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1	Estimate of the magnetic anisotropy effect on the
2	archaeomagnetic inclination of ancient bricks
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8	
9	Abstract
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11	The magnetic fabric of 59 bricks coming from 5 ancient kilns has been studied by
12	measuring the anisotropy of magnetic susceptibility (AMS) and the anisotropy of
13	isothermal (AIRM), anhysteretic (AARM) and thermal (ATRM) remanent
14	magnetization. The bricks are characterized by a well developed magnetic fabric that
15	matches their flat shape. The shape of the anisotropy ellipsoids is in almost all cases
16	oblate with the maximum and intermediate axes lying parallel to the large face of the
17	brick and the minimum axis perpendicular to it. The directions of the principal axes
18	are almost the same irrespectively of the type of anisotropy measured, whereas the
19	degree of anisotropy of the AIRM, AARM and ATRM is much higher than the AMS.
20	As the bricks lie horizontally within the kiln, the planar magnetic fabric results in an
21	inclination shallowing of the archaeomagnetic direction with respect to that of the
22	Earth's magnetic field at the time of their last cooling. Estimation of this effect on the
23	grounds of ATRM measurements yields a shallowing that varies from 4° to 10° for
24	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 morethan two centuries.
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28 Keywords: Bricks; Magnetic fabric; Inclination error; Archaeomagnetic dating

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30 1. Introduction

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32 Archaeomagnetism is based on the principle that archaeological artifacts fired at high temperatures acquire a remanent magnetization parallel to the local 33 34 geomagnetic field during their cooling. This assumption is generally true but various 35 mechanisms can cause a bias of the recorded magnetic direction. Magnetic anisotropy 36 is one of them. It is the preferential alignment of the magnetic grains which results in 37 a deviation of the remanence direction with respect to the external field (Fig. 1). 38 Several archaeomagnetic artifacts such as tiles, bricks and ceramics, may be 39 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 40 41 al., 2000; Hedley, 2001; Hus et al., 2002; 2004) that is mainly related to their mode of 42 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

50 important and highly influenced by the shape of the bricks (Hus et al., 2003). If the 51 bricks were then placed horizontally in an archaeological structure (e.g. a kiln), the 52 ambient magnetic field recorded by the magnetic grains would be deflected towards 53 the direction of the long axes of the ferromagnetic particles and thus its direction 54 would differ from that of the Earth's magnetic field (Fig. 1b). Such a bias is important 55 for inclination while declination is less influenced; shaping strain forces magnetic 56 particles to lie horizontally but does not control the direction of their long axis. 57 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 58 59 each brick is random. Any possible bias on declination is, thus, reduced by calculating 60 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 61 62 a systematic inclination shallowing. Such significant deviation between the inclination 63 of the remanence vector and that of the ancient geomagnetic field has important 64 implications on archaeomagnetic dating.

The anisotropy of magnetic susceptibility (AMS) is the most frequently used 65 66 measurement of magnetic anisotropy. AMS measurements are simple and rapid and 67 they provide a first estimation of the magnetic fabric. For strongly magnetic minerals 68 like magnetite, titanomagnetite or titanomagnemite, AMS reflects preferential linear or planar alignment of the grains' long axes (Stephenson, 1994). However, AMS 69 70 depends critically on the size of the particles; maximum susceptibility is parallel to the 71 long axis in multi-domain (MD) grains and perpendicular to it in single-domain (SD) 72 (Stephenson et al., 1986). Moreover, AMS is the sum of the susceptibility anisotropies 73 of all the mineral components in a rock, including the diamagnetic and paramagnetic 74 fractions. To avoid these effects, the anisotropy of magnetic remanence (ARM) is

75 increasingly being applied to magnetic fabric studies. The ARM only depends on the 76 ferromagnetic particles which actually carry the remanence and in this case the 77 maximum remanence is parallel to the grain's long axis irrespective of its size. The 78 anisotropies of isothermal remanent magnetization (AIRM) and anhysteretic remanent 79 magnetization (AARM) are currently the most common applied types of ARM, since 80 they provide reasonably good analogues of the anisotropy of thermoremanent 81 magnetization (ATRM), whose measurements are by far more complex and time 82 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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91 2. Magnetic anisotropy and remanent magnetization: Some theoretical
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In the presence of a weak magnetic field, such as that of the Earth (F < 70 µT), the induced magnetization (J) is linearly related to the magnetizing field (H): J =% H, where κ 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 κ is direction-dependent and mathematically described by a second-rank symmetric tensor [k_{ij}]:

