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The directional occurrence of the Levantine geomagnetic field anomaly: New data from Cyprus and abrupt directional changes

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Abstract: We present new directional archaeomagnetic results from five archaeological sites in Cyprus. All studied materials come from in situ baked clay structures such as small hearths and ovens, dated from 2000 BCE to 1400 CE. Magnetic mineralogy experiments indicate the presence of a mineral close to magnetite as the main carrier. The Characteristic Remanent Magnetization (ChRM) was determined by stepwise alternating field demagnetization and the mean archaeomagnetic directions obtained are very well-defined. The ten new directions are added to the scant reference dataset for Cyprus and are used for further considerations together with data from nearby countries. To investigate the directional variations of the geomagnetic field in the Eastern Mediterranean and Middle East, we calculated a palaeosecular variation curve covering the last four millennia, using a critical selection of reference data from Cyprus, Israel, Turkey and Syria.. This curve shows several periods characterized by abrupt directional changes while a maximum change in curvature is clearly observed around 900 BCE. The new curves confirm the hypothesis that during the Levantine Iron Age Anomaly, apart the extreme intensity values, the geomagnetic field was characterized by steep inclinations and important directional change. Other periods of important curvature change are identified and deserve further investigation.

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Dear Editor,

please find attached the electronic version of the manuscript:

**" Investigation of the directional occurrence of the Levantine geomagnetic field anomaly: New data from Cyprus and abrupt directional changes"**

by

Tema, E., Hedley, I., Pavón-Carrasco, F.J., Ferrara, E., Gaber, P., Pilides, D., Toumazou, M.,  
Violaris, Y., Webb, J., Frankel, D.

that we submit for publication at *Earth and Planetary Science Letters*.

Our paper investigates the important Levantine Iron Age Anomaly (LIAA), presenting new high-quality data from Cyprus and a first directional paleosecular Variation curve for Cyprus and Middle East. Our results show important directional changes during the last four millennia. The maximum curvature change, characterized by fast directional variation, is detected around 900 BCE, showing that apart the extreme intensity values, the geomagnetic field during the LIAA was characterized by steep inclinations and important directional change. The geographical occurrence of the LIAA is also investigated showing that the secular variation trend depicted by data from Israel is also seen in the Cypriot data.

We hope that this contribution is of interest for publication in *Earth and Planetary Science Letters*.

Yours sincerely

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## **Highlights**

- New directional archaeomagnetic data from Cyprus
- Palaeosecular variation curve for Eastern Mediterranean and Middle East
- Directional curvature changes during the last four millennia
- Insights on the directional occurrence of the Levantine anomaly

1 **Investigation of the directional occurrence of the Levantine geomagnetic field**  
2 **anomaly: New data from Cyprus and abrupt directional changes**

3  
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5 Toumazou, M.<sup>10</sup>, Violaris, Y.<sup>9</sup>, Webb, J.<sup>11</sup>, Frankel, D.<sup>11</sup>

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32

### 33 **Abstract**

34 We present new directional archaeomagnetic results from five archaeological sites in Cyprus. All  
35 studied materials come from *in situ* baked clay structures such as small hearths and ovens, dated  
36 from 2000 BCE to 1400 CE. Magnetic mineralogy experiments indicate the presence of a mineral  
37 close to magnetite as the main carrier. The Characteristic Remanent Magnetization (ChRM) was  
38 determined by stepwise alternating field demagnetization and the mean archaeomagnetic  
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40 dataset for Cyprus and are used for further considerations together with data from nearby  
41 countries. To investigate the directional variations of the geomagnetic field in the Eastern  
42 Mediterranean and Middle East, we calculated a palaeosecular variation curve covering the last  
43 four millennia, using a critical selection of reference data from Cyprus, Israel, Turkey and Syria..  
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45 change in curvature is clearly observed around 900 BCE. The new curves confirm the hypothesis  
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47 field was characterized by steep inclinations and important directional change. Other periods of  
48 important curvature change are identified and deserve further investigation.

49

50 **Keywords:** Secular Variation; Geomagnetic field direction; Levantine anomaly; Cyprus; Middle  
51 East

52

## 53 **1. Introduction**

54 The Earth's magnetic field, generated by complex magnetohydrodynamic processes deep in  
55 the Earth's liquid outer core, is of vital importance for life on the Earth as it protects our planet  
56 from damaging solar radiation, acting as a huge natural shield. Although of a general long-term  
57 dipolar nature when averaged over thousands of years, it is known that it continuously varies on  
58 shorter time scales and over small geographical areas. Reconstructing and modelling such short-  
59 term geomagnetic field changes, known as Secular Variation (SV), is very important for  
60 obtaining a valuable insight into the processes and mechanisms responsible for the geomagnetic  
61 field's generation, its evolution and its applications to the core (Jackson and Finlay, 2015).

62 In the last decades, attention has been focused on the study of particular features of the  
63 Earth's magnetic field SV characterized by intense and short-lived changes that occur at decadal  
64 and centennial time scales. Based on archaeomagnetic data obtained from well dated  
65 archaeological artifacts in France, several periods of rapid geomagnetic field change have been  
66 identified, characterized by sharp changes in the direction, which coincide with intensity maxima,  
67 named *archaeomagnetic jerks* (e.g. Gallet et al., 2003). In several other studies, particularly high  
68 field intensity values associated with rapid SV rates have been observed (e.g. Ben-Yosef et al.,  
69 2009; Gómez-Paccard et al., 2016; Hervé et al., 2017). Such high intensities are a surprising and  
70 particularly interesting feature of the past SV, also known as *geomagnetic intensity spikes*. High  
71 intensity spikes have been identified in several geographical areas and during different  
72 chronological periods but undoubtedly the most documented so far is that one observed around  
73 1000 BCE in the Levantine area and known as the Levantine Iron Age Anomaly, LIAA (see  
74 Shaar et al, 2016 and references therein).

75           The Levantine Anomaly was reported by Ben-Yosef et al. (2009) and Shaar et al. (2011)  
76 who observed high intensities in Middle East around 1000 BCE. Further data from Turkey  
77 (Ertepinar et al., 2012) also showed unusually high archaeointensity values. Shaar et al. (2016)  
78 carefully revised the available Levantine data suggesting the presence of extreme regional  
79 intensities with two spikes (around 11<sup>th</sup> and 8<sup>th</sup> centuries BCE). More recently, Shaar et al. (2018)  
80 presented a large compilation of archaeomagnetic directions from Israel that cover the last four  
81 millennia, showing that the Levantine intensity anomaly is also accompanied by significant  
82 directional changes. Indeed, the directions from Israel show high inclination and high declination  
83 values during the 9<sup>th</sup> century BCE, providing more evidence for a regional field anomaly in  
84 Middle East during the beginning of the first millennium BCE.

85           Even though, abrupt variations on the direction and/or the intensity of the Earth's magnetic  
86 field are a particularly interesting feature of the geomagnetic field, their origin, geographical  
87 occurrence and explanation through core-flow dynamics are still under investigation (e.g.  
88 Livermore et al., 2014; Davies and Constable, 2018; Korte and Constable, 2018). Unfortunately,  
89 the global palaeomagnetic reconstructions cannot help in this debate as they cannot clearly  
90 reproduce such rapid variations, mainly due to the sparse and uneven global data distribution and  
91 the uncertainties in their dating (Korte and Constable, 2018). The contribution of new, high  
92 quality and well dated archaeomagnetic data from Eastern Mediterranean and Middle East is thus  
93 very important to explore the geographical and temporal distribution of such geomagnetic field  
94 anomalies. Even though great effort has been focused on the acquisition of new intensity records  
95 from these areas (e.g. Ben-Yosef et al., 2011; Shaar et al., 2015; Gallet et al., 2015), the  
96 directional data obtained from the study of *in situ* baked clay structures are still very few (e.g.  
97 Speranza et al., 2006; Tema et al., 2018; Ertepinar et al., 2019). For this purpose, we present here  
98 new directional archaeomagnetic data from Cyprus, in order to enrich the reference directional  
99 dataset in the Eastern Mediterranean and contribute to the investigation of the directional  
100 occurrence of the Middle East anomaly in areas near to Israel, such as Cyprus.

101

## 102 **2. Archaeological context and sampling**

103 Archaeomagnetic samples were collected from 13 *in situ* baked clay structures, coming  
104 from 5 different archaeological sites in Cyprus: Marki-Alonia, Idalion, Athienou-Malloura,  
105 Palaion Demarcheion (Lefkosia) and Agios Georgios (Lefkosia) (Fig. 1a).

### 106 2.1 Archaeological sites

#### 107 - *Marki-Alonia (MKA)*.

108 The Marki Alonia archaeological site (35.02° N, 33.33° E) is situated in central Cyprus, 15  
109 km south of the capital Lefkosia, and was excavated by the Australian Cyprus Expedition during  
110 several seasons from 1990 to 2000. The excavations revealed an extended Bronze Age settlement,  
111 occupied for several centuries from the Bronze Age (about 2400 BCE) to the Middle Cypriot II  
112 (about 1800 BCE) (Frankel and Webb, 2000). Within the excavated area several architectural  
113 households have been identified. Most of them consist of yards with enclosed small rooms, where  
114 hearths and clay ovens were often found (Frankel and Webb, 2006). Clear evidence of rebuilding  
115 and frequent renovation of the structures suggests a complex history of the site. However, the  
116 relatively fine-scale changes recognized in the excavated area contributed to the division of the  
117 development of the Marki sequence into nine phases, based on stratigraphic, architectural and  
118 ceramic evidence (Frankel and Webb, 2006). For this study, we sampled the wall of a small oven  
119 originally built in Phase C (Context 1897), and then rebuilt and remodeled in Phase D (Context  
120 3346) (Frankel and Webb 2006: 22, pl. 10e–f). The oven (Fig. 1b) was last used after its  
121 reconstruction and can thus be dated in the Early Cypriot Phase II, around 2150-2050 BCE.

