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

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Abstract

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

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

1. Introduction

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

The particularly solid Bulgarian database and deriving SVCs (Kovacheva et al., 2014; Kostadinova-Avramova et al., 2020, 2021) have partly accounted also for some Greek archaeomagnetic data, especially from N. Greece, allowing datings to be performed. Systematic archaeomagnetic investigations started in Greece, in the late nineties (see Tema & Kondopoulou, 2011 and De Marco et al., 2014 for a review) and are continuously increasing both in directional and intensity results (Kondopoulou et al., 2015, 2017; Aidona et al., 2018, 2021). Together with some results from Serbia and South Hungary, the Bulgarian and Greek data provide an almost continuous reconstruction of the full geomagnetic field vector variations in the Balkan area for the last 8000 years. However, the temporal distribution of the Balkan data is still uneven and several issues regarding the reliability of some of the published old Greek archaeointensity data have been outlined (De Marco et al., 2008; Tema & Kondopoulou, 2011; Tema et al., 2012; Genevey et al., 2018; Rivero-Montero et al., 2021). For instance, the scarcity of archaeomagnetic data from the 4th millennium BCE, is due to several occupation gaps attested in many sites of N. Greece, as well as in Bulgaria (Maniatis, 2014 and references therein; Tsirtsoni, 2016). Two other important features may be observed for the Prehistoric period in the Balkans: the uneven temporal distribution of the data during the entire Bronze age (3rd and 2nd millennia BCE) and the systematically lower Greek archaeointensities, in comparison with the Bulgarian ones, for the late 6th to the late 3rd millennium BCE (Tema & Kondopoulou, 2011), but also for later periods, e.g Early Byzantine (Genevey et al., 2018). The considerable amount of Bulgarian prehistoric data was obtained only from "*in situ*" structures, providing thus full-vector values, while Greek data for this period are obtained, to a big extent, from ceramics and pottery. Prehistoric collections are abundant in Greece, very often well studied as far as their clay characteristics are concerned and accurately dated (e.g., Reingruber & Thyssen, 2009; Papadatos & Nodarou, 2018; Hein & Kilikoglou, 2012; Wardle et al., 2014; Gimatzidis & Weininger 2020, among others). Nevertheless, their access remains often difficult due to the long periods between excavations and publications which hampers their potential availability.

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

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

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

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

2. Description of the archeological sites

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

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

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

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

Archontiko (ARCII, III)

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

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

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

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

Bouratza-Eretria (BOU)

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

One of the key excavations in the settlement took place in the Bouratzas plot between 1979-1981 where the pottery recovered was not well stratified and not in good condition due to post–deposition factors and the presence of a high-water table (Muller-Celka et al., 2018). This pottery is attributed mostly to the EH III (2200-2000 BCE) and, to a smaller extent, to the previous phase EH II (c.2500-2300 BCE).

All fragments selected for our study belong to the petrographic and chemical group FG8, that is the fine local pottery, according to Muller-Celka et al. (2018), which corresponds to the EH IIB slipped and burnished fine ware. The identification of all ware groups was accompanied by extensive investigations of local resources expanding to geological samples from other regions in Central Euboea as well. The predominant component of the locally available sediments are fine grained metamorphic rocks (Muller-Celka et al., 2018). This integrated study allowed us to select with certainty a group of certified local origin with fragments of various wares like handles, fragments of open or closed recipients, or jars and bowls of various colors ranging from brown-grey to red brown. Their fabrication was assigned to workshops in Central Euboea.

Cretan Phryktoriae (SX, SKA)

During an extended archaeological survey in Crete, conducted by archaeologist N. Panagiotakis, within the area of Pediada (plain), NE Crete, between 1982-1989, an old, unique system of communications with the use of fire was discerned. It was not rare for fire to be used to exchange messages between two distant areas, since it had already been used in the region where Syria stands today (Mari, beginning of the 2nd millennium BCE). This system was initiated in ancient Greece during the Minoan times, especially from 1900 to 1700 BCE (Protopalatial period). Pediada was a naturally wealthy area, feeding two of the most important Bronze Age Palatial domains, Knossos and Malia (Panagiotakis et al., 2013). This network persisted during the Neo-Palatial period (1700-1400 BCE) but progressively declined afterwards.

