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# Estimate of the magnetic anisotropy effect on the 

 archaeomagnetic inclination of ancient bricksEvdokia Tema<br>Dipartimento di Scienze della Terra, Università degli Studi di Torino. Via Valperga<br>Caluso 35, 10125, Torino, Italy


#### Abstract

The magnetic fabric of 59 bricks coming from 5 ancient kilns has been studied by measuring the anisotropy of magnetic susceptibility (AMS) and the anisotropy of isothermal (AIRM), anhysteretic (AARM) and thermal (ATRM) remanent magnetization. The bricks are characterized by a well developed magnetic fabric that matches their flat shape. The shape of the anisotropy ellipsoids is in almost all cases oblate with the maximum and intermediate axes lying parallel to the large face of the brick and the minimum axis perpendicular to it. The directions of the principal axes are almost the same irrespectively of the type of anisotropy measured, whereas the degree of anisotropy of the AIRM, AARM and ATRM is much higher than the AMS. As the bricks lie horizontally within the kiln, the planar magnetic fabric results in an inclination shallowing of the archaeomagnetic direction with respect to that of the Earth's magnetic field at the time of their last cooling. Estimation of this effect on the grounds of ATRM measurements yields a shallowing that varies from $4^{\circ}$ to $10^{\circ}$ for individual samples. Such inclination difference may significantly bias archeomagnetic


dating; for the case of the Canosa late-Roman kiln it leads to a dating error of more than two centuries.

Keywords: Bricks; Magnetic fabric; Inclination error; Archaeomagnetic dating

## 1. Introduction

Archaeomagnetism is based on the principle that archaeological artifacts fired at high temperatures acquire a remanent magnetization parallel to the local geomagnetic field during their cooling. This assumption is generally true but various mechanisms can cause a bias of the recorded magnetic direction. Magnetic anisotropy is one of them. It is the preferential alignment of the magnetic grains which results in a deviation of the remanence direction with respect to the external field (Fig. 1). Several archaeomagnetic artifacts such as tiles, bricks and ceramics, may be characterized by a strong magnetic anisotropy (Rogers et al., 1979; Aitken et al., 1981; Veitch et al., 1984; Lanos, 1987; Sternberg, 1989; Yang et al., 1993; Chauvin et al., 2000; Hedley, 2001; Hus et al., 2002; 2004) that is mainly related to their mode of fabrication.

Ancient techniques for the production of bricks and tiles involved the preparation of a clay-water mixture that was extruded or molded usually as rectangular blocks. Manual pressure was usually applied in order to give the bricks a flat form. Due to the strain applied during shaping, the magnetic grains included in the clay mixture tend to be oriented parallel to the horizontal depositional surface. The azimuthal orientation of the grains is casual but their long axes preferentially lie parallel to the brick's flat surface (Fig. 1a). In these cases magnetic anisotropy is
important and highly influenced by the shape of the bricks (Hus et al., 2003). If the bricks were then placed horizontally in an archaeological structure (e.g. a kiln), the ambient magnetic field recorded by the magnetic grains would be deflected towards the direction of the long axes of the ferromagnetic particles and thus its direction would differ from that of the Earth's magnetic field (Fig. 1b). Such a bias is important for inclination while declination is less influenced; shaping strain forces magnetic particles to lie horizontally but does not control the direction of their long axis. Moreover, bricks positioned in a kiln loose the azimouthal orientation they had when manufactured, so that the preferential direction, if any, of the grain long axes within each brick is random. Any possible bias on declination is, thus, reduced by calculating the mean value of the remanence directions of a large number of samples. On the contrary, the horizontal position of the bricks in the kilns' walls or baking floor causes a systematic inclination shallowing. Such significant deviation between the inclination of the remanence vector and that of the ancient geomagnetic field has important implications on archaeomagnetic dating.

The anisotropy of magnetic susceptibility (AMS) is the most frequently used measurement of magnetic anisotropy. AMS measurements are simple and rapid and they provide a first estimation of the magnetic fabric. For strongly magnetic minerals like magnetite, titanomagnetite or titanomaghemite, AMS reflects preferential linear or planar alignment of the grains' long axes (Stephenson, 1994). However, AMS depends critically on the size of the particles; maximum susceptibility is parallel to the long axis in multi-domain (MD) grains and perpendicular to it in single-domain (SD) (Stephenson et al., 1986). Moreover, AMS is the sum of the susceptibility anisotropies of all the mineral components in a rock, including the diamagnetic and paramagnetic fractions. To avoid these effects, the anisotropy of magnetic remanence (ARM) is
increasingly being applied to magnetic fabric studies. The ARM only depends on the ferromagnetic particles which actually carry the remanence and in this case the maximum remanence is parallel to the grain's long axis irrespective of its size. The anisotropies of isothermal remanent magnetization (AIRM) and anhysteretic remanent magnetization (AARM) are currently the most common applied types of ARM, since they provide reasonably good analogues of the anisotropy of thermoremanent magnetization (ATRM), whose measurements are by far more complex and time consuming (Jackson, 1991; Potter, 2004).