#### 122 - *Idalion (IDN)*.

123 The ancient city of Idalion (35.02 °N, 33.42 °E) is situated in the Mesaoria Plain, near to  
124 the village of Dhali, about 25 km south-east of Lefkosia. The excavations conducted in the area

125 since the middle of the 19<sup>th</sup> century, revealed rich architectural, numismatic and epigraphic  
126 findings. The Idalion city-kingdom was founded by Eteocyprists around 1220 BCE but it reached  
127 its greatest prosperity during the 7<sup>th</sup> and 6<sup>th</sup> centuries. In 450 BCE the city was occupied by  
128 Phoenicians, who held it until the Hellenistic occupation around 300 BCE and it eventually  
129 declined under their rule. The archaeological excavations brought to light a large number of coins  
130 attributed to the Kings of Idalion, sculptures, inscriptions, as well as a large collection of pottery  
131 and remains of metallurgical activity (Hadjicosti, 1997). In this study, a large sunken dolia (Str. 3,  
132 Square 10) was sampled (Fig. 1c). According to the stratigraphic information and the diagnostic  
133 pottery found in the surrounding area, the structure was dated at 1200-1050 BCE.

134 - *Athienou-Malloura (MLR)*.

135 The Athienou-Malloura archaeological site (35.08 °N, 33.58 °E) is situated around 6 km  
136 southwest of the village of Athienou, in Larnaca district, halfway between Lefkosia and Larnaca.  
137 Archaeological excavations have been conducted since 1990, coordinated by the American  
138 archaeological team of the University of Davidson (North Carolina, USA). The excavations  
139 brought to light important archaeological finds comprising two cemeteries (one from the Archaic  
140 to the Roman period and the other from the Venetian), a settlement (from the Roman to Ottoman  
141 Period) and a sanctuary of male gods (from the Archaic to the Roman period). The thousands of  
142 objects and artifacts found at the site reveal the rich archaeological heritage of the area. In the  
143 present study, a baked clay wall in sector 32 and a flat hearth in sector 14 were sampled (EU28-  
144 MLR1 and EU94-MLR2, respectively). The former was almost certainly part of a domestic oven  
145 while the latter was likely a hearth or an altar (Fig. 1d). According to archaeological evidence  
146 based on ceramics they are dated to the Cypro-Archaic II (600-480 BCE) and Cypro-Archaic I  
147 (750-600 BCE) periods, respectively.

148 - *Palaion Demarcheion, Lefkosia (PLND)*.

149           The archaeological site of Palaion Demarcheion (35.17 °N, 33.37 °E) is situated in the  
150 center of the old city of Lefkosia, within the Venetian walls. The emplacement was used as a  
151 municipal car-park since the 1960's and the archaeology was discovered in 2002 when the area  
152 was cleared for the construction of the new Lefkosia City Hall. Rescue excavations were  
153 conducted by the Department of Antiquities from June 2002 up to October 2006. The excavated  
154 areas revealed a part of the Byzantine and medieval city, including churches with cemeteries,  
155 monumental buildings, many workshop areas (for the production of glass, jewelry and pottery) and  
156 other architectural remains. The rich findings indicate that the site was occupied from the 11<sup>th</sup> to  
157 the 20<sup>th</sup> centuries CE (Chrysostomou and Violaris, 2018). The architectural remains of two  
158 churches, each associated with a cemetery, are perhaps amongst the most important findings of the  
159 excavations. The foundations of the northern part of the first church (Church A) are associated  
160 with pottery dating to the 12<sup>th</sup> century CE, while the southern part has two architectural phases that  
161 date to the second half of the 12<sup>th</sup> century or the beginning of the 13<sup>th</sup> century CE. The second  
162 church (Church B) is associated with an architectural phase that dates towards the end of the 11<sup>th</sup>  
163 or early 12<sup>th</sup> century CE, and burials surrounding the church date at least from the 12<sup>th</sup> century  
164 (Chrysostomou and Violaris, 2018). During the early 13<sup>th</sup> century, Church B was destroyed by fire,  
165 it was rebuilt, but it was subsequently destroyed again. In this study a flat domestic hearth  
166 (PLND1) excavated in square L6-D and a small circular metallurgical hearth (PLND2) excavated  
167 in square M6 were sampled (Fig. 1e), dated at 13<sup>th</sup>-14<sup>th</sup> centuries CE and 12<sup>th</sup> century CE,  
168 respectively, based on the stratigraphy and archaeological finds.

169           - *Agios Georgios, PA.SY.D.Y., Lefkosia (PSY).*

170           The archaeological site of Agios Georgios (known as PA.SY.D.Y) is situated on the hill of  
171 Agios Georgios (35.17° N, 33.35° E), in central Lefkosia. Excavations began in 1996, following  
172 the decision to build the new House of Representatives on the site. Excavations were then carried  
173 out from 1996 to 2006, revealing an extensive settlement that included workshop areas for the

174 manufacture of terracotta, limestone and metal objects. Occupation of the site dates from the  
175 Archaic period to the end of the Hellenistic period. Furthermore, some remains assignable to the  
176 early Christian period until the 16<sup>th</sup> century CE were also found. In this study, our sampling was  
177 focused on the baked clay ovens and hearths found at the site, in the areas VI, XI, XII, XIII, XVI  
178 (Pilides et al., 2007). In particular, oriented samples were collected from seven baked clay  
179 structures: structure 13 (PSY1), 15a (PSY2), 60 (PSY3), 21 (PSY4), 65 (PSY5), 55 (PSY6) and  
180 61a (PSY7). Most of the structures studied were circular ovens (Fig. 2) or metal-working  
181 installations (Pilides et al., 2007). Even though the exact time of the last firing of each one of the  
182 sampled hearths is difficult to ascertain and will be the aim of a future detailed archaeological  
183 study, they all belong to Late Classical and Hellenistic periods based on coin and ceramic finds.  
184 They can thus be safely dated from the end of the 4<sup>th</sup> century BCE to the half of the 1<sup>st</sup> century  
185 BCE.

## 186 2.2 *In-situ* magnetic susceptibility mapping of the Agios Georgios hearths

187 In the case of Agios Georgios, a Bartington MS2 portable magnetic susceptibility meter  
188 with an F-type probe was first used to measure the variation of the initial magnetic susceptibility  
189 on the surface of three of the flat hearths. A detailed magnetic image of each hearth can provide  
190 evidence as to its function in antiquity. The variation of the magnetic susceptibility can also be  
191 useful to define those parts that were better fired and thus more suitable for archaeomagnetic  
192 sampling, taking into consideration that firing leads to an enhancement of the magnetic  
193 susceptibility (Jordanova et al., 2001; Carrancho and Villalain, 2011; Tema and Ferrara, 2019).

194 The sensitivity of the F-probe decreases rapidly with distance such that 90% of the signal  
195 comes from a 6 mm depth below the flat tip of the sensor (manufacturer's specification). As  
196 measurements on experimental fires have shown that the maximum temperature achieved  
197 decreases rapidly with depth (Linford et al., 2001), the F-probe was ideally suited to examine the  
198 magnetic susceptibility variation on the Agios Georgios flat hearths.

199 Magnetic susceptibility mapping revealed an inhomogeneous pattern indicating that some  
200 parts of the studied hearths had been heated at higher temperatures (Fig. 2). Our survey shows that  
201 the maximum susceptibility values are not concentrated in the center of the hearths, as would be  
202 expected and observed in previous studies (Morinaga et al., 1999). The PSY1 hearth shows a  
203 pronounced maximum susceptibility at the south-west side, where the baked clay was also  
204 characterized by a darker color (Fig. 2 a, b). Similarly, the PSY2 hearth shows an asymmetrical  
205 magnetic susceptibility variation with higher values at the northern part, although without any  
206 clear difference in color of the baked clay. (Fig. 2 c, d). PSY4 hearth is the least magnetic of the  
207 hearths studied, with maxima at the south and north edges (Fig. 2 e, f).

208 Distinct areas of higher magnetic susceptibility (hot spots) on the surface of these hearths  
209 would suggest the use of a controlled air draft or even some form of forced ventilation (Rehder,  
210 1994). This is compatible with the evidence of metal working at the Agios Georgios site. The  
211 susceptibility values registered in all surveyed structures are high, suggesting the suitability of the  
212 structures for archaeomagnetic investigation.

### 213 2.3 Archaeomagnetic sampling

214 Archaeomagnetic sampling was carried out during several field campaigns made between  
215 1999 and 2006. In all cases, following the magnetic susceptibility survey results, samples were  
216 collected from the parts of the structures that showed evident signs of heating. Generally, the upper  
217 parts of the structures' floors or the lower parts of the walls seemed to be better baked and were  
218 thus preferred. Oriented samples suitable for a directional investigation were collected by gluing  
219 22 mm diameter plastic disks on the baked clay's upper surface. The orientation of the horizontal  
220 line drawn on each disc was measured using a Brunton compass and an Anglestar electronic  
221 clinometer. A sun compass was also used, in order to correct the azimuth of the samples for any  
222 local magnetic disturbance. Between 7 and 19 independently oriented samples were collected from  
223 each structure.

