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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 insights on the directional occurrence of the Levantine Iron Age Anomaly (LIAA) through the analysis of new and previously published directional archaeomagnetic data from Cyprus and nearby countries. The new directions, obtained from *in situ* baked clay structures such as small hearths and ovens from five Cypriot archaeological sites, dated from 2000 BCE to 1400 CE, are very well defined and are added to the scant reference dataset for Cyprus. The new records together with literature data from nearby countries are used to investigate the directional variations of the geomagnetic field in the Eastern Mediterranean and Middle East. The first directional palaeosecular variation curve for Middle East is calculated using a critical selection of reference data from Cyprus, Israel, Turkey and Syria. The curve covers the last four millennia and shows several periods characterized by abrupt directional changes. A maximum change in curvature is clearly observed around 900 BCE, characterized by a change rate as high as 13.2° per century. The new curve confirms that during the Levantine Iron Age Anomaly notable for extreme intensity values, the geomagnetic field was characterized by steep inclinations and important directional change too. The maximum curvature is shifted by around one century from the two distinct intensity spikes previously observed in Levant around the 10th and 8th centuries BCE. Other periods of important curvature change are also identified and deserve further investigation.

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1. Introduction

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

In the last decades, attention has been focused on the study of particular features of the Earth's magnetic field SV characterized by intense and short-lived changes that occur at decadal and centennial time scales. Based on archaeomagnetic data obtained from well dated archaeological artifacts in France, several periods of rapid geomagnetic field change have been identified, characterized by sharp changes in the direction, which coincide with intensity maxima, named *archaeomagnetic jerks* (e.g. Gallet et al., 2003). In several other studies, particularly high field intensity values associated with rapid SV rates have been observed (e.g. Ben-Yosef et al., 2009; Gómez-Paccard et al., 2016; Hervé et al., 2017; Osete et al., 2020). Such high intensities are a surprising and particularly interesting feature of the past SV, also known as *geomagnetic intensity spikes*. High intensity spikes have been identified in several geographical areas and during different chronological periods but undoubtedly the most documented so far is that one observed around 1000 BCE in the Levant, the area of the Eastern Mediterranean around Syria, Lebanon, Jordan, Israel, and southern Turkey, and known as the Levantine Iron Age Anomaly, LIAA (see Shaar et al., 2016 and references therein).

The Levantine Anomaly was reported by Ben-Yosef et al. (2009) and Shaar et al. (2011) who observed high intensities in the Middle East around 1000 BCE. Further data from Turkey (Ertepinar et al., 2012) also showed unusually high archaeointensity values. Shaar et al. (2016) carefully revised data from Israel suggesting the presence of extreme regional intensities with two spikes (around the 10th and 8th centuries BCE). More recently, Shaar et al. (2018) presented a large compilation of archaeomagnetic directions from Israel that cover the last four millennia, showing that the Levantine intensity anomaly is also accompanied by significant directional changes. Indeed, the directions from Israel show high inclination and high declination values during the 9th century BCE, providing more evidence for a regional field anomaly in the Middle East during the beginning of the first millennium BCE.

Even though abrupt variations in the direction and/or the intensity of the Earth's magnetic field are a particularly interesting feature of the geomagnetic field, their origin, geographical occurrence and explanation through core-flow dynamics are still under investigation (e.g. Livermore et al., 2014; Davies and Constable, 2017; Korte and Constable, 2018). The global palaeomagnetic reconstructions could contribute to this debate but for the moment they cannot clearly reproduce such rapid variations as long as not enough, homogeneously globally distributed and precisely dated data are available (Korte and Constable, 2018). In fact, even though Israeli data are very interesting, more data from the broader area with precise dating are necessary to confirm the Levantine full geomagnetic field SV path. In this perspective, the contribution of new, high quality archaeomagnetic data from the Eastern Mediterranean and Middle East are needed to explore the geographical and temporal distribution of such geomagnetic field anomalies. Even though great effort has been focused on the acquisition of new intensity records from these areas (e.g. Ben-Yosef et al., 2011; Shaar et al., 2015; Gallet et al., 2015), the directional data obtained from the study of *in situ* baked clay structures are still very few (e.g. Speranza et al., 2006; Tema et al., 2018; Ertepinar et al., 2020). For this purpose, we present here new directional archaeomagnetic data from Cyprus, in order to enrich the reference directional dataset in the Eastern Mediterranean and contribute to the investigation of the directional occurrence of the Middle East anomaly in areas near to Israel, such as Cyprus.

2. Archaeological sites and sampling

Archaeomagnetic samples were collected from 13 *in situ* baked clay structures, coming from 5 different archaeological sites in Cyprus: Marki-Alonia (MKA), Idalion (IDN), Athienou-Malloura (MLR), Palaion Demarcheion (PLND, Nicosia) and Agios Georgios (PSY, Nicosia) (Fig. 1). All sites are reliably dated based on archaeological evidence, stratigraphic analysis and radiocarbon dating. Detailed description of the archaeological sites and sampled materials is provided in Supplementary material.

