Dating of ancient kilns: A combined archaeomagnetic and thermoluminescence analysis applied to a brick workshop at Kato Achaia, Greece

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A B S T R A C T

We present here the results of a detailed archaeomagnetic and thermoluminescence investigation performed on bricks from two ancient kilns excavated at Kato Achaia, Greece. Magnetic mineralogy measurements have been carried out to determine the main magnetic carrier of the samples. The directions of the characteristic remanent magnetization of each structure have been obtained from standard thermal demagnetisation procedures and the absolute archaeointensity has been determined with the Thellier method, accompanied by regular partial theromagnetization (pTRM) checks. The full geomagnetic field vector was used for the archaeomagnetic dating of the two kilns, after comparison with the reference secular variation curves calculated directly at the site of Kato Achaia. Independent dating has also been obtained from thermoluminescence (TL) analysis on four brick samples from each kiln. The dating results obtained from the two methods have been compared and the last firing of each kiln has been estimated from the combination of the two techniques. Using the independent date offered by TL dating, the new archaeomagnetic data have been compared with other data from the same time period and they can further be used as reference points to enrich our knowledge about the past secular variation of the Earth’s magnetic field in Greece.

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1. Introduction

Dating of archaeological remains is essential in archaeological research, in order to place in chronological order findings and civilizations. Inscribed objects sometimes bear an explicit date, or preserve the name of a known individual (e.g. a king or an emperor) but, in general, this is not always the case and often the contribution of a scientific dating technique is necessary. During the last decades, several dating methods such as radiocarbon dating, obsidian hydration, dendrochronology, potassium-argon, archaeomagnetic and luminescence dating have been increasingly used in archaeology. Each one of these dating techniques however has its own advantages and limitations, mostly related to the availability of appropriate material, the type and characteristics of the studied samples, their preservation conditions and the chronological period. For this reason, when possible, the combination of more dating techniques together with the available archaeological evidence may offer the best approach for obtaining a more precise chronological framework for an archaeological site.

Archaeomagnetic dating is based on the principle that the magnetic minerals contained in many baked clay archaeological artefacts (e.g., kilns, hearths, bricks, pottery), when heated at high temperatures and cooled in the presence of the Earth’s magnetic field, may acquire a thermal remanent magnetization (TRM) with direction parallel and magnitude proportional to the ambient magnetic field. For the regions where a detailed reference secular variation (SV) curve is available, archaeomagnetic dating is possible after the comparison of the remanent magnetization measured on the undisturbed archaeological artefacts with the reference SV.
During last decades, important progress on archaeomagnetic dating has been done and it has been successfully applied in several case studies in the Mediterranean area, mainly involving the study of the direction of the geomagnetic field vector (e.g. [1–7]).

In an analogous way, luminescence dating is based on the fact that naturally-occurring minerals like quartz and feldspars act as natural dosimeters and preserve a record of irradiation dose, i.e. energy per unit mass, received through time. This dose results mainly from the decay of natural radionuclides, i.e., $^{232}\text{Th}$, $^{40}\text{K}$ and natural U, along with cosmic rays, which provide a constant source of low-level ionizing radiation. The accumulated dose is stored by means of trapped charge in crystal defects, which is stable over long periods of time but can be released either by heating or exposing the crystal to light. This release can take place accidentally in a natural way or alternatively artificially, at the laboratory, giving thus rise to thermoluminescence (TL) and optically stimulated luminescence (OSL) respectively [8–10]. The brightness of the luminescence signal reflects the amount of trapped charge. Consequently, it is also proportional to the total irradiation dose accumulated and thus to the total age. The number of trapped electrons is increasing as long as the material is irradiated. However, every time that the material is subjected to prolonged heating (as in the case of firing pottery) or intense light exposure (as in the case of sunlight), electrons are evicted and traps are emptied. In that case, the signal is totally zeroed. Then, energy starts to accumulate in the form of trapped electrons in order to refill the empty traps once again. The total number of trapped electrons forms a luminescent “clock” which starts measuring from the beginning ($t = 0$) every time that these traps are zeroed. Therefore, light-exposed materials could be dated to their last exposure to light, while burnt materials to their last heating. Kilns belong to the latter case and TL can effectively date their last use.

