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► To cite this version:

E. Tema, F. Fantino, E. Ferrara, A. Lo Giudice, J. Morales, et al.. Combined archaeomagnetic and thermoluminescence study of a brick kiln excavated at Fontanetto Po (Vercelli, Northern Italy). *Journal of Archaeological Science*, 2013, 40 (4), pp.2025-2035. 10.1016/j.jas.2012.12.011 . hal-01992752

HAL Id: hal-01992752

<https://hal.science/hal-01992752>

Submitted on 18 Sep 2022

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Combined archaeomagnetic and thermoluminescence study of a brick kiln excavated at Fontanetto Po (Vercelli, Northern Italy)

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ARTICLE INFO

Article history:

Received 9 July 2012

Received in revised form

14 November 2012

Accepted 2 December 2012

Keywords:

Rescue excavation

Archaeomagnetism

Thermoluminescence dating

Kiln

Italy

ABSTRACT

A combined archaeomagnetic and thermoluminescence study was carried out as part of a rescue archaeological excavation on a kiln discovered during the installation of methane gas pipelines beneath a rice field, along the southern border of Fontanetto Po village (Vercelli province, Italy). A total of 23 independent brick samples have been collected, oriented *in situ* with an inclinometer; the use of magnetic and sun compass was not possible due to the existence of metallic tubes beneath the kiln and a plastic cover above it. Standard archaeomagnetic procedures have been used for the determination of the archaeomagnetic inclination and absolute geomagnetic intensity. Stepwise thermal demagnetization shows a very stable characteristic remanent magnetization and the calculated mean inclination of the 23 samples is $I = 65.3^\circ$ with $\alpha_{95} = 2.4^\circ$ and $k = 156$. Archaeointensity experiments have been performed using the classical Thellier method as modified by Coe, with regular partial thermoremanent magnetization (pTRM) checks. The cooling rate and remanence anisotropy effects upon thermoremanent magnetization (TRM) have been investigated in all the specimens. A total of 19 archaeointensity determinations (at specimen level) that correspond to linear NRM–TRM plots were used for the calculation of the site mean archaeointensity that is $46.4 \pm 2.9 \mu\text{T}$. Archaeomagnetic dating results show two possible dating intervals for the last 1000 years, calculated at 95% confidence interval: a first one from 1511 to 1614 AD, and a second one from 1768 to 1872 AD. Thermoluminescence (TL) study has been also performed on two brick samples from the kiln's internal wall, using conventional laboratory procedures. According to the thermoluminescence results the kiln's last usage lies between 1796 and 1914 AD. This age is in good agreement with the second dating interval obtained by the archaeomagnetic analysis. The combined archaeomagnetic and thermoluminescence results suggest that the last firing of the kiln could have occurred between the end of the 18th century and the beginning of 20th century.

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1. Introduction

Dating of archaeological material is a key issue in the archaeological research as it can significantly contribute to determine the age and duration of the human occupation of a site and define the chronology of cultural and economic development of a certain area. A wide variety of established and newly developed archaeometric techniques can offer valuable dating tools and in some cases different techniques can be applied to the same artefacts. Archaeomagnetic and thermoluminescence dating methods can, under

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certain conditions, be applied to the same materials, like baked clays (Becker et al., 1994). There are, however, two essential requirements: the degree of ancient heating should have been sufficiently high (400–500 °C) and the material must have remained undisturbed since cooling down from its last firing.

Archaeomagnetic dating is based on the fact that many archaeological artefacts (e.g., kilns, hearths, bricks, pottery) contain magnetic particles that, 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 local 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 artefacts with reference secular variation (SV) curves that report the chronological geomagnetic field variations within a certain region (Le Goff et al., 2002; Lanos et al., 2005; Pavón-Carrasco et al., 2011).

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 reference SV curve for the given territory. In Europe, well established SV curves are available for several regions, e.g., France (Bucur, 1994; Gallet et al., 2002), Bulgaria (Kovacheva et al., 1998), Hungary (Márton and Ferencz, 2006), Germany (Schnepf and Lanos, 2005), and the Balkan Peninsula (Tema and Kondopoulou, 2011) while for Italy only a preliminary directional SV curve is available, spanning the last three thousand years (Tema et al., 2006). During the last years, great progress on geomagnetic field modelling at regional scale has been done and nowadays geomagnetic field models, able to represent the past geomagnetic field vector variation in a certain region, are available. These models can provide reference curves for a precise location (Pavón-Carrasco et al., 2009, 2010) and be used for archaeomagnetic dating (Pavón-Carrasco et al., 2011). However, since the geomagnetic field fluctuates periodically, the comparison of the experimental data with the reference curves can yield multiple potential dating intervals over several centuries; in this case, additional information based on classical archaeological evidences is essential to overcome the multiple dating problem, while comparison with another independent dating technique can confer further reliability to the results (Becker et al., 1994).

Thermoluminescence (TL) is another dating tool frequently used for age determination of archaeological artefacts (Martini and Sibilia, 2001). This technique can be applied exactly at the same materials that can be dated through archaeomagnetism (e.g., kilns, bricks, pottery) and date exactly the same event (last heating of the material). The TL techniques enable the evaluation of the time elapsed since mineral crystallised grains were last exposed to daylight or heated to a few hundred degrees Celsius (for example the heating of the walls of a kiln during its last use). Thermoluminescence dating is based on the principle that during exposure to light or heat the charges trapped in structural defects within the grains of several minerals, such as quartz and feldspar, are released (optically bleached or thermally annealed). Once the grains are sealed from daylight and remain at ordinary environmental temperatures, the charges induced by naturally occurring radioactivity due to decay processes (Preusser et al., 2008) start to accumulate in the structural defects. The quantity of charges trapped can be measured by means of thermoluminescence signal and it is proportional to the time elapsed since last bleaching or annealing. The TL dating requires the measurement of two quantities: P , that is the total accumulated absorbed radiation dose in selected minerals (so-called archaeological dose or Palaeodose)

measured in Gray (Gy), and D , that is the annual dose due to the natural radioisotope content of the sample and its surrounding environment, expressed in Gy per year. From these two measurements, the TL age can be subsequently calculated from the basic equation: $\text{Age} = P/D$.

This paper presents the combined archaeomagnetic and thermoluminescence study of a brick kiln brought into light during a rescue excavation at Fontanetto Po, Northern Italy. In parallel with archaeomagnetic and TL dating, the heating processes experienced by the bricks of the kiln's wall are studied through measurement of their magnetic properties acquired after thermal treatments. The archaeomagnetic age of the kiln was obtained using the Matlab archaeomagnetic dating tool proposed by Pavón-Carrasco et al. (2011). This tool is based on the Bayesian approach (Lanos, 2004) and uses the palaeosecular variation curves given by the regional SCHA.DIF.3K model (Pavón-Carrasco et al., 2009) at the kiln's coordinates. The obtained archaeomagnetic dating interval was further restricted after combination with the TL dating results.

