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# An archaeomagnetic investigation of a Roman amphorae workshop in Albinia (Italy)

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## SUMMARY

An intensive archaeomagnetic investigation of an Italian Roman amphorae workshop has been carried out in order to produce high quality data to enhance the European archaeomagnetic database. Additionally, and importantly, this study also investigates within and between structure variations and, the influence of anisotropy and cooling rate corrections. Eighty-six oriented samples were taken from five kilns for full geomagnetic vector (directions and intensity) determination. Additionally, cores from 39 amphorae found at the site were drilled for archaeointensity analysis. The site is archaeologically dated as being between 2nd century BC and 1st century AD, and the amphorae as being 1st century BC. A full suite of rock magnetic experiments were carried out which indicate the samples' suitability for archaeointensity experiments. The classical Thellier method with correction for anisotropy of thermal remanence (TRM) was used to determine the direction of the characteristic remanence and the archaeointensity. Differences between fast and slow cooling during remanence acquisition were investigated and a cooling rate correction applied to the archaeointensity estimates. After correction for anisotropy of TRM, the scatter about the kiln (amphorae) mean value is reduced and the scatter between kilns is also reduced for both directions and archaeointensity, demonstrating the necessity of carrying out the anisotropy of TRM correction for these samples. Application of the cooling rate correction results in a decrease in archaeointensity as expected on theoretical grounds for single domain grains. The correction, whilst not reducing scatter in the mean archaeointensity results, does result in a reduction in the scatter found between the kilns. The directional results are compared to the French, and a preliminary Italian, secular variation (SV) curve and suggest that the kilns may be towards the older limit of the archaeologically given age however the master curves are not well constrained in this time interval. Instead, the five new directional data should be used to help constrain future curves. The Albinia archaeointensity data are consistent with the broad trends seen in the limited high quality Western European and Mesopotamian data sets and with the newly constructed archaeointensity SV curve for Greece. Similar to other studies whilst the archaeointensity results for each kiln (the amphorae) are well constrained (4–7 per cent scatter about the mean) variations are seen between the kilns (mean archaeointensity 62–70 μT). This further supports the suggestion that it is necessary to obtain a number of archaeointensity data for each time

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interval in order to reliably record variations of the Earth's magnetic field from archaeological material. The archaeointensity result for the set of amphorae which has the better constrained age falls within the archaeointensity values from the kilns. Combining the results from the five kilns and the amphorae gives a mean archaeointensity of 64 ± 3 μT at Albinia (69 ± 3 μT relocated to Paris) during 200 BC–100 AD.

**Key words:** archaeointensity, archaeomagnetism, Italy, Roman.

## INTRODUCTION

High quality, full geomagnetic vector data are needed to fully describe the evolution of the Earth's magnetic field. Burnt archaeological material that has remained *in situ* since the last heating event, such as kilns and hearths, are ideal recorders for the last few millennia. Geomagnetic field models, such as that of Korte & Constable (2005) now include intensity as well as directional information. Whilst these models are rapidly improving, it is recognised that many more data are needed for a complete description of the field and hence a complete understanding of field processes. Regional directional secular variation (SV) curves for archaeomagnetic dating have been constructed and are continually being developed (e.g. France Gallet *et al.* 2002; Germany Schnepp & Lanos 2005). However, there are still many regions that lack data and there is a general lack of archaeointensity data. The global archaeointensity database for the last 7000 yr (Korte *et al.* 2005) contains only 3138 individual archaeointensity data points of variable quality, compared to 16 000 inclination data.