Archaeomagnetic sampling was carried out during several field campaigns made between 1999 and 2006. In the case of the Agios Georgios site, a Bartington MS2 portable magnetic susceptibilitymeter with an F-type probe was first used to map the variation of the magnetic susceptibility on the surface of three hearths in order to better identify the parts that were heated at higher temperatures and thus more suitable for archaeomagnetic sampling. The detailed results of the *in situ* magnetic susceptibility survey are provided in the Supplementary material. Generally, the upper parts of the structures' floors and the lower parts of the walls seemed to be better baked and were thus preferred. Oriented samples suitable for a directional investigation were collected by gluing 22 mm diameter plastic disks on the baked clay's upper surface. The orientation of the horizontal line drawn on each disc was measured using a Brunton compass while the dip of the disc's surface was measured with an Anglestar electronic clinometer. A sun compass was also used, in order to correct the azimuth of the samples for any local magnetic disturbance. Between 7 and 19 independently oriented discs with attached material were collected from each structure.

3. Methods

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, Qn, ($0.6 < Qn < 1.8$) as well as very dispersed NRM directions, suggesting insufficient heating to acquire a stable and representative record of the ancient geomagnetic field. These three structures were therefore excluded from any further analyses. The samples were stored for years at the Geneva University laboratory and they were only recently systematically studied in 2019, after storing for at least one month in a zero-field shielded room. All samples were 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 on small fragments (mass < 100 mg) 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.

4. Results

4.1. Magnetic mineralogy

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. 2a), suggesting the presence of a low-coercivity mineral. The back-field curves also indicate the presence of a soft magnetic mineral with remanence coercivity being in all cases less than 50 mT, except for sample PSY7-2 coming from the more vitrified structure 61, that is characterized by a higher coercivity (Fig. 2b). Hysteresis loops (corrected for the para/diamagnetic contributions) further confirm these results (Fig. 2c). They indicate the presence of soft magnetic minerals, such as magnetite and Ti-magnetite, as the main carriers of the magnetic moment. This is assumed from the tight shape of the hysteresis loops accompanied by low coercive fields: H_C values are in the range 5-15 mT except from sample PSY 7-2 that has higher H_c of around 35 mT, as already indicated by the IRM back field curve.

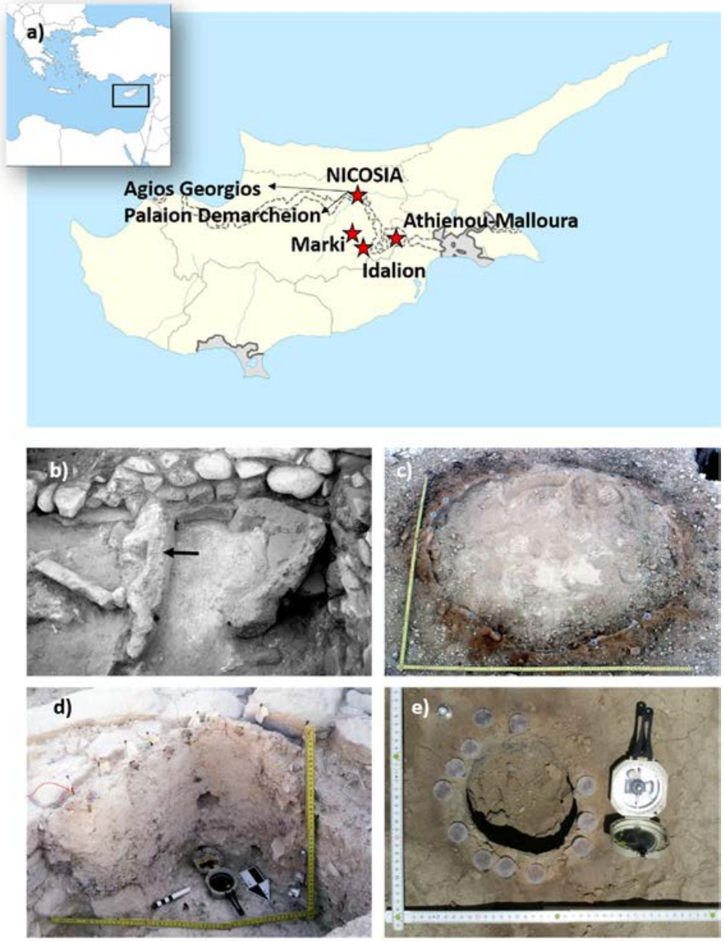


Fig. 1. *a) Location of the newly studied archaeological sites and photos of the structures from b) Marki; c) Idalion; d) Malloura (MLR); e) Palaion Demarcheion (PLND2).*

The magnetic parameters provided by the hysteresis loops of representative samples (i.e. coercive field H_C , magnetic remanence M_{RS}, and magnetic saturation M_S) together with the remanence coercivity values, H_{CR}, provided by the back-field curves, were plotted on a Day Plot (Fig. 2d). All samples show magnetic granulometry that lies in the pseudo single domain (PSD) part of the Day plot (Dunlop, 2002). Thermomagnetic curves of the magnetic moment versus temperature up to 600° C or 700° C show Curie temperatures of around 580° C, indicating the presence of magnetite as the main magnetic mineral (Fig. 3). In most cases they are not reversible, with cooling curves being always higher, probably due to the formation of new minerals during heating. Such curves also suggest that the heating temperatures experienced by the baked structures during their use were probably lower than 600-700° C.