In the present study, the AMS, AIRM and AARM of brick samples collected from five ancient kilns are studied. A simplified ATRM estimation involving three heating positions is proposed. The results of the different methods are compared and the magnetic anisotropy effect on the remanence inclination is calculated. The effect of inclination shallowing on archaeomagnetic dating is lastly discussed with reference to an archaeologically dated kiln.

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2. Magnetic anisotropy and remanent magnetization: Some theoretical considerations
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In the presence of a weak magnetic field, such as that of the Earth ( $\mathrm{F}<70$ $\mu \mathrm{T}$ ), the induced magnetization ( J ) is linearly related to the magnetizing field $(\mathrm{H}): \mathbf{J}=$ $\kappa \mathbf{H}$, where $\kappa$ is the magnetic susceptibility represented by a single constant in the case of isotropic materials. In contrast, materials characterized by a developed fabric are magnetically anisotropic and therefore $\kappa$ is direction-dependent and mathematically described by a second-rank symmetric tensor $\left[\mathrm{k}_{\mathrm{ij}}\right]$ :

$$
\mathbf{J}=\left[\mathrm{k}_{\mathrm{ij}}\right] \mathbf{H}
$$

This tensor is expressed by its principal eigenvalues and eigenvectors $\mathrm{k}_{\max }>\mathrm{k}_{\text {int }}>\mathrm{k}_{\text {min }}$ representing the maximum, intermediate and minimum axes of susceptibility, respectively. Similarly, the AMR may as well be described by a symmetric secondrank tensor with $\mathrm{R}_{\max }>\mathrm{R}_{\mathrm{int}}>\mathrm{R}_{\min }$ corresponding to the maximum, intermediate and minimum axes of remanence.

Magnetic anisotropy results in a deviation of the remanence direction acquired by a magnetic mineral with respect to that of the ambient field and lead to important deviations and even to infidelity of the RM record (Stephenson et al., 1986). This problem has been investigated by several authors in order to understand and estimate mathematically and experimentally the effect of magnetic anisotropy on the direction of TRM (Strangway, 1961; Uyeda et al., 1963; Stacey \& Banerjee, 1974; Coe, 1979; Veitch et al., 1984). Uyeda et al. (1963) proposed a quantitative relationship for the deviation of TRM direction due to shape anisotropy in terms of the shape demagnetizing factors and the susceptibility of induced magnetization. According to this relationship:

$$
\begin{equation*}
\tan \mathrm{I}_{\mathrm{f}}=\mathrm{P} \tan \mathrm{I}_{\mathrm{m}} \tag{1}
\end{equation*}
$$

where $I_{f}$ is the inclination of the ambient field during cooling, $I_{m}$ is the palaeomagnetic inclination recorded by the studied material and P is the degree of the anisotropy of the magnetic remanence susceptibility. Stephenson et al. (1986) comparing the anisotropy of magnetic susceptibility and remanent magnetization in rocks and minerals showed that remanence anisotropy is a more sensitive and reliable measure of the magnetic fabric. Further studies by Stephenson and Potter (1989) confirmed that AMS measurements in some cases seriously underestimate the true magnitude of anisotropy depending on the presence of MD and/or SD magnetic
grains. Jackson (1991) underlined the advantages of the magnetic remanence anisotropy for certain geological applications and suggested that the anisotropy degree of remanent magnetization should be used for correcting the directional deviations caused by anisotropy. Using artificial sediments deposited in the laboratory, Jackson et al. (1991) suggested that inclination errors in detrital remanent magnetization (DRM) may be recognized and corrected using the AARM. Potter (2004) compared the various remanence anisotropy methods and concluded that the shape of the anisotropy ellipsoid of AIRM and AARM is very close to the shape of the ATRM ellipsoid acquired in the Earth's magnetic field and is therefore a good substitute for the more complicated and more time consuming calculation of the ATRM.

