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DETAILED ARCHAEOMAGNETIC STUDY OF A CERAMIC WORKSHOP AT KATO ACHAIA: NEW DIRECTIONAL DATA AND ARCHAEOMAGNETIC DATING IN GREECE

Tema E.[1]

[1]*Dipartimento di Scienze della Terra, Università degli studi di Torino, via Valperga Caluso 35, 10123, Torino, Italy, evdokia.tema@unito.it*

Abstract

New archaeomagnetic results from two ancient kilns excavated at Kato Achaia, southern Greece, are presented. According to archaeological evidence, both kilns were part of a bigger ceramic workshop, probably used for the production of bricks or ceramics. Systematic archaeomagnetic sampling was carried out collecting 9 brick samples from the first kiln (KL3) and 12 brick samples from the second kiln (KL5). Magnetic mineralogy measurements have been carried out in order to determine the main magnetic carrier of the samples and to check their thermal stability. Standard thermal demagnetization procedures have been used to determine the archaeomagnetic direction registered by the bricks during their last firing. The direction of the Characteristic Remanent Magnetization (ChRM) has been obtained from principal component analysis and the kilns mean directions were calculated using Fisher statistics. The archaeomagnetic ages of both kilns were determined using the most recent developments in data elaboration and were calculated after comparison of the kilns declination and inclination with the reference curves produced by the SCHA.DIF.3K European regional geomagnetic field model. Dating results are in good agreement with archaeological evidence of the site and suggest that both kilns were in use during Hellenistic times.

Key words: *Archaeomagnetism, magnetic mineralogy, kilns, Kato Achaia, Greece.*

Περίληψη

Στην παρούσα εργασία παρουσιάζονται τα αποτελέσματα από την αρχαιομαγνητική μελέτη δυο αρχαίων κλιβάνων που ανακαλύφθηκαν στην Κάτω Αχαΐα. Σύμφωνα με τα ευρήματα της αρχαιολογικής ανασκαφής, οι δυο αυτοί κλίβανοι αποτελούσαν μέρος ενός μεγαλύτερου κεραμικού εργαστηρίου που λειτουργούσε στην περιοχή, πιθανότατα για την παραγωγή τούβλων ή κεραμικών. Συστηματική αρχαιομαγνητική δειγματοληψία πραγματοποιήθηκε σε συνεργασία με τους αρχαιολόγους και συνολικά λήφθηκαν 9 δείγματα από τον πρώτο κλίβανο (KL3) και 12 από τον δεύτερο (KL5). Συστηματικές μετρήσεις της μαγνητικής ορυκτολογίας των δειγμάτων πραγματοποιήθηκαν με σκοπό τον καθορισμό του βασικού φορέα της μαγνήτισης των δειγμάτων. Η διεύθυνση της Χαρακτηριστικής Παραμένουσας Μαγνήτισης καθορίστηκε κατόπιν ανάλυσης της κύριας συνιστώσας μαγνήτισης και οι μέσες τιμές διεύθυνσης για τους δυο κλιβάνους υπολογίστηκαν σύμφωνα με την στατιστική του Fisher. Η ηλικία των κλιβάνων υπολογίστηκε χρησιμοποιώντας τις πιο σύγχρονες εξελίξεις στην αρχαιομαγνητική έρευνα και κατόπιν σύγκρισης της διεύθυνσης των *κλιβάνων με τις καμπύλες αναφοράς, όπως αυτές υπολογίστηκαν από το SCHA.DIF.3K γεωμαγνητικό μοντέλο που περιγράφει την μεταβολή του μαγνητικού πεδίου στον Ευρωπαϊκό χώρο. Τα αποτελέσματα της αρχαιομαγνητικής χρονολόγησης συμφωνούν πολύ ικανοποιητικά με τις αρχαιολογικές ενδείξεις για την περίοδο χρήσης των κλιβάνων και υποδεικνύουν ότι οι κλίβανοι ήταν σε χρήση κατά την διάρκεια της ελληνιστικής περιόδου και εγκαταλείφτηκαν προς το τέλος αυτής.*