Archaeomagnetic and TL dating techniques share the same rationale, dating exactly the same event that is the last heating of baked clay artefacts. Therefore, simultaneous application of both techniques to the same archaeological materials, such as bricks from kilns, yields the important advantage of crosschecking ages. Even though their combination can offer a powerful tool for dating of archaeological artefacts during Holocene, up to now such combined studies are extremely limited [6,11–13]. We present here the results of a detailed archaeomagnetic and TL investigation performed on bricks collected from the structure of two ancient kilns excavated at Kato Achaia, Greece. The dating results obtained from the two methods have been compared and the last firing of each kiln has been estimated from the combination of the two techniques. Using the independent date offered by TL dating, the new archaeomagnetic data can be further used as reference points at the construction of the secular variation of the Earth’s magnetic field in the past.

### 2. Archaeological site and sampling

The studied kilns were discovered during the works for the establishment of the fundamentals of a new building in the corner of Parodos Ag. Ioannou and Papaflesa, Kato Achaia, and are part of the extensive ceramic workshop found in the west part of the ancient city of Dyme, situated at the same wide plateau of the modern city of Kato Achaia (38.15° N, 21.55° E), Peloponnes, Southern Greece. The archaeological research in this plot revealed a cluster of ceramic kilns of various dimensions with additions and modifications which denote the timeframe of function and activity of the workshop during the whole Hellenistic period. For the present study, two circular kilns were sampled, named KL3 and KL5 (Fig. 1).
KL3 is situated on the N-S axis and during its original construction it was circular, and internally covered by a clay layer. The central heating chamber is 4 m in external diameter, with a surviving height of around 1.35–1.50 m. The entrance of the kiln is located at the north and bears the form of a pointed arch, 1.48 m height and 0.27–0.72 m wide (Fig. 1b). During the second phase of its use, the orientation of the KL3 kiln was changed. The central mouth-opening in the north was blocked, and a new one was opened on the west side, 1.54 m height and 0.56 m wide. Furthermore, a 0.50 m wide wall made of bricks, tiles and soil was constructed inside the area of the heating chamber thus limiting its dimensions to 2.30–2.50 m. Consequently, a new chamber with different capacity was created. The internal of the heating chamber bears successive clay layers, a common feature aimed to retain a steady temperature and avoid heat dispersal. Cuts on the upper part of the circular wall give evidence of the existence of the supports of the baking floor (eschara). KL5 is situated at a small distance and at the eastern side of the KL3 kiln (Fig. 1). Its construction is similar to KL3 with a 2 m external diameter and a 0.70 m high central cylindrical support gradually widening on the upper part (Fig. 1c). Both KL3 and KL5 kilns were probably constructed at the same period and were contemporaneously used for a long period of time, a fact which becomes evident not only by the pottery found inside but also by the functionality denoted by the common orientation of the mouth-fire entrances of the two kilns. A first overview of the pottery products of the two kilns such as fragments of tiles, bricks, clay masses, toxylia, and the pottery deposit west of the fire entrance, date the abandonment of the kilns not earlier than the end of the first century BC. More specifically, and with reference to the pottery recovered from the kilns and from the vicinity area the following may be deduced. The existence of several shapes of coarse ware in percentage 90% compared to fine ware with red – black slip or black slip, denoted that the production was concentrated mostly in every day use pots, rather than in more expensive fine ones. In KL3 two pieces with counting marks were also identified, a common practice for potters, enabling them to keep track of the orders. The majority of the material found dates the site to the middle and late Hellenistic period.

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 brick samples collected were part of the main structure of the kilns and 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 (Fig. 1d, e). 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. Four brick samples from each kiln have also been collected for thermoluminescence analysis.

3. Archaeomagnetic analysis

3.1. Magnetic mineralogy

Rock-magnetic measurements were carried out on several representative samples from both kilns at the ALP - Alpine Palaeomagnetic Laboratory (Peveragno, Italy). Isothermal remanent magnetization (IRM) acquisition curves were obtained by applying stepwise increasing magnetic fields up to 1.2 T, with an ASC pulse magnetizer and the magnetic remanence was measured with
a JR6 spinner magnetometer (AGICO). Stepwise thermal demagnetisation of a composite three axes IRM was also performed after applying first a maximum field (1.6 T) along the cylinder–axis (Z), then an intermediate field (0.5 T) along the Y-axis and finally a minimum field (0.1 T) along the X-axis.