Collombat et al. (1993) calculated an AARM ratio using a four position AARM method in order to correct the inclination shallowing observed in deep sea sediments. Gattacceca and Rochette (2002) measured the AMS, AARM and ATRM of pyroclastic deposits and found no general relation between the degree of AMS and AARM, while the degree of AARM and ATRM were almost identical. They concluded that a reliable correction may be applied to palaeomagnetic directions using in equation (1) the degree of the AARM.

Little literature is available on the application of anisotropy corrections to archaeomagnetic data. Several authors have applied anisotropy corrections on the determination of archaeointensities by measuring the ATRM during the Thellier experiments (Veitch et al., 1984; Yang et al., 1993; Chauvin et al., 2000; Genevey \& Gallet, 2002). Nevertheless, the deviation of the archaeomagnetic directions due to magnetic anisotropy, even if studied by several authors, very rarely has been quantified. Recently, a great number of directional archaeomagnetic data have been published for several European countries (Gallet et al., 2002; Schnepp et al., 2004;

Gomez-Paccard et al., 2006; Tema et al., 2006). Only in few cases, however, the magnetic anisotropy has been studied and anisotropy corrected directions are included in the databases, even if often systematic shallow inclinations in bricks and floor baked clay are reported (Schnepp et al., 2004). Hus et al. (2002) studied the magnetic fabric in ancient bricks showing that they are characterized by a well developed shape-related AMS and they proposed a partial AARM at 30 mT as the best substitute of the ATRM ellipsoid. In their case, however, they concluded that anisotropy is unlikely to be responsible for the discrepancy between the archaeomagnetic and presumed historical age of the studied brick kiln.

## 3. Samples and experimental procedures

A total of 59 bricks have been sampled from five archaeological kilns excavated in southern (Ascoli Satriano, Vagnari, Canosa) and central Italy (Roma 1 and Roma 2) and 246 specimens have been prepared and studied. In all cases the bricks have been oriented in situ using a magnetic and a solar compass. Hand samples have been collected and cylinders of standard size $($ diameter $=25.4 \mathrm{~mm}$, height $=22$ mm ) have then been cut in the laboratory perpendicular to the brick's flat surface; in this way the x , y axes of the specimen reference system lie within the brick's large side while the z axis is orthogonal to it. All samples are bricks coming from different parts of the kilns' walls with only exception Ascoli Satriano where the collected bricks come from the kiln's baking floor.

Magnetic mineralogy has been investigated by isothermal remanent magnetization (IRM) and back-field curves (Fig. 2a) that show the occurrence of a low-
coercivity ferromagnetic mineral (thorough discussion in Tema, 2006). Thermal demagnetization of IRM components (Lowrie, 1990) shows the dominating role of the magnetically soft fraction with unblocking temperatures ranging between 480 and 580 ${ }^{\circ} \mathrm{C}$ (Fig. 2b), pointing to magnetite and/or Ti-magnetite as the main magnetic carrier. Minor intermediate- and hard-coercivity components do not significantly contribute to the IRM. The alternating field (AF) demagnetization curves (Lowrie \& Fuller, 1971) show that the NRM and the IRM have similar coercivity distribution (Fig. 2c). At 60 to 70 mT peak field more than $90 \%$ of the NRM and IRM is canceled. The IRM acquisition plotted versus its AF demagnetization curve shows a non symmetric behavior; demagnetization curve has a steeper decay at low fields and points to the presence of PSD and/or MD grains (Cisowski, 1981). Archaeomagnetic directions are well defined with the presence of one stable component of magnetization while very minor secondary components are easily removed at low temperatures or in low peak field (Fig. 3).