2. Archaeological site and sampling

The studied kiln was discovered near to the small village of Fontanetto Po, Vercelli Province, Northern Italy (Fig. 1), at the locality called Mulino San Giovanni (45.19° N, 8.19° E). It is a large (combustion chamber dimensions: 6.40 × 4.40 m), rectangular kiln, unearched during a rescue excavation for the installation of methane gas pipelines, carried out between November 2009 and March 2010. In the vicinity of the sampled kiln, at least three other similar structures have been identified and according to the archaeologists they probably were part of an important workshop for the production of bricks in the area (Barello et al., 2012). According to an initial hypothesis, the use of the workshop could be connected to the need of a large quantity of bricks for the construction of the Fontanetto Po fortified walls, which were probably built immediately after the village's foundation in 1323 AD (Panero, 1988). Another possibility is the use of the bricks to the construction of the San Giovanni mill dated around 1460 AD; both hypothesis suggest that the kiln could have been in use during medieval times but they do not exclude the continuation of its use till more recent times. In fact, no ceramic fragments or other archaeological findings exist to permit a more precise archaeological dating of the kiln's last use. The only available information

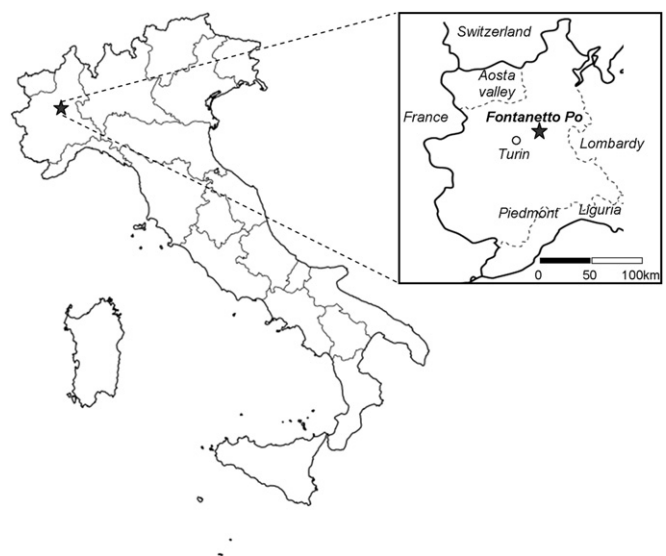


Fig. 1. Location of the Fontanetto Po kiln (45.19° N, 8.19° E).

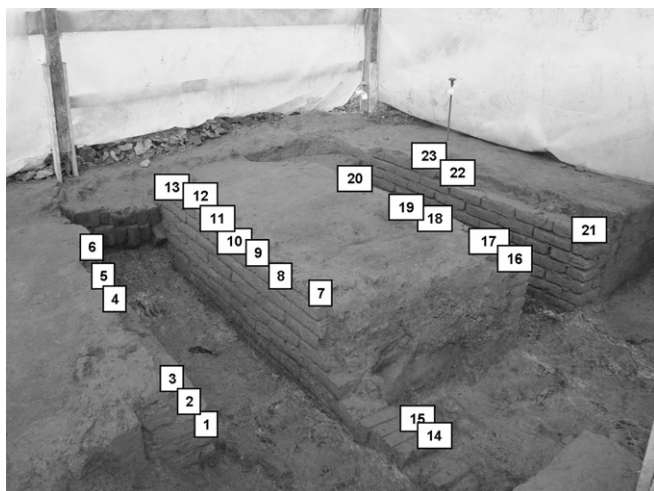


Fig. 2. Studied kiln and position of the samples.

comes from the size of the kiln's bricks ($27 \times 13 \times 7$ cm) that excludes any connection with roman times; their size and form is typical of that used during medieval times and conserved up to nowadays (Mannoni and Milanese, 1988).

The metallic methane pipelines already situated at a depth of about one meter below the structure prevented the reliable use of a magnetic compass and the wooden and plastic protection coverage mounted to protect the kiln from adverse weather conditions made impossible the use of sun compass. The archaeomagnetic study was therefore limited to archaeoinclination and archaeointensity determinations. In the laboratory, at least three cylindrical cores with standard dimensions (diameter = 25.4 mm, height = 22 mm) were drilled from each sample (named with small letters a, b, c; e.g. for sample F1 we prepared specimens F1-a, F1-b, F1-c). For few long cores it was possible to prepare more sub-specimens, e.g. F1-a1 and F1-a2. Ceramic materials extracted from two bricks have been used for TL dating.

3. Rock magnetic analysis

3.1. Magnetic mineralogy experiments

The magnetic properties of the collected bricks have been investigated in order to identify the main magnetic carriers of the samples and investigate their suitability for archaeomagnetic determinations. Isothermal remanent magnetization (IRM) acquisition curves, IRM-back field curves, thermal demagnetization of the IRM components (Lowrie, 1990) and continuous thermomagnetic curves were measured for pilot samples.

The IRM acquisition and back field curves of representative samples were investigated at the ALP Palaeomagnetic laboratory (Peveragno, Italy) with an ASC pulse magnetizer to impart the IRM, applying stepwise increasing magnetic fields up to 2 T, and a JR6 spinner magnetometer (AGICO) to measure the remanent magnetization. Thermomagnetic curves showing the variation of the magnetic moment versus temperature have been measured at INRIM (Torino) with a Vibrating Sample Magnetometer (VSM model: vector 7410 Lakeshore); thermal treatments were carried out in successive 100°C increasing temperature steps up to 800°C . Heating was directly applied in the VSM using a thermal-resistance set-up along with a constant field $H = 0.1$ T applied to the sample. The temperature dependence of low-field magnetic susceptibility from ambient temperature up to 700°C was monitored at the Palaeomagnetic Laboratory of Thessaloniki (Greece) using

a Bartington MS2B susceptibility metre in combination with a MS2WF heating unit.

3.2. Rock magnetic results

The IRM acquisition curves show that in most cases saturation is reached at applied fields of 0.1–0.4 T while in few cases samples remain unsaturated after 2 T peak field (see e.g., sample F19, Fig. 3a). The application of a back field after the 2 T peak field acquisition (Fig. 3b) evidences the dominant presence of a magnetic mineral of low remanent coercive force (around 50 mT) such as magnetite or Ti-magnetite accompanied in some cases by a high coercivity mineral, most probably haematite. Stepwise thermal demagnetization of composite IRM (Lowrie, 1990) shows a dominant low- and intermediate-coercivity components removed together with a minor high-coercivity component at temperatures around 460 – 520°C (Fig. 4a). These results confirm that low-Ti magnetite is the main ferromagnetic mineral in the samples, with the presence of minor Ti-haematite content in some samples.

Thermomagnetic curves are useful indicators of the thermal stability of baked materials and consequently of their suitability for archaeomagnetic studies. The heating and cooling curves provide evidence for a good reversibility (Fig. 4b) for most of the samples indicating that no important mineralogical changes took place during heating up to 600°C ; at higher temperatures, important modification of the ferrimagnetic constituents can occur (see Fig. 5); e.g. the deployment of haematite in the silicate matrix above 800°C .