4.2. Archaeomagnetic direction

To investigate any possible deviation of the ChRM direction due to the anisotropy of the samples, the anisotropy of the magnetic susceptibility (AMS) on 44 samples from Idalion (IDN), Athienou- Malloura (MLR1 and MLR2) and Marki-Alonia (MKA) was measured before applying demagnetization procedures. The mean anisotropy parameters (L: magnetic lineation; F: magnetic foliation; P: degree of anisotropy; T: shape factor) obtained according to Jelinek (1981) using the Anisoft software are given in Table S.1 (Supplementary material). The AMS degree (P_{AMS}) is in all cases very low, varying from P_{AMS} = 1.001 for Idalion to P_{AMS} = 1.018 for Marki. These results confirm that the anisotropy of baked clays coming from un-modeled structures like small hearths and ovens is very low and should not significantly influence the magnetic direction recorded by the clays during their last firing (e.g. Kovacheva et al., 2009; Tema et al., 2016).

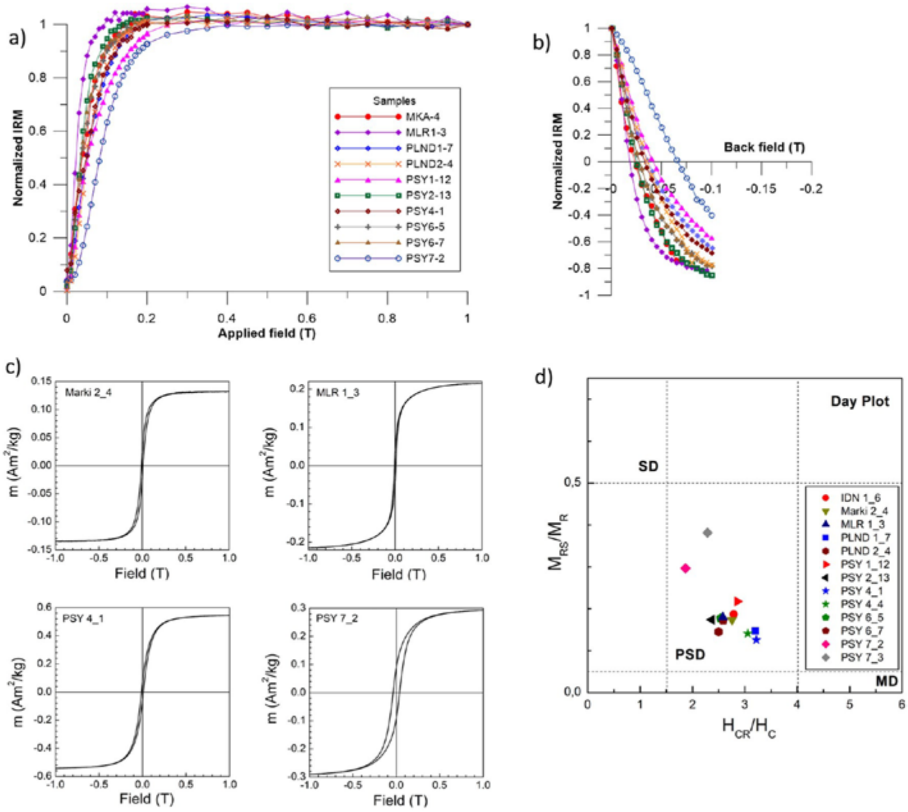


Fig. 2. *a) Representative Isothermal Remanent Magnetization (IRM) acquisition curves; b) back-field IRM curves; c) hysteresis loops after correction for the para/diamagnetic contribution; d) hysteresis ratios displayed on a Day plot (Dunlop, 2002). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)*