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

101 This tensor is expressed by its principal eigenvalues and eigenvectors $k_{max} > k_{int} > k_{min}$ 102 representing the maximum, intermediate and minimum axes of susceptibility, 103 respectively. Similarly, the AMR may as well be described by a symmetric second-104 rank tensor with $R_{max} > R_{int} > R_{min}$ corresponding to the maximum, intermediate and 105 minimum axes of remanence.

106 Magnetic anisotropy results in a deviation of the remanence direction acquired 107 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 108 109 problem has been investigated by several authors in order to understand and estimate 110 mathematically and experimentally the effect of magnetic anisotropy on the direction of TRM (Strangway, 1961; Uyeda et al., 1963; Stacey & Banerjee, 1974; Coe, 1979; 111 112 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 113 114 demagnetizing factors and the susceptibility of induced magnetization. According to 115 this relationship:

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$$\tan I_{\rm f} = P \tan I_{\rm m} \tag{1}$$

117 where I_f is the inclination of the ambient field during cooling, I_m is the 118 palaeomagnetic inclination recorded by the studied material and P is the degree of the 119 anisotropy of the magnetic remanence susceptibility. Stephenson et al. (1986) 120 comparing the anisotropy of magnetic susceptibility and remanent magnetization in 121 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) 122 123 confirmed that AMS measurements in some cases seriously underestimate the true 124 magnitude of anisotropy depending on the presence of MD and/or SD magnetic

125 grains. Jackson (1991) underlined the advantages of the magnetic remanence 126 anisotropy for certain geological applications and suggested that the anisotropy degree 127 of remanent magnetization should be used for correcting the directional deviations 128 caused by anisotropy. Using artificial sediments deposited in the laboratory, Jackson 129 et al. (1991) suggested that inclination errors in detrital remanent magnetization (DRM) may be recognized and corrected using the AARM. Potter (2004) compared 130 131 the various remanence anisotropy methods and concluded that the shape of the 132 anisotropy ellipsoid of AIRM and AARM is very close to the shape of the ATRM 133 ellipsoid acquired in the Earth's magnetic field and is therefore a good substitute for 134 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.

142 Little literature is available on the application of anisotropy corrections to 143 archaeomagnetic data. Several authors have applied anisotropy corrections on the determination of archaeointensities by measuring the ATRM during the Thellier 144 145 experiments (Veitch et al., 1984; Yang et al., 1993; Chauvin et al., 2000; Genevey & 146 Gallet, 2002). Nevertheless, the deviation of the archaeomagnetic directions due to 147 magnetic anisotropy, even if studied by several authors, very rarely has been 148 quantified. Recently, a great number of directional archaeomagnetic data have been 149 published for several European countries (Gallet et al., 2002; Schnepp et al., 2004;

150 Gomez-Paccard et al., 2006; Tema et al., 2006). Only in few cases, however, the 151 magnetic anisotropy has been studied and anisotropy corrected directions are included in the databases, even if often systematic shallow inclinations in bricks and floor 152 153 baked clay are reported (Schnepp et al., 2004). Hus et al. (2002) studied the magnetic 154 fabric in ancient bricks showing that they are characterized by a well developed 155 shape-related AMS and they proposed a partial AARM at 30 mT as the best substitute 156 of the ATRM ellipsoid. In their case, however, they concluded that anisotropy is 157 unlikely to be responsible for the discrepancy between the archaeomagnetic and presumed historical age of the studied brick kiln. 158

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161 **3. Samples and experimental procedures**

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163 A total of 59 bricks have been sampled from five archaeological kilns 164 excavated in southern (Ascoli Satriano, Vagnari, Canosa) and central Italy (Roma 1 165 and Roma 2) and 246 specimens have been prepared and studied. In all cases the 166 bricks have been oriented in situ using a magnetic and a solar compass. Hand samples 167 have been collected and cylinders of standard size (diameter = 25.4 mm, height = 22168 mm) have then been cut in the laboratory perpendicular to the brick's flat surface; in 169 this way the x, y axes of the specimen reference system lie within the brick's large 170 side while the z axis is orthogonal to it. All samples are bricks coming from different 171 parts of the kilns' walls with only exception Ascoli Satriano where the collected bricks come from the kiln's baking floor. 172