The IRM curves obtained from different samples from both kilns indicate that the saturation of the magnetization is generally reached at low fields varying from 0.2 to 0.4 T, indicating the presence of a low-coercivity mineral such as magnetite and/or Ti-magnetite (Fig. 2a). In some samples (mainly from KL5 kiln e.g., KL5-4 and KL5-6), saturation is not completely reached at 1.2 T showing that a small amount of a high-coercivity mineral, most probably hematite, may also be present. These results are also confirmed by the thermal demagnetisation experiments of a three component IRM [14]. The obtained demagnetisation curves [Fig. 2b] show the dominance of the magnetically soft fraction (<0.1 T) while the medium and high-coercivity components are generally very small. These results point to magnetite or Ti-magnetite as the main magnetic carrier in the studied samples, with possibly some small content of hematite in some cases.

3.2. Archaeomagnetic direction

The natural remanent magnetization (NRM) of all specimens was measured at the ALP laboratory with a JR-6 spinner magnetometer. One to three specimens from each sample, according to the material availability, have been stepwise thermally demagnetized up to 560 °C using a TSD-2 Schonstedt furnace. The demagnetization results are illustrated as orthogonal vector projections of the remanent magnetization (Zijderveld plots) (Fig. 3). Zijderveld diagrams 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 viscous component is also visible but it is easily removed during thermal demagnetization.

The direction of the ChRM has been obtained from principal component analysis [15,16] using the Remasoft software [17]. Directions calculated at specimen level are well defined with maximum angular deviation (MAD) angles generally less that 3° (with only exceptions specimens KL3-3a, KL5-1b and KL5-8a). All results at specimen level from kiln KL3 and KL5 are reported in Table 1. Mean directions for each sample were calculated according to Fisher statistics [18] and are reported in Table 1, together with the mean archaeomagnetic direction calculated for each kiln. Equal-area projections of the ChRM directions at sample level (Fig. 4) show a very good concentration around the mean value. The calculated mean direction for kiln KL3 is: D = 353.0°, I = 56.6°, k = 245, α95 = 3.6° and for kiln KL5 is: D = 350.4°, I = 57.7°, k = 219, α95 = 3.5°. The very similar directions obtained for the two kilns (statistically indistinguishable) suggest that the two kilns were in use contemporaneously and were abandoned at the same time period. These results have been previously presented by [19] and are here complemented by the archaeointensity determination.

3.3. Archaeointensity determination

Archaeointensity determinations have been carried out at the LIMNA palaeomagnetic laboratory of UNAM (Campus Morelia, Mexico) with the classical Thellier method [20] as modified by Coe [21,22]. One to four cubic specimens of similar dimensions
Table 1
Archaeomagnetic directional results.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Temperature range (°C)</th>
<th>D (°)</th>
<th>I (°)</th>
<th>MAD</th>
<th>Sample mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>KL3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>KL3-1a</td>
<td>400–560</td>
<td>348.8</td>
<td>58.6</td>
<td>1.8</td>
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</tr>
<tr>
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<td>56.5</td>
<td>1.8</td>
<td></td>
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<tr>
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<td>351.9</td>
<td>58.0</td>
<td>1.9</td>
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<tr>
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<td>52.3</td>
<td>1.1</td>
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<tr>
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<td>55.6</td>
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<tr>
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<td>55.9</td>
<td>1.0</td>
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<td>6.5</td>
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<td>1.2</td>
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<td>53.4</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>KL3-7c</td>
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<td>50.6</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
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<td>60.8</td>
<td>1.1</td>
<td></td>
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<tr>
<td>KL3-8b</td>
<td>280–520</td>
<td>5.4</td>
<td>56.6</td>
<td>1.6</td>
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<tr>
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<td>11.4</td>
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<td>1.3</td>
<td></td>
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<tr>
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<td>3.3</td>
<td>61.5</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
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<td>220–520</td>
<td>16.1</td>
<td>61.6</td>
<td>1.4</td>
<td></td>
</tr>
</tbody>
</table>

Mean value

<table>
<thead>
<tr>
<th>N = 8</th>
<th>n = 20</th>
<th>Dm = 353.0°</th>
<th>Iα95 = 56.6°</th>
<th>K = 245</th>
<th>α95° = 3.6°</th>
</tr>
</thead>
</table>

Columns: specimen; Temperature interval used for the calculation of the direction of the ChRM at specimen level; Declination (°); Inclination (°); MAD: Maximum Angular Deviation; Mean D (°) and I (°) calculated at sample level; Mean value for each kiln: N = number of independently oriented samples; n = number of specimens; Dm = mean declination; Iα95 = mean inclination; k = precision parameter; α95° = 95% semi-angle of confidence.