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### 3. Methods

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### 4. Results

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#### 4.1 Magnetic mineralogy

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The bulk magnetic susceptibility and the Natural Remanent Magnetization (NRM) of most of the samples were measured shortly after sampling at the Petrophysics Laboratory, Geneva University (Switzerland) with a Bartington MS2B susceptibility meter and a Minispin magnetometer. The structures MLR2, PSY3 and PSY5 showed very low Q-ratio values,  $Q_n$ , ( $0.6 < Q_n < 1.8$ ) as well as very dispersed NRM directions, suggesting insufficient heating to acquire a stable and representative ancient geomagnetic field record; they were therefore excluded from any further analysis. For all the remaining structures, samples were systematically stepwise demagnetized at the Alpine Palaeomagnetic Laboratory (ALP), at Peveragno (Italy) with a D-2000 ASC demagnetizer and their magnetic remanence was measured with a JR6 Spinner magnetometer (AGICO). The magnetic anisotropy of representative samples was investigated with a KLY3 Kappabridge (AGICO). Magnetic mineralogy experiments including Isothermal Remanent Magnetization (IRM) acquisition and back field curves, magnetic moment monitoring up to 700 °C, and hysteresis loops were carried out at the ALP laboratory and at the Istituto Nazionale di Ricerca Metrologica (INRIM), at Torino (Italy). Hysteresis loops and thermomagnetic curves were measured at INRIM with a Lake Shore 7400 Vibrating Sample Magnetometer (VSM) equipped with a thermo-resistance oven operating in an inert Argon atmosphere on small fragments (mass < 100 mg).

The IRM curves obtained for one sample from each structure show that saturation is reached in all cases at applied fields of around 0.2-0.4 T (Fig. 3a), suggesting the presence of a

248 low-coercivity mineral. The back-field curves also indicate the presence of a soft magnetic mineral  
249 with remanence coercivity being in all cases lower than 50 mT, except for sample PSY7-2 coming  
250 from the more vitrified structure 61, that is characterized by a higher coercivity (Fig. 3b).  
251 Hysteresis loops (corrected for the para/diamagnetic contributions) further confirm these results  
252 (Fig. 3c). They indicate the presence of soft magnetic minerals, such as magnetite and Ti-  
253 magnetite, as the main carriers of the magnetic moment. This is assumed from the tight shape of  
254 the hysteresis loops accompanied by low coercive fields:  $H_c$  values are in the range 5- 15 mT  
255 except from sample PSY 7-2 that has higher  $H_c$  of around 35 mT, as already indicated by the IRM  
256 back field curve. The magnetic parameters provided by the hysteresis loops of representative  
257 samples (i.e. coercive field  $H_C$ , magnetic remanence  $M_{RS}$ , and magnetic saturation  $M_S$ ) together  
258 with the remanence coercivity values,  $H_{CR}$ , provided by the back-field curves, were plotted on a  
259 Day Plot (Fig. 3d). All samples show magnetic granulometry that fits in the pseudo single domain  
260 (PSD) part of the Day plot (Dunlop, 2002). Thermomagnetic curves of the magnetic moment  
261 versus temperature up to 600 °C or 700 °C show Curie temperatures of around 580 °C, indicating  
262 the presence of magnetite as the main magnetic mineral (Fig. 4). In most cases they are not  
263 reversible, with cooling curves being always higher, probably due to the formation of new  
264 minerals during heating. Such curves also suggest that the heating temperatures experienced by the  
265 baked structures during their use were probably lower than 600-700 °C.

#### 266 4.2. Magnetic anisotropy

267 Archaeological structures and artifacts such as kilns, tiles, bricks and pottery can in some  
268 cases be highly anisotropic and several studies have shown that their pronounced magnetic fabric  
269 may influence not only their archaeointensity values but also the direction of the recorded  
270 geomagnetic field vector (Hus et al., 2003; Tema, 2009; Palencia-Ortas et al., 2017). Generally,  
271 baked clays from small hearths, ovens and fireplaces are not anisotropic (e.g. Kovacheva et al.,  
272 2009; Tema et al., 2016). However, to investigate any possible deviation of the ChRM direction in

273 the samples studied here, we have measured the anisotropy of the magnetic susceptibility (AMS)  
274 on 44 samples from Idalion (IDN), Athienou-Malloura (MLR1 and MLR2) and Marki-Alonia  
275 (MKA). The mean anisotropy parameters (L: magnetic lineation; F: magnetic foliation; P: degree  
276 of anisotropy; T: shape factor) are obtained according to Jelinek (1981) using the Anisoft software  
277 (Table S.1, Supplementary material). The AMS degree ( $P_{AMS}$ ) is in all cases very low, varying  
278 from  $P_{AMS}= 1.001$  for Idalion to  $P_{AMS}=1.018$  for Marki. These results confirm that the anisotropy  
279 of baked clays coming from unmodeled structures like small hearths is very low and it should not  
280 influence the magnetic direction recorded by the clays during their last firing.

#### 281 4.3 Archaeomagnetic direction

282 The results of the stepwise AF demagnetization experiments were plotted in equal area  
283 projections, intensity decay curves and Zijderveld diagrams (Zijderveld, 1967) and were  
284 interpreted using the Remasoft3.0 software. The results obtained generally show linear Zijderveld  
285 diagrams and the Characteristic Remanent Magnetization (ChRM) component is easily and clearly  
286 isolated (Fig. 5). Secondary components, if any, are cancelled during the first steps of the AF  
287 demagnetization, usually at fields  $<20$  mT. The direction of the ChRM at sample level was  
288 calculated according to principal component analysis while the mean direction for each structure  
289 studied was obtained assuming a Fisherian distribution (Fisher, 1953). In all cases the mean  
290 directions are very well defined (Fig. 6) and characterized by small  $\alpha_{95}$  angles of confidence ( $\alpha_{95} \leq$   
291  $3.1^\circ$ ) and high precision parameter,  $k$ , ( $k > 150$ ), apart from the structures PLND1, PSY-4 and  
292 PSY-7 that are characterized by more dispersed directions and thus higher  $\alpha_{95}$  values. The obtained  
293 directions at structure level are given in Table 1, together with their archaeological age.

294

## 295 5. Discussion

### 296 5.1 New directional data from Cyprus

297           The first archaeomagnetic directional data from Cyprus came from seven *in situ* baked clay  
298 structures excavated at the copper smelting site of Agia Varvara-Almyras (Tema et al., 2018). No  
299 other directional data are available so far, even though Cypriot slags and ceramics have been  
300 successfully used for archaeointensity studies (e.g. Shaar et al., 2015; Ertepinar et al., 2020). The  
301 new directions presented in this study aim to enrich this scant directional dataset whilst the data  
302 from the Palaion Demarcheion archaeological site are actually the only directional records from  
303 Cyprus for the last 2000 years.

304           Due to the very limited directional data from Cyprus, we compare our new data with  
305 published data from sites in the Middle East and Anatolia, both areas known to be characterized by  
306 extreme geomagnetic field variability (e.g. Shaar et al., 2018; Ertepinar et al., 2020). Shaar et al.  
307 (2018) recently published an extensive catalogue of archaeomagnetic directional records from  
308 Israel. This catalogue includes 76 directions; 47 of them are classified as of high quality, satisfying  
309 selection criteria based on the number of specimens and statistical quality parameters (Shaar et al.,  
310 2018). The most prominent feature of these data is the high declination and inclination values  
311 observed at the beginning of the first millennium BCE while they also show other periods with fast  
312 secular variation rates. Apart from Israel, more directional data are available from countries  
313 neighboring Cyprus such as Turkey (Ertepinar et al., 2012; 2016; 2020) and Syria (Speranza et al.,  
314 2006). More recently, Ertepinar et al. (2020), published new archaeomagnetic data from the  
315 Eastern Mediterranean, including directional results from four archaeological sites in Turkey with  
316 ages ranging from 3300 BCE to 672 BCE, and with intensity data from both Turkey and Cyprus  
317 that further support extreme field variations in the region.

318           In order to compare our data with the directional data from the literature, we have relocated  
319 them to the geographical coordinates of Lefkosia (35.17 °N, 33.36 °E) using the virtual  
320 geomagnetic pole method (Noel and Batt, 1990). The new data from Agios Georgios  
321 archaeological site are in good agreement with literature data from Agia Varvara (Tema et al.,

2018) and Israel (Shaar et al., 2018), apart from the PSY4 hearth that shows much lower inclination than the other contemporaneous records (Fig. 7). The data from Idalion and from Athienou-Malloura are also in agreement with data from Israel and they seem to support the presence of a short lived Levantine anomaly, showing increasing declination and inclination values before the peak values observed at Israel around 1000-900 BCE, and a clear decreasing trend after that period. Data from Marki, dated around 2000 BCE, show a low declination with respect to slightly younger data from Turkey, even though the inclination fits well with the Turkish data. Unfortunately, there are no available data for the 10-14<sup>th</sup> centuries CE to compare the new records from Palaion Demarcheion. However, they seem to show a high declination around 1100 CE and a low inclination around 1300 CE, following a general trend suggested by the Israeli data (Fig. 7).

## 5.2 Directional Secular Variation path in Eastern Mediterranean and Middle East

The geographical position of Cyprus, situated between Turkey, Syria and Israel, makes it particularly interesting for reconstructing the Secular Variation path in the area of Eastern Mediterranean and Middle East. This area is of great geomagnetic interest due to the Levantine anomaly characterized by unusual high intensities. To investigate the directional occurrence of such anomaly and to explore other eventual abrupt directional changes in this area, we have calculated a directional SV curve based on the new and previously published archaeomagnetic reference data from Cyprus, Israel, Turkey and Syria. To guarantee internal consistency to the reference dataset, we adopted the selection criteria applied by Shaar et al. (2018) to the Israel data and we therefore rejected all data that are based on less than 8 specimens, have age error more than 100 years and  $\alpha_{95}$  angle of confidence greater than  $6^\circ$ . As well as the archaeomagnetic data, historical directional data from the HISTMAG database (Arneitz et al., 2017), located within a circular area of 600 km radius around Lefkosia, were also used to better constrain the geomagnetic field path during the last few centuries. All data are relocated to Lefkosia (35.17 °N, 33.36 °E) via the pole method.