The magnetic behaviour exhibited during experimentally controlled heating of small brick fragments (mass ~ 20 – 40 mg) extracted from samples F7, F10, F12, F18, F19, and F22 has been investigated. The samples were subsequently heated and cooled down at room temperature at 100°C increasing temperature steps, from 400°C up to 900°C . All thermomagnetic curves (Fig. 5) show a collapse of magnetization corresponding to the Curie point of magnetite and/or Ti-magnetite (~ 480 – 520°C). In few samples (e.g.

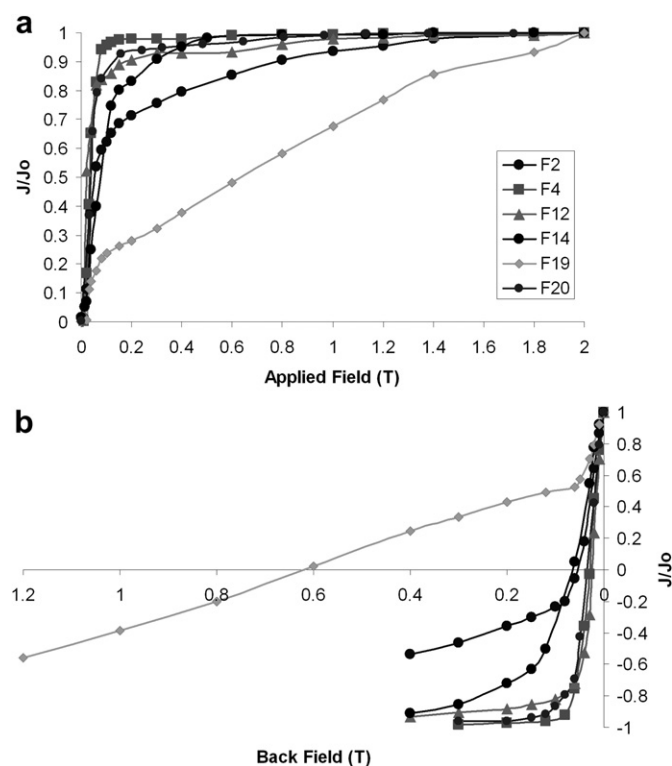


Fig. 3. a) IRM acquisition and b) IRM back-field curves of selected samples.

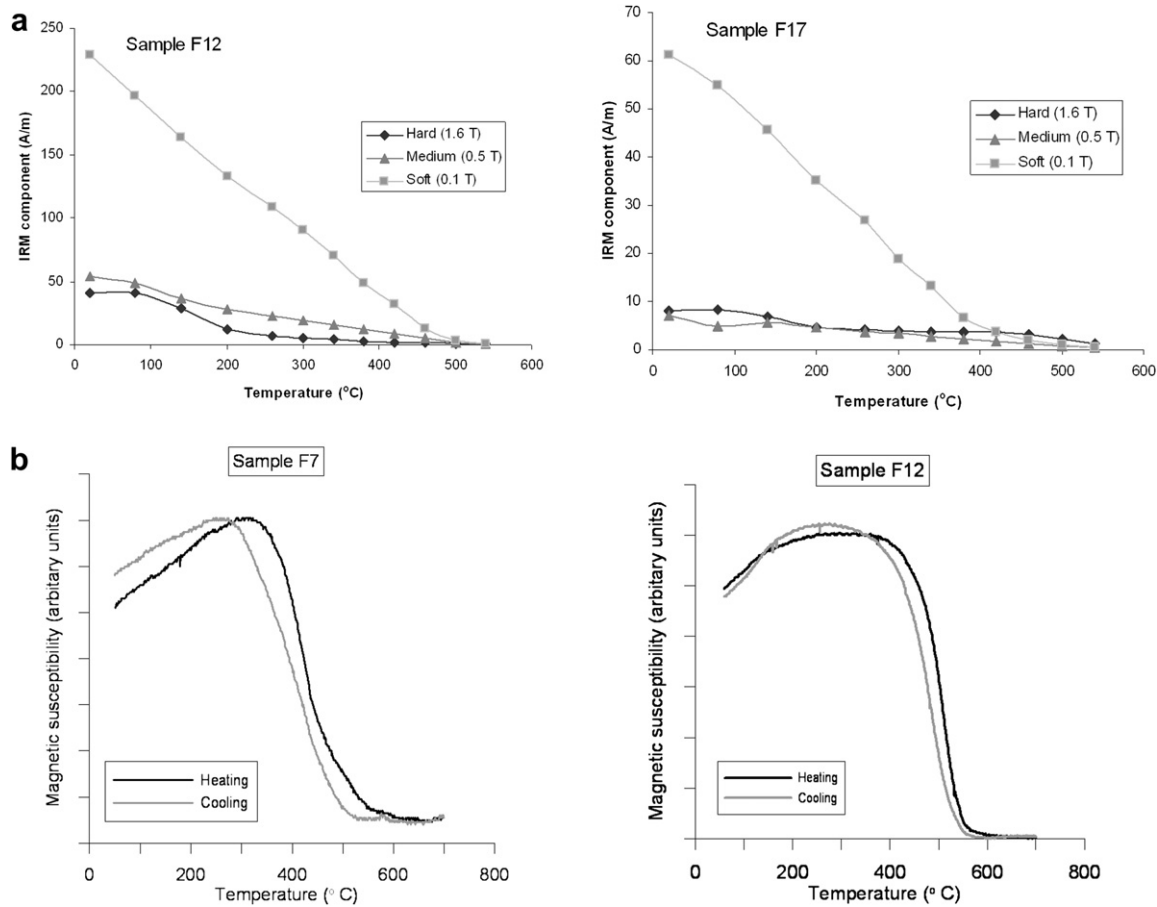


Fig. 4. a) Stepwise thermal demagnetization of three IRM components for representative samples. Symbols: square = Soft – (0.1 T); triangle = Medium – (0.5 T); diamond = Hard – (1.6 T) coercivity component; b) Representative continuous magnetic susceptibility versus temperature curves.

F22) a second Curie point at temperature around 700–750 °C can be observed indicating the presence of some haematite and/or Ti-haematite as already shown by the IRM curves. Samples F7, F10, F19 and F22 show quite stable heating–cooling curves up to temperatures of 500–600 °C while at higher temperatures important changes in their magnetization are observed. Sample F12 shows quite stable magnetic behaviour also at high temperatures (600–800 °C); on the contrary sample F18 is the less stable one, with a continuously increasing magnetization after each temperature treatment from 400 to 800 °C. These results suggest that most samples are quite stable at temperatures up to 500 °C and can be therefore used for archaeointensity determinations for which the thermal stability of the samples is an important factor for successful experiments. Few samples (e.g. F18) that show thermal unstable behaviour during heating may present low success rate during the archaeointensity experiments. The obtained thermal results also show that during the use of the kiln, all samples have experienced temperatures ranging from 500 to 700 °C, depending on their position in the kiln. Such temperatures are high enough to reset the magnetic remanence and thermoluminescence signals in the past and guarantee reliable results for both archaeomagnetic and TL dating.