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

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

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

The exact dating of the "Soroi" is problematic due to their aleatory distribution and the lack of excavations. Nevertheless, the presence of pottery within the constructions and the topographical connections with the Old Palaces settlements (Protopalatial, 1900-1700 BCE) could suggest this period as their dating, at least for part of the sites. Given that these structures lasted until more recent times -see above- and in order to clarify this uncertainty, OSL experiments were performed on 5 samples in total (3 from SX and 2 from SKA). The obtained results indicate younger ages than the archaeological estimation, being 1521 ± 40 BCE for SKA and 1690 ± 77 BCE for SX. The description of the method and the detailed results are given in the supplementary material and Table 1s.

Kirrha ceramics(KIC)

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

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

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

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

3. 3. Experimental procedures

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

Kappabridge KLY3 (at Montpellier), coupled with a MS2WF furnace and the Agico CS3 furnace, respectively. The experiments were carried out in air at a heating rate of 1° C/min. Magnetic susceptibility changes were recorded continuously from room temperature up to 600° C (heating curve) and down to room temperature (cooling curve).

Hysteresis loops were recorded at room temperature with a P.A.R.155 Vibrating Sample Magnetometer (VSM) calibrated by means of a NIST certified Ni reference sample, in applied fields up to 2 T. We selected 11 representative samples from the six collections (two samples from ARC, SKA, SX, BOU and three from KIC). Each fragment was crushed gently in an agate mortar under the exact same procedure to produce similarly homogenized powders.

The classical Thellier – Thellier method (Thellier and Thellier, 1959) with pTRM checks and corrections for the TRM anisotropy and cooling rate was applied in the Geophysical Laboratory (AUTH, GR) for the determination of the archaeointensity in four collections (ceramics ARCII, III, baked clays SKA-SX). The remanent magnetization was measured with a Minispin spinner magnetometer (Molspin, Newcastle, UK) while the heating of the samples was performed in a thermal demagnetizer MMTD-80 (Magnetic Measurements, UK). The protocol used consists of double heating –cooling runs at each temperature step with a laboratory field (55 μT in the present study) applied in both directions of a specimen axis (+z, −z). The temperature was progressively increased from 100° C with a 50° C step up to 400° C followed by smaller steps of 40-30° C up to 570° C. Partial thermoremanent magnetization (pTRM) checks have been performed every two steps to detect possible magnetic mineral alteration in the samples during the experiment. The TRM anisotropy tensor was determined by measuring in 6 positions (+x, −x, +y, −y, +z and −z axes) followed by a stability check (Chauvin et al., 2000). The TRM anisotropy measurements were performed at different temperatures, when the NRM loss was around 70%. Finally, we applied the cooling rate correction following Gómez-Paccard et al., (2006) protocol, with a slow cooling over 24 h.

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

The data were processed with a linear regression analysis assuming a physical model compliant with the Fabian and Leonhardt's (2010) theoretical considerations that describe the relationship between the response variable and the explanatory variable. To this end, we anchored the fitting line to the point (0,-1). Prior the regression analysis, following the Fabian and Leonhardt's recommendations, we selected "a posteriori" the samples for which the ratio between the fraction of NRM overprinted by the laboratory pTRM and the total NRM is between 0.2 and 0.8. In addition, only samples for which the angle between the NRM and the NRM remaining after the laboratory pTRM overprint is lower than a threshold angle here arbitrarily chosen to be 15°, have been selected. Moreover, because the MSP protocols involve for practical reasons to process with a regression analysis on a small number of data, it is obvious that MSP results are especially vulnerable to influential outliers. Thus, when influential outliers are clearly identified, here by means of the Cook's distance, we chose to discard them from the analysis.

4. Results

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

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

The thermomagnetic analyses display partially reversible curves (Fig. 3a). In the case of ARC and SX samples the heating curves are higher than the cooling ones and the calculated Curie temperatures, using the second derivative method, range from 520-556^{o} C, indicating the presence of magnetite-like magnetic minerals. On the contrary, samples from BOU and KIC show a different behavior. Cooling curves are always higher than heating curves pointing to the creation of new magnetic phases during heating. The shape of the curves shows a continuous decay of the magnetic susceptibility zeroing at the range of 550-600^{o} C. However, due to this smooth decay the Curie points could not be derived.

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

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

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

For the SKAA and SKAC samples, a similar observation is evident in the loops although the coercive force H_c seems to have a small variability, indicating a multidomain character. Nucleation type procedures of magnetic domains in titanomagnetites grains or the presence of other phases like hematite may serve as possible explanation for the widening of the loop in intermediate fields.