347           The new time-continuous directional SV curve was computed following the method  
348 described by Molina-Cardin et al. (2018), where a local paleomagnetic full-vector  $\vec{M}$  is modeled  
349 by means of penalized cubic b-splines in time. Since the available data cover the last 4 millennia,  
350 we fixed the temporal basis of splines every 25 years within a time window from 2000 BCE to  
351 1900 CE. It is worth noting that the paleomagnetic full-vector includes all the palaeofield  
352 elements, i.e., declination, inclination and intensity, while our study is only focused on directional  
353 data. To solve the lack of the intensity, we normalized the vector of the unknown coefficients  $\vec{C}$  by  
354 the first coefficient  $c_1$  (see Text S3 of the Supplementary material in Molina-Cardin et al., 2018),  
355 providing a complete solution for both declination and inclination. The final time-continuous curve  
356 is obtained by choosing an optimal damping parameter in the modeling inversion providing the  
357 best fitting in terms of curve complexity and data residual. In addition, the curve uncertainties  
358 were estimated by applying a bootstrap approach, using both random homogeneous and Gaussian  
359 distributions based on the dating and measurement errors, respectively (for historical data a  
360 constant  $\alpha_{95}$  of  $0.25^\circ$  was assumed without a dating error). The directional curve computed is given  
361 in Table S.2 (Supplementary material).

362           The new curves for declination and inclination are plotted in Figure 8 along with the  
363 reference historical measurements and the selected reference archaeomagnetic data. They are the  
364 first directional curves available for Cyprus and they are valid for the investigation of the  
365 geomagnetic field's behavior in the area of Eastern Mediterranean and Middle East. For the last  
366 two millennia, the new curves show high declination values around 200 CE, 600 CE and 1200 CE  
367 and clearly low inclination values around 200 CE and 1300 CE. However, for the last 2000 years  
368 the available high-quality data are quite scarce, and the low and high peaks seen in the curves are  
369 constrained by only few data. On the contrary, the curves during the first two millennia BCE are  
370 well detailed, and they clearly show high inclination values around 900 BCE, accompanied by  
371 eastern declinations of around  $10^\circ$ . Although single declination values are as high as  $25^\circ$  the curves

372 do not show a clear declination peak due to the dispersion of the declination data for this period. It  
373 is also interesting to note a clear low inclination observed around 1800 BCE, accompanied by  
374 slightly western declination of around  $-5^{\circ}$ .

375 To further explore these aspects, we have compared our curves with the predictions of  
376 some of the most recent global paleomagnetic field models (Fig. 8). Such paleomagnetic  
377 reconstructions use all the available palaeomagnetic data spanning the last few millennia to  
378 provide a time-continuous picture of the past geomagnetic field at any location over the Earth's  
379 surface. Some of them are based on a combination of archaeomagnetic, volcanic and sediment  
380 data, such as the pfm9k.1b (Nilsson et al., 2014) and the HFM.OL1.AL1 (Constable et al., 2016)  
381 models, while others have excluded sediment data due to their known smoothed and post  
382 depositional time-delay problems, using only archaeomagnetic and volcanic data (e.g.  
383 SHA.DIF.14k, Pavón-Carrasco et al., 2014; ARCH10k.1, Constable et al., 2016; and the SHAWQ-  
384 family, Campuzano et al., 2018 and Osete et al., 2019). All the cited global models cover the last  
385 four millennia, except from the SHAWQ-family that only spans the last three millennia.  
386 Comparison of our new curves with these models shows that during the last two millennia the  
387 inclination curve is in good agreement with the models' predictions while the declination peaks of  
388 around 200 CE and 600 CE are not seen in any of the models. For the BCE period, our new curves  
389 show a better agreement with the SHAWQ-family model, even if the agreement with the  
390 SHA.DIF.14k and ARCH10K.1 models can also be considered to be satisfactory.

### 391 5.3 Directional occurrence of LIAA and abrupt directional changes

392 With a view to further analyze the directional changes of the palaeofield in Cyprus and also  
393 to investigate the directional occurrence of the LIAA, we have plotted the new curves in Bauer  
394 plots of declination and inclination for 4 different time periods (Fig. 9a). Furthermore, we have  
395 also calculated the curvature of the curve (Fig. 9b), to detect periods with rapid directional  
396 changes. From 2000 BCE to 1000 BCE, the SV curve shows an east-west zigzag pattern in

397 declination with a continuous increase of inclination. In this millennium, the most abrupt change  
398 occurs around 1400 BCE (Fig. 9), when the curvature parameter reaches its maximum value. For  
399 the first millennium BC (1000 BCE – 0 CE) the declination swings to the west with abrupt  
400 changes around 900 BCE, 600 BCE and 200 BCE (Fig. 9a, b). The first event at 900 BCE is  
401 characterized by the highest curvature parameter and the highest inclination values of the last 4  
402 millennia. The first millennium CE (0 CE – 1000 CE) is also characterized by west-east zigzag  
403 declination values with increasing inclinations, with some peaks in the curvature parameter around  
404 0 CE, 250 CE and 800 CE. Finally, the last millennium (1000 CE – 1900 CE) shows a westward  
405 drift in the declination values with inclinations ranging between 50° and 60° without important  
406 abrupt changes, as shown by the close-to-zero curvature parameter (Fig. 9).

407         The Bauer plots and the curvature calculation presented here successfully show several  
408 abrupt directional variations with the most prominent characteristic of the directional SV in Cyprus  
409 during the last four millennia being the maximum curvature change depicted around 900 BCE.  
410 Such important curvature change can be clearly associated with the LIAA, confirming that apart  
411 the extreme intensity values, the geomagnetic field at that time was simultaneously characterized  
412 by very steep inclinations and directional variation. To quantify the directional variation around  
413 900 BCE, we used the new curves to estimate the temporal rates before and after the curvature  
414 maximum. Before 900 BCE the declination is characterized by a rate of +3.2°/century moving  
415 towards east, and an increase rate of +1.8°/century for the inclination. After the maximum  
416 curvature, the declination moves towards the west with a rate of -5.7°/century while the inclination  
417 decreases around -3.6°/century. If we calculate such rates using the reference data themselves,  
418 instead of the curves, the temporal rates obtained are even higher as the curves are inevitably  
419 affected by some smoothing. Indeed, in this case before 900 BCE the declination changes by  
420 +7.0°/century and the inclination increases by +5°/century, while after 900 BCE the declination  
421 moves from east to west at a rate of 13.2°/century and the inclination decreases by -7.4°/century.

422 Such temporal change ranges are quite high and similar to those reported in Iberian Peninsula  
423 (Osete et al., 2020).

424         Apart from the 900 BCE directional change, the curvature peak observed around 600 BCE  
425 could be related to the high intensity values observed in Western Europe (Osete et. al, 2020) while  
426 the curvature change at 200 CE seems to perfectly coincide with the one observed by Gallet et al.  
427 (2003). Even though detecting rapid directional fluctuations from regional SV curves is often hard,  
428 due to the reference data uncertainties and to the smoothing introduced during computational  
429 processes (Le Goff and Gallet, 2019), it would be interesting to further investigate these important  
430 directional changes with new data, and if possible with full-geomagnetic field records (including  
431 both directional and intensity determinations).

432

## 433         **6. Conclusions**

434         We present 10 new directional data from Cyprus from 5 archaeological sites with ages  
435 ranging from 2000 BCE to 1400 CE. These new directions enrich the reference data for Cyprus  
436 and together with data from nearby Israel, Turkey and Syria are used to reconstruct the directional  
437 geomagnetic field path in the area of Eastern Mediterranean and Middle East during the last four  
438 millennia. A time-continuous SV curve was computed and used to investigate the directional  
439 occurrence of the LIAA anomaly and abrupt directional changes. Our investigation shows a  
440 maximum curvature change peak at around 900 BCE, confirming the hypothesis that the LIAA  
441 was accompanied by an abrupt directional change. Other important directional changes are also  
442 observed in several other BCE periods while during the last two millennia CE, the most important  
443 change is observed around 200 CE. Further investigation of these changes in curvature is still  
444 needed to better understand their non-dipole origin and explore their connection with intensity  
445 maxima.

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648

649 **Figure captions**

650 Fig. 1 a) Location of the newly studied archaeological sites and photos of the structures from b)  
651 Marki; c) Idalion; d) Malloura (MRK2); e) Palaion Demarcheion (PLND2).

652 Fig. 2 Photos of the studied structures (left) from Agios Georgios and maps of the in-situ measured  
653 bulk magnetic susceptibility variations (right) from a, b) PSY1; c, d) PSY2 and e, f) PSY4.

654 Fig. 3 a) Representative Isothermal Remanent Magnetization (IRM) acquisition curves; b) back-  
655 field IRM curves; c) hysteresis loops after correction for the para/diamagnetic contribution; d)  
656 hysteresis ratios displayed on a Day plot (Dunlop, 2002).

657 Fig. 4 Magnetic moment vs temperature curves obtained for samples from a) PLND1; b) PLND2; c)  
658 PSY1; d) PSY2; e) PSY6; f) MKA

659 Fig. 5 Stepwise alternative field demagnetization results plotted in orthogonal vector projections  
660 (Zijderveld diagrams).

661 Fig. 6 Mean archaeomagnetic directions (red star) calculated for each structure, plotted in equal area  
662 projections together with the alpha-95 angle of confidence (pink ellipsoid).