4. Archaeomagnetic dating

4.1. Archaeomagnetic inclination: experiments and results

The NRM of the 23 bricks has been measured with a JR-5 spinner magnetometer at the ALP palaeomagnetic laboratory at Peveragno, Italy. Cylinder specimens drilled from the bricks have been

stepwise thermally demagnetized up to 580 °C using a TSD-2 Schonstedt furnace. Demagnetization diagrams (Fig. 6) show that the magnetic remanence is very stable and it consists of one well defined ChRM component while secondary components, if any, are easily removed at low temperature (<140 °C).

The inclination of the ChRM for each sample has been obtained from principal component analysis (Zijderveld, 1967; Kirschvink, 1980) and is reported in Table 1. Due to the missing *in situ* azimuth orientation of the samples, the declination values were not taken in consideration and the mean inclination of the 23 samples has been calculated according to Arason and Levi (2010) and is: $I = 65.3^\circ$, with uncertainty and precision parameters $\alpha_{95} = 2.4^\circ$ and $k = 156$, respectively (Table 1).

4.2. Archaeomagnetic intensity: experiments and results

Archaeointensity measurements have been carried out at the LIMNA palaeomagnetic laboratory of UNAM (Campus Morelia, Mexico). The Thellier–Coe type experiments (Thellier and Thellier, 1959; Coe, 1967) were performed with an ASC Scientific TD48-SC furnace; all heating/cooling runs were performed in air. Ten temperature steps were distributed from 250 °C to 540 °C. The direct laboratory field of $30.0 \pm 0.05 \mu\text{T}$ was applied during heating and cooling along the cylindrical axis (z) of the samples. The magnetic remanence was measured with a JR5 spinner magnetometer. Regular partial thermoremanent magnetization (pTRM) checks were done at every three temperature steps together with additional pTRM tail checks (Riisager and Riisager, 2001) performed at two intermediate temperatures (350 °C and 450 °C).

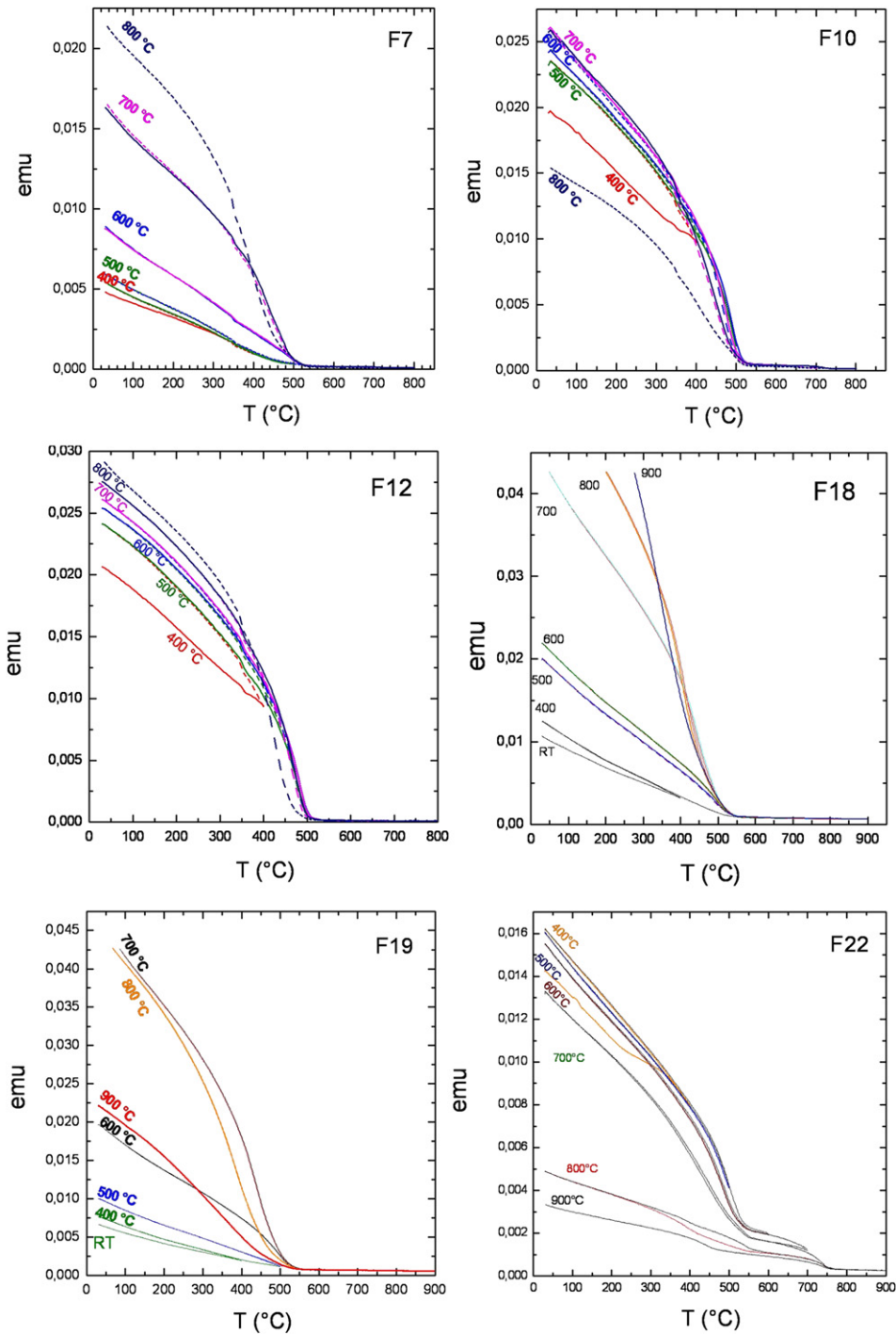


Fig. 5. Magnetization versus temperature measured using a VSM, for samples F7, F10, F12, F18, F19, and F22. Continuous thermo-magnetic curves obtained during heating and cooling the samples in the VSM.

Estimations of the original cooling time in this type of kilns, from the highest temperature (probably around 700 °C) to ambient temperature are around 6–10 h, whereas average cooling time in laboratory (using a TD48 thermal demagnetizer with fan on) ranges from 30 to 45 min; this means a difference of one order of magnitude between the natural and experimental cooling rate. According to experimental results on synthetic SD-type particles, this difference may produce an archaeointensity overestimation up to 7 percent (Fox and Aitken, 1980; McClelland-Brown, 1984). Very few studies are devoted to the cooling rate effect on the TRM

acquisition by pseudo-single-domain (PSD) grains – the most abundant magnetic grain size typology of materials in rocks and burned archaeological artifacts. It is therefore evident the need of cooling rate corrections on raw Thellier-type intensities. The cooling rate dependence of TRM was here investigated following a modified procedure to that described by Chauvin et al. (2000) (see Morales et al., 2009), using a slow cooling time of 6 h from 540 °C to 20 °C.