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

5. Discussion

5.1. New directional data from Cyprus

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

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

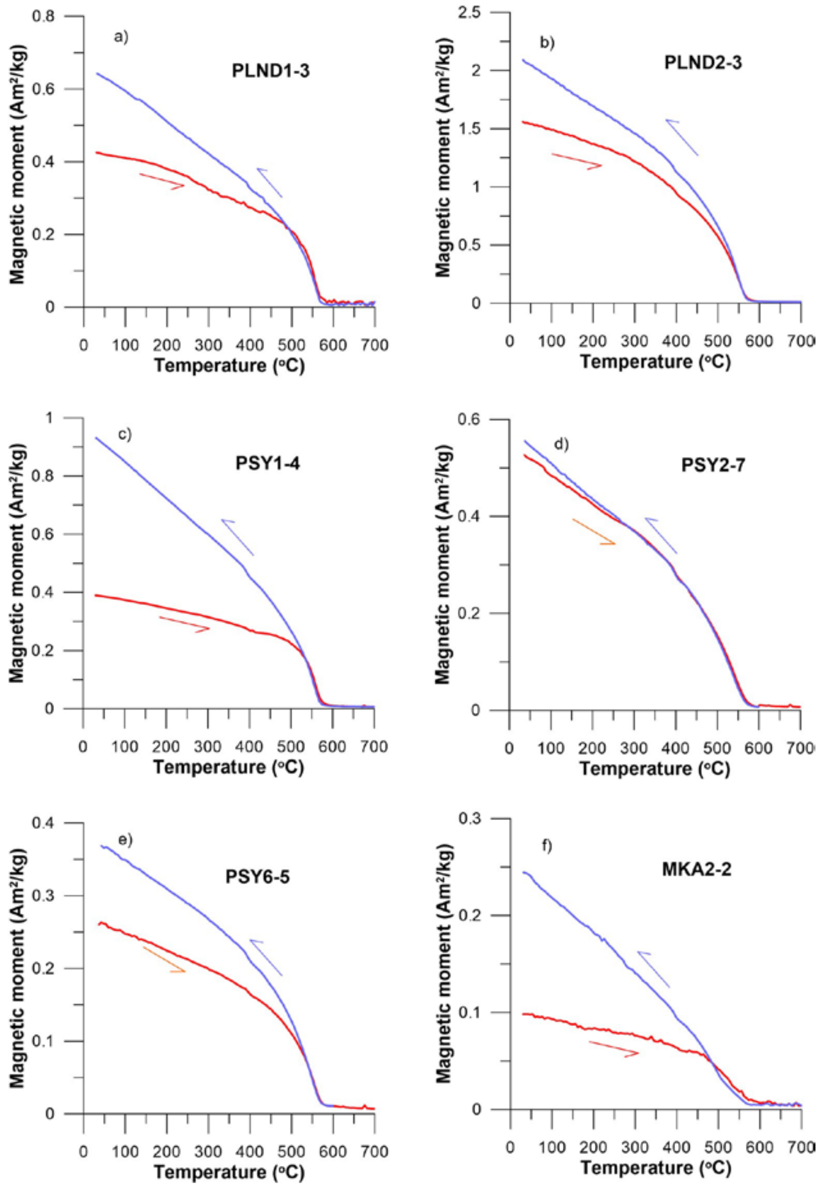


__Fig. 3.__ Magnetic moment vs temperature curves obtained for samples from a) PLND1; b) PLND2; c) PSY1; d) PSY2; e) PSY6; f) MKA2.

In order to compare our data with the directional data from the literature, we have relocated them to the geographical coordinates of Nicosia (35.17° N, 33.36° E) using the virtual geomagnetic pole method (Noel and Batt, 1990). Relocating the directional data to a common point, inevitably introduces an error. Nevertheless, this is a common practice when dealing with local and regional data, contrary to the global modelling techniques where no relocation is needed (e.g. Lodge and Holme, 2009; Pavón-Carrasco et al., 2014). In our case, dealing with data coming from a small area, the introduced error can be considered negligible (Casas and Incoronato, 2007). The new data from the Agios Georgios 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. 6). The data from Idalion and from Athienou-Malloura are also in agreement with data from Israel and they support the presence of a short lived Levantine anomaly, showing increasing declination and inclination values before the peak values observed in Israel around 1000-900 BCE, and a clear decreasing trend after that period.

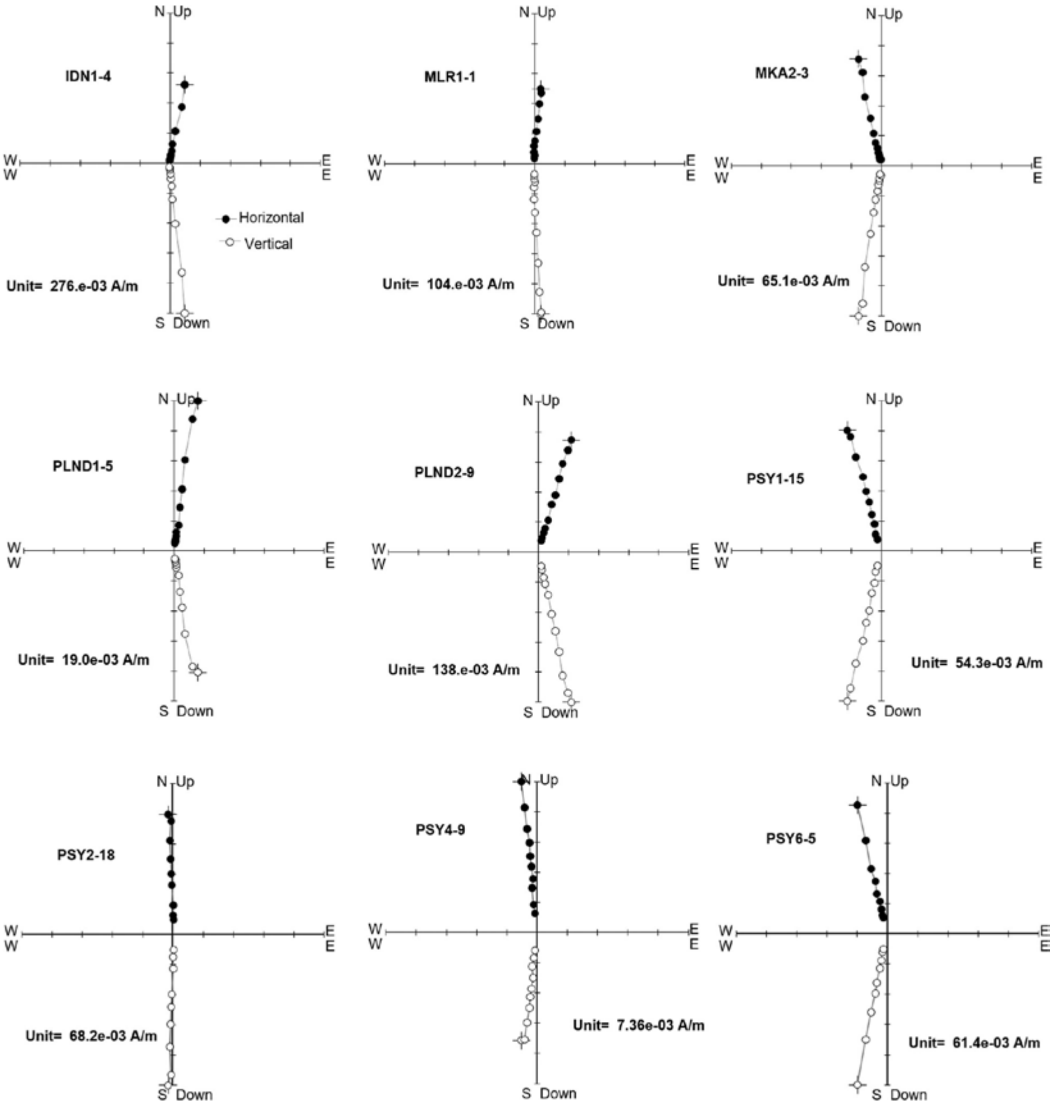


Fig. 4. *Stepwise alternating field demagnetization results plotted in orthogonal vector projections (Zijderveld diagrams).*