663 Fig. 7 Comparison of the new directional results for Cyprus with literature data from nearby  
664 countries available for the last four millennia. All data are relocated at the geographic coordinates of  
665 Lefkosia (35.17 °N, 33.36 °E).

666 Fig. 8 New paleosecular variation curves for a) declination and b) inclination for the Eastern  
667 Mediterranean (dark red curves with error bands at 1 sigma of probability). Black and grey dots  
668 represent the archaeomagnetic and historical data, respectively. Different color curves show the  
669 global model predictions (see legend).

670 Fig. 9 a) Bauer diagram of the new paleosecular variation curve divided in four periods between  
671 2000 BCE and 1900 CE. Declinations correspond to the meridian lines (from 30° W to 30° E

672 equally spaced every 5°), while inclinations are represented by the parallel curves (from 40° to 70°  
673 equally spaced every 5°). Tie points every 200 years are indicated in the different panels, with  
674 alternating red and yellow colors every century. b) Curvature of the paleosecular variation curve  
675 assuming the projection of the directional paleomagnetic elements in a horizontal plane at the  
676 Earth's surface.

677

678 **Table caption**

679 Table 1. Summary of the archaeomagnetic directions obtained from the studied structures.

680 Columns: Archaeological site; structure studied; Lat. ( $^{\circ}$ ); Long. ( $^{\circ}$ ); N= number of independently  
681 oriented samples considered for the calculation of the mean direction; D= mean declination ( $^{\circ}$ ); I=  
682 mean inclination ( $^{\circ}$ );  $\alpha_{95}$ = 95% semi-angle of confidence; k= precision parameter (Fisher, 1953);  
683 archaeological age.

684

685 **Supplementary material**

686 Table S.1. Summary of the anisotropy of the magnetic susceptibility results.

687 Columns: Archaeological site; N= number of samples studied; L= magnetic lineation; F= magnetic  
688 foliation; P= degree of anisotropy; T= shape parameter.

689

690 Table S.2. Palaeosecular Variation Curve for for Eastern Mediterranean and Middle East for the last  
691 4 millennia.

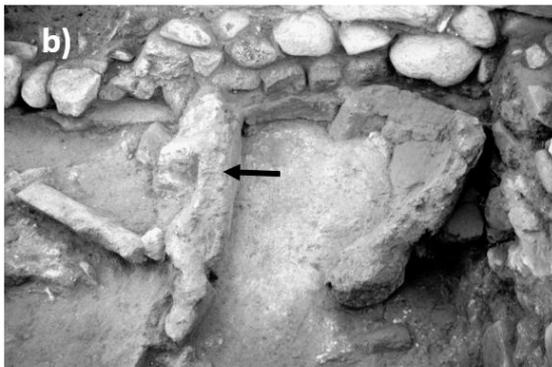
692 Columns: Date (from 2000 BC to 1900 AD with step of 50 yr.); Declination value ( $^{\circ}$ ) and its  
693 uncertainty ( $^{\circ}$ ) at 1-sigma of probability; Inclination value ( $^{\circ}$ ) and its uncertainty ( $^{\circ}$ ) at 1-sigma of  
694 probability.

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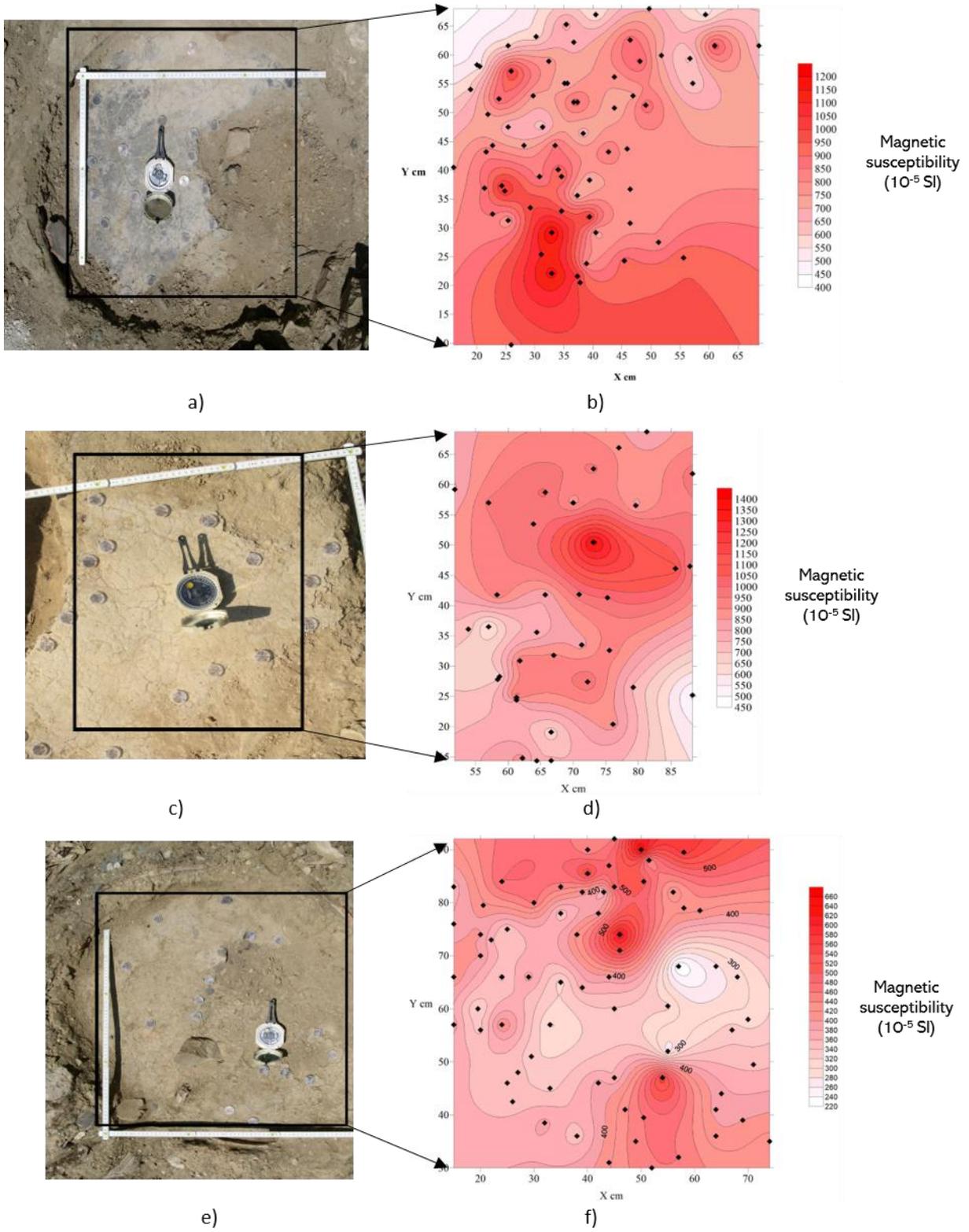
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Fig. 1

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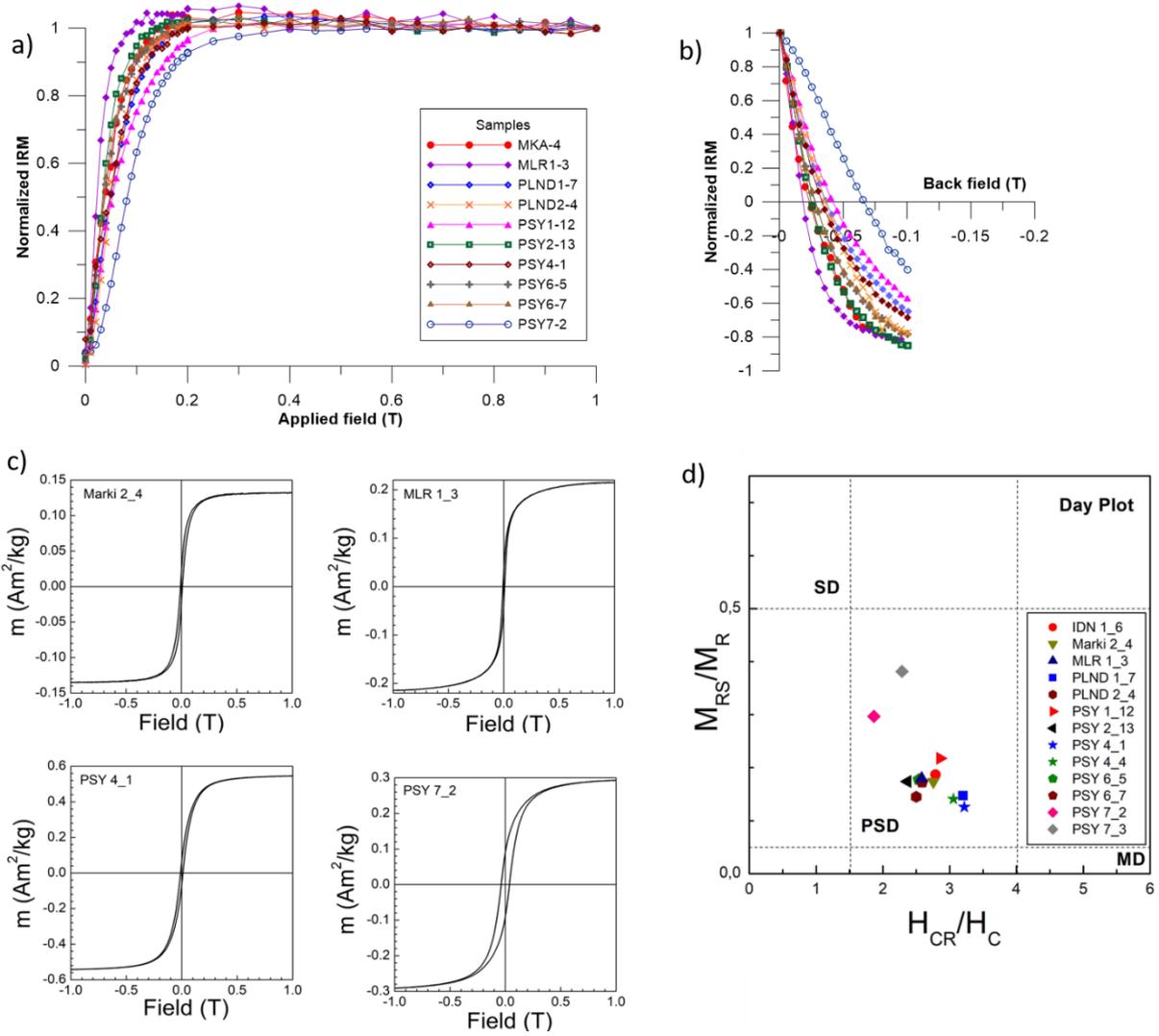
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Fig. 2