Measurements of the TRM anisotropy (ATRM) have been carried out at the palaeomagnetic laboratory of Géosciences Montpellier

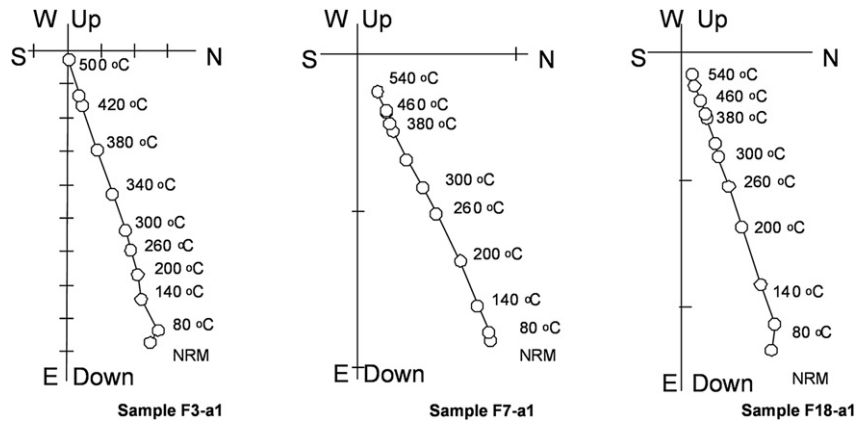


Fig. 6. Representative Zijderveld diagrams from stepwise thermal demagnetization (open dots = apparent inclination).

(France), by inducing in the sample a pTRM from 540 °C to room temperature along six directions (i.e. $+x$, $+y$, $+z$, $-x$, $-y$, $-z$) with a magnetic field of 50 μT . Zero-field thermal demagnetizations at 560 °C before each pTRM acquisition were used as a baseline. TRM tensors were measured on the same specimens used for archaeointensity determination after the last heating step. The TRM anisotropy tensor and the relative anisotropy factors for TRM anisotropy correction were then calculated following the Veitch et al. (1984)'s protocol.

Archaeointensity data were interpreted using NRM–TRM plots (Arai plots, Fig. 7). In order to be considered as reliable estimations of the ancient field, archaeointensity determinations obtained in this study have to fulfil several acceptance criteria (Morales et al., 2009):

- 1) Directions of natural remanent magnetization (NRM) end-points at each step obtained from archaeointensity experiments

Table 1

Archaeomagnetic inclination results for Fontanetto Po kiln. Columns: Sample; Temperature interval used for the calculation of the characteristic inclination (I_{ChRM}) at specimen level; Calculated inclination (I) at specimen level; I_{ChRM} = kiln's mean inclination; α_{95} = 95% semi-angle of confidence; k = precision parameter; N = number of samples; n = number of specimens. The kiln's mean value was calculated according to Arason and Levi (2010).

Sample	Temperature range (°C)	I_{ChRM} (°)
F1-a	80–500	69.1
F2-a1	80–500	71.6
F3-a1	80–500	67.2
F4-a	80–540	60.0
F5-a1	80–500	71.8
F6-a1	80–500	59.5
F7-a	80–540	61.4
F8-a1	80–540	66.1
F9-a	80–500	62.6
F10-a1	140–540	67.8
F11-a1	200–540	59.8
F12-a	100–540	60.2
F13-a1	80–540	63.0
F14-a2	80–540	63.9
F15-a1	80–540	68.6
F16-a1	80–540	67.9
F17-a1	200–540	69.9
F18-a1	80–540	67.6
F19-a	80–540	63.8
F20-a	80–500	68.3
F21-a1	80–540	69.8
F22-a2	80–540	55.9
F23-a1	80–500	57.5

Mean inclination				
$I_{\text{ChRM}} = 65.3^\circ$	$\alpha_{95} = 2.4^\circ$	$k = 156$	$N = 23$	$n = 23$

have to fall along a straight line, trending towards the origin in the interval chosen for archaeointensity determination.

- 2) No significant deviation of NRM directions towards the applied field direction should be observed, as revealed in vector (Zijderveld) plots.
- 3) A number of aligned points (N) on the NRM–pTRM diagram ≥ 5 ; specimens suspected to carry viscous remanent magnetization acquired *in situ* are rejected.
- 4) The fraction of the total extrapolated ChRM spanned by the least squares line segment (f , Coe et al., 1978) ≥ 0.3 . This means that at least 30 percent of the initial ChRM was used for archaeointensity determination (in most of our samples $f > 0.5$).
- 5) A quality factor $q = (f^*g)/\beta$ (Coe et al., 1978) ≥ 5 (generally above 10, Table 2); g is the gap factor (Coe et al., 1978) and β the relative standard deviation of the slope.
- 6) 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 (Levi, 1977; Kostrov et al., 1998).
- 7) Positive pTRM checks, i.e., the deviation of 'pTRM' checks should be less than 15%.

Evaluation of pTRM–tail checks performed at two different temperatures was in most cases lower than 20%. Seven out of 22 specimens show tail remanences at 350 °C higher than this cut off value, up to 45%. We note that MD grains may show pTRM–tails as large as 50% (Dunlop and Özdemir, 2000). At 475 °C, however, only three specimens retain tail remanences above this critical value.

Cooling rate corrections were applied to specimens, for which the corresponding change in TRM acquisition capacity was below 15% (Chauvin et al., 2000). The cooling rate procedure followed (Morales et al., 2011) provided for most of the samples cooling rate correction factors (f_{CR}) between 0.988 and 1.140, which corresponds to an overall decrease of the raw intensity values by 7% on average. In few samples the cooling rate correction factors were negative; in these cases no correction was applied (Table 2). The kiln's mean archaeointensity is $46.4 \pm 2.9 \mu\text{T}$, and was calculated from 19 specimen results (13 independent samples), after ATRM and cooling rate corrections (Table 2).

4.3. Archaeomagnetic dating results

The mean inclination and intensity values obtained for Fontanetto Po kiln have been used for the archaeomagnetic dating of the kiln after comparison with the reference secular variation curves calculated from the SCHA.DIF.3K model (Pavón-Carrasco et al., 2009).