173 Magnetic mineralogy has been investigated by isothermal remanent 174 magnetization (IRM) and back-field curves (Fig. 2a) that show the occurrence of a low-

175 coercivity ferromagnetic mineral (thorough discussion in Tema, 2006). Thermal 176 demagnetization of IRM components (Lowrie, 1990) shows the dominating role of the magnetically soft fraction with unblocking temperatures ranging between 480 and 580 177 ^oC (Fig. 2b), pointing to magnetite and/or Ti-magnetite as the main magnetic carrier. 178 179 Minor intermediate- and hard-coercivity components do not significantly contribute to 180 the IRM. The alternating field (AF) demagnetization curves (Lowrie & Fuller, 1971) 181 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 182 acquisition plotted versus its AF demagnetization curve shows a non symmetric 183 184 behavior; demagnetization curve has a steeper decay at low fields and points to the 185 presence of PSD and/or MD grains (Cisowski, 1981). Archaeomagnetic directions are 186 well defined with the presence of one stable component of magnetization while very 187 minor secondary components are easily removed at low temperatures or in low peak 188 field (Fig. 3).

189 The AMS of all specimens was measured with a KLY-3 Kappabridge. The 190 principal magnetic susceptibilities and their directions were obtained with the Agico, Anisoft program and the most important anisotropy parameters: lineation $L = k_{max}/$ 191 k_{int} , foliation F = k_{int}/k_{min} , degree of anisotropy P = k_{max}/k_{min} , and shape factor T = [2 192 193 $\ln (k_{int}/k_{min}) / \ln (k_{max}/k_{min})$]-1, were calculated according to Jelinek (1981). The 194 AIRM and AARM were measured for a collection of specimens. To evaluate the 195 AIRM, specimens were first tumbling demagnetized at a 90 mT peak field, after 196 which no or a very small residual remanence survived (Fig. 2c and Fig. 3). Following, 197 they were given a 20 mT direct field using a PUM-1 Pulse Magnetizer and the 198 resulting IRM was measured with a JR-6 spinner magnetometer. A 20 mT field is 199 considered high enough for AIRM experiments on materials dominated by low-

200 coercivity PSD and/or MD grains (Stephenson et al., 1986; Hrouda, 2002). Specimens 201 were then tumbling AF demagnetized at 60 mT and the IRM was given along a 202 different direction. This operation was repeated for six different sample orientations. 203 In each position the field was applied twice, in two opposite directions: in this way, 204 residual remanence, if any, not erased during the preceding AF demagnetization was 205 cancelled out by averaging the two IRM measurements. In total 12 independent 206 measurements were made and they were used to derive the AIRM tensor. AARM 207 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 208 209 demagnetizing coil and a 60 mT peak field. Again a 12 position procedure was 210 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 211 212 (1993) theory. The mean anisotropy results for each site are summarized in Table 1.

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215 **4. Results**

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217 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).

224 Measurements of AIRM and AARM show similar results. The magnetic fabric 225 is dominated by flattening and the AIRM and AARM ellipsoids agree within few 226 degrees with both each other and the AMS ellipsoid (Fig. 6 a,b). This agreement 227 shows that no significant amount of SD grains does occur in the bricks. In all cases 228 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 229 230 remanence ellipsoids, the normalized AMS principal axes have been plotted against 231 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 232 233 minimum and maximum axes coinciding each other (Fig. 8 a,b). The straight lines 234 pass through the point (1/3, 1/3) and have a positive slope, characteristic of anisotropic samples containing multidomain magnetite (Stephenson & Potter, 1989). 235 236 However, even if the orientations of the principal axes of the three ellipsoids are 237 similar, the shapes of the susceptibility and remanence tensors are significantly 238 different. The slope of the lines in the plots of AMS versus AIRM and, AMS versus AARM (Fig. 8 a,b) is different than 1, that would indicate identical ellipsoid shapes 239 240 (Stephenson et al., 1986), and clearly shows that AMS is less than AIRM and AARM. 241 Consequently, even if AMS measurements yield a reliable orientation of the 242 anisotropy axes, they underestimate the actual value of the anisotropy degree, which 243 is systematically lower than the degree of the anisotropy of remanence (Fig. 6 c and 244 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 $p_0 \neq 0$, which shows that the two ellipsoids have not identical shapes, it

however indicates that they are quite similar to each other. AARM ellipsoid is slightlymore anisotropic than the AIRM.