Table 1

Summary of the archaeomagnetic directions obtained from the studied structures. Columns: Archaeological site; structure studied; Lat. (°); Long. (°); N = number of independently oriented samples considered for the calculation of the mean direction; D = mean declination (°); I = mean inclination (°); α_{95} = 95% semi-angle of confidence; k = precision parameter (Fisher, 1953); archaeological age.

Archaeological site	Structure	Lat.	Long.	N	D (°)	I (°)	α_{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

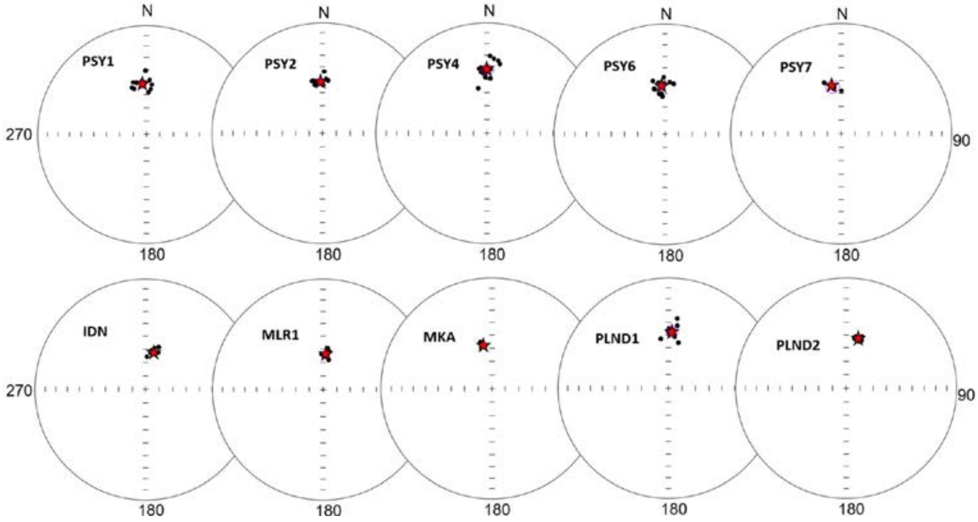


Fig. 5. *Mean archaeomagnetic directions (red star) calculated for each structure, plotted in equal area projections together with the alpha-95 angle of confidence (pink ellipsoid).*

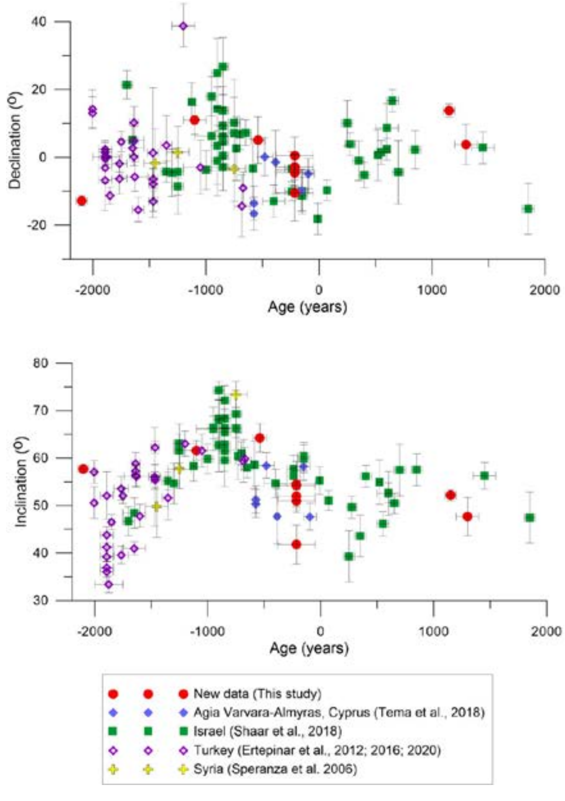


Fig. 6. *Comparison of the new directional results for Cyprus with literature data from nearby countries available for the last four millennia. All data are relocated at the geographic coordinates of Nicosia (35.17° N, 33.36° E).*

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 10-14th 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. 6). The new data offer an important contribution on the reference data for the area, clearly enriching and complementing the existing data and providing the first data for the first half of the first millennium CE.

5.2. *Directional Secular Variation path in the 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 the 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 ensure the use of the most reliable reference data and to eliminate eventual outliers, a selection of the best data is commonly used. However, it is not always a simple task to decide which are the best criteria to apply and in some cases applying no selection criteria could also be a solution. In this study, we adopted data selection criteria similar to those applied by Shaar et al. (2018), to guarantee internal consistency to the reference dataset. We therefore rejected all data that are based on less than 6 directional values (either specimens or samples as unfortunately in most of the original publications it is hard to distinguish if the data presented correspond to independently oriented samples or not), have age error more than 100 years and α_{95} angle of confidence greater than 6°.

