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Open Journal of Archaeometry 2018; volume 4:7171

Archaeomagnetism of four pottery kilns in central Portugal: Implications for secular variation and dating

Michael Edwin Evans,[1]
Antonio Correia[2]

[1]Physics Department, Institute for Geophysical Research, University of Alberta, Edmonton, Canada; [2]Physics Department, Institute of Earth Sciences, University of Évora, Évora, Portugal

Abstract

We report archaeomagnetic results from four pottery kilns in Portugal which are thought to belong to the period of Roman rule (3rd Century BCE-4th Century CE). Very few details have been published to date, so this broad assignment is based on the general archaeological context at each site. Our motivation was to see if a more precise chronology could be established by means of archaeomagnetic dating. Concomitant goals were to compare these results from Portugal to their counterparts in Spain and to expand geographic coverage of the regional geomagnetic secular variation reference curve. Experimentally, all the samples behaved in a very coherent manner during progressive alternating-field demagnetization and yielded high-precision mean archaeomagnetic directions (a_{95}<3°) for each site. The results suggest that two of the kilns, Castelo de Vide and Peniche, were most likely in use during the late 1st/early 2nd centuries CE, whereas the two kilns at Seixal are somewhat younger, dating to the late 2nd to early 4th centuries CE.

Introduction

The fact that magnetic north varies as a function of time was recognized as long ago as the 17th century. This so-called secular variation is rather slow, involving time spans of centuries to millennia. This prompted early efforts to obtain pre-observatory records in the form of permanent magnetization carried by fired archaeological features. This undertaking has been pursued for well over a century, dating back at least as far as Giuseppe Folgheraiter's early studies in Italy (Folgheraiter, 1899). Sustained investigations, however, did not really get underway until the seminal work of Émile Thellier in France (Thellier, 1936), and its somewhat later counterpart in Britain (Cook and Belshé, 1958; Aitken and Weaver, 1962). Since then, a substantial body of data has been built up from several European countries including Austria (Schnepp and Lanos, 2006), Belgium (Hus and Geeraerts, 1998; Spassov *et al.*, 2008), Britain (Zananiri *et al*., 2007), Bulgaria (Kovacheva *et al*., 2014), Denmark (Abrahamsen, 1996), France (Thellier, 1981; Bucur, 1994), Germany (Schnepp and Lanos, 2005), Greece (Evans, 2006; De Marco *et al*., 2014), Hungary (Márton, 2003), and Italy (Evans and Hoye, 2005; Tema *et al*., 2006). For Spain, a few preliminary data appeared sporadically, but the first systematic compilation was published by Gómez-Paccard *et al*. (2006a). The only published archaeomagnetic directional data for Portugal were obtained from a vitrified wall at a Late Bronze Age settlement (Catanzariti *et al*., 2008). Here, we report new archaeodirectional results from four well-preserved Roman pottery kilns in central Portugal.

Materials and Methods

The kilns studied are located near the town of Castelo de Vide (kiln CD, 39.48°N, 7.40°W), at Peniche (kiln PN, 39.38°N, 9.36°W), and at Seixal (kilns QR and QS, 38.63°N, 9.10°W). Kiln CD (Figure 1) is a large rectangular (3×4 m) structure resting firmly on solid bedrock. It is in an excellent state of preservation up to the level of the firing chamber floor. Much of this perforated floor is intact, as are its supporting arches. Where it is missing, the basal parts of several arches remain in place. Kiln PN (Figure 2) is of circular construction with a diameter of 3.25 m. Three-quarters of the perforated floor, and about 1m of the firing chamber wall, remain. The underlying combustion chamber has five sturdy arches reaching a height of two metres. Peniche has been an important harbour since ancient times, and this kiln was used for the production of amphorae (Dressel 7-11 and 14, Haltern 70) destined for use in the local fishing industry. Some amphora fragments bear identifiable stamps attributed to the 1st Century CE (Cardoso *et al*., 1998). Kilns QR (Figure 3) and QS are somewhat smaller than kilns CD and PN, measuring approximately 2×3 m. Nothing remains of the firing chambers, but the combustion chambers and their access corridors are well preserved. Due to time constraints, solar bearings were not determined for samples from kiln QS. Declination is therefore unknown, but the inclination-only results obtained provide useful information. Seixal is situated on the left bank of the Tagus estuary, and the pottery finds indicate that amphorae for the fishing industry were produced in these kilns. But a wide variety of other pottery items were made here, including kitchenware, tableware, and oil lamps.