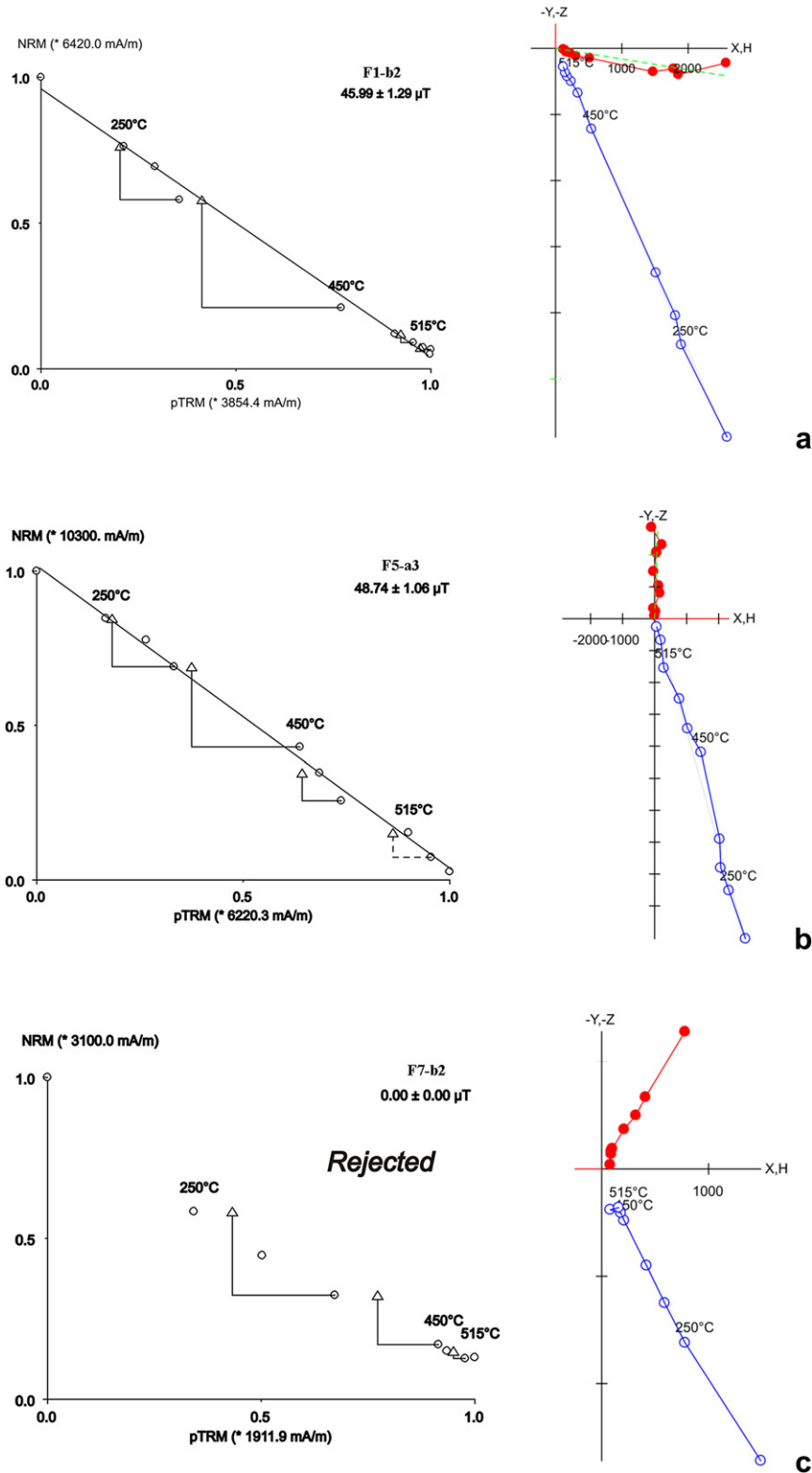


Fig. 7. Examples of NRM–TRM plots and associated Zijderveld diagrams from successful (a and b) and rejected (c) archaeointensity experiments.

The SCHA.DIF.3K is a regional archaeomagnetic model that represents the geomagnetic field variations in Europe for the last 3000 years modelling 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. The SCHA.DIF.3K model predicts the geomagnetic field

at the site of interest, avoiding this way any eventual relocation error. It also has the advantage that it can provide well-constrained palaeosecular variation curves for regions with poor coverage of archaeomagnetic data, such as Italy (Tema, 2011).

Archaeomagnetic dating of the Fontanetto Po kiln has been carried out using the Matlab *archaeo_dating* tool (Pavón-Carrasco

Table 2
Archaeointensity results at specimen level. Columns: Specimen; Palaeointensity in μT before any correction; Palaeointensity in μT after TRM anisotropy correction; Palaeointensity in μT after ATRM and cooling rate correction (at the specimens indicated with * no cooling rate correction has been applied because of cooling rate factor $\text{CR} < 0$); σ : standard deviation in μT ; T_{min}, T_{max}: minimum and maximum temperatures used for the intensity determination; N: the number of heating steps used for the intensity determination; slope: slope of the best fit; β : ratio of the standard error of the slope to the absolute value of the best-fit slope for the data on the NRM–TRM diagram; f, the fraction of NRM used for intensity determination; g: the gap factor; q: the quality factor as defined by Coe et al. (1978); MAD: Maximum angular deviation, DRAT: difference ratio as defined by Selkin and Tauxe (2000); N/R: no result; *Specimens in italics were rejected and therefore not used for the calculation of the site mean.*

Specimen	Palaeoint (μT)	Palaeoint ATRM corr	Palaeoint ATRM + CR corr	σ (μT)	T _{min} ($^{\circ}\text{C}$)	T _{max} ($^{\circ}\text{C}$)	N	Slope	β	f	g	q	Mad	Drat
F1-b2	46.0	45.1	43.9	1.3	20	560	10	−1.53	0.03	0.950	0.750	25.6	2.1	3.2
F1-c1	45.3	43.1	42.1	1.9	20	560	10	−1.51	0.04	0.900	0.740	16.2	1.5	4.3
<i>F2-b2</i>	<i>43.7</i>	<i>42.9</i>	<i>TRM₁₋₃ > 15%</i>	<i>1.7</i>	<i>20</i>	<i>560</i>	<i>10</i>	<i>−1.46</i>	<i>0.04</i>	<i>0.980</i>	<i>0.730</i>	<i>18.9</i>	<i>1.4</i>	<i>4.0</i>
F3-a2	46.1	46.9	43.9	1.3	20	515	8	−1.54	0.03	0.720	0.840	22.2	2.3	1.5
F3-c1	47.0	47.3	47.3*	2.9	20	450	5	−1.57	0.06	0.890	0.690	9.9	1.5	4.1
F5-a2	48.1	47.7	43.5	1.3	20	475	6	−1.60	0.03	0.650	0.770	18.4	3.5	1.7
F5-a3	48.7	48.1	44.4	1.1	20	560	10	−1.62	0.02	0.960	0.840	37.4	2.5	2.3
F6-a2	53.6	52.1	46.6	1.3	250	475	5	−1.78	0.02	0.520	0.660	14.5	3.0	1.5
F7-b2	N/R													
F7-c1	51.2	49.9	48.6	2.7	20	350	4	−1.71	0.05	0.550	0.490	5.1	2.7	1.9
F8-a2	53.9	53.8	48.2	2.3	20	515	8	−1.80	0.04	0.880	0.750	15.8	2.9	2.5
F9-b1	50.1	50.7	44.5	0.5	20	515	8	−1.67	0.01	0.870	0.790	71.0	1.6	2.5
F9-c1	55.5	53.8	48.9	1.8	20	515	8	−1.85	0.03	0.830	0.820	20.6	3.6	3.5
F9-c2	58.3	54.6	47.4	1.7	20	560	10	−1.94	0.03	0.960	0.850	27.7	3.8	3.7
F11-b1	49.5	48.9	43.8	1.5	20	450	5	−1.65	0.03	0.520	0.670	11.7	2.3	0.6
F12-c1	48.9	48.1	44.3	0.7	20	540	9	−1.63	0.01	0.950	0.850	56.2	1.8	1.6
F12-d	45.6	50.3	47.8	1.0	20	560	10	−1.52	0.02	0.960	0.860	39.6	1.6	1.3
<i>F16-a2</i>	<i>37.8</i>	<i>36.5</i>	<i>36.5</i>	<i>2.6</i>	<i>350</i>	<i>560</i>	<i>7</i>	<i>−1.26</i>	<i>0.07</i>	<i>0.460</i>	<i>0.510</i>	<i>3.4</i>	<i>1.2</i>	<i>14.8</i>
F17-b1	50.6	50.9	50.9*	2.4	20	350	4	−1.69	0.05	0.630	0.610	8.0	6.4	1.4
F18-c1	52.0	51.0	51.0*	0.8	20	350	4	−1.73	0.02	0.570	0.480	17.8	1.9	0.5
F19-c1	53.5	51.9	51.1	1.9	20	350	4	−1.78	0.04	0.600	0.340	5.7	3.2	0.4
F21-a2	45.8	43.6	43.6*	3.4	20	540	9	−1.53	0.07	0.970	0.750	9.9	2.8	9.5
Site mean =	50.0	49.3	46.4											
Std dev =	3.7	3.3	2.9											