Italy has a limited archaeomagnetic data set despite its rich archaeological past. A preliminary directional secular variation curve for Italy going back to 1300 BC has recently been constructed by Tema *et al.* (2006) using Bayesian statistical modelling of 74 individual data points. The data come from new data presented in their paper, the work of Evans & Hoye (2005), a number of published studies from single sites by various authors plus excavation reports. In addition to burnt archaeological material, the Italian volcanoes of Mt. Etna, Mt. Vesuvius and Mt. Arso also provide suitable material for archaeomagnetic study (e.g. Incoronato *et al.* 2002; Tanguy *et al.* 2003). However, whilst the ages of some flows are very precisely known (e.g the 79 AD eruption of Mt. Vesuvius) and have been included in the preliminary SV curve, there is significant uncertainty surrounding others. In fact, archaeomagnetism has been used in order to date some of the flows by making comparisons to other Italian data and the French secular variation curve (e.g. Principe *et al.* 2004).

There are only three published studies (Evans 1986, 1991; Hedley & Wagner 1991) that contain Italian archaeointensity data derived from archaeological material. Archaeointensity investigations have also been carried out using Etna lava flows (Tanguy 1975; Rolph & Shaw 1986) however as already mentioned there is uncertainty regarding the ages of some flows. Additionally, the very recent Etna lava flows can be notoriously problematic for determining archaeointensity (e.g. Haag *et al.* 1995; Calvo *et al.* 2002).

This study presents an intensive full geomagnetic vector (directions and intensity) study of five kilns from a first millennium BC Tuscan Roman amphorae workshop along with an archaeointensity study of a set of 39 amphorae. These new results enhance the European archaeointensity data set and will contribute to the future refinement of the preliminary directional secular variation curve for Italy.

## SITE AND SAMPLING

A Roman centre for wine amphorae production is located near to the present town of Albinia (Community of Orbetello, Province of Grosseto), Tuscany, Italy (latitude 42°30′N longitude 11°12′E) (Fig. 1). Production was on a large scale in order to transport the

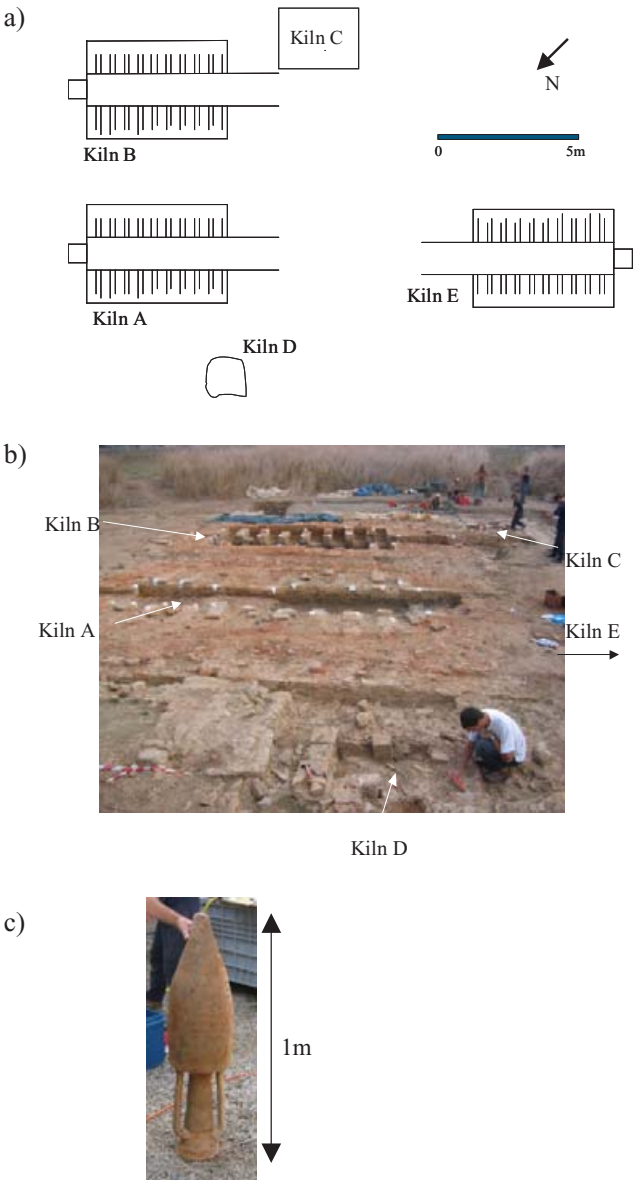



**Figure 1.** The site at Albinia with the location of Kilns A, B, C, D and E indicated (a) rough plan (b) photograph and (c) one of the amphora (upside down) from which a core was drilled from its base.