(~ 10 mm length) were cut in the laboratory from each sample, using the remaining material of the drilled cylindrical samples, previously used for directional analysis. A total of 16 specimens from kiln KL3 and 26 from kiln KL5 have been prepared and studied. All specimens were heated and cooled in a ASC Scientific TD48-SC furnace and the remanence was measured with a JR6 spinner magnetometer. Heating/cooling cycles were performed in air. Fourteen temperature steps were distributed from 25 °C to 490 °C. A direct laboratory field of 65.0 ± 0.05 μT was applied during heating and cooling of the different specimens. Two pTRM checks were performed in order to detect possible changes in the pTRM acquisition capacity. Additionally, a pTRM tail check [23] was performed at a temperature of 350 °C. Cooling rate dependence of TRM was investigated following a procedure similar to that described by [24]. At the end of the archaeointensity experiments, all specimens were heated three more times at 490 °C in the presence of the same laboratory field used during the archaeointensity determination. The first time, a new TRM (TRM1) was given in the same conditions as
that gained during the last step of the Thellier experiment, using a short cooling time of around 45 min. Then a second TRM (TRM₂) was given with a longer cooling time (~6 h) and finally a third TRM (TRM₃) was created using the same short cooling time as that used during the TRM₁ (approximately 45 min). The cooling rate correction factors were calculated as the variation between the intensity acquired during a short and a long cooling time [24]. The cooling rate correction was applied only when the corresponding change in TRM acquisition capacity was below 15%.

The obtained results, interpreted using NRM–TRM plots (Fig. 5), are reported in Table 2 together with the statistical parameters calculated according to [22]. To be considered as trustworthy estimations of the ancient field, archaeointensity determinations obtained in this study had to fulfill the following acceptance criteria [25]:

- directions of natural remanent magnetization (NRM) end-points at each step obtained from archaeointensity experiments have to fall along a straight line, trending toward the origin in the interval chosen for archaeointensity determination;
- no significant deviation of NRM directions towards the applied field direction should be observed, as revealed in vector (Zijderveld) plots;
- a number of aligned points (N) on the NRM-pTRM diagram ≥ 9;
- NRM fraction factor \( f \geq 0.5 \). This means that at least 50 per cent of the initial NRM was used for archaeointensity determination;
- a quality factor \( q = (f \times g) / \beta \geq 5 \) (generally above 10, Table 2); \( g \) is the gap factor [22] and \( \beta \) the relative standard deviation of the slope;
- archaeointensity results obtained from NRM-pTRM diagrams must not show an evident concave up shape, since in such cases remanence is probably associated with the presence of MD grains [26,27];
- positive pTRM checks, i.e., the deviation of “pTRM” checks should be less than 15%.

Average cooling rate correction factors close to 0.98 were applied to raw archaeointensity data. Evaluation of pTRM-tail checks was in most cases lower than 2%. Although individual intensity determinations obtained range from 53.2 to 74.5 \( \mu T \) for the kiln KL3 and from 54.9 to 73.4 \( \mu T \) for kiln KL5, corresponding mean value per kiln are similar: 61.3 ± 6.0 \( \mu T \) and 62.4 ± 5.2 \( \mu T \), respectively.

3.4. Archaeomagnetic dating

The full geomagnetic field vector (declination, inclination and intensity) obtained for each kiln has been used for the archaeomagnetic dating of the two structures after comparison with the reference secular variation curves calculated from the SCHA.DIF.3 K model [28]. The SCHA.DIF.3 K 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 periods, the directional curve obtained from the SCHA.DIF.3 K model is statistically the same with the Greek SV curve calculated using the Bayesian statistics [7]. For this reason, both curves should give the same dating results. In this study, the SCHA.DIF.3 K 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 archaeoint. dating tool [29]. Reference SV 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, inclination and intensity. The final dating of the two kilns is obtained after the combination of the separate density functions (Fig. 6). For each kiln several possible dating intervals occur. However, taking into account the archaeological context of the site and the archaeological findings that propose a Hellenistic age, it is suggested that the last use of the kilns KL3 and KL5 occurred in the time intervals 97 BC- 133 AD and 85 BC- 37 AD respectively, calculated at 95% of probability.