Λέξεις κλειδιά: *Αρχαιομαγνητισμός, μαγνητική ορυκτολογία, κλίβανοι, Κάτω Αχαΐα, Ελλάδα.*

1. Introduction

During last decades, important progress in archaeomagnetic studies has been done and archaeomagnetism is now established as a useful tool in archaeological research. One of the most common applications of this method is the archaeomagnetic dating. This dating technique is based on the ability of several archaeological structures and artifacts (e.g., kilns, hearths, bricks, pottery) to acquire, under certain conditions, a thermal remanent magnetization (TRM) with direction parallel and magnitude proportional to the local field when heated at high temperatures and cooled in the presence of the Earth’s magnetic field. The date of the TRM acquisition can thus be determined by comparing the geomagnetic field elements (Declination, D, Inclination, I and intensity, F) obtained from the remanent magnetization measured on the undisturbed archaeological artifacts with reference secular variation (SV) curves that report the chronological geomagnetic field variations within a certain region.

The accuracy of archaeomagnetic dating depends on several factors such as the suitability of the studied materials as recorders of the Earth’s magnetic field, the experimental uncertainty, the rate of change of the geomagnetic field in the considered period and the availability of a detailed reference SV curve for the given territory. In Europe, well established directional SV curves have been recently published for several countries, e.g. France (Gallet et al. 2002), the United Kingdom (Zananiri et al., 2007), Iberian Peninsula (Gómez-Paccard et al., 2006), Italy (Tema et al., 2006), Germany (Schnepp & Lanos 2005), Hungary (Márton, 2010), Bulgaria (Kovacheva et al., 2009), Balkan Peninsula (Tema & Kondopoulou, 2011). In Greece, archaeomagnetic investigations started at the early 60’s and since then various studies have been carried out (e.g. Liritzis & Thomas, 1980; Downey & Tarling, 1984; Papamarinopoulos, 1987; Kovacheva et al., 2000; Spatharas et al. 2000, 2011; De Marco et al., 2008a, 2008b; Spassov et al., 2010; Aidona & Kondopoulou, 2012; Fanjat et al., 2012; Tema et al., 2012; De Marco et al., 2013 and references there in). Recently, De Marco et al. (2013, *submitted*) compiled a database with all the available up to now directional results from Greece and proposed a reference secular variation curve for the last 4500 years.

Apart from the secular variation curves available for single countries, during the last years, great progress on geomagnetic field modeling at regional scale has also been done. Nowadays geomagnetic field models, able to represent the past geomagnetic field vector variation in Europe, are available. These models can provide reference curves for a precise location (Pavón-Carrasco et al., 2009, 2010) and be used for archaeomagnetic dating in Europe (Pavón-Carrasco et al., 2011). Regional models present the advantage to predict the geomagnetic field at the site of interest, avoiding this way any eventual relocation error. They can also provide well-constrained palaeosecular variation curves for regions and time periods that are poorly covered by archaeomagnetic data of local scale.

This paper presents the results of the archaeomagnetic investigation of two circular brick kilns excavated at Kato Achaia, southern Greece. The rock magnetic properties of the studied material have been investigated and the calculated mean archaeomagnetic direction for each kiln has been used for archaeomagnetic dating. The most probable dates of the last firing of the kilns have been obtained using recent developments on data statistical treatment and archaeomagnetic dating (Pavón-Carrasco et al., 2011).

2. Archaeological Context and Archaeomagnetic Sampling

The studied kilns were excavated in an habitation area of Kato Achaia village (38.15° N, 21.55° E), Parodos Papaflessa street, during the works for the construction of a new building. Both of the sampled kilns, named KL3 and KL5, are circular (Figure 1) and were part of a bigger production workshop. At least three other kilns were found in the same excavation area and according to archaeological evidence they were used for the production of bricks or ceramics. Based on some ceramics found in the site, archaeologists suggest that both kilns were in use during Hellenistic times (Tsaknaki 2013, personal communication).