filled amphorae by boat from the nearby coast (Olmer & Vitali 2002; Vitali *et al.* 2005). Excavations have so far revealed at least six kilns as well as amphorae of type Greek-Italic, Dressel 1 and Dressel 2/4. The amphorae typology dates the site as being second century BC to first century AD (Vitali in press; Benquet & Mancino in press). Hundreds of almost intact amphorae of type Dressel 1 were found lying horizontally in the ground to aid drainage (Vitali *et al.* 2005). Cores were drilled from the base of 39 of these amphorae for archaeointensity study (Fig. 1c). The selected amphorae were of type Dressel 1b (archaeologically dated as being first century BC) and all contain the same stamp (AE) indicating that they were manufactured by the same person.

Five kilns (identified here as kilns A, B, C, D and E) were sampled (see Figs 1a and b). Kilns A, B and E are large rectangular kilns (approximately 5 m × 4 m), kiln C is also rectangular but smaller (approximately 1 m × 1.5 m) and kiln D is a small round kiln (diameter approximately 1 m). There are no strict stratigraphic constraints between the kilns however kiln B is presumed older than kiln A as it is at the same level as a kiln (un sampled) found beneath kiln A.

Large oriented block samples (approximately 15 $cm^3$) were taken from the five kilns. The samples were taken from bricks making up the sides of the kilns. Samples were oriented by placing plaster hats on the top surface (levelled horizontal using a bubble) and oriented using a sun compass. A circular saw was used to remove the block samples. A total of 86 oriented samples were taken (eight to 30 samples per kiln). Back in the laboratory at the Université Rennes 1 one oriented standard palaeomagnetic core was drilled from each block sample. This core was then sub sampled to provide a sample for Thellier archaeointensity analysis and material for rock magnetic measurements.

## ROCK MAGNETISM

A variable field translation balance (MMVFTB) at the University of Liverpool was used to measure isothermal remanent magnetisation (IRM) acquisition curves, back field coercivity, hysteresis loops and Curie curves, in order to determine rock magnetic properties. 118 out of the 125 samples were investigated (all samples except four amphorae samples and three from kiln A). There is no evidence for a high coercivity material such as haematite with all samples saturating by 300 mT during IRM acquisition and all hysteresis loops closing. Hysteresis properties along with the multi domain (MD) + single domain (SD) magnetite mixing curves of Dunlop (2002a,b) are plotted on a Day plot (Day *et al.* 1977) in Fig. 2(a). The samples lie close to, or above, SD + MD mixing curve 3. Samples lying away from the mixing curves indicate the presence of super paramagnetic (SP) grains or that the main magnetic mineral is not magnetite. Examples of Curie curves are shown in Fig. 2(b). 75 per cent of samples exhibit a single high temperature, near magnetite, Curie temperature, 11 per cent a single Curie temperature less than 500°C and, 14 per cent contain both a low and a high Curie temperature. In all cases the heating and cooling curves are similar indicating that the samples are stable to heating to a temperature of 700 °C. The rock magnetic experiments suggest that the dominant magnetic mineral is either titanomagnetite with varying amounts of titanium, stable substituted maghaemite or Al substituted magnetite (e.g. Dunlop & Özdemir 1997).

The kilns show heterogeneous behaviour which is also seen in the variability in the colour of the samples (grey to red). The amphorae on the other hand are much more homogenous both in colour (red) and rock magnetic properties. From the rock magnetic characteristics all samples appear suitable for archaeointensity experiments.