Samples from well-fired parts of the kilns were collected by bonding 2×2 cm plastic squares onto each structure at convenient points to provide a planar surface to be orientated by solar bearings and bubble-inclinometer. Once removed from the surface, the samples were carefully wrapped in kitchen paper for transport to the laboratory. If they appeared to be fragile, a coating of varnish was first applied. Typically, samples have a mass of 10 to 20 grams and are irregular in shape. In the laboratory each sample was set in plaster in a 5 cm-diameter cylindrical mould. Conventional spinner and cryogenic magnetometers cannot accept such large samples, so we used a Molspin

Correspondence: Michael Edwin Evans, Physics Department, Institute for Geophysical Research, University of Alberta, T6G 2G7, Edmonton, Canada.
Tel.: +1.7804327864.
E-mail: tedevans.evans403@gmail.com

Key words: Archaeomagnetism; Pottery kilns; Portugal.

Contributions: Both authors participated in the field work and in the writing of the manuscript. All the experimental work was carried out by MEE.

Conflict of interest: the authors declare no potential conflict of interest.

Acknowledgments: the authors would like to thank Guilherme Cardoso, Joaquim Carvalho, and Jorge Raposo, archaeologists. This work would have been impossible without their advice and generous assistance. The authors also thank Gerry Hoye for helping with Matlab

Funding: financial support provided by the Natural Sciences and Engineering Research Council of Canada and the Geophysical Centre of the University of Évora.

Received for publication: 3 April 2017.
Revision received: 30 August 2017.
Accepted for publication: 31 August 2017.

Open Journal of Archaeometry 2018; 4:7171
doi:10.4081/arc.2018.7171

large sample spinner magnetometer (Figure 4). A blank plaster sample gave no detectable signal. Magnetic stability was checked by standard progressive alternating-field (AF) demagnetization. Isothermal remanent magnetizations (IRMs) were given by means of a 2G660 Pulse Magnetizer.

Results and Discussion

Test samples from each kiln responded to AF demagnetization in a straightforward manner, decaying monotonically to the origin with little evidence of significant secondary magnetic overprints (Figure 5A). Median destructive fields (MDFs) lie in the range 15-40 mT, with significant remanence (10-20%) remaining at the highest demagnetization steps (Figure 5B). The lower coercivities can be attributed to magnetite and/or titanomagnetite, but the higher coercivities imply a contribution from hematite (Dankers, 1981). This was confirmed by IRM experiments. We use the d factor defined by Butler (1982) as d=[(IRM_{600}mT-IRM_{300}mT)/IRM_{300}mT], low values of which imply dominance of magnetite/titanomagnetite. Samples PN08, QR03 and CD07 yield values of 0.02, 0.04, and 0.14, respectively. The coercivity spectra, as reflected by MDF and d values, are

Figure 1. Kiln CD near the town of Castelo de Vide. The perforated floor of the firing chamber, and the underlying combustion chamber, are clearly visible. The basal part of the next arch supporting the (now removed) continuation of the firing chamber floor is visible in the lower right.

Figure 2. Kiln PN at Peniche. The perforated floor of the firing chamber is clearly visible. Part of this floor has collapsed, allowing the underlying combustion chamber to be seen at the lower left. The positions of some of the samples are visible as small white plastic squares.

Figure 3. Kiln QR at Seixal. Only the combustion chamber and its access corridor are preserved. The positions of some of the samples are visible as small white plastic squares. Kiln QS is essentially identical to QR and is situated 4 m to the North.

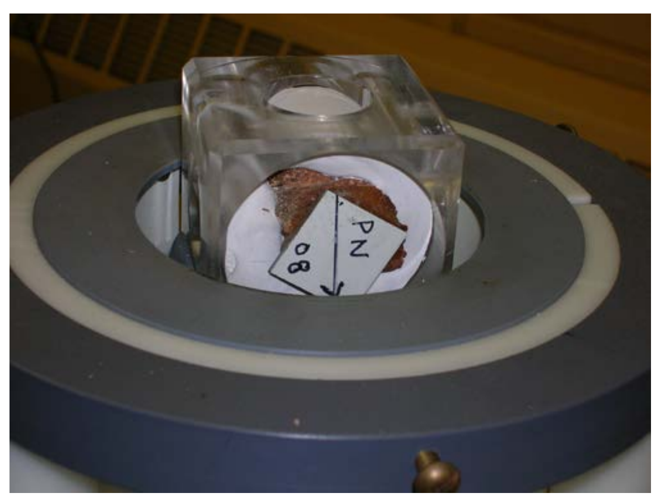

Figure 4. A typical sample being lowered into the cylindrical magnetic shield of the Molspin spinner magnetometer. The plastic square measures 2×2cm.