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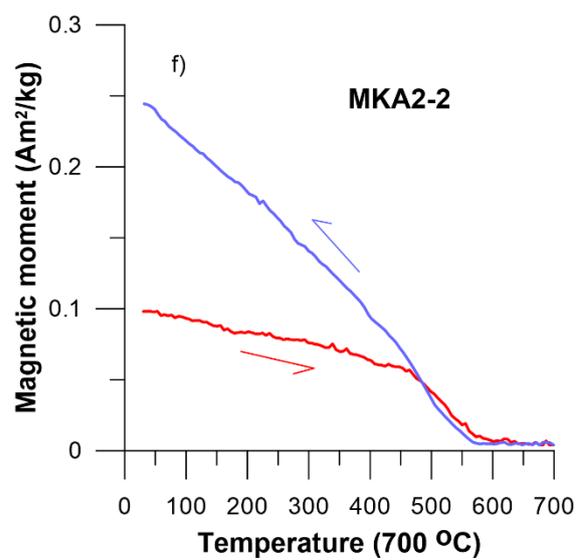
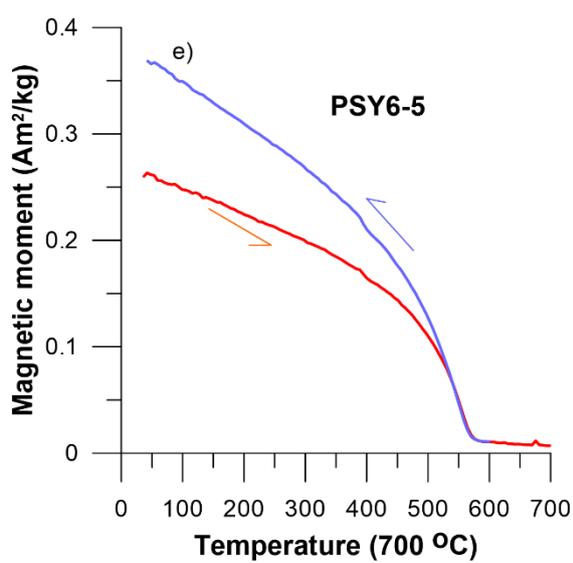
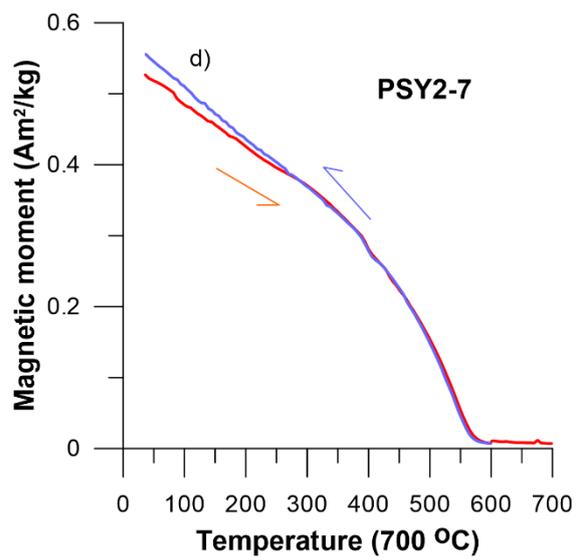
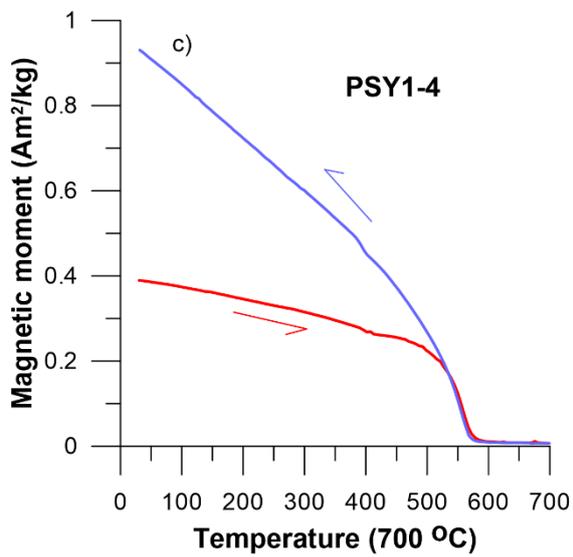
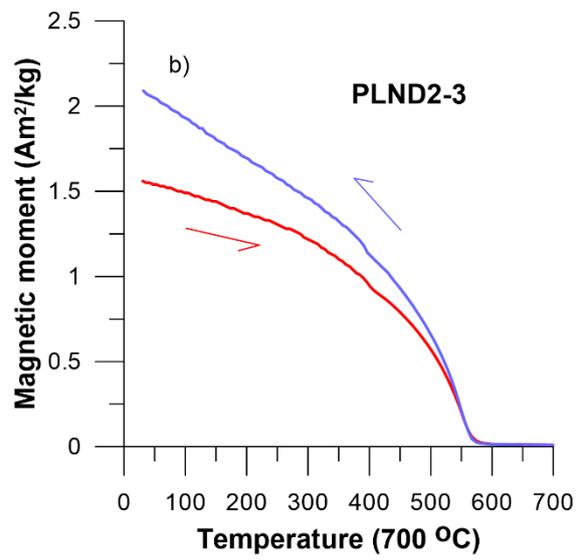
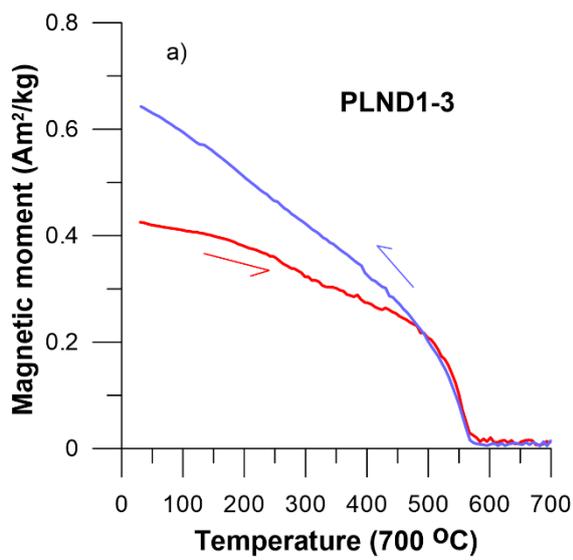
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Fig. 3