The AMS of all specimens was measured with a KLY-3 Kappabridge. The principal magnetic susceptibilities and their directions were obtained with the Agico, Anisoft program and the most important anisotropy parameters: lineation $\mathrm{L}=\mathrm{k}_{\max } /$ $\mathrm{k}_{\text {int }}$, foliation $\mathrm{F}=\mathrm{k}_{\text {int }} / \mathrm{k}_{\min }$, degree of anisotropy $\mathrm{P}=\mathrm{k}_{\max } / \mathrm{k}_{\min }$, and shape factor $\mathrm{T}=[2$ $\left.\ln \left(\mathrm{k}_{\text {int }} / \mathrm{k}_{\text {min }}\right) / \ln \left(\mathrm{k}_{\max } / \mathrm{k}_{\text {min }}\right)\right]$-1, were calculated according to Jelinek (1981). The AIRM and AARM were measured for a collection of specimens. To evaluate the AIRM, specimens were first tumbling demagnetized at a 90 mT peak field, after which no or a very small residual remanence survived (Fig. 2c and Fig. 3). Following, they were given a 20 mT direct field using a PUM-1 Pulse Magnetizer and the resulting IRM was measured with a JR-6 spinner magnetometer. A 20 mT field is considered high enough for AIRM experiments on materials dominated by low-
coercivity PSD and/or MD grains (Stephenson et al., 1986; Hrouda, 2002). Specimens were then tumbling AF demagnetized at 60 mT and the IRM was given along a different direction. This operation was repeated for six different sample orientations. In each position the field was applied twice, in two opposite directions: in this way, residual remanence, if any, not erased during the preceding AF demagnetization was cancelled out by averaging the two IRM measurements. In total 12 independent measurements were made and they were used to derive the AIRM tensor. AARM determination was done in an analogous way; specimens were given an ARM using a 0.1 mT steady field produced by a small coil inside and coaxial to the AF demagnetizing coil and a 60 mT peak field. Again a 12 position procedure was followed for eliminating any residual field. The anisotropy tensor and the anisotropy parameters, P, L and F were calculated using the AREF program based on Jelinek's (1993) theory. The mean anisotropy results for each site are summarized in Table 1.

## 4. Results

### 4.1 Comparison of AMS, AIRM and AARM

Equal-area projections of the principal AMS ellipsoid axes show that in almost all cases there is a well developed magnetic fabric. The maximum and intermediate susceptibility axes lie parallel to the large face of the brick with no preferential orientation while the minimum axis is systematically perpendicular to it (Fig. 4). The shape of the AMS ellipsoid is oblate for the $95 \%$ of specimens and the anisotropy degree ranges from 1.03 to 1.16 with small variations from kiln to kiln (Fig. 5).

Measurements of AIRM and AARM show similar results. The magnetic fabric is dominated by flattening and the AIRM and AARM ellipsoids agree within few degrees with both each other and the AMS ellipsoid (Fig. 6 a,b). This agreement shows that no significant amount of SD grains does occur in the bricks. In all cases AMS and ARM results show a well developed magnetic foliation while magnetic lineation is poor (Fig. 7). In order to compare the shapes of the susceptibility and remanence ellipsoids, the normalized AMS principal axes have been plotted against the normalized AIRM and AARM principal axes (Stephenson et al., 1986). A strong linear relationship is clear and both sets of ellipsoid axes are coincident with minimum and maximum axes coinciding each other (Fig. 8 a,b). The straight lines pass through the point $(1 / 3,1 / 3)$ and have a positive slope, characteristic of anisotropic samples containing multidomain magnetite (Stephenson \& Potter, 1989). However, even if the orientations of the principal axes of the three ellipsoids are similar, the shapes of the susceptibility and remanence tensors are significantly different. The slope of the lines in the plots of AMS versus AIRM and, AMS versus AARM (Fig. $8 \mathrm{a}, \mathrm{b}$ ) is different than 1, that would indicate identical ellipsoid shapes (Stephenson et al., 1986), and clearly shows that AMS is less than AIRM and AARM. Consequently, even if AMS measurements yield a reliable orientation of the anisotropy axes, they underestimate the actual value of the anisotropy degree, which is systematically lower than the degree of the anisotropy of remanence (Fig. 6 c and Table 1).

On the other hand, the slope of the best fitting straight line between the AIRM and AARM principal axes is not far from 1, with axis intercept $p_{0}=0.094$ (fig. 8c). Even if $\mathrm{p}_{\mathrm{o}} \neq 0$, which shows that the two ellipsoids have not identical shapes, it
however indicates that they are quite similar to each other. AARM ellipsoid is slightly more anisotropic than the AIRM.

### 4.2 Results of ATRM experiments

The primary remanent magnetization acquired by baked archeological artifacts like bricks is a TRM. From this perspective the most appropriate method for investigating the magnetic fabric is the measurement of the anisotropy of the TRM. In order to determine the ATRM, specimens are heated above the Curie point of their ferromagnetic minerals and then cooled in the presence of a weak steady field. The heating-cooling cycles are repeated for different orientations in respect to the applied field (Stephenson et al., 1986). This technique however is very time consuming. Stephenson et al. (1986) have shown that the various types of remanence anisotropy measured on a specimen do share the same principal axes, and only the degree of anisotropy changes as a function of the type of remanence. In the case the orientation of the anisotropy ellipsoid of the specimen is already known, the degree of ATRM can thus be calculated from only two heatings; the steady field during cooling being applied parallel once to the maximum axis $\mathrm{R}_{\max }$ and once to the minimum axes $\mathrm{R}_{\min }$.