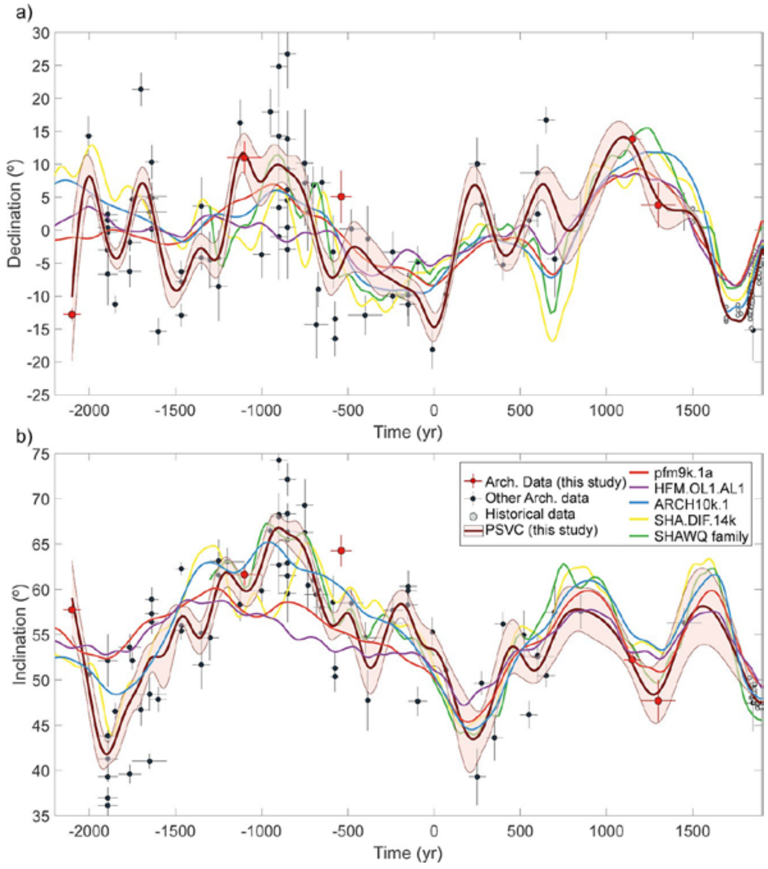


Fig. 7. *New palaeosecular variation curves for a) declination and b) inclination for the Eastern Mediterranean (dark red curves with error bands at 1 sigma of probability). Black and grey dots represent the archaeomagnetic and historical data, respectively. Different color curves show the global model predictions (see legend).*

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 Nicosia, were also used to better constrain the geomagnetic field path during the last few centuries. All data are relocated to Nicosia via the pole method.

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

The new curves for declination and inclination are plotted in Fig.7 along with the reference historical measurements and the selected reference archaeomagnetic data. They are the first directional curves available for Cyprus and they are valid for the investigation of the geomagnetic field's behavior in the area of the Eastern Mediterranean and Middle East. For the last two millennia, the new curves show high declination values around 200 CE, 600 CE and 1200 CE and clearly low inclination values around 200 CE and 1300 CE. However, for the last 2000 years the available high-quality data are quite scarce, and the low and high peaks seen in the curves are constrained by only few data. On the contrary, the curves during the first two millennia BCE are well detailed, and they clearly show high inclination values around 900 BCE, accompanied by eastern declinations of around 10°. Although single declination values are as high as 25° the curves do not show a clear declination peak due to the dispersion of the declination data for this period. Indeed, the available directional data for 900-800 BCE show differences of almost 30° that could be due to either very fast field variation or to possible dating errors. In fact, the precise dating of the data available in the archaeomagnetic database is always a critical point as it is often hard (or even impossible) to control. Another interesting aspect that is worth noticing, is a clear low inclination observed around 1800 BCE, accompanied by a slightly western declination of around −5°.

To further explore these aspects, we have compared our curves with the predictions of some of the most recent global palaeomagnetic field models (Fig. 7). Such palaeomagnetic reconstructions use all the available palaeomagnetic data spanning the last few millennia to provide a time-continuous picture of the past geo-magnetic field at any location over the Earth's surface. Some of them are based on a combination of archaeomagnetic, volcanic and sediment data, such as the pfm9k.1b (Nilsson et al., 2014) and the HFM.OL1.AL1 (Constable et al., 2016) models, while others have excluded sediment data due to their known smoothed and post depositional time-delay problems, using only archaeomagnetic and volcanic data (e.g. SHA.DIF.14k, Pavón-Carrasco et al., 2014; ARCH10k.1, Constable et al., 2016; and the SHAWQ-family, Campuzano et al., 2019 and Osete et al., 2020). All the cited global models cover the last four millennia, except from the SHAWQ- family that only spans the last three millennia. Comparison of our new curves with these models shows that during the last two millennia the inclination curve is in good agreement with the models' predictions while the declination peaks of around 200 CE and 600 CE are not seen in any of the models. For the BCE period, our new curves show a better agreement with the SHAWQ-family model, even if the agreement with the SHA.DIF.14k and ARCH10K.1 models can also be considered to be satisfactory.