Table 1. Summary of archaeomagnetic results for each kiln.

Site	N	k	α_{95}	α_{63}	Ds	Is	Dm	Im	d
CD (39.48, 7.40)	12	356	2.1	1.2	–1.4	54.4	–1.0	55.3	332
PN (39.38, 9.36)	7	439	2.5	1.5	0.2	54.0	0.8	55.1	496
QR (38.63, 9.10)	8	316	2.8	1.6	–3.9	51.7	–3.2	53.3	503
QS (38.63, 9.10)	7	405	2.6	1.5	–	50.9	–	52.5	503

Site (latitude North, longitude West); N, number of samples; k, Fisher' s precision parameter; α_{95}, α_{63}, semi-angle of cone of confidence at 95% and 63% probability levels (the latter corresponds to the angular standard error); Ds, site mean declination; Is, site mean inclination; Dm, Im, after relocation to Madrid using the Virtual Geomagnetic Pole method of Noël and Batt (1990) except QS, for which the inclination was adjusted assuming a geocentric axial dipole; d, great circle distance from Madrid (km). McFadden and Reid (1982) method was used to analyse the inclination-only data from kiln QS.

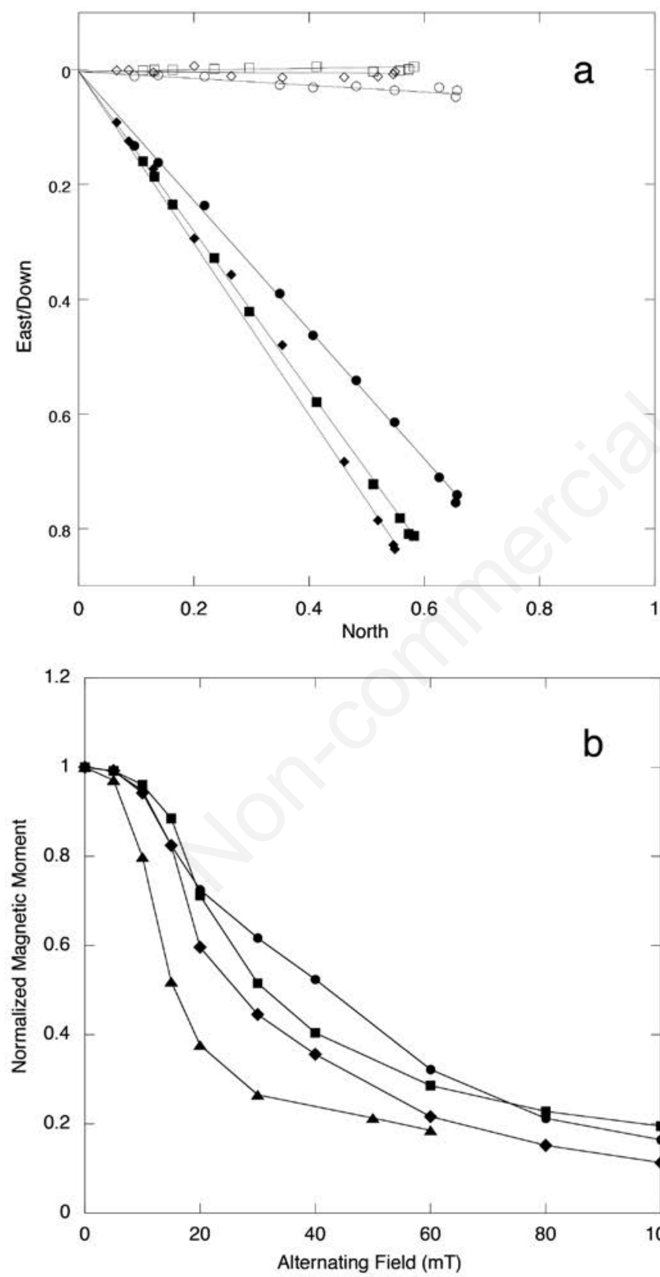

Figure 5. A) Normalized vector end-point plots for samples from kilns CD, PN, and QR. Closed (open) symbols are on the vertical (horizontal) plane; B) Corresponding normalized demagnetization curves. Squares=CD07, diamonds=PN08, circles=QR03, triangles=QS09

typical of baked archaeological materials. In a survey of 92 samples from 37 sites in Greece, Italy, North Africa, and China (including bricks, kiln wall fragments, and pottery sherds), Evans and Jiang (1996) found an MDF distribution with values of 17mT, 19mT, and 29mT for the first quartile, median, and third quartile, respectively. Corresponding values for the distribution of d are 0.02, 0.04, and 0.07.