Seven cylindrical specimens from Roma 1 kiln have been heated up to $600^{\circ} \mathrm{C}$ in the small, non-magnetic Bartington oven (normally used to monitor magnetic susceptibility changes versus temperature), using the Earth's magnetic field at the laboratory $(\approx 44-45 \mu \mathrm{~T})$ as steady field. In order to make easier the orientation, the specimens chosen had the best match between the magnetic fabric and the brick's shape: the minimum anisotropy axis orthogonal to the bricks' flat surface and
therefore parallel to the cylinder axis, and the maximum axis parallel the bricks' flat surface and therefore orthogonal to the cylinder axis.

The oven and specimen orientation was checked using a Bartington 3-axes fluxgate magnetometer. The first heating/cooling cycle was run to give a TRM in the $\mathrm{R}_{\min }$ direction. The cylinder was fixed in an inclined position in order to have its minimum anisotropy axis oriented parallel to the laboratory magnetic field. In the second cycle, the basis of the cylinder was set vertical and parallel to the field and the cylinder rotated around its axis in order to make the field to coincide with the $R_{\max }$ direction. Following this procedure, the degree of anisotropy is given by:

$$
\mathrm{P}_{\text {ATRM }}=\mathrm{R}_{\max } / \mathrm{R}_{\min }=\mathrm{J}_{\max } / \mathrm{J}_{\min }
$$

where $J_{\min }$ and $J_{\max }$ are the remanence values measured at the end of each heating/cooling cycle.

The experiment was repeated a third time placing the specimen in the furnace with the axis of the cylinder vertical and the reference mark on its top side along the azimuthal direction measured in situ during sampling. This position is almost the same with the position that the brick had in the kiln during its last cooling, apart a small difference in magnetic declination due to secular variation.

The $\mathrm{P}_{\text {ATRM }}$ calculated for the 7 specimens ranges between $1.086<\mathrm{P}_{\text {ATRM }}<$ 1.302 with mean value $\bar{P}_{\text {ATRM }}=1.165$. Plots of the $\mathrm{P}_{\text {AMS }}$ versus the $\mathrm{P}_{\text {AIRM }}, \mathrm{P}_{\text {AARM }}$ and $P_{\text {ATRM }}$ show that the degree of remanence anisotropy is always higher than the $P_{\text {AMS }}$ (Fig. 9a), even if no systematic relationship occurs between the values of these parameters. This absence of relationship may tentatively be attributed to the contribution of different magnetic grain sizes to the anisotropy susceptibility and remanence as already noticed and discussed by Gattacceca and Rochette (2002) for the case of pyroclastic deposits. However, a better correlation occurs between the
anisotropy degrees of the different types of remanence $\mathrm{P}_{\text {AIRM }}, \mathrm{P}_{\text {AARM }}$ and $\mathrm{P}_{\mathrm{ATRM}}$ (Fig. $9 b)$. A linear correlation between IRM, ARM and TRM anisotropy has been reported by several authors and has been often suggested that AIRM and AARM measurements can efficiently substitute the more complicated ATRM measurements (Jackson et al., 1991; Gattacceca \& Rochette, 2002; Collombat et al., 1993; Hus et al., 2002).

The inclination recorded after heating with the specimen placed in the same position as it was in the kiln structure, results in interesting observations concerning the inclination deviations of TRM due to anisotropy. The inclination values recorded by the specimens are significantly lower (Table 2) than the inclination of the laboratory Earth's magnetic field namely $59-60^{\circ}$. The inclination shallowing $\Delta \mathrm{I}(\Delta \mathrm{I}=$ $\mathrm{I}_{\mathrm{m}}-\mathrm{I}_{\mathrm{f}}$, where $\mathrm{I}_{\mathrm{m}}$ is the inclination measured after the experiment and $\mathrm{I}_{\mathrm{f}}$ the inclination of the Earth's magnetic field), is for some specimens as high as $10^{\circ}$ (Table 2). The recorded inclination is in all cases significantly biased towards the horizontal plane following the planar orientation of the magnetic grains (Fig. 10). Between $\mathrm{P}_{\text {ATRM }}$ and $\Delta I$ a good correlation according to the theoretical relationship $\tan \mathrm{I}_{\mathrm{f}}=\mathrm{P} \tan \mathrm{I}_{\mathrm{m}}$, does exist (Table 2). Using the mean values in Table 2, we obtain $\mathrm{I}_{\mathrm{f}}=57.4^{\circ}$ that is in good accordance with the expected value of $59-60^{\circ}$, taking into consideration an error of few degrees due to possible errors in the orientation of the specimens.

