407 temperatures together with the magnetic minerals included.

408 Two of them exhibit the neo-crystallization of a new mineral phase akermanite (melilite),  
409 an indication which assigns a firing T ≈750-800° C whereas the other two samples have  
410 been fired at lower temperatures, between 550 and 750° C. The low temperature ≈550-600°  
411 C for one sample has been established by the preservation of all mica's reflections which  
412 confirms that the dehydration was not completed. Magnetic minerals are incorporated in  
413 the mineralogical composition of all examined samples. Detailed analysis is shown in  
414 Table 4s (Rathossi, 2012 pers. communication).

415 The high success rate of the Thellier experiment (84% for SKA and 83% for SX) is possibly  
416 related to the high content of Fe-oxides and the high firing temperature.

417 Bouratza (BOU)

418 This collection has been thoroughly studied through a combination of petrographic and  
419 chemical analyses (WD-XRF) and the outcome for the group of origin of our samples  
420 (FG8) gives important information on their high content in Fe<sub>2</sub>O<sub>3</sub> (7.87 wt%) and the low  
421 one in TiO<sub>2</sub> (0.88 wt%).

422 The above information can be compared with the ones from the hysteresis loops which  
423 suggest a high coercivity mineral, the thermomagnetic analyses with a possible T<sub>c</sub> around  
424 600° C and the IRM curves which deviate from the saturation at about 1T, implying the co-  
425 presence of a high coercivity mineral.

426 Kirra (KIC)

427 The high firing temperatures, though calculated on other groups of pottery, can ensure  
428 similar ones for our fragments based on exploitation continuity as suggested above.

429 The presence of bauxite entails a strong contribution of iron-oxides. At the same time,  
430 calcium presence strongly affects the clay's properties, including formation of high  
431 amounts of iron oxides upon heating (Maniatis et al.,1981).

432 Our experiments provided interesting information on their composition referring to the  
433 magnetic minerals. The hysteresis loops displayed variable properties, with one fragment  
434 (KIC3-4) differing substantially from the other two which have a mixed pseudo- and multi-  
435 domain behavior. The IRM curves have a mixed pattern confirming the hysteresis, and the  
436 thermomagnetic curves, fully reversible, show a T<sub>c</sub> around 550° C.

437 ***The new archaeointensity results***

438 In order to evaluate the new high quality archaeointensities obtained in the present study,  
439 a comparison with the Greek intensity curve as well as with different geomagnetic field  
440 models is attempted. All curves and data are relocated to Thessaloniki. In Figure 6 the  
441 results of the present study are plotted together with all previous Greek data divided in two  
442 main categories. The grey dots represent the more reliable results used for the construction  
443 of the Greek curve (until 2008 ) using the classification of Kondopoulou et al., (2017), and  
444 in color all the data that have been published afterwards and are considered as high quality.  
445 The new data are in very good agreement with the Greek SVC apart from KIC which  
446 displays a lower intensity value. Nevertheless, there is a considerable lack of data for the  
447 specific period and consequently the Greek curve is only “estimated” and not calculated  
448 on real data. At the same time, there is a satisfactory agreement of the KIC result with the  
449 SHA.DIF.14K model. Two of our new F values are of similar age with previous Greek  
450 data. ARC results can be directly compared with SKS (Tema et al., 2012) showing an  
451 excellent agreement. Additionally, the obtained results from SKA are very close  
452 chronologically with the data from Mochlos (MLO, Rivero-Montero et al., 2021). The  
453 MLO results show a remarkable diversity within the assemblage which is attributed to the  
454 decadal variation of the GMF in this period. Nevertheless, our new SKA data converge  
455 well with their average value as well as with the SHA and CALS models.

456

457 *Overview of existing archaeomagnetic research on the Bronze age of the broader*  
458 *Eastern Mediterranean area*

459 During the last decade a growing number of archaeomagnetic studies have been conducted  
460 in the area extending from Cyprus to Syria, Mesopotamia, Israel and Lebanon (Gallet et

461 al., 2014, 2015, 2020; Shaar et al., 2016, 2020; Stilliger et al., 2015). A considerable  
462 amount of this research has focused to the Bronze age, as a natural consequence of the rich  
463 heritage from flourishing civilizations in the area. We report briefly on the main outcome  
464 of those studies which deal with the same period examined in our present research, that is  
465 the late third and the second millennium BCE. A first concise pattern of the GMF intensity  
466 variations within this period was obtained from a dataset in Syria (Ebla, Gallet et al., 2014).  
467 When compiled with data from other Syrian regions, the Levant and Anatolia, a pattern  
468 emerges with maxima at 2300-2000 BCE, 1550-1350 BCE and the beginning of the first  
469 millennium BCE with a much higher value than the previous ones. This prominent  
470 maximum was further documented by data from Israel (Shaar et al., 2016) while data from  
471 Turkey (both full-vector and only intensities) confirm the largescale variations from 2100-  
472 1350 BCE (Ertepinar et al., 2016). A recent compilation of GMF intensity variations in the  
473 Levant, between 2300-1500 BCE, together with a new dataset, allowed for a solid  
474 synchronization of the records, thus strengthening the pattern of the strong fluctuations  
475 registered during the Bronze age in the area (Shaar et al., 2020).