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- 252 **4.2 Results of ATRM experiments**

The primary remanent magnetization acquired by baked archeological artifacts 253 254 like bricks is a TRM. From this perspective the most appropriate method for 255 investigating the magnetic fabric is the measurement of the anisotropy of the TRM. In 256 order to determine the ATRM, specimens are heated above the Curie point of their 257 ferromagnetic minerals and then cooled in the presence of a weak steady field. The 258 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. 259 260 Stephenson et al. (1986) have shown that the various types of remanence anisotropy 261 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 262 263 of the anisotropy ellipsoid of the specimen is already known, the degree of ATRM can 264 thus be calculated from only two heatings; the steady field during cooling being 265 applied parallel once to the maximum axis R_{max} and once to the minimum axes R_{min}.

Seven cylindrical specimens from Roma 1 kiln have been heated up to 600 °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 µT) 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' flatsurface 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 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:

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$$P_{ATRM} = R_{max} / R_{min} = J_{max} / J_{min}$$

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 P_{ATRM} calculated for the 7 specimens ranges between $1.086 < P_{ATRM} <$ 289 1.302 with mean value $\overline{P}_{ATRM} = 1.165$. Plots of the P_{AMS} versus the P_{AIRM}, P_{AARM} and 290 291 P_{ATRM} show that the degree of remanence anisotropy is always higher than the P_{AMS} 292 (Fig. 9a), even if no systematic relationship occurs between the values of these 293 parameters. This absence of relationship may tentatively be attributed to the 294 contribution of different magnetic grain sizes to the anisotropy susceptibility and 295 remanence as already noticed and discussed by Gattacceca and Rochette (2002) for 296 the case of pyroclastic deposits. However, a better correlation occurs between the

anisotropy degrees of the different types of remanence P_{AIRM}, P_{AARM} and P_{ATRM} (Fig.
9b). 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).

303 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 304 305 the inclination deviations of TRM due to anisotropy. The inclination values recorded 306 by the specimens are significantly lower (Table 2) than the inclination of the 307 laboratory Earth's magnetic field namely 59-60°. The inclination shallowing ΔI ($\Delta I =$ I_m - I_f , where I_m is the inclination measured after the experiment and I_f the inclination 308 309 of the Earth's magnetic field), is for some specimens as high as 10° (Table 2). The recorded inclination is in all cases significantly biased towards the horizontal plane 310 following the planar orientation of the magnetic grains (Fig. 10). Between PATRM and 311 ΔI a good correlation according to the theoretical relationship tan $I_f = P$ tan I_m , does 312 exist (Table 2). Using the mean values in Table 2, we obtain $I_f = 57.4^{\circ}$ that is in good 313 314 accordance with the expected value of 59-60°, taking into consideration an error of 315 few degrees due to possible errors in the orientation of the specimens.

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318 **5. Discussion and conclusions**

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320 During recent years great interest has been focused on archaeomagnetism as a 321 method of reliable and accurate dating of lava flows and archaeological materials.

322 Great progress has also been made regarding the construction of robust reference secular variation curves as well as the mathematical approach for comparing 323 archaeomagnetic directions to reference curves (Lanos, 2004; Lanos et al., 2005). 324 325 Bricks are often used in archaeomagnetic studies because they carry a very 326 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, 327 328 AARM and ATRM measurements presented in this study reveal a well developed 329 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 $(4^{\circ} \text{ to } 10^{\circ} \text{ in the present})$ 330 331 study), much larger than the alpha-95 values usual obtained in archaeomagnetic 332 studies. The case of Canosa kiln is here taken as an example. It is well dated to around the 6th century AD according to abundant archaeological evidence (Volpe et al., 333 334 2003). Moreover, all bricks were horizontally placed in the kiln's wall. The magnetic 335 fabric does therefore systematically affect the inclination of the remanence, whereas 336 the bias on declination may be assumed as negligible due both to the absence of a 337 definite magnetic lineation and the casual azimuthal orientation of the bricks in the 338 kiln walls.