## EXPERIMENTAL METHODS

The classical Thellier method (Thellier & Thellier 1959) with partial thermal remanent magnetisation (pTRM) checks was used. Samples were heated and cooled in an MMTD oven and remanence was measured with a Molspin spinner magnetometer at the Université Rennes 1. Progressive thermal demagnetisation information was obtained as part of the Thellier experiment so that directional and intensity

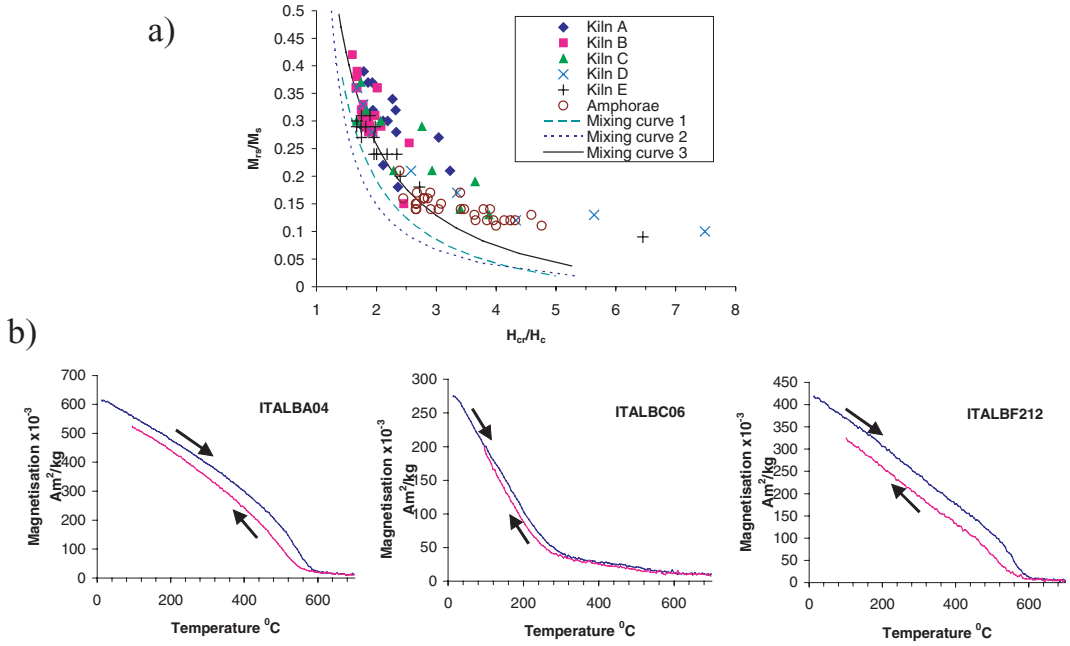



**Figure 2.** Rock magnetic properties (a) Hysteresis properties plotted on a Day plot (Day *et al.* 1977) along with the Dunlop mixing curves 1, 2 and 3 (Dunlop 2002a,b) (b) three examples of Curie curves from left to right from Kiln A, C and an amphora. Arrows indicate heating and cooling curves.

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information was obtained from the same sample simultaneously. The field in the oven was set (at 50 or 60 μT) along the long ($Z$) axis of the sample and left on throughout the whole experiment. Samples were heated twice at each temperature with the samples rotated 180° between the two heating steps. Between 10 and 16 temperature steps were carried out until less than 10 per cent of the original remanence remained. PTRM checks were carried out, at a minimum, after every other heating step. Room temperature bulk susceptibility was measured after each heating step as an additional check for alteration. PTRM checks were deemed acceptable if they differed by no more than 10 per cent of the total TRM.