476 As far as the Greek data are concerned, both published and the new ones, no prominent  
477 maxima are observed between 2200-2000 BCE while high values of the GMF intensity are  
478 recorded around 1550-1350 BCE and even higher ones for the beginning of the Greek Iron  
479 age (1100-1000 BCE, Rivero-Montero et al., 2021). A remarkably high intensity is  
480 reported for site SKO dated at 2451 $\pm$  168 BCE, but this value must be confirmed by  
481 additional samplings in groups earlier than 2400 BCE which were almost impossible to  
482 locate, if our dating and material quality restrictions were to be respected.

483 There has been considerable research dealing with the potential relation of intense climatic  
484 changes with extreme values of the GMF in the perimediterranean region and the impact  
485 to ancient civilizations (Gallet et al., 2005, 2006, 2009).

486 The end of the 3<sup>rd</sup> as well as the second millennium BCE hosted three major environmental  
487 events associated to climate change and human agency. They can be placed around  
488 2200BCE, 1600 BCE and 1200-1100 BCE. These events are discussed by different authors,  
489 and we summarize below the key-points in relation with the periods we studied expanding  
490 within the whole Greek region, both continental and insular.

491 According to Wiener (2014), the well-known 4.2 Ka cal. BP (or 2200 BCE) as well as the  
492 one which occurred circa 1000 yrs later, at 1200 and 1120-1080 BCE were associated with  
493 dryness and drought, epidemics etc. The nature and causes of the 4.2ka event are still  
494 unclear but recent studies point to a North Hemisphere- scale drought event documented,  
495 in the Near East, at ca.2150 BCE (the collapse of Akkadian Empire) in Anatolia, through  
496 the destruction of Troy, late III-V (2200-1900 BCE) and in Cyprus, where the Philia phase  
497 of the EBA breaks down at ca.2200 BCE (Frankel & Webb, 2012). In Greece, though more  
498 rain is falling, there is evidence for dryness in the south in the late 3<sup>rd</sup> BCE, accounting for  
499 the well-known 2200 BCE phase of aridity (Bintliff, 2012).

500 By combining archaeological and natural sciences Meller et al., (2015) approach the  
501 definition of ‘events’ in human history by focusing to three periods within the Bronze Age  
502 in Europe, that is 3300 BCE, 2200 BCE, and 1600 BCE, the last one being  
503 contemporaneous with the well-known Santorini eruption. The 2200 BCE period is the  
504 closest one to our present study and topics addressed in the above publication refer, among  
505 others, to palaeoclimatic changes between 2300 and 2100 BCE. This period is significant

506 due to the weakening of the monsoonal rain belt and following dryness in the southern  
507 Mediterranean and the Middle East.  
508 Though the above-described events affected also the broader Greek region (Drake, 2012;  
509 Tsirtsoni, 2021), our new data for this period do not reflect these major changes through  
510 the intensity results which appear to be rather smooth. This observation is contradictory to  
511 the broad research performed in the Middle East (Gallet et al., 2014, 2015). At a local scale,  
512 the paleoenvironmental event traced in the area of Archontiko at around 2000 BCE  
513 (Syrides et al., 2009) is not equally witnessing a connection with abrupt intensity changes.  
514 We rather favor a pattern of a less prominent V-shape than the one suggested by Shaar et  
515 al., (2020) with low F values of similar duration but shifted slightly to earlier dates.

516

## 517 **6. Conclusions**

518 We performed a complete archaeomagnetic study of six collections including pottery and  
519 baked clays, belonging to the end of the Middle and the first half of the Late Greek Bronze  
520 Age. The material used had a variety of provenance, related to different geological  
521 environments. In spite of this, we observed a similarity in the contents of magnetic carriers  
522 and, in one case, (ARC), similar magnetic properties with a previously studied collection  
523 of the Final Bronze Age. Though we used two different protocols for the archaeointensity  
524 calculation, the obtained results are convergent.

525 The Thellier protocol has shown a high success rate for the baked clays in Crete, despite  
526 the frequent irreversibility of the thermomagnetic curves. We attribute this apparent  
527 controversy to the high content of magnetic minerals and the repeated heatings of the clays  
528 due to their use as firing places for several centuries. The obtained F values enrich the



529 available reference curves for Greece and the Balkans and will contribute to improve the  
530 regional and global models. Nevertheless, we must precise that we did not observe the high  
531 values indicated by other studies in the broader area for the period around 2200 to 2000  
532 BCE. We suggest that these could be found at an earlier period, around 2500-2400 BCE  
533 where one single result cannot attest them and should be confirmed by additional studies.

534

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544

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