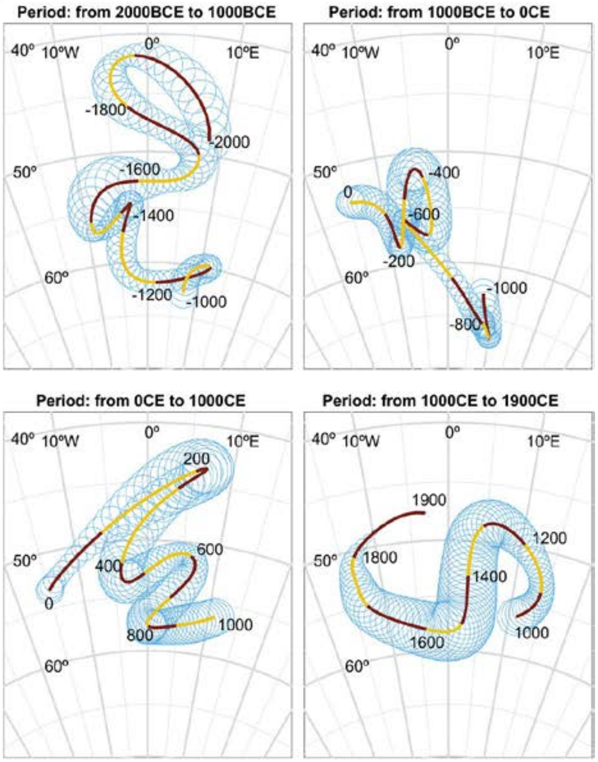
5.3. Directional occurrence of LIAA and abrupt directional changes

With a view to further analyze the directional changes of the palaeofield in Cyprus and also to investigate the directional occurrence of the LIAA, we have plotted the new curves in Bauer plots of declination and inclination for 4 different time periods (Fig. 8a). Furthermore, we have also calculated the curvature of the curve to detect periods with rapid directional changes (Fig. 8b). From 2000 BCE to 1000 BCE, the SV curve shows an east-west zigzag pattern in declination with a continuous increase of inclination. In this millennium, the most abrupt change occurs around 1400 BCE (Fig. 8), when the curvature parameter reaches its maximum value. For the first millennium BC (1000 BCE – 0 CE) the declination swings to the west with abrupt changes around 900 BCE, 600 BCE and 200 BCE (Fig. 8a, b). The first event at 900 BCE is characterized by the highest curvature parameter and the highest inclination values of the last 4 millennia. The first millennium CE (0 CE – 1000 CE) is also characterized by west-east zigzag declination values with increasing inclinations, with some peaks in the curvature parameter around 0 CE, 250 CE and 800 CE. Finally, the last millennium (1000 CE – 1900 CE) shows a westward drift in the declination values with inclinations ranging between 50° and 60° without important abrupt changes, as shown by the close-to-zero curvature parameter (Fig. 8).

The Bauer plots and the curvature calculation presented here successfully show several abrupt directional variations with the most prominent characteristic of the directional SV in Cyprus during the last four millennia being the maximum curvature change depicted around 900 BCE. Such important curvature change can be associated with the LIAA, confirming that apart from the extreme intensity values, the geomagnetic field at that time was simultaneously characterized by very steep inclinations and directional variation. Similar high declinations and inclination values around 900 BCE have been also observed in data from Bulgaria (Kovacheva et al., 2014), suggesting that it may be a more extended geomagnetic field feature, captured also in the Balkan peninsula (Tema and Kondopoulou, 2011).

To quantify the directional variation around 900 BCE, we used the new curves to estimate the temporal rates before and after the curvature maximum. Before 900 BCE the declination is characterized by a rate of $+3.2^{\circ}$ /century moving towards east, and an increase rate of +1.8° /century for the inclination. After the maximum curvature, the declination moves towards the west with a rate of −5.7° /century while the inclination decreases around −3.6° /century.

a) Bauer diagram



b) Curvature

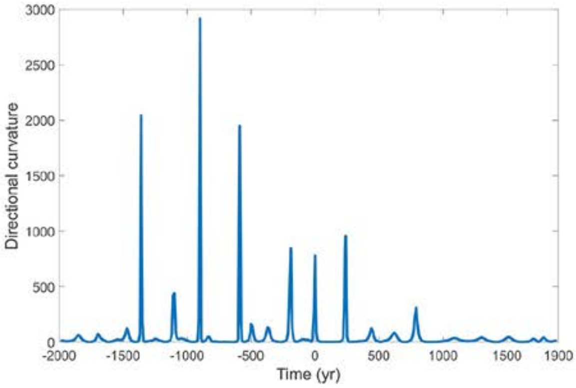


Fig. 8. a) Bauer diagram of the new palaeosecular variation curve divided in four periods between 2000 BCE and 1900 CE. Declinations correspond to the meridian lines (from 30° W to 30° E equally spaced every 5°), while inclinations are represented by the parallel curves (from 40° to 70° equally spaced every 5°). Tie points every 200 years are indicated in the different panels, with alternating red and yellow colors every century. b) Curvature of the palaeosecular variation curve assuming the projection of the directional palaeomagnetic elements in a horizontal plane at the Earth's surface.

If we calculate such rates using the reference data themselves, instead of the curves, the temporal rates obtained are even higher as the curves are inevitably affected by some smoothing. Indeed, in this case before 900 BCE the declination changes by +7.0° /century and the inclination increases by +5° /century, while after 900 BCE the declination moves from east to west at a rate of 13.2° /century and the inclination decreases by −7.4° /century.