## 5. Discussion and conclusions

During recent years great interest has been focused on archaeomagnetism as a method of reliable and accurate dating of lava flows and archaeological materials.

Great progress has also been made regarding the construction of robust reference secular variation curves as well as the mathematical approach for comparing archaeomagnetic directions to reference curves (Lanos, 2004; Lanos et al., 2005).

Bricks are often used in archaeomagnetic studies because they carry a very stable TRM, they are easy to sample and orientate, and they need no consolidation, but they may be strongly magnetically anisotropic. The systematic AMS, AIRM, AARM and ATRM measurements presented in this study reveal a well developed magnetic fabric that matches the flat shape of the bricks. Such a strong planar fabric may bias the TRM inclination of an amount of some degrees $\left(4^{\circ}\right.$ to $10^{\circ}$ in the present study), much larger than the alpha-95 values usual obtained in archaeomagnetic studies. The case of Canosa kiln is here taken as an example. It is well dated to around the $6^{\text {th }}$ century AD according to abundant archaeological evidence (Volpe et al., 2003). Moreover, all bricks were horizontally placed in the kiln's wall. The magnetic fabric does therefore systematically affect the inclination of the remanence, whereas the bias on declination may be assumed as negligible due both to the absence of a definite magnetic lineation and the casual azimuthal orientation of the bricks in the kiln walls.

The mean archaeomagnetic direction for Canosa kiln is: $\mathrm{D}=359.4^{\circ}, \mathrm{I}=51.3^{\circ}$ with $\alpha_{95}=3.1^{\circ}$ (Tema et al., 2006). If we use the mean degree of AARM ( $\mathrm{P}_{\text {AARM }}=$ 1.351) and the equation (1) to correct the inclination value we obtain $\mathrm{I}_{\text {cor }}=59.3^{\circ}$. To date this structure the French reference curve (dataset from Gallet et al. 2002, treated with Lanos algorithm, Lanos, 2004) has been used; using the Italian secular variation (SV) curve would lead to misleading results because the archaeodirection of Canosa kiln has been used as reference point for the construction of the Italian SV curve (Tema et al., 2006). D, I and $\mathrm{I}_{\text {cor }}$ have been reduced via pole method (Noel \& Batt,
1990) to Paris, where the French SV curves are referred to (Gallet et al., 2002) and compared with the D and I reference curves separately (Fig. 11a,b,c). The comparison has been done using the Bayesian statistic approach (Lanos, 2004) that allows the estimation of the calendar date interval of an archaeological feature by calculating the probability densities separately for each geomagnetic field element (declination, inclination and intensity when available) after comparison with the reference SV curves. The final dating interval is obtained by combining the separate probability densities and the most probable solution (Lanos, 2004) is calculated at $95 \%$ probability (Fig. 11c, f).

Archaeomagnetic dating of Canosa kiln using the uncorrected I value, places its last firing in the time interval 117-366 AD (Fig. 11c), that is about two centuries before the archaeological age of the structure. It is interesting to remark that the older age mainly results from the lower mean inclination recorded by the bricks studied in respect to the inclination variation given by the French SV curve for the VI century AD (Fig. 11b). The declination value, on contrary, fits well the curve (Fig. 11a). Dating the same structure using the $\mathrm{I}_{\text {corr }}$ value, results in an age around 365-615 AD, in good agreement with the archaeological age. The other two possible ages, 309 BC 103 AD and 1587-1632 AD, are a priori rejected due to the archaeological context of the site.

Comparison of the archaeomagnetic directions of the other sites (Vagnari, Ascoli Satriano, Roma 2) with the Italian archaeomagnetic data from literature (Tema et al., 2006) relocated at Paris, and the French SV curve (Fig. 12) shows similar results; the declination values fit well the curve, whilst the inclination values are lower than expected for their archaeological age. The only exception consists of Roma 1 kiln where, even if individual samples are strongly anisotropic, the different
orientation of the bricks within the kiln structure (horizontal, vertical, inclined) significantly reduces the shallowing effect (Fig. 12b).

In conclusion, this study confirms that magnetic fabric of bricks may significantly bias their archaeomagnetic directions and a method for estimating this effect on inclination values of horizontally placed bricks is proposed. AARM measurements can be used for defining the orientation of the magnetic remanence ellipsoid and all specimens, already thermally demagnetised for the determination of their characteristic remanent magnetization, can then be heated two more times. In this way the ATRM degree can be calculated and used for correcting the archaeomagnetic inclination.