Behaviour during AF demagnetization (vector decay plots and MDFs) parallels experience at Italian and Greek sites (Evans and Hoye, 2005; Evans, 2006). Consequently, the bulk of the samples were treated at 5, 10, and 15 mT. The site mean directions are very stable as demagnetization proceeds, movements being no more than 1 or 2 degrees. We take the data after 10 mT demagnetization as best representing the characteristic remanent magnetization, but the choice is not critical. We also found that Principal Component Analysis (PCA) (Kirschvink, 1980) yielded very similar results to our procedure. For example, by our method sample QR03 gives declination (D)=2.8° and inclination (I)=48.6°, whereas PCA on the 10-100 mT demagnetization steps yields D=2.9°, I=47.9° (maximum angular deviation=1.5°). The difference between the two methods is negligible. The site results obtained by our procedure are summarized in Table 1.

For comparison with the regional secular variation (SV) reference curve proposed by Gómez-Paccard *et al*. (2006b) these new archaeodirections are relocated to Madrid via the virtual geomagnetic pole method. The sites all lie within the 600 km *inner cir-*

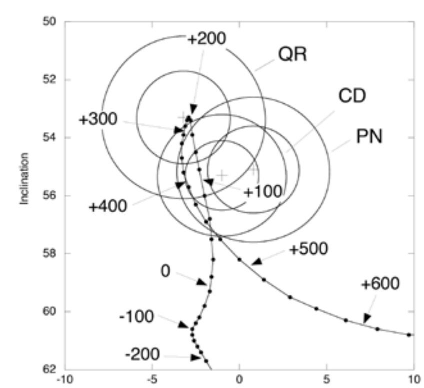

Figure 6. Archaeomagnetic directions for kilns CD, PN, and QR transposed to Madrid via the Virtual Geomagnetic Pole method. The larger (smaller) circles indicate the α_{95} (α_{63}=angular standard error) confidence cones for each kiln. The relevant part of the secular variation curve of Gómez-Paccard *et al.* (2006b) is shown. Negative (positive) dates are BCE. Equirectangular projection.