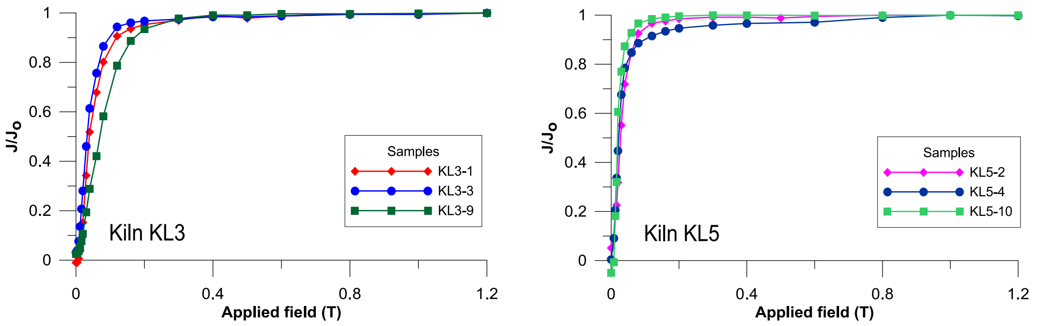
(a) (b)

Figure 1 - Photos of the studied kilns where the position of the collected samples is shown: a) kiln KL3 and b) kiln KL5.

Systematic archaeomagnetic sampling was carried out collecting 9 brick samples from the first kiln (KL3) and 12 brick samples from the second kiln (KL5). All samples were oriented *in situ* using a magnetic and a solar compass. Most of the bricks were positioned horizontally in the kilns' walls and the central pillar (Figure 1). From each independently oriented sample, one to three cylindrical specimens of standard dimensions (diameter = 25.4 mm, height = 22 mm) were drilled in the laboratory.

3. Magnetic Mineralogy

The magnetic properties of representative samples collected from both kilns have been investigated by isothermal remanent magnetization (IRM) acquisition curves and thermal demagnetization of three IRM components (Lowrie, 1990). All measurements have been performed at the ALP Palaeomagnetic laboratory (Peveragno, Italy). The IRM was given by applying stepwise magnetic fields, with an ASC pulse magnetizer, up to 1.2 T. The magnetic remanence was measured with a JR6 spinner magnetometer (AGICO). The IRM acquisition curves obtained for different specimens are quite similar for both kilns and show that more than 90% of saturation is reached at applied fields of 0.2-0.4 T while no fraction remains unsaturated after 1.2 T peak field (Figure 2 a and b), indicating the presence of a low coercivity mineral such as magnetite and/or Ti-magnetite.



(a) (b)

Figure 2 - Representative IRM acquisition curves from selected samples from a) kiln KL3 and b) kiln KL5.

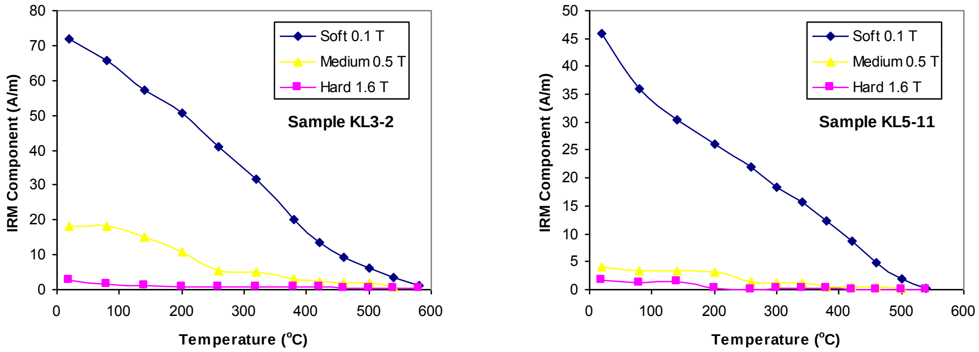


Figure 3 - Stepwise thermal demagnetization of three IRM components for a) sample KL3-2 (kiln KL3) and b) sample KL5-11 (kiln KL5).