The mean archaeomagnetic direction for Canosa kiln is: $D=359.4^{\circ}$, $I=51.3^{\circ}$ 339 with $\alpha_{95} = 3.1^{\circ}$ (Tema et al., 2006). If we use the mean degree of AARM (P_{AARM}= 340 1.351) and the equation (1) to correct the inclination value we obtain I_{cor} = 59.3°. To 341 342 date this structure the French reference curve (dataset from Gallet et al. 2002, treated 343 with Lanos algorithm, Lanos, 2004) has been used; using the Italian secular variation 344 (SV) curve would lead to misleading results because the archaeodirection of Canosa 345 kiln has been used as reference point for the construction of the Italian SV curve 346 (Tema et al., 2006). D, I and Icor have been reduced via pole method (Noel & Batt,

347 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 348 has been done using the Bayesian statistic approach (Lanos, 2004) that allows the 349 350 estimation of the calendar date interval of an archaeological feature by calculating the 351 probability densities separately for each geomagnetic field element (declination, inclination and intensity when available) after comparison with the reference SV 352 353 curves. The final dating interval is obtained by combining the separate probability 354 densities and the most probable solution (Lanos, 2004) is calculated at 95% 355 probability (Fig. 11c, f).

356 Archaeomagnetic dating of Canosa kiln using the uncorrected I value, places 357 its last firing in the time interval 117 - 366 AD (Fig. 11c), that is about two centuries 358 before the archaeological age of the structure. It is interesting to remark that the older 359 age mainly results from the lower mean inclination recorded by the bricks studied in 360 respect to the inclination variation given by the French SV curve for the VI century 361 AD (Fig. 11b). The declination value, on contrary, fits well the curve (Fig. 11a). Dating the same structure using the I_{corr} value, results in an age around 365 - 615 AD, 362 in good agreement with the archaeological age. The other two possible ages, 309 BC-363 364 103 AD and 1587-1632 AD, are a priori rejected due to the archaeological context of 365 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 374 375 significantly bias their archaeomagnetic directions and a method for estimating this 376 effect on inclination values of horizontally placed bricks is proposed. AARM 377 measurements can be used for defining the orientation of the magnetic remanence 378 ellipsoid and all specimens, already thermally demagnetised for the determination of 379 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 380 381 archaeomagnetic inclination.

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546	Table caption
547	
548	Table 1. Mean values of bulk magnetic susceptibility and principal anisotropy
549	parameters of AMS, AIRM and AARM of the studied sites. Symbols: n/N= number
550	of specimens/ number of samples; L = lineation; F = foliation; P = anisotropy degree;
551	T = shape factor of susceptibility ellipsoid.
552	
553	Table 2. Experimental results of ATRM; $\Delta I = I_f - I_m$; $P_{ATRM} = R_{max}/R_{min}$ (see text for
554	explanation). Specimens come from independently oriented samples from Roma 1
555	kiln.
556	
557	
558	
559	Figure captions
560	
561	Fig. 1. a) Magnetic grains are aligned with their long axes parallel to the flat surface
562	of the brick causing the record of b) a shallower inclination of remanence respecting
563	that of the ambient field during the brick's last firing. Symbols: white ellipsoids =
564	magnetic grains; $I_{f_{s}}$ = Inclination of the Earth's magnetic field; I_{m} = recorded
565	inclination; $F = Earth's$ magnetic field.
566	
567	Fig. 2. a) Isothermal remanent acquisition (IRM) and back field curves; b) thermal
568	demagnetization of IRM components. Symbols: triangle = low-; square =
569	intermediate-; dot = high-coercivity component; c) IRM acquisition curve and
570	alternating field demagnetization (AF) of the NRM and the IRM acquired in a steady