et al., 2011). Inclination and intensity reference curves have been directly calculated at the geographic coordinates of Fontanetto Po and have been used for the calculation of probability density functions separately for site mean inclination and intensity values. The final dating of the kiln is obtained after the combination of the separate density functions for inclination and intensity (Fig. 8). Two possible dating intervals result for the last 1000 years calculated at 95% confidence interval: a first one from 1511 to 1614 AD, and a second one from 1768 to 1872 AD.

5. Thermoluminescence dating

Thermoluminescence (TL) dating has been carried out at the Physics Department (University of Torino). Two bricks from the internal kiln wall (samples F18 and F19; Fig. 1) have been studied applying the fine grains method (Aitken, 1985). Due to the position of the analysed bricks, the calculated thermoluminescence age is related to the kiln's last use.

5.1. Archaeological dose evaluation

The archaeological dose or palaeodose (P) is the sum of two terms: the equivalent dose (ED) and the supralinearity (I), a phenomenon that occurs at low irradiation doses, i.e., at the initial history of the sample after its fabrication (Aitken, 1985). In order to evaluate the archaeological dose, about two grams of clay have been extracted from each brick avoiding surface material. The chemical procedure described by Vieilleigne et al. (2007) was applied for sample preparation. The equivalent dose, ED, was determined using the additive dose method for multiple aliquots (Fleming, 1970); a calibrated radioactive Sr-90 beta source was used to supply the artificial dose. After irradiation, a pre-heating was performed in oven at 150 $^{\circ}\text{C}$ for 120 s to reduce the contribution to the TL signal coming from unstable traps. All thermoluminescence measurements were carried out by means of a TL2000-Ipses reader in nitrogen

atmosphere using a 10 $^{\circ}\text{C}/\text{s}$ heating rate. The measured TL glow curves for sample F19 are shown in Fig. 9. By means of the plateau test, the range 280 $^{\circ}\text{C}$ –320 $^{\circ}\text{C}$ was identified for integration and comparison of TL signals between natural and irradiated samples. In Fig. 10 the results and the linear fit for the ED calculation are shown.

In order to measure the supralinearity, a second glow analysis at low artificial irradiation doses was carried out after removing natural TL by means of a four-hour 450 $^{\circ}\text{C}$ heating in oven (Aitken, 1985).

Finally, the anomalous fading was also estimated. Sample aliquots were irradiated with 12 Gys and stored in dark at room temperature for 2 month with other aliquots not irradiated. Then the aliquots not irradiated were exposed to the same dose and the TL signals compared with aliquots irradiated 2 month before. For the samples under investigation no anomalous fading was detected. All the results of ED, I and archaeological dose for F18 and F19 are shown in Table 3.

5.2. Annual dose evaluation

The annual dose can be calculated as the sum of contributions to the dose from alpha, beta and gamma particles generated during radioactive decays. About one gram of untreated clay from each brick was employed to perform alpha decay counting by means of CALPH-Ipses apparatus. The measured radioactive activity was utilized to calculate the annual dose due to alpha particles supposing an equal contribution to the activity from uranium and thorium decay chains and applying the correction factor k (Table 3). The k -factor that depends on the material, is the efficiency of the alpha particles compared to beta particles in producing a TL signal. It was calculated comparing the measured ED values obtained respectively by means of alpha (Am-241 in vacuum) and beta particle artificial irradiations.

The measured alpha particle activity was also utilized to calculate the annual dose due to beta particles from uranium and