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Fig. 4

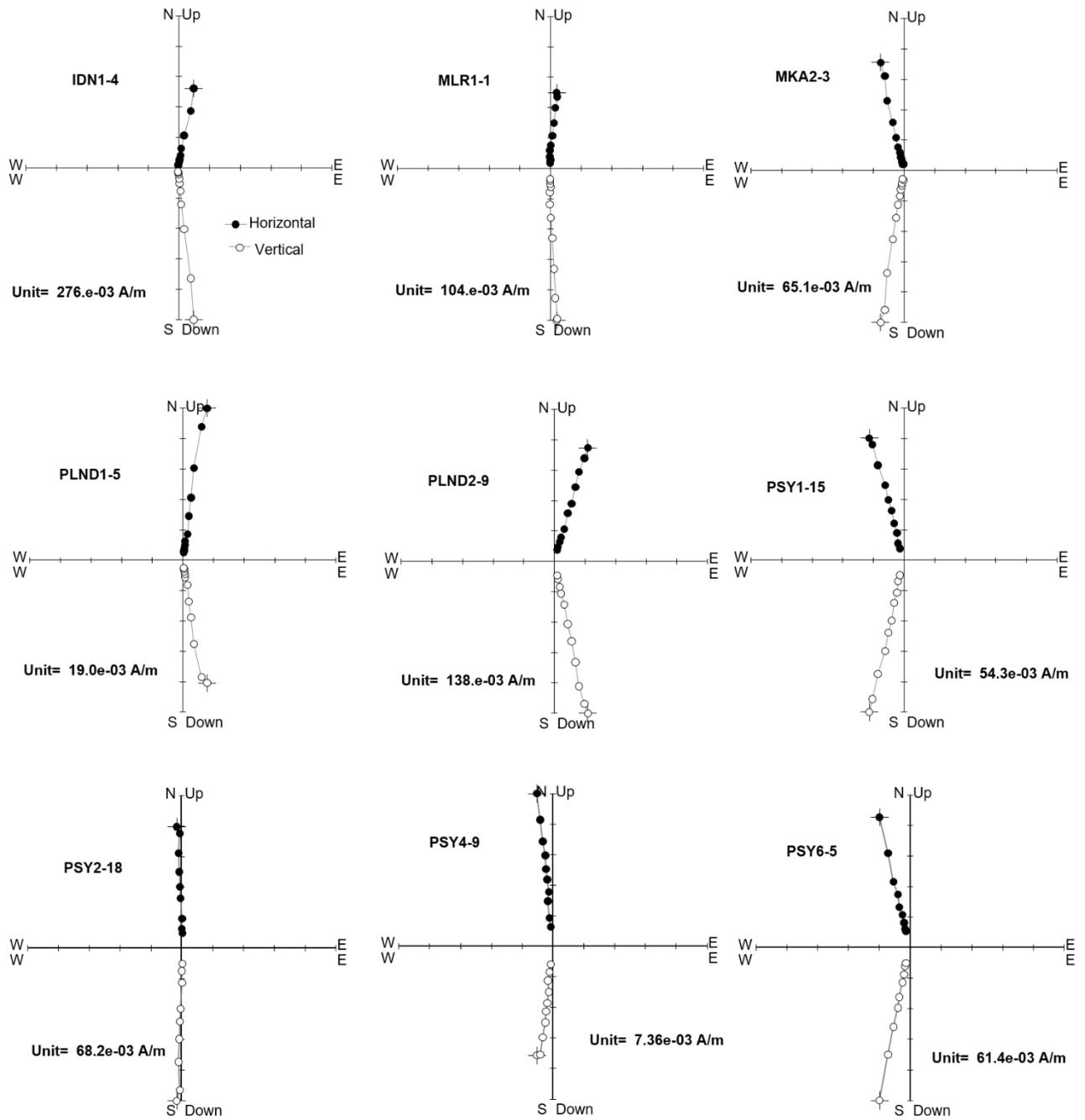


Fig. 5

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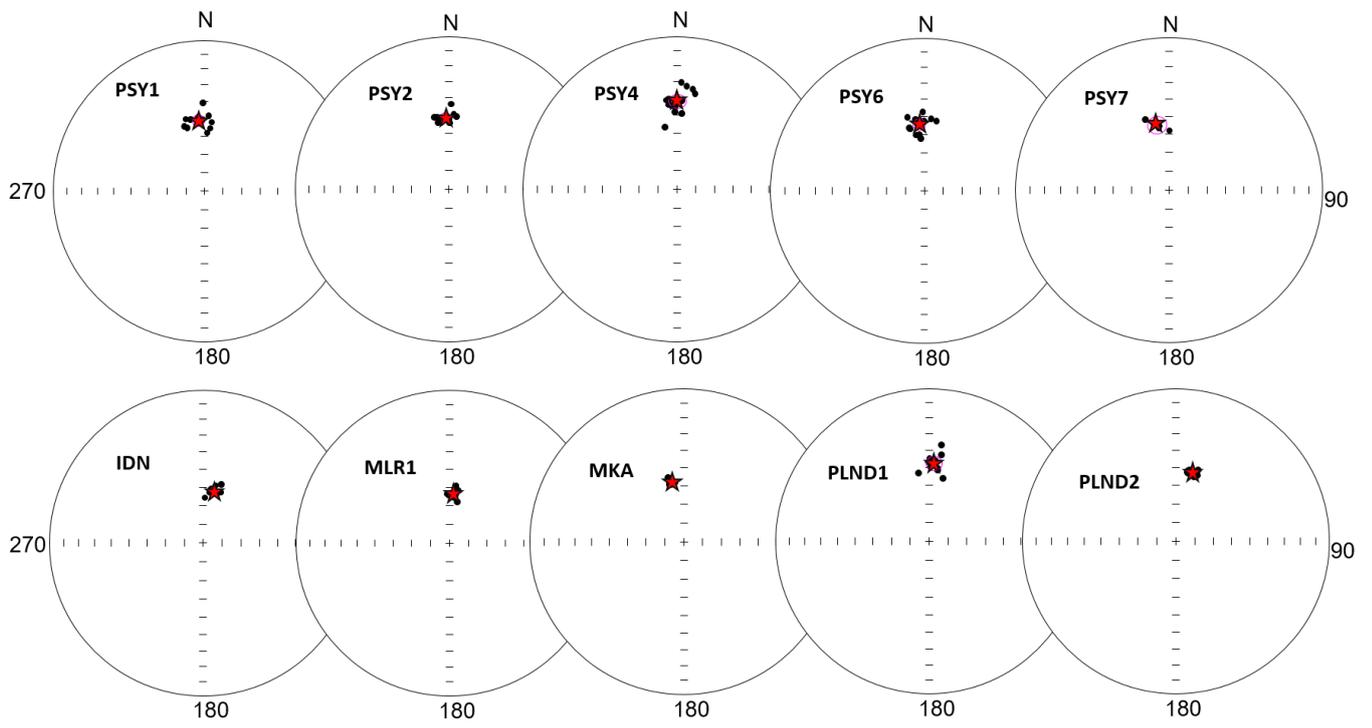
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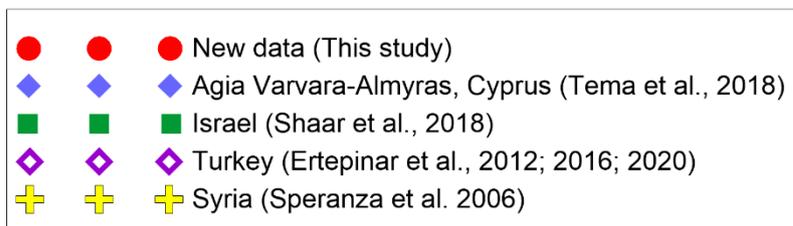
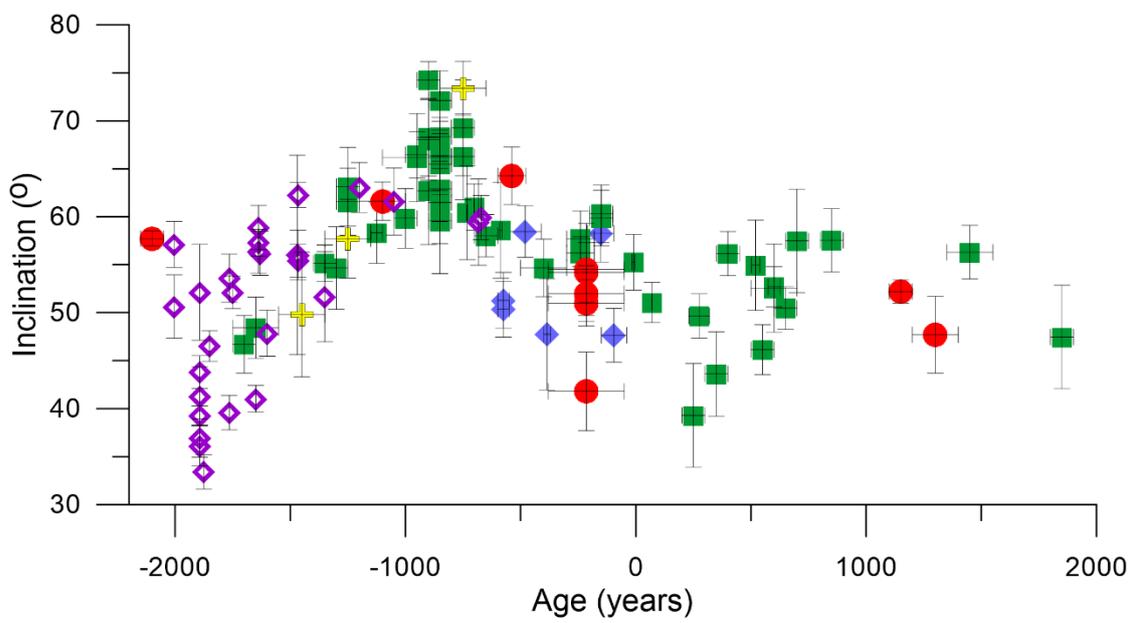
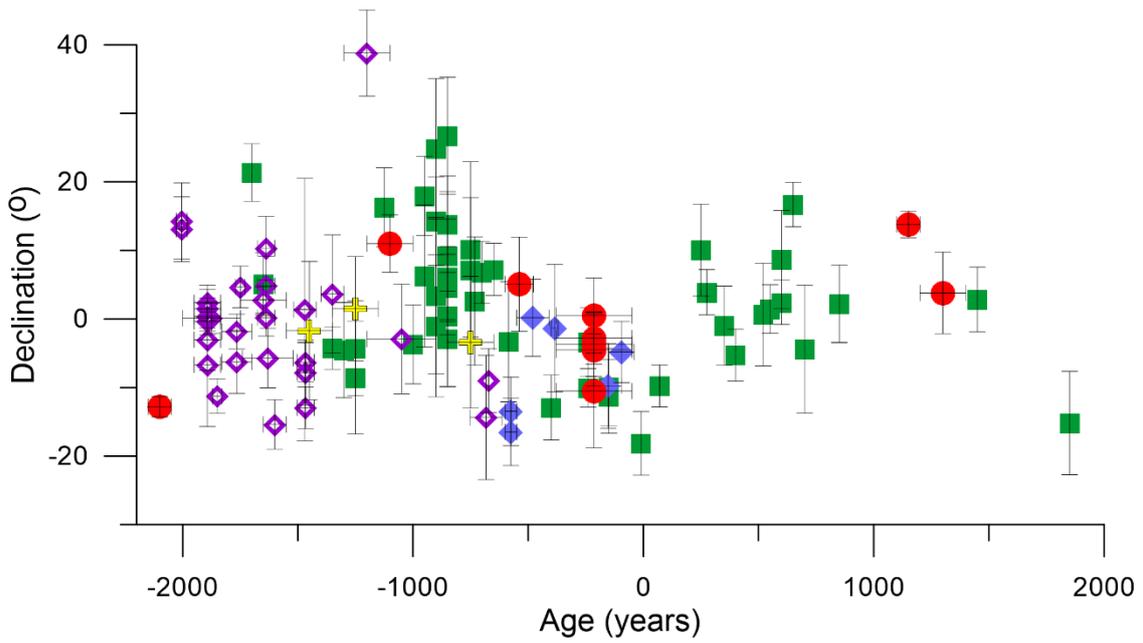
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Fig. 6