Stepwise thermal demagnetization of the three IRM components (Lowrie, 1990) induced along the three sample axes, applying first the maximum field (1.6 T) along Z-axis, then the intermediate field (0.5 T) along the Y-axis and finally the minimum field (0.1 T) along the X-axis, shows thedominating role of the magnetically soft fraction (< 0.1 T) with unblocking temperatures ranging between 460 and 540 °C (Figure 3). These results point to magnetite or Ti-magnetite as the main magnetic carrier in the studied samples.

4. Archaeomagnetic Direction: Experiments and Results

The Natural Remanent Magnetization (NRM) of all specimens has been measured using a JR-6 spinner magnetometer. Subsequently, specimens have been stepwise thermally demagnetized up to 580 °C using a TSD-2 Schonstedt furnace. Demagnetization results (Figure 4) show that the magnetic remanence is very stable and it consists of one well defined Characteristic Remanent Magnetization (ChRM). In some samples (mainly from KL3 kiln) a secondary component is also visible but it is easily removed during thermal demagnetization.

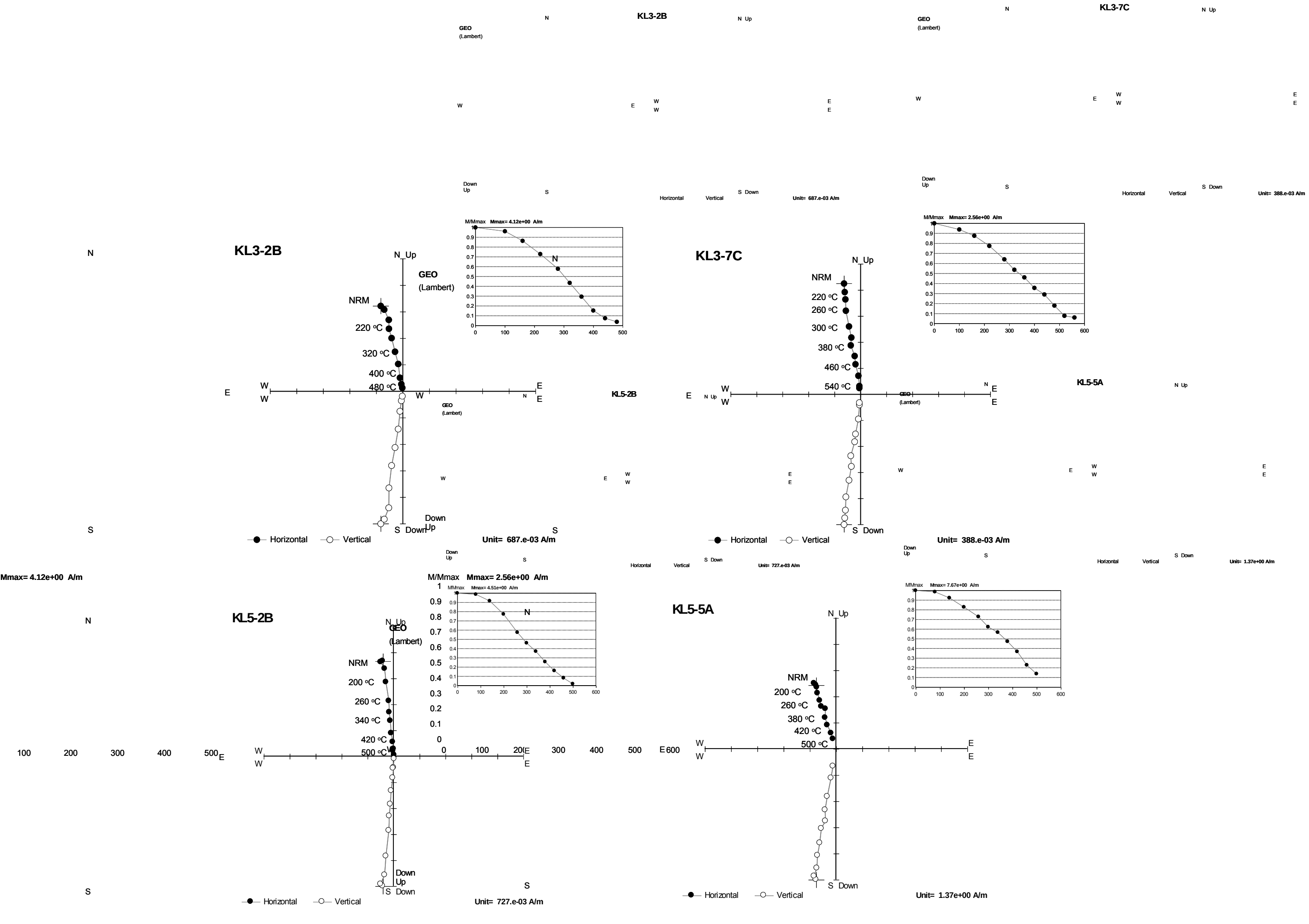
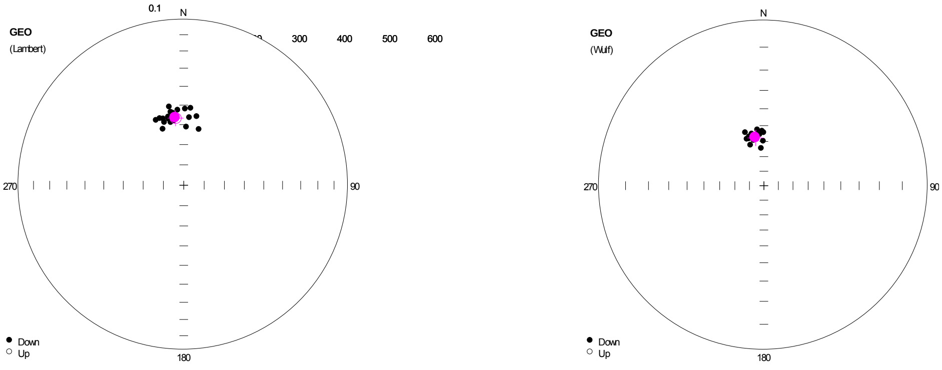


Figure 4 - Zijderveld diagrams and demagnetization curves from stepwise thermal demagnetization of representative samples from KL3 (upper part) and KL5 (lower part) kilns.



(a) (b)

Figure 5 - Equal area projection of the ChRM directions for kiln a) KL3 and b) KL5.

The direction of the ChRM for each specimen has been obtained from principal component analysis (Zijderveld, 1967; Kirschvink, 1980) using the Remasoft software (Chadima & Hrouda, 2006). All results at specimen level from kiln KL3 and KL5 are reported in Table 1 and Table 2 respectively, together with the mean direction for each kiln, calculated according to Fisher statistics (Fisher, 1953). Equal-area projections of the ChRM directions (Figure 5) show a good concentration around the mean directions. The calculated mean direction for kiln KL3 is: D= 353.0°, I= 56.5°, k= 147, α_{95}= 2.7° and for kiln KL5 is: D= 350.1°, I= 57.3°, k= 246, α_{95}= 2.4°.

Table 1 - Archaeomagnetic directional results for kiln KL3.