The manufacture of archaeological baked material often results in magnetic anisotropy (Rogers *et al.* 1979). The TRM anisotropy tensor and thus appropriate correction factor was determined for each sample by comparing remanence acquired in six perpendicular orientations (Veitch *et al.* 1984; Chauvin *et al.* 2000). In core coordinates these were the $+Z$, $-Z$, $+X$, $-X$, $+Y$, and $-Y$ directions. The anisotropy experiments were carried out when approximately 30 per cent of the NRM remained following Chauvin *et al.* (2000). To check for alteration, an additional heating step was carried out at the end of the six anisotropy heating steps with the sample in the same orientation as for the first remanence acquisition step ($+Z$). If the difference in the remanence was more than 15 per cent (and could not be accounted for by measurement error) then the anisotropy correction was not deemed reliable and the sample rejected from further analysis.

Cooling rate experiments were carried out on all samples using custom built ovens at the Université Rennes 1 to investigate the differences in remanence acquisition between the fast cooling used in the laboratory Thellier experiments and the slower cooling used when the original remanence was acquired (e.g. Fox & Aitken 1980; Chauvin *et al.* 2000). A slow, linear cooling time of around 24 hr was chosen to approximate the natural cooling. The exact length of slow cooling is not critical as has been demonstrated by Genevey *et al.* (2003) and Gómez-Paccard *et al.* (2006). Samples were heated to a temperature 5–15°C higher than their last heating for the Thellier experiment and subjected to four heating steps. The applied field ($F_{\mathrm{lab}}$) was the same as that used for the Thellier experiment. The heating steps were as follows:

(1) Applied field $+F_{\mathrm{lab}}$, natural cooling in about 1.5 hr inducing remanence T1.

(2) Applied field $-F_{\mathrm{lab}}$, natural cooling in about 1.5 hr inducing remanence T2.

(3) Applied field $+F_{\mathrm{lab}}$, cooling time of approximately 24 hr inducing remanence T3.

(4) Applied field $-F_{\mathrm{lab}}$, natural cooling in about 1.5 hr inducing remanence T4.

By comparing steps (1) and (3) the cooling rate correction $T_{\mathrm{cor}}$ was evaluated, and comparing steps (2) and (4) provides a reproducibility (alteration) check $T_{\mathrm{check}}$.

$T_{\mathrm{cor}} = (\mathrm{T3} - \mathrm{T1})/\mathrm{T1}$ and $T_{\mathrm{check}} = (\mathrm{T4} - \mathrm{T2})/\mathrm{T2}$.