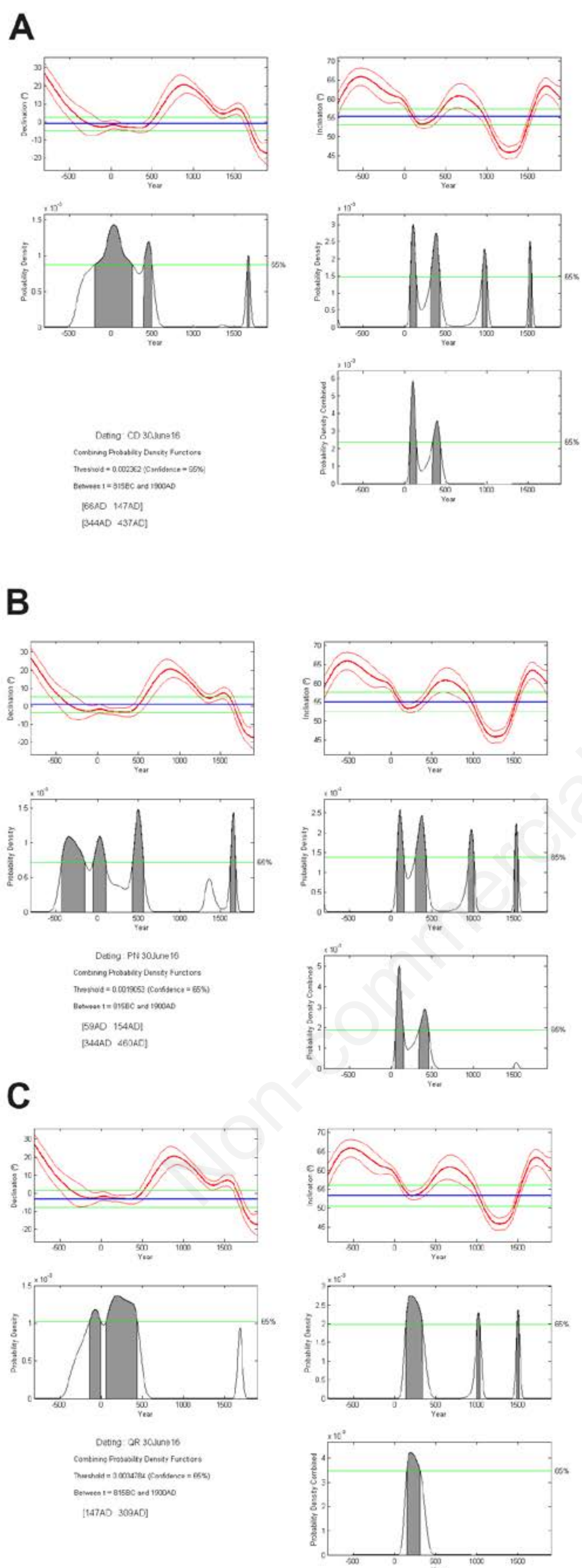

Figure 7. Probability-age density functions obtained from the Matlab tool of Pávon-Carrasco et al. (2011) for kilns A) CD, (B) PN, and C) QR.

cle of Gómez-Paccard and her co-authors. The inclination-only result for kiln QS was adjusted to Madrid on the assumption of a geocentric axial dipole. The mean archaeodirections for kilns CD, PN, and QR are shown on a rectangular plot in Figure 6. For relatively small areas, this type of plot offers a virtually distortion-free alternative to the traditional equal-area projection. No result is plotted for kiln QS because there is no associated declination value, but the inclination value (52.5°) agrees well with the other kiln at Seixal (QR). Indeed, all the kiln archaeodirections lie close to one another, with considerable mutual overlap of the associated confidence circles. The relevant part of the reference curve (from table n. 2 of Gómez-Paccard *et al*., 2006b) is also shown. The Bayesian approach used to construct the reference curve leads to irregular time intervals. For convenience, we indicate the turn of each century, with negative (positive) values being BCE (CE). The new Portuguese results support the published reference curve and expand its geographical coverage. However, the potential of archaeomagnetic dating during the Roman period is limited by the very nature of the secular variation itself. Pávon-Carrasco *et al*. (2011) point out that this restricted geomagnetic change severely limits the ability of modern computational schemes (including their own) to provide high-resolution dates for Roman sites. This is not a new problem, it merely shows that what was true of, say, the earlier French data (Thellier, 1981) is also true for the modern Iberian data. Nevertheless, a common-sense approach – that the best estimate for the age of an archaeological feature corresponds to the point on the reference curve that is closest to its mean direction – suggests that kilns CD and PN date to about 100 CE, whereas kiln QR dates to about 200 CE. The mathematical procedure of Pávon-Carrasco *et al*. (2011) confirms these visual assessments and provides quantitative estimates of their associated uncertainty. The probability peaks and 65% age brackets are virtually identical for CD and PN. For CD, the peak occurs at 103 CE, with brackets of 66-147 CE (Figure 7A). For PN, the corresponding values are 102 CE and 59-154 CE (Figure 7B). The peak for QR occurs at 196 CE, with a wider range (147-309 CE) due to the fact that the geomagnetic field was essentially stationary for the whole of the 3rd century (Figure 7C). The repetitive nature of the SV curve leads to the appearance of smaller peaks near 400 CE for kilns CD and PN. While these later dates cannot be rejected as formal possibilities, their acceptance would lead to the awkward difficulty of why the earlier peaks – which are twice as high – should be ignored. More archaeological information could potentially settle the matter. Currently, the only relevant evidence available are the amphora stamps at Peniche. These favour the earlier date.

Conclusions

Archaeodirectional results are reported from four Roman kilns at three sites in central Portugal. All samples exhibit excellent demagnetization characteristics, and the kiln means are tightly constrained (95% confidence limits ≤2.8°, angular standard errors ≤1.6°). These robust results support the published regional secular variation reference curve, and extend its geographic coverage. They imply that the kilns at Castelo de Vide and Peniche were both in operation during the late 1st/early 2nd centuries CE, whereas those at Seixal date between the late 2nd and earliest 4th centuries CE.

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