Sample	**Temperature range (°C)**	**D (°)**	**I (°)**
KL3-1a	400-560	348.8	58.6
KL3-1b	400-560	350.2	56.5
KL3-1c	280-560	351.9	58.0
KL3-2a	220-480	1.6	52.3
KL3-2b	220-480	347.7	55.6
KL3-2c	220-480	343.7	55.9
KL3-3a	320-480	5.8	51.7
KL3-3b	160-520	337.2	55.3
KL3-4a	280-480	347.7	56.7
KL3-4b	280-520	351.7	54.0
KL3-6a	400-560	343.3	57.8
KL3-6b	220-560	340.6	55.2
KL3-7a	220-560	355.9	52.8
KL3-7b	160-520	350.4	53.4
KL3-7c	220-560	349.9	50.6
KL3-8a	100-520	340.0	60.8
KL3-8b	280-520	5.4	56.6
KL3-8c	280-520	11.4	55.5
KL3-9a	400-520	3.3	61.5
KL3-9c	220-520	16.1	61.6

Mean value:

N= 8	n= 20	D_m= 353.0°	I_m= 56.5°	k=147	α_{95}= 2.7°

Columns: Sample; Temperature interval used for the calculation of the direction of the ChRM at specimen level; Declination (°); Inclination (°); N= number of independently oriented samples; n= number of specimens; D_m= mean declination; I_m= mean inclination; k= precision parameter; α_{95}= 95% semi-angle of confidence.

Table 2 - Archaeomagnetic directional results for kiln KL5.

Sample	Temperature range (°C)	D (°)	I (°)
KL5-1a	200-500	351.7	56.0
KL5-1b	200-500	343.8	56.2
KL5-2a	200-500	347.4	54.8
KL5-2b	140-500	354.0	52.8
KL5-3a	140-500	358.9	53.8
KL5-3b	140-500	0.5	54.7
KL5-4a	140-500	356.9	64.9
KL5-5a	140-500	342.3	61.5
KL5-5b	80-500	348.1	59.0
KL5-7b	200-500	341.1	52.9
KL5-8a	300-500	348.1	59.0
KL5-8b	200-500	356.1	56.0
KL5-10a	140-500	0.1	60.2
KL5-11a	140-500	342.6	57.3
KL5-11b	140-500	340.4	57.1

Mean value:

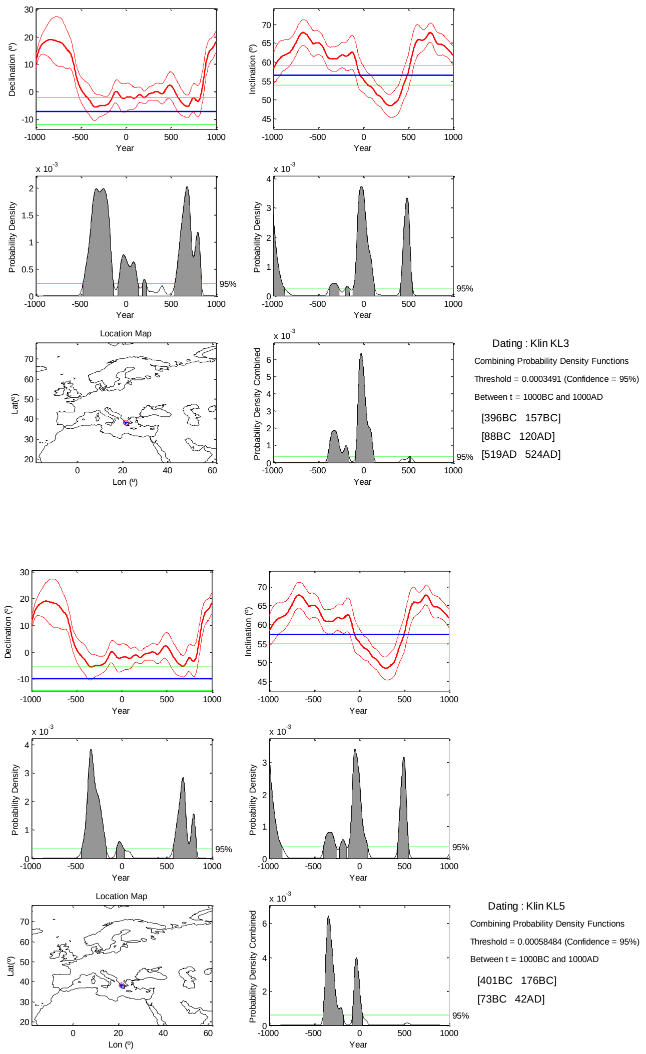
N= 9	n= 15	D_m= 350.1°	I_m= 57.3°	k=246	α_{95}= 2.4°