4. Thermoluminescence analysis

4.1. Experimental procedure

For TL dating, two different physical quantities are required; the total accumulated dose during the past, termed as palaeodose or equivalent dose (expressed in units of Gy), as well as the rate at which this energy-dose is accumulated, termed as dose rate (expressed in units of Gy/yr). The ratio of these two quantities, i.e. the palaeodose \( (D_E) \) over the dose-rate \( (DR) \), represents the age of the sample. A total of eight brick samples, four from each kiln, were subjected to TL dating. Treatment and preparation were undertaken in subdued red filtered light conditions. An almost 0.5 cm
thick, outer layer was removed from each sample in the laboratory to eliminate the light-subjected portions. The chemical procedure described by [30] was applied for sample preparation. Finally, grains with dimensions in the range 4–12 μm were extracted, suspended in acetone and finally precipitated onto 1 cm diameter aluminium discs [31].

For the equivalent dose estimation, the multiple aliquot, additive dose procedure (MAAD) in TL was applied; a detailed description of the procedure can be found in [8,9,32] (for an outline, readers could also refer to [33]). All TL measurements were carried out using a Risø TL/OSL reader (model TL/OSL DA-15), equipped with a 50Sr(β)Y beta particle source, delivering a nominal dose rate of 0.071 Gy/s. A 9635QA photomultiplier tube was used for light detection. The detection optics consisted of a combination of a Pilkington HA-3 heat absorbing and a Corning 7–59 (320–440 nm) blue filter. All TL measurements were performed in a nitrogen atmosphere with a low constant heating rate of 1 °C/s, in order to avoid significant temperature lag, up to the maximum temperature of 500 °C. The additive doses applied were 7, 15 and 22 Gy.

The dose rate is calculated based on the decay of naturally occurring radionuclides inside the clay matrix, i.e., 40K, 232Th and natural U, along with cosmic rays, which provide a constant source of low-level ionizing radiation. The latter two were measured in units of part per million (ppm) using thick source alpha counting [34], while 40K could be estimated by Scanning Electron Microscopy (SEM, [35]). Dose-rate calculations were made using the conversion factors of [36].

4.2. $D_E$ estimation

Natural TL glow curves for all samples exhibit the same main characteristics, namely a glow curve that has the form of a continuum with two prominent overlapping TL peaks centered around 275 and 350 °C (Fig. 7). Each glow curve is the mean value of three independently measured glow curves. Equivalent doses were calculated with 1σ error values; a typical plot of $D_E$ against glow curve temperature is presented in Fig. 8. Errors derived mainly from the uncertainties in curve fitting, are ±1σ and were calculated by standard error propagation analysis [37]. In all cases, $D_E$ plateaus are wide enough, over 90 °C wide. The equivalent doses were obtained as the mean values of the best plateaus for each sample. Only linear fittings were performed to the dose response curves. This linearity was strongly established. In the inset A of Fig. 8 representative example of additive build-up curve is also presented as filled squares for the temperature corresponding to the temperature in the middle of the plateau range, along with the corresponding linear fit. This inset figure strongly supports the linearity monitored for the case of the dose response. In the same figure, inset B presents the corresponding second glow TL dose response curve after applying low doses, indicating the presence of supra-linearity in the low-dose region [31]. The corresponding supra-linearity correction was estimated as the intercept of the linear part of the second glow TL with the dose axis; supra-linearity correction, $I$, equals to zero if this interception passes from the origin of the axis. The values of $I$ are then plotted versus temperature and a mean value is yielded in the same temperature region where the plateau is monitored [38]. A summary of the TL dating data is provided in Table 3. In the case of kiln KL5, which yielded supra-linearity, the corresponding index $I$ was added to the equivalent dose value, applying this way a form of the slide method.