571	field of 1 T. Symbols: black diamond = IRM acquisition; black squares = AF
572	demagnetization of the NRM; open squares = AF demagnetization of the IRM.
573	
574	Fig. 3. Representative Zijderveld diagrams of thermal and AF demagnetization.
575	Symbols: full dot = declination; open dot = inclination; figures: temperature (°C) or
576	AF peak-field (mT).
577	
578	Fig. 4. Equal-area projections, in sample coordinates, of the principal axis of the AMS
579	ellipsoids from individual samples from Ascoli, Canosa and Roma 1 and Roma 2
580	kilns. Symbols: light grey square = maximum; grey triangle = intermediate; black dot
581	= minimum axis.
582	
583	Fig. 5. Plots of the shape parameter T, versus the anisotropy degree, P_{AMS} for samples
584	from Vagnari, Ascoli, Canosa, Roma 1 and Roma 2 kilns. In almost all cases the
585	shape of the anisotropy ellipsoids is oblate.
586	
587	Fig. 6. Magnetic anisotropy results from Roma 2 kiln. a) Equal-area projections of the
588	principal axes of AMS, AIRM and AARM ellipsoids; b) Comparison of the directions
589	of the principal axes of AMS, AIRM and AARM ellipsoids for the specimens Tr1b
590	and Tr5c; c) Distribution of the degrees of anisotropy P_{AMS} , P_{AIRM} and P_{AARM} .
591	
592	Fig. 7. Magnetic lineation (L) versus magnetic foliation (F) of a) AMS, b) AARM and
593	c) AIRM ellipsoids for samples from Roma 2 kiln.

595 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

- 598 dot = minimum ellipsoid axes. The star is at (1/3, 1/3). Results from Roma 2 kiln.
- 599

597

- 600 Fig. 9. a) Plots of the P_{AMS} versus the P_{AIRM}, P_{AARM} and P_{ATRM}. b) Plots of P_{AARM}-
- P_{AIRM} (left) and P_{ATRM} - P_{AARM} (right) for samples from Roma 1 kiln.
- 602

Fig. 10. Representation of a cylindrical brick specimen. a) Inclination, If, of the 603 604 Earth's magnetic field, F; b) Inclination, I_m, of the remanence vector, R. In an 605 anisotropic specimen, R is deflected towards the preferred direction of the magnetic 606 grains resulting in the recording of a lower inclination, $I_m < I_f$. Symbols: white ellipsoids = magnetic grains; F = Earth's magnetic field; F_z , F_h = vertical and 607 608 horizontal component of the F; I_f = inclination of the Earth's magnetic field; R = remanent magnetization; R_z , R_h = vertical and horizontal component of the 609 610 remanence; I_m = recorded inclination.

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- 612

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, I_{cor} , f) final dating intervals after anisotropy correction obtained by

620 combining the probability densities of (d) and (e). The black lines represent the 621 French SV curves with their error envelopes while the grey areas at c) and f) represent 622 the probability density obtained from comparison with the reference curves. All data 623 are reduced to Paris via pole method (Noel and Batt, 1990).

624

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.





(c)

Fig. 2



Fig. 3

Received to the second second







Fig. 6



Fig. 7



(c)

Fig. 8







Fig. 10



Fig. 11



(a)



(b)

Fig. 12

		AMS				AIRM			AARM					
OLITE	Bulk susceptibility			-	D				F				-	P
SILE	(10 51)	n/n	L	Г	P		n/N	L	Г	٢	n/n	L	Г	٢
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

Measured	ΔI (°)	P _{ATRM}	
inclination (°)			
55.2	- 4.5	1.095	
49.4	- 10.4	1.302	
53.2	- 6.8	1.140	
54.6	- 5.2	1.085	
54.5	- 4.5	1.148	
56.7	- 5.4	1.086	
49.2	-10.1	1.300	
53.3	-6.7	1.165	
	Measured inclination (°) 55.2 49.4 53.2 54.6 54.5 56.7 49.2 53.3	Measured ΔI (°) inclination (°) 55.2 - 4.5 49.4 - 10.4 53.2 - 6.8 54.6 - 5.2 54.5 - 4.5 56.7 - 5.4 49.2 -10.1 53.3 -6.7 -6.7	Measured inclination (°) ΔI (°) P _{ATRM} 55.2 -4.5 1.095 49.4 -10.4 1.302 53.2 -6.8 1.140 54.6 -5.2 1.085 54.5 -4.5 1.148 56.7 -5.4 1.086 49.2 -10.1 1.300 53.3 -6.7 1.165