Columns: (as in Table 1).

5. Archaeomagnetic Dating

The mean direction values obtained for each kiln have been separately used for the archaeomagnetic dating of the two structures after comparison with the reference secular variation curves calculated from the SCHA.DIF.3K model (Pavón-Carrasco et al., 2009). The SCHA.DIF.3K is a regional archaeomagnetic model that represents the geomagnetic field variations in Europe for the last 3000 years modeling together the three geomagnetic field elements. It is based on reference data coming from instrumental measurements for the last 400 years and on data from archaeological material for older times. For the 400 BC-500 AD period the directional curve obtained from the SCHA.DIF.3K model is statistically the same with the Greek SV curve calculated using the Bayesian statistics (De Marco et al., 2013, *submitted*). For this reason, both curves should give the same dating results. In this study, the SCHA.DIF.3K model reference curve was used because, in respect to the local SV curves, it presents the advantage that predicts the geomagnetic field at the site of interest, avoiding this way any eventual relocation error.

Archaeomagnetic dating of the KL3 and KL5 kilns has been carried out using the Matlab *archaeo_dating* tool (Pavón-Carrasco et al., 2011). Reference curves have been directly calculated at the geographic coordinates of Kato Achaia and have been used for the calculation of probability density functions separately for declination and inclination. The final dating of the two kilns is obtained after the combination of the separate density functions (Figure 6).



a)

b)

Figure 6 - Archaeomagnetic dating results for a) KL3 and b) KL5 kilns. Dating intervals have been calculated at 95% of probability using the matlab *archaeo_dating* tool (Pavón-Carrasco et al., 2011).

Archaeomagnetic dating of KL3 and KL5 kilns calculated at 95% of probability shows several dating intervals in the 1000 BC-1000 AD period (Figure 6). However, taking into consideration the archaeological information available for the studied site, indicating that the kilns were in use during Hellenistic times, the older time intervals can be excluded. It is thus suggested that the last use of KL3 kiln took place around 88 BC to 120 AD while kiln KL5 was abandoned between 73 BC and 42 AD.

6. Conclusions

Archaeomagnetic investigation of two ancient kilns brought into light during a rescue excavation at Kato Achaia (Southern Greece), showed that the studied materials were heated at high temperatures and proved to be reliable recorders of the Earth's magnetic field at the time of their last firing. Thermal demagnetization procedures yielded well defined archaeodirection values for both kilns. The obtained results were compared with the reference curves produced by the SCHA.DIF.3K European regional geomagnetic field model and the archaeomagnetic dates of the kilns last use were calculated at 95% of probability. The obtained dating intervals are in very good agreement with the archaeological evidence, suggesting that both kilns were in use during Hellenistic times and were abandoned around 88 BC-120 AD for KL3 and 73 BC-42 AD for KL5 kiln. These results suggest that KL5 kiln could have been abandoned slightly before the KL3; nevertheless such short time differences should be cautiously interpreted because up to nowadays variations of the Earth's magnetic field in the past at time scales less than 100 years can not be reconstructed with such precision. Future investigation of the archaeointensity of the Earth's magnetic field registered by the kilns could further restrict the obtained dating intervals. These results show that precise archaeomagnetic dating in Greece is possible and can be used as a valuable dating tool in archaeological research.

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