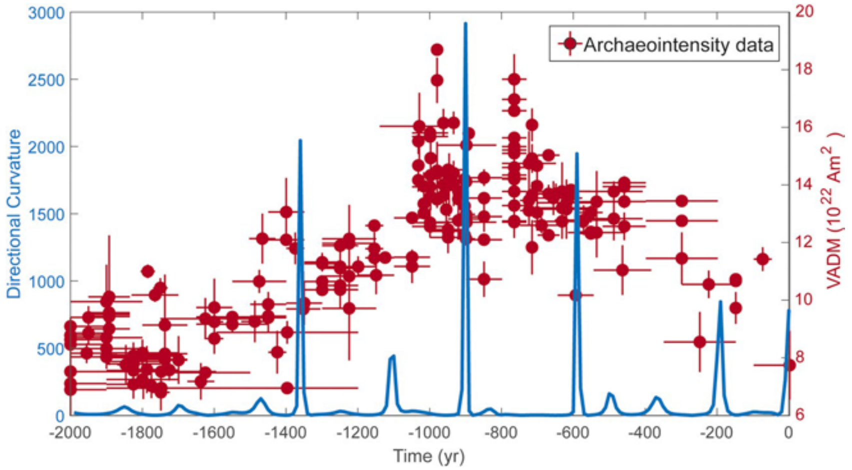


Fig. 9. *Comparison of the curvature changes of the directional curve with the Levantine intensity data (from Shaar et al., 2016) for the last two millennia BCE.*

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

Finally, to further explore the connection of the directional changes with the extreme intensity values previously observed in the Levant area, we have compared the curvature changes with the intensity dataset presented by Shaar et al. (2016) for the last two millennia BCE (Fig. 9). Such comparison shows that the most important directional curvature change clearly evidenced at 900 BCE is situated between the two intensity spikes reported around the 10th and 8th century BCE by Shaar et al. (2016). Actually, it is interesting to notice that the maximum curvature seen at the directional curve at 900 BCE seems to occur around a century later in respect to the high intensity values observed around 1000 BCE while the second intensity high detected at 800-700 BCE could be possibly related to the curvature change seen at 600 BCE, always with some delay. The curvature change accompanied by high intensity values seen in the Levant could be the result of a geomagnetic pole movement towards Eastern Europe, even though the high intensities could be also due to local non dipole sources. However, the new curve provides clear evidence that the geomagnetic field was characterized by anomalous behavior (with important directional and intensity changes) in the Eastern Mediterranean for at least a couple of centuries around 900 BCE. Definitely, it would be interesting to have more precisely dated intensity data for the 9th century BCE to further investigate if the field had constantly high intensity values during the directional curvature or if it was characterized by two clearly distinct spikes.

The curvature change observed around 1400 BCE seems to be accompanied by high intensity values too, even though with lower values in respect to those observed during the LIAA. The curvature peak of 600 BCE could be also related to the high intensity values observed in Western (Osete et al., 2020) and Eastern Europe (Kovacheva et al., 2014) while the curvature change at 200 CE seems to perfectly coincide with the sharp change in geomagnetic field direction and intensity observed in archaeomagnetic data from Western Europe and the Eastern Mediterranean by Gallet et al. (2003), although no high intensity records are seen in the Levant data (Fig. 9). Even if detecting rapid directional fluctuations from regional SV curves is often difficult, due to the uncertainties in the reference data and to the smoothing introduced during computational processes (Le Goff and Gallet, 2019), it would be interesting to further investigate these important directional and intensity changes with new data. Possibly with full-geomagnetic field records that include both directional and intensity determinations.

6. Conclusions

We present 10 new directional data from Cyprus from 5 archaeological sites whose ages range from 2000 BCE to 1400 CE. These new directions enrich the reference data for Cyprus and together with data from nearby Israel, Turkey and Syria are used to reconstruct the directional geomagnetic field path in the area of the Eastern Mediterranean during the last four millennia. The new data clearly complement the previously published data from the Eastern Mediterranean and they reinforce the trend of the SV path in the Middle East and the bordering area, confirming its regional extent. A time-continuous SV curve was computed and used to investigate the directional occurrence of the LIAA anomaly and abrupt directional changes. Our investigation shows a maximum curvature change peak at around 900 BCE, confirming that the LIAA was accompanied by an abrupt directional change. Such peak is located between the two distinct intensity spikes observed in the

Levant during the 10th and 8th centuries BCE. Other important directional changes are also observed in several other BCE periods that however do not always correspond to extreme intensity values. During the last two millennia CE, the most important directional change is observed around 200 CE. Further investigation of these changes in curvature is still needed to better understand their non-dipole origin and explore their connection with intensity maxima.

CRediT authorship contribution statement

Evdokia Tema: Conceptualization, methodology, laboratory analysis, investigation, data curation, writing-original draft, visualization, supervision. **Ian Hedley:** Methodology, field work, lab- oratory analysis, investigation, data curation, writing - review & editing. **Javier Pavón-Carrasco:** Methodology, formal analysis, data curation, writing - review & editing. **Enzo Ferrara:** Methodology, laboratory analysis, data curation, writing - review & editing. **Pamela Gaber:** Field work, resources, review & editing. **Despina Pilides:** Field work, resources, review & editing. **Michael Toumazou:** Field work, resources, review & editing. **Yiannis Violaris:** Field work, recourse, review & editing. **Jennifer Webb:** Field work, resources, review & editing. **David Frankel:** Field work, resources, review & editing.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2020.116731.

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