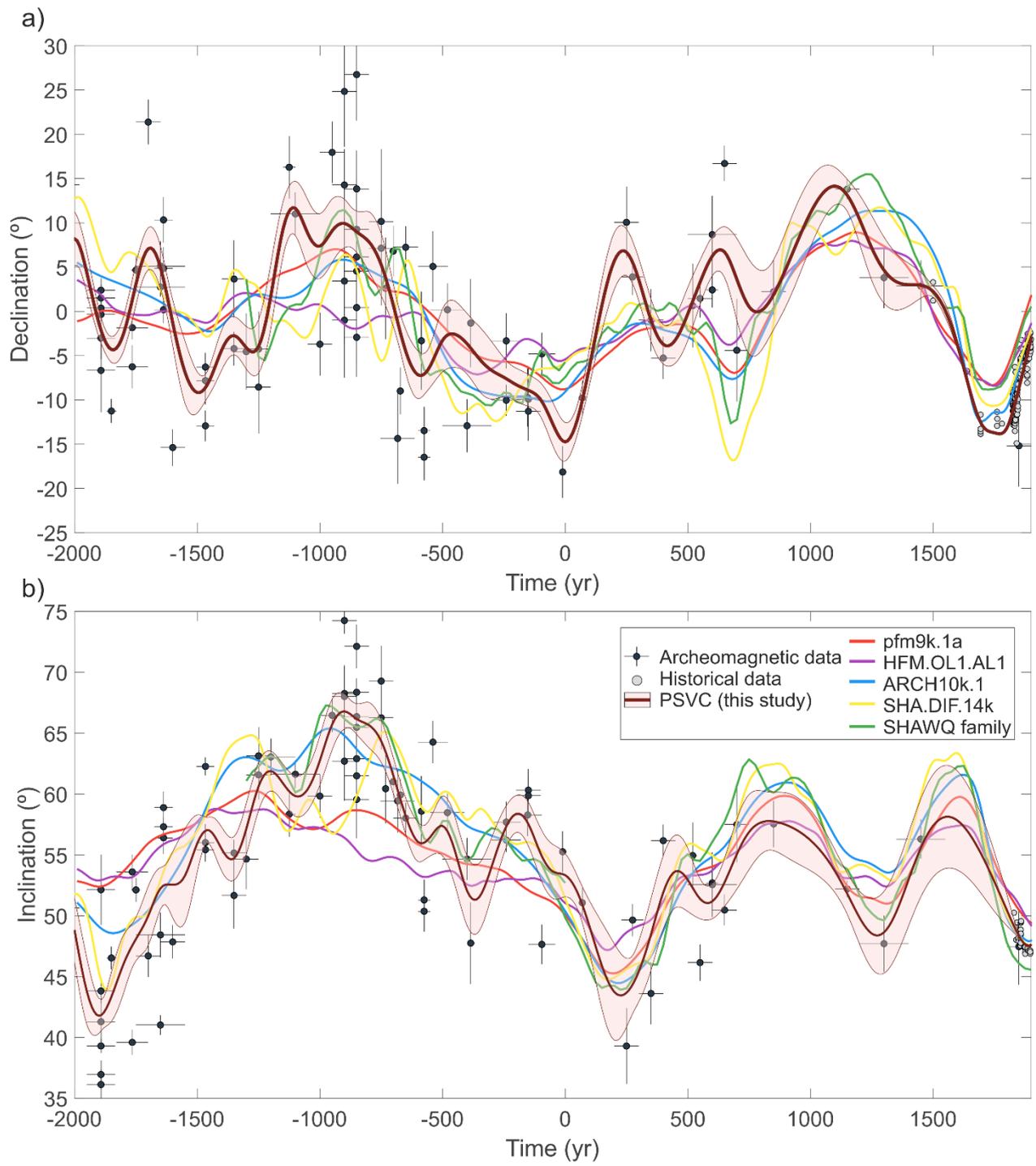


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Fig. 7



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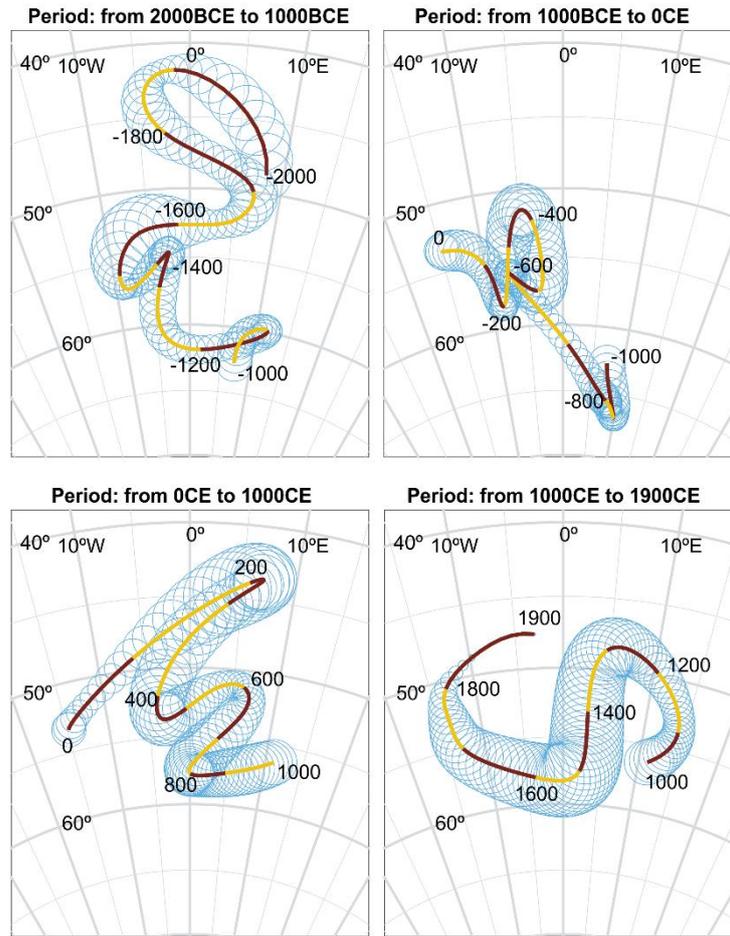
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Fig. 8

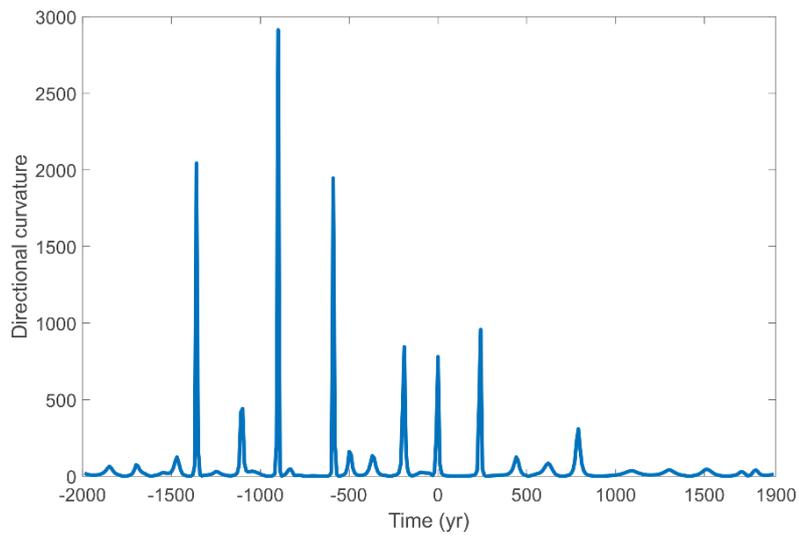
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a) Bauer diagram



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b) Curvature



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Fig. 9



Archaeological Site	Structure	Lat.	Long.	N	D (°)	I (°)	$\alpha_{95}$	k	Archaeological Age
Marki	MKA (3346)	35.02° N	33.33° E	10	347.3	57.6	0.8	3669	2150-2050 BCE
Idalion	IDN	35.02° N	33.42° E	10	11.0	61.5	2.0	597	1200-1000 BCE
Athienou-Malloura	MLR2 (EU94)	35.08° N	33.58° E	7	5.0	64.2	3.0	401	600-480 BCE
Agios Georgios	PSY1 (13)	35.17° N	33.35° E	14	356.3	52.0	2.9	184	380-50 BCE
Agios Georgios	PSY2 (15a)	35.17° N	33.35° E	12	357.2	51.0	2.4	332	380-50 BCE
Agios Georgios	PSY4 (21)	35.17° N	33.35° E	14	0.5	41.8	4.1	97	380-50 BCE
Agios Georgios	PSY6 (55)	35.17° N	33.35° E	13	355.5	54.2	3.1	181	380-50 BCE
Agios Georgios	PSY7 (61a)	35.17° N	33.35° E	5	349.5	54.5	4.8	253	380-50 BCE
Palaion Demarcheion	PLND1	35.17° N	33.37° E	10	3.8	47.7	4.0	146	1200-1400 CE
Palaion Demarcheion	PLND2	35.17° N	33.37° E	13	13.8	52.2	1.2	1196	1100-1200 CE

Table 1

**Supplementary material for online publication only**

[Click here to download Supplementary material for online publication only: Table S.1.docx](#)

**Supplementary material for online publication only**

[Click here to download Supplementary material for online publication only: Table S.2.docx](#)

**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.