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Table caption

Table 1. Mean values of bulk magnetic susceptibility and principal anisotropy parameters of AMS, AIRM and AARM of the studied sites. Symbols: $\mathrm{n} / \mathrm{N}=$ number of specimens/ number of samples; $\mathrm{L}=$ lineation; $\mathrm{F}=$ foliation; $\mathrm{P}=$ anisotropy degree; $\mathrm{T}=$ shape factor of susceptibility ellipsoid.

Table 2. Experimental results of ATRM; $\Delta I=I_{f}-I_{m} ; P_{\text {ATRM }}=R_{\max } / R_{\min }$ (see text for explanation). Specimens come from independently oriented samples from Roma 1 kiln.

## Figure captions

Fig. 1. a) Magnetic grains are aligned with their long axes parallel to the flat surface of the brick causing the record of $b$ ) a shallower inclination of remanence respecting that of the ambient field during the brick's last firing. Symbols: white ellipsoids $=$ magnetic grains; $\mathrm{I}_{\mathrm{f}},=$ Inclination of the Earth's magnetic field; $\mathrm{I}_{\mathrm{m}}=$ recorded inclination; $\mathrm{F}=$ Earth's magnetic field.

Fig. 2. a) Isothermal remanent acquisition (IRM) and back field curves; b) thermal demagnetization of IRM components. Symbols: triangle $=$ low-; square $=$ intermediate-; dot = high-coercivity component; c) IRM acquisition curve and alternating field demagnetization (AF) of the NRM and the IRM acquired in a steady
field of 1 T. Symbols: black diamond $=\mathrm{IRM}$ acquisition; black squares $=\mathrm{AF}$ demagnetization of the NRM; open squares $=\mathrm{AF}$ demagnetization of the IRM.

Fig. 3. Representative Zijderveld diagrams of thermal and AF demagnetization. Symbols: full dot $=$ declination; open dot $=$ inclination; figures: temperature $\left({ }^{\circ} \mathrm{C}\right)$ or AF peak-field (mT).

Fig. 4. Equal-area projections, in sample coordinates, of the principal axis of the AMS ellipsoids from individual samples from Ascoli, Canosa and Roma 1 and Roma 2 kilns. Symbols: light grey square $=$ maximum; grey triangle $=$ intermediate; black dot $=$ minimum axis.

Fig. 5. Plots of the shape parameter $T$, versus the anisotropy degree, $\mathrm{P}_{\text {AMS }}$ for samples from Vagnari, Ascoli, Canosa, Roma 1 and Roma 2 kilns. In almost all cases the shape of the anisotropy ellipsoids is oblate.

Fig. 6. Magnetic anisotropy results from Roma 2 kiln. a) Equal-area projections of the principal axes of AMS, AIRM and AARM ellipsoids; b) Comparison of the directions of the principal axes of AMS, AIRM and AARM ellipsoids for the specimens Tr1b and $\operatorname{Tr} 5 \mathrm{c} ; \mathrm{c}$ ) Distribution of the degrees of anisotropy $\mathrm{P}_{\text {AMS }}, \mathrm{P}_{\text {AIRM }}$ and $\mathrm{P}_{\text {AARM }}$.

Fig. 7. Magnetic lineation (L) versus magnetic foliation (F) of a) AMS, b) AARM and c) AIRM ellipsoids for samples from Roma 2 kiln.

Fig. 8. Plots of the normalized AMS principal axes versus the normalized a) AIRM and b) AARM axes. c) Plot of the normalized AIRM versus the normalized AARM principal anisotropy axes. Symbols: squares $=$ maximum, triangle $=$ intermediate and dot $=$ minimum ellipsoid axes. The star is at $(1 / 3,1 / 3)$. Results from Roma 2 kiln.

Fig. 9. a) Plots of the $P_{\text {AMS }}$ versus the $P_{\text {AIRM }}, P_{\text {AARM }}$ and $P_{\text {ATRM. }}$ b) Plots of $\mathrm{P}_{\text {AARM }}{ }^{-}$ $\mathrm{P}_{\text {AIRM }}$ (left) and $\mathrm{P}_{\text {ATRM }}-\mathrm{P}_{\text {AARM }}$ (right) for samples from Roma 1 kiln.