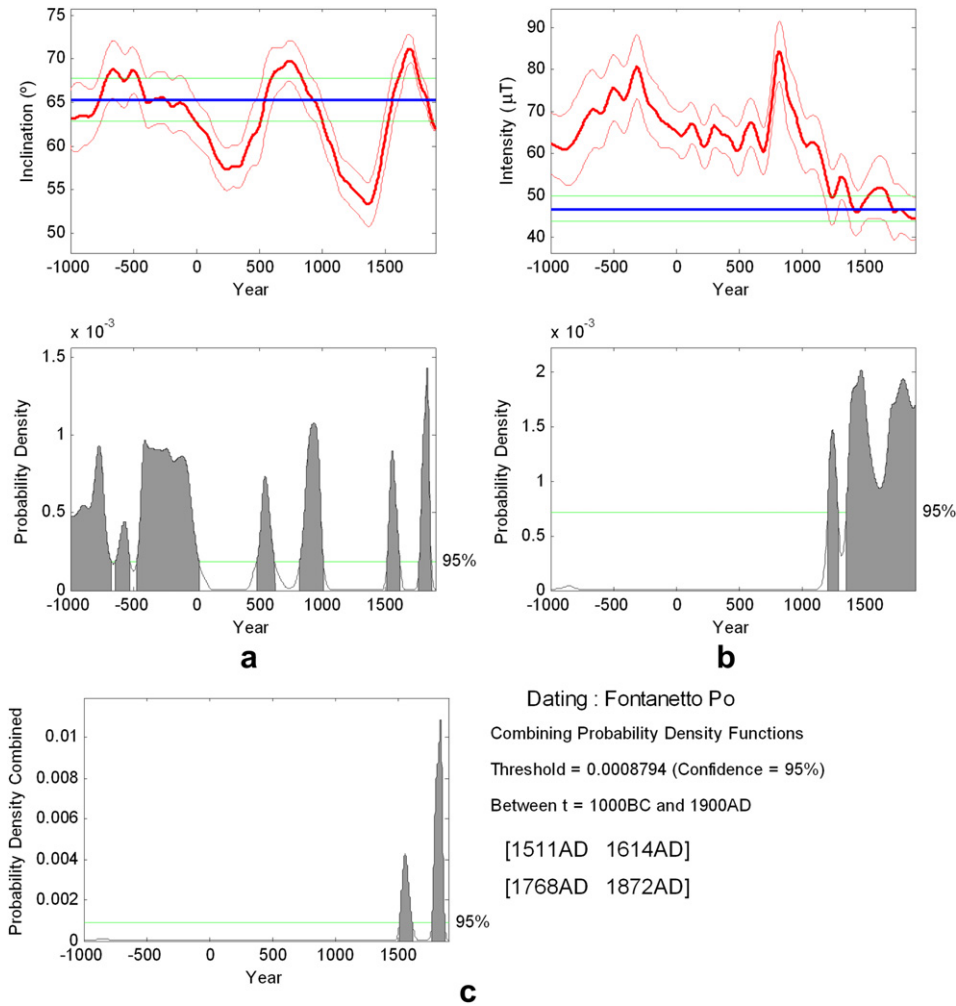


Fig. 8. Archaeomagnetic dating results obtained using the matlab *archaeo_dating* tool (Pavón-Carrasco et al., 2011). a) Up: inclination reference secular variation curve calculated from the SCHA.DIF.3K model (red curve with error band) and the kiln's measured inclination (blue line with green error band), down: calculated probability density function for inclination; b) Up: intensity reference secular variation curve calculated from the SCHA.DIF.3K model (red curve with error band) and the kiln's measured archaeointensity (blue line with green error band), down: calculated probability density function for intensity; c) combined probability density function for inclination and intensity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thorium decay chains. The beta contribution to annual dose from potassium was calculated after measuring its contents by means of ICP (Ion Coupled Plasma). Since it was not possible to carry out measurements of environmental dose *in situ*, gamma ray contribution to the annual dose was estimated by means of gamma

counting (HPGe-ORTEC detection system). Gamma ray measurements were carried out on clay and on excavated soil. In fact, as a first approximation and taking in account the position of the samples F18 and F19 (Fig. 2), it was assumed that gamma ray contribution to annual dose from the environment was given by the

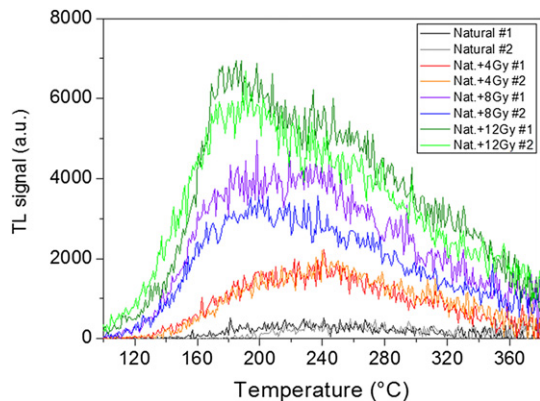


Fig. 9. Measured TL glow curves for sample F19. Beta irradiations were performed in the range 4 Gy–12 Gy. For each irradiation two samples were prepared and measured.

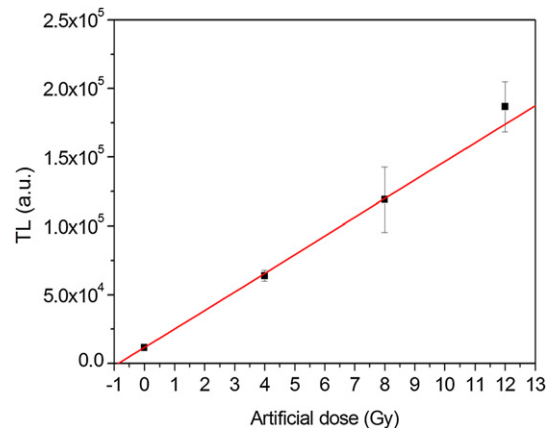


Fig. 10. Linear fit for Equivalent Dose (ED) calculation.

Table 3
Summary of the thermoluminescence dating results. No anomalous fading was recognized on F18 and F19 samples and the plateau test was successful in the range 280–320 °C. Gamma dose was estimated by means of gamma ray measurements on clay and on excavated soil.

Sample	ED (Gy)	I (Gy)	P (Gy)	Alfa counts (counts/ks)	Potassium (%)	Water (%)	k-value	Alfa dose (mGy/year)	Beta dose (mGy/year)	Gamma dose (mGy/year)	Annual dose (mGy/year)	Age (AD)
F18	0.61 ± 0.04	0.51 ± 0.05	1.12 ± 0.06	13.0 ± 0.1	0.89 ± 0.02	18 ± 1	0.29 ± 0.07	4.9 ± 1.2	1.40 ± 0.17	1.34 ± 0.35	7.6 ± 1.3	1864 ± 25
F19	0.86 ± 0.05	0.21 ± 0.07	1.07 ± 0.09	12.9 ± 0.1	0.84 ± 0.02	21 ± 1	0.24 ± 0.05	4.1 ± 1.1	1.33 ± 0.17	1.34 ± 0.35	6.8 ± 1.2	1854 ± 29

kiln bricks for half of the entire solid angle and to the soil for the remaining. A value of 1.34 ± 0.35 mGy/years was estimated.

Finally, the annual dose contributions were corrected for the bricks porosity; the environmental moisture was arbitrary considered $F = 80 \pm 20\%$ (Aitken, 1985). All the results on annual dose are summarized in Table 3.

5.3. Thermoluminescence dating results

On the basis of archaeological dose and annual dose the age of the last heating of the bricks was calculated. There is a good agreement between the values obtained for the two samples. Sample F18 is dated at $1864 \text{ AD} \pm 25$ and sample F19 at $1854 \text{ AD} \pm 29$ (Table 3). At 95% confidence interval, the proposed thermoluminescence dating of the last firing of the kiln is 1796–1914 AD. This age is in very good agreement with the second dating interval obtained by the archaeomagnetic analysis.

6. Conclusions

Archaeomagnetic study on 23 independent brick samples from the Fontanetto Po kiln yielded very well defined archaeoinclination and archaeointensity values. These values were compared with the reference curves produced by the SCHA.DIF.3K European regional geomagnetic field model and two possible dating intervals were proposed: a first one from 1511 to 1614 AD, and a second one from 1768 to 1872 AD. Further refinement of this dating was offered by the thermoluminescence study on two bricks collected from the internal kiln's wall that resulted in an age between 1796 and 1914 AD. This age is in very good agreement with the second dating interval obtained by the archaeomagnetic analysis and the combined archaeomagnetic and thermoluminescence results suggest that the last firing of the kiln has probably occurred between the end of the 18th century and the beginning of the 20th century AD. This dating does not contradict the hypothesis of the archaeologists that the kiln was constructed during medieval times but it suggests that the kiln continued to be in use till recent time. The results of this study show that the archaeomagnetic and TL dating techniques can be successfully combined and they can offer a powerful tool for precise dating of backed archaeological artefacts. Their main advantage is that they can be applied at exactly the same material and both methods date exactly the same event (the last firing of the archaeological material). Moreover, thanks to the independent dating information offered by the TL, the obtained archaeoinclination and archaeointensity values can be used as reference points in the secular variation curves and can improve our knowledge about the geomagnetic field's variations in the past. This is particularly important for older time periods for which the only source of information about the Earth's magnetic field variation is the archaeomagnetic results of well dated archaeological artefacts and/or lava flows.

Acknowledgements

The authors warmly thank Dr. Alessandro Re (National Institute of Nuclear Physics) for his help in thermoluminescence measurements

and data analysis. Evdokia Tema acknowledges the Palaeomagnetic laboratory of Thessaloniki for hospitality during the performance of the thermomagnetic experiments. Dr. Javier Pavón-Carrasco and an anonymous reviewer are highly acknowledged for their useful comments on the manuscript.

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