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

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

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

During the Thellier-Thellier experiment (ARC, SKA, SX), forty-one specimens from twenty-one ceramic fragments were measured and 26 of them gave reliable results reaching ~61% mean success rate (Fig. 4a). Nine of the studied specimens failed during the experiment and the six were rejected during the analysis of the results as they did not meet the required criteria (Fig. 4b). The acceptance criteria used in the present study are as follows: The NRM fraction (f) should be more than 50% and the quality factor (q) more than 5 (Gómez-Paccard et al., 2006). Arai plots (NRM-TRM diagrams) must be linear and defined by at least 5 steps. Additionally, the maximum angular deviation (MAD) and the deviation angles (DANG) should be lower than 5° and 10° respectively. Finally, β, (the ratio of the error in the slope to the slope of the linear best fit line) should not exceed 0.1 (Shaar et al., 2016). The calculation of the above parameters was performed with ThellierTool (4.22) by Leonhardt et al., (2004). Our intensity results passing TTA and TTB criteria were classified as class A and B, respectively (Table 3s).

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

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

5. Discussion

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

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

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

Archontiko-ARC

The hysteresis loops display a pseudo-single domain behavior and indicate magnetite or titanomagnetite with low-Ti content. This converges with the thermomagnetic analysis where the Tc varies from 520-556ºC and the IRM one which features the dominance of low-coercivity minerals. Despite this promising pattern, the Thellier experiment was only 45% successful (10 successful specimens out of 22). In order to find a possible explanation, we used information published in our previous publication (Kondopoulou et al., 2017) on another group from the same settlement but of younger age, the final horizon I (1516-1414 BCE). In this study, a detailed XRPD analysis on 8 fragments suggested two groups of firing temperatures (550-600º C and 750-800º C). Layered magnetization measurements through hysteresis loops exhibit inhomogeneous compositional contents ref. to magnetic minerals. The success rate in the Thellier experiment was comparable to the present one. Despite the 300 years gap between this later material and the one studied here, there is evidence of continuity in clay selection for ceramics though the production of the EBA horizons seems to have taken place in open fires or pits (Deliopoulos et al., 2014). This is ascertained by the existence of color- layered surfaces related to inhomogeneous firing conditions, characteristic of open firing (Rice,1987).

Cretan Phryktoriae- SKA-SX

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

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

An additional input is found in a detailed study on the chemical and mineralogical properties of the Cretan Red Clays (Hein et al., 2004) which include the broader area of provenance for our samples (Thrapsano). The analyses on representative samples from this area gives a concentration of Fe_2O_3 at 8.43-8.60 wt% with a much lower TiO_2 of 1.09-1.14 wt%. Additionally, four samples from the same Phryktoriae formations (two from SKA and two from SX) were subjected to XRPD analyses in order to estimate their firing temperatures together with the magnetic minerals included.

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

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

Bouratza (BOU)

This collection has been thoroughly studied through a combination of petrographic and chemical analyses (WD-XRF) and the outcome for the group of origin of our samples (FG8) gives important information on their high content in Fe_2O_3 (7.87 wt%) and the low one in TiO_2 (0.88 wt%).

The above information can be compared with the ones from the hysteresis loops which suggest a high coercivity mineral, the thermomagnetic analyses with a possible Tc around 600^{o} C and the IRM curves which deviate from the saturation at about 1T, implying the co-presence of a high coercivity mineral.

Kirrha (KIC)

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

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

Our experiments provided interesting information on their composition referring to the magnetic minerals. The hysteresis loops displayed variable properties, with one fragment (KIC3-4) differing substantially from the other two which have a mixed pseudo- and multi-domain behavior. The IRM curves have a mixed pattern confirming the hysteresis, and the thermomagnetic curves, fully reversible, show a Tc around 550^{o} C.

The new archaeointensity results

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

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

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

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

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

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

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

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

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

6. Conclusions

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

The Thellier protocol has shown a high success rate for the baked clays in Crete, despite the frequent irreversibility of the thermomagnetic curves. We attribute this apparent controversy to the high content of magnetic minerals and the repeated heatings of the clays due to their use as firing places for several centuries. The obtained F values enrich the available reference curves for Greece and the Balkans and will contribute to improve the regional and global models. Nevertheless, we must precise that we did not observe the high values indicated by other studies in the broader area for the period around 2200 to 2000 BCE. We suggest that these could be found at an earlier period, around 2500-2400 BCE where one single result cannot attest them and should be confirmed by additional studies.

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