Finally, since samples are expected to contain feldspars, the anomalous fading was also estimated. For the present study the procedure previously applied by [6] was adopted; however the dose applied here was similar to the equivalent dose of each kiln while the storage time was three months. No anomalous fading was

Fig. 5. Representative examples of NRM–TRM diagrams and associated Zijderveld plots from successful archaeointensity experiments.
Table 2
Archaeointensity results.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>N</th>
<th>T\textsubscript{min}−T\textsubscript{max} (°C)</th>
<th>m</th>
<th>sigma</th>
<th>f</th>
<th>g</th>
<th>q</th>
<th>H (μT)</th>
<th>σ (μT)</th>
<th>H\textsubscript{m} (μT)</th>
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<td>KL3-1a</td>
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<td>0.080</td>
<td>0.529</td>
<td>0.797</td>
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<td>67.3</td>
<td>5.2</td>
<td>66.5</td>
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<tr>
<td>KL3-1b</td>
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<td>3.2</td>
<td>61.0</td>
</tr>
<tr>
<td>KL3-2a</td>
<td>11</td>
<td>20–490</td>
<td>−0.891</td>
<td>0.028</td>
<td>0.932</td>
<td>0.766</td>
<td>25.5</td>
<td>57.9</td>
<td>1.8</td>
<td>56.4</td>
</tr>
<tr>
<td>KL3-2b</td>
<td>12</td>
<td>20–490</td>
<td>−0.885</td>
<td>0.038</td>
<td>0.896</td>
<td>0.875</td>
<td>20.6</td>
<td>57.5</td>
<td>2.5</td>
<td>55.9</td>
</tr>
<tr>
<td>KL3-3a</td>
<td>9</td>
<td>20–490</td>
<td>−0.936</td>
<td>0.022</td>
<td>0.888</td>
<td>0.492</td>
<td>19.9</td>
<td>60.8</td>
<td>1.4</td>
<td>60.5</td>
</tr>
<tr>
<td>KL3-3b</td>
<td>11</td>
<td>20–490</td>
<td>−0.925</td>
<td>0.031</td>
<td>0.885</td>
<td>0.694</td>
<td>19.8</td>
<td>60.1</td>
<td>2.0</td>
<td>59.9</td>
</tr>
<tr>
<td>KL3-3c</td>
<td>11</td>
<td>20–490</td>
<td>−0.866</td>
<td>0.036</td>
<td>0.837</td>
<td>0.758</td>
<td>17.6</td>
<td>56.3</td>
<td>2.3</td>
<td>55.5</td>
</tr>
<tr>
<td>KL3-4a</td>
<td>10</td>
<td>20–490</td>
<td>−0.828</td>
<td>0.034</td>
<td>0.703</td>
<td>0.863</td>
<td>17.8</td>
<td>53.8</td>
<td>2.2</td>
<td>53.2</td>
</tr>
<tr>
<td>KL3-4b</td>
<td>10</td>
<td>20–490</td>
<td>−0.861</td>
<td>0.066</td>
<td>0.657</td>
<td>0.851</td>
<td>8.5</td>
<td>56.0</td>
<td>4.3</td>
<td>−</td>
</tr>
<tr>
<td>KL3-4c</td>
<td>10</td>
<td>20–490</td>
<td>−0.823</td>
<td>0.038</td>
<td>0.674</td>
<td>0.831</td>
<td>14.7</td>
<td>53.5</td>
<td>2.5</td>
<td>−</td>
</tr>
</tbody>
</table>

Mean value: H\textsubscript{m} = 61.4 ± 6.3

| Kiln KL5 |    |                                 |      |       |     |     |     |        |        |                  |
|----------|----|---------------------------------|      |       |     |     |     |        |        |                  |
| KL5-1a   |    |                                 |      |       |     |     |     |        |        |                  |
| KL5-1b   |    |                                 |      |       |     |     |     |        |        |                  |
| KL5-2b   |    |                                 |      |       |     |     |     |        |        |                  |
| KL5-2c   |    |                                 |      |       |     |     |     |        |        |                  |
| KL5-3    | 5  | 20–425                          | −0.720 | 0.024 | 0.738 | 0.656 | 20.2 | 46.8   | 1.6    | −               |

Mean value: H\textsubscript{m} = 63.6 ± 5.9

Columns: Specimen; N: the number of heating steps used for the intensity determination; T\textsubscript{min}–T\textsubscript{max}: minimum and maximum temperatures used for the intensity determination; m: slope of the best fit; sigma: standard deviation of m; f: the fraction of NRM used for intensity determination; g: the gap factor; q: the quality factor as defined by Coe et al. (1978) [22]; H: Archaeointensity before any correction; σ: standard deviation of H; Hcr: Archaeointensity after cooling rate correction. The mean values for each kiln have been calculated only from specimens that have passed all selection criteria (see text for more explanation).