Fig. 10. Representation of a cylindrical brick specimen. a) Inclination, $I_{f}$, of the Earth's magnetic field, $F$; b) Inclination, $I_{m}$, of the remanence vector, R. In an anisotropic specimen, R is deflected towards the preferred direction of the magnetic grains resulting in the recording of a lower inclination, $\mathrm{I}_{\mathrm{m}}<\mathrm{I}_{\mathrm{f}}$. Symbols: white ellipsoids $=$ magnetic grains; $\mathrm{F}=$ Earth's magnetic field; $\mathrm{F}_{\mathrm{z}}, \mathrm{F}_{\mathrm{h}}=$ vertical and horizontal component of the $\mathrm{F} ; \mathrm{I}_{\mathrm{f}}=$ inclination of the Earth's magnetic field; $\mathrm{R}=$ remanent magnetization; $\mathrm{R}_{\mathrm{z}}, \mathrm{R}_{\mathrm{h}}=$ vertical and horizontal component of the remanence; $\mathrm{I}_{\mathrm{m}}=$ recorded inclination.

Fig. 11. Archaeomagnetic dating of Canosa kiln at $95 \%$ of probability level, after comparison with the French SV curves (dataset Gallet et al., 2002) using Lanos's method (Lanos, 2004). a), b) Probability densities obtained by the declination and inclination curve using $D$ and $I_{m}$ respectively, c) final dating interval obtained by combining the probability densities of (a) and (b); d), e) probability densities obtained by the declination and inclination curve, using D and the anisotropy corrected inclination, $\mathrm{I}_{\mathrm{cor}}$, f) final dating intervals after anisotropy correction obtained by
combining the probability densities of (d) and (e). The black lines represent the French SV curves with their error envelopes while the grey areas at c) and f) represent the probability density obtained from comparison with the reference curves. All data are reduced to Paris via pole method (Noel and Batt, 1990).

Fig. 12. a) Declination and b) inclination values of Italian archaeomagnetic data plotted versus the French SV curves (black line surrounded by the $95 \%$ error envelope in grey color- dataset Gallet et al., 2002). Larger black dots indicate the sites referred in this study. Declination values are in good agreement with other data with similar age while inclination values result lower than expected. All data are reduced to Paris.


Fig. 1

(a)

(b)

(c)

Fig. 2


Fig. 3


Fig. 4




Fig. 5

(b)

(c)

Fig. 6


Fig. 7

(a)

(b)

(c)

Fig. 8


Fig. 9


Fig. 10


Fig. 11

(a)

(b)

Fig. 12

|  |  | AMS |  |  |  |  | AIRM |  |  |  | AARM |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| SITE | $\left(10^{-3} \mathrm{SI}\right)$ | n/N | L | F | P | T | $n / N$ | L | F | P | $n / N$ | L | F | P |
| Vagnari | 8.350 | 32/9 | 1.025 | 1.043 | 1.069 | 0.334 | 9/3 | 1.051 | 1.123 | 1.186 |  |  |  |  |
| Ascoli | 8.649 | 25/5 | 1.020 | 1.050 | 1.071 | 0.412 | 15/5 | 1.037 | 1.107 | 1.157 |  |  |  |  |
| Canosa | 6.102 | 104/26 | 1.020 | 1.053 | 1.074 | 0.420 | 24/8 | 1.053 | 1.191 | 1.253 | 18/7 | 1.057 | 1.287 | 1.351 |
| Roma 1 | 1.923 | 53/11 | 1.015 | 1.052 | 1.069 | 0.465 | 11/11 | 1.046 | 1.061 | 1.116 | 10/10 | 1.044 | 1.070 | 1.122 |
| Roma 2 | 9.033 | 32/8 | 1.011 | 1.042 | 1.053 | 0.619 | 21/8 | 1.049 | 1.088 | 1.137 | 23/9 | 1.052 | 1.152 | 1.223 |

Table 1

| Specimen | Measured <br> inclination $\left({ }^{\circ}\right)$ | $\Delta \mathrm{I}\left({ }^{\circ}\right)$ | $\mathrm{P}_{\text {ATRM }}$ |
| :---: | :---: | :---: | :---: |
| T1d | 55.2 | -4.5 | 1.095 |
| T 2 c | 49.4 | -10.4 | 1.302 |
| T 3 c | 53.2 | -6.8 | 1.140 |
| T6c | 54.6 | -5.2 | 1.085 |
| T7b | 54.5 | -4.5 | 1.148 |
| T8c | 56.7 | -5.4 | 1.086 |
| T11c | 49.2 | -10.1 | 1.300 |
| Mean value: | 53.3 | -6.7 | 1.165 |

Table 2