4.3. Dose rate assessment

The dose rate was assumed to be mainly derived from natural radioactivity in the kiln. The annual dose can be calculated as the sum of contributions to the dose from alpha, beta and gamma detected. Similar signals without anomalous fading for materials including feldspars were also reported in the literature by [39] and [40]. This lack of anomalous fading in conjunction with the glow curve prominent peaks, typical of quartz, suggests the dominant presence of quartz in the studied material.

Table 3
A summary of the TL dating data, the content of natural radio-nuclides as well as the experimentally obtained ages for each individual kiln fragment. Each value is accompanied by the corresponding error inside parenthesis.

<table>
<thead>
<tr>
<th>Sample</th>
<th>D\textsubscript{T} (Gy)</th>
<th>Plateau ΔT (°C)</th>
<th>I (Gy)</th>
<th>D\textsubscript{T} + I (Gy)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K (%)</th>
<th>DR (Gy/ka)</th>
<th>Age BP (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiln KL3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KL3-2</td>
<td>8.11 (0.53)</td>
<td>95</td>
<td>−</td>
<td>8.11 (0.53)</td>
<td>4.12 (0.15)</td>
<td>6.48 (0.25)</td>
<td>1.15 (0.02)</td>
<td>4.102</td>
<td>1977 (±175)</td>
</tr>
<tr>
<td>KL3-3</td>
<td>8.93 (0.62)</td>
<td>95</td>
<td>−</td>
<td>8.93 (0.62)</td>
<td>4.62 (0.18)</td>
<td>6.94 (0.27)</td>
<td>1.21 (0.03)</td>
<td>4.472</td>
<td>1997 (±183)</td>
</tr>
<tr>
<td>KL3-4</td>
<td>8.52 (0.64)</td>
<td>90</td>
<td>−</td>
<td>8.52 (0.64)</td>
<td>4.56 (0.25)</td>
<td>7.12 (0.22)</td>
<td>1.15 (0.03)</td>
<td>4.406</td>
<td>1934 (±199)</td>
</tr>
<tr>
<td>KL3-5</td>
<td>8.42 (0.63)</td>
<td>90</td>
<td>−</td>
<td>8.42 (0.63)</td>
<td>4.53 (0.19)</td>
<td>6.82 (0.25)</td>
<td>1.13 (0.02)</td>
<td>4.329</td>
<td>1944 (±195)</td>
</tr>
<tr>
<td>Kiln KL5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KL5-1</td>
<td>5.84 (0.36)</td>
<td>110</td>
<td>0.77 (0.11)</td>
<td>6.61 (0.47)</td>
<td>2.89 (0.10)</td>
<td>5.68 (0.19)</td>
<td>1.07 (0.01)</td>
<td>3.305</td>
<td>1999 (±179)</td>
</tr>
<tr>
<td>KL5-2</td>
<td>6.05 (0.35)</td>
<td>95</td>
<td>0.82 (0.17)</td>
<td>6.87 (0.52)</td>
<td>3.02 (0.13)</td>
<td>5.58 (0.18)</td>
<td>1.11 (0.02)</td>
<td>3.396</td>
<td>2023 (±201)</td>
</tr>
<tr>
<td>KL5-3</td>
<td>5.78 (0.29)</td>
<td>100</td>
<td>0.75 (0.12)</td>
<td>6.53 (0.41)</td>
<td>2.62 (0.14)</td>
<td>5.46 (0.22)</td>
<td>1.09 (0.02)</td>
<td>3.163</td>
<td>2058 (±187)</td>
</tr>
<tr>
<td>KL5-4</td>
<td>5.61 (0.33)</td>
<td>110</td>
<td>0.75 (0.13)</td>
<td>6.36 (0.46)</td>
<td>2.56 (0.09)</td>
<td>5.72 (0.17)</td>
<td>1.06 (0.02)</td>
<td>3.139</td>
<td>2026 (±189)</td>
</tr>
</tbody>
</table>
Fig. 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 [29].

particles generated during radioactive decays. In the studied kilns, the contribution of the gamma rays mainly arises from the main body of kiln (see samples position in Fig. 1). About one gram of untreated clay from each sample was employed to perform thick source alpha counting with a ZnS detector. The measurements were performed both in the integral and in the pair counting mode, for the discrimination between Th and U [34]. It was assumed that U and $^{232}$Th concentrations were uniformly distributed all over
Reheats could present a problem, and it is usual to present the average of three individually measured glow curves. The sample gave sealed over unsealed ratio of 1.054, which is considered as to represent insignificant Rn escape under laboratory conditions [8]. The k-factor, i.e. the efficiency of the alpha particles compared to beta particles was adopted to be 0.1 [41]. Table 3 presents also the outline of the dose rate assessment procedure.

4.4. TL dating

TL dating was calculated separately for each one of the four samples per kiln and the obtained results at sample level are analytically presented in Table 3. Based on these results, the final dating interval for each kiln was calculated as the mean value of the four studied samples: this is 1963 (±29) (±96) BP for KL3 kiln and 2027 (±25) (±98) for KL5 kiln. Each mean value is accompanied by two errors: (a) the standard deviation on the mean value; low values indicate the repeatability of the individual ages yielded from each sample of the same kiln and b) the error estimated according to each individual error value (around 200 years) according to standard error propagation analysis [37]. Taking into consideration both of these errors, the age of the last firing of KL3 kiln is 46 BC - 146 AD and for KL5 kiln 112 BC - 84 AD.

5. Discussion

The brick samples collected from the two kilns at Kato Achaia, proved to be very good recorders of both the past geomagnetic field and the TL signal, suggesting that these two dating techniques can be successfully combined in the case of fired archaeological structures, such as kilns. Directional and archaeointensity data have been successfully obtained for all studied samples with only 7 rejected archaeointensity determinations. The full geomagnetic field vector has been used for the archaeomagnetic dating of the two kilns and the obtained ages have been compared with the TL dating (Fig. 9). Archaeomagnetic and TL dating results are in very good agreement suggesting that both kilns were in use contemporaneously, and abandoned most probably at the end of the 1st BC and the beginning of the 1st AD century, even though the KL3 kiln could have been abandoned slightly later. These results are also in very good agreement with the archaeological findings in the site. This study shows that archaeomagnetic dating based on the full geomagnetic field can give more precise results compared to the dating based only on directions [19] and can offer a very promising dating tool for archaeology, mainly for the time periods for which a detailed reference curve is available, as for example Hellenistic and Roman periods in Europe.

Using the independent dating provided by the TL results, the new archaeomagnetic data presented here are compared with previous literature data from the Balkan Peninsula [42]. All available data for the 200 BC to 200 AD period have been relocated to Thessaloniki (40.60°N, 23.00°E) and plotted in Fig. 10, together with the Balkan SV curves and the SCHAFIE3 E K European geomagnetic field model. Such comparison shows that the new data fit very well to the previous literature data as well as to the available regional and European SV curves. They are high quality data and can be used as reference points to the Greek SV curves contributing to the enrichment of the Greek data for the 1st AD century, for which only very few directional data are available [7].

This study shows that the combination of archaeomagnetic and TL studies can be a very promising tool for both archaeology and geomagnetism. Archaeomagnetism and TL present the great advantage to date exactly the same event that is the last firing of a baked clay archaeological artefact and can thus offer precise crosschecked dating, particularly important in the case of rescue excavations where the archaeological site usually get destroyed, preventing any possibility to further in situ information acquisition. At the same time, dating information offered by TL combined to archaeomagnetic investigation of the same material can be used for reconstructing the past geomagnetic field variations. This is very important mainly for the time periods for which only few well dated archaeological findings are available, and thus well dated reference archaeomagnetic data are missing, e.g. the medieval period in Greece. We hope that this study would encourage a closer cooperation between these two methods of dating.

![Fig. 7.](image1) a: Natural and (b-d) natural-plus-beta dose glow curves for sample KL5-12. The additive doses delivered were 7, 15 and 22 Gy (curves b, c and d, respectively). Reheats have been subtracted. Each glow curve plotted is the average of three individually measured glow curves.

![Fig. 8.](image2) Equivalent dose plateau plotted versus temperature where the wide temperature range of the plateau can be noticed. Insets: A representative NTL plus beta (filled squares, inset A) and regeneraged (second glow, filled dots, inset B) plot for the temperature of 300° C. The arrows indicate the equivalent dose and supra-linearity correction from insets A and B respectively.

![Fig. 9.](image3) Combined TL and archaeomagnetic dating results.
collaboration between archaeologists, archaeomagnetists and TL physicians contributing to the rescue of our cultural heritage and improving our knowledge about the past Earth's magnetic field variations during Holocene.

Acknowledgements

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