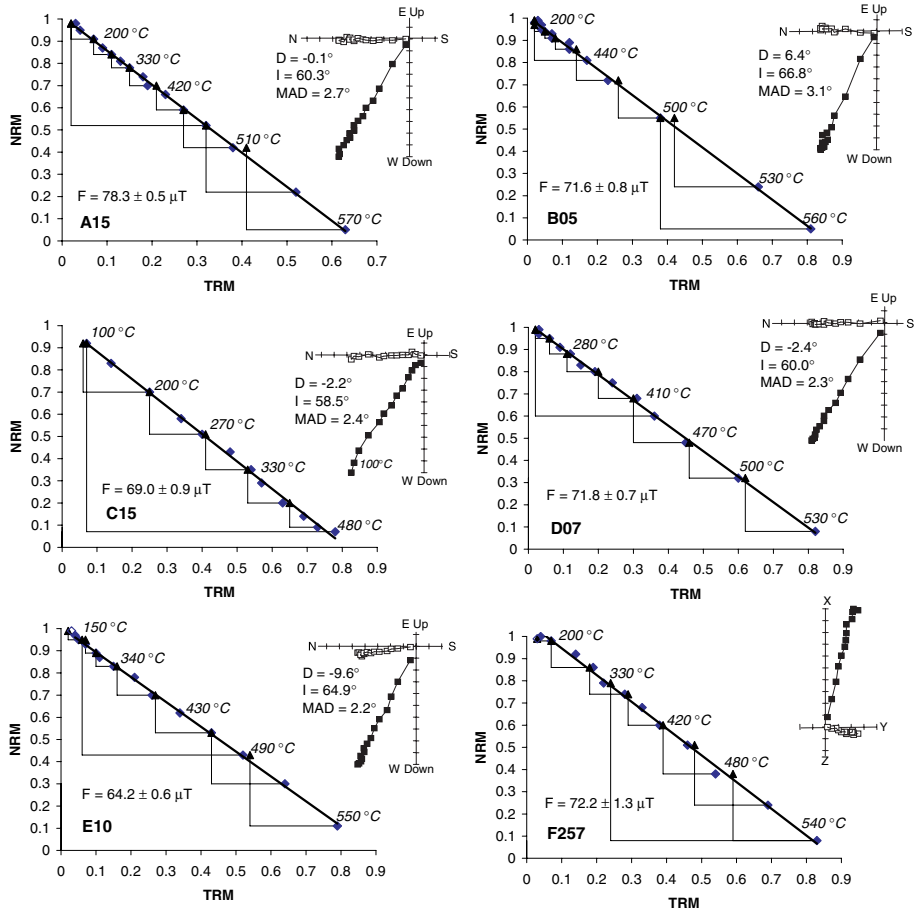



**Figure 3.** Examples of NRM/TRM plots and orthogonal vector plots (OVP) where solid (open) symbols represent vertical (horizontal) projections. One example from each kiln is given plus sample F257 which is an amphora sample (hence OVP in core coordinates).

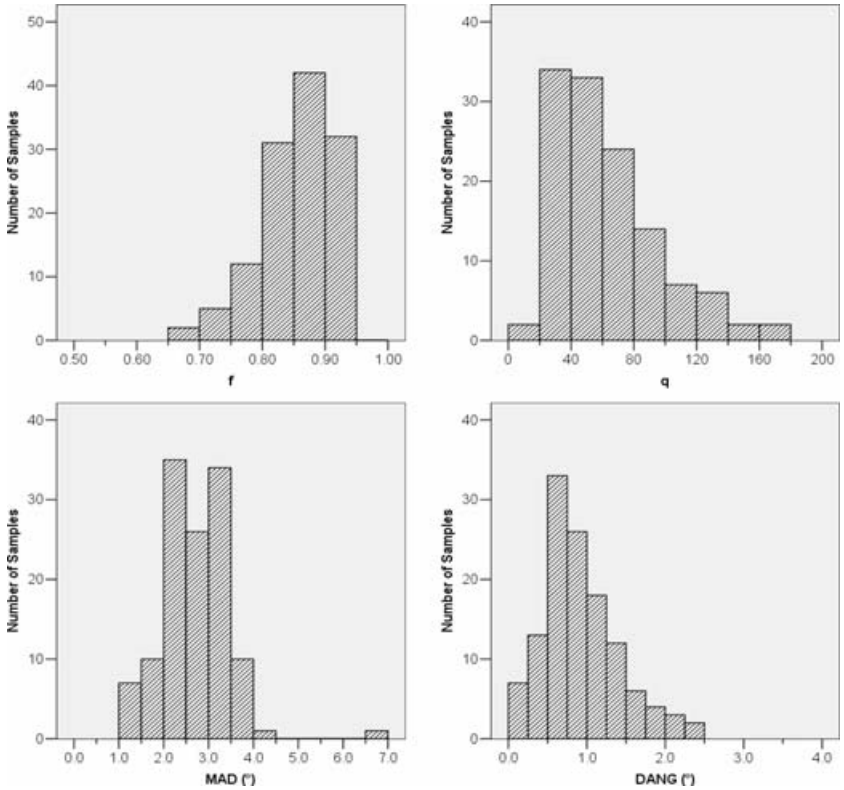



**Figure 4.** Histograms of selected quality parameters for the 124 samples, f the NRM fraction used to define the best straight line on the NRM/TRM plot, q the palaeointensity quality parameter as defined by Coe *et al.* (1978), the maximum angular deviation MAD and the deviation angle DANG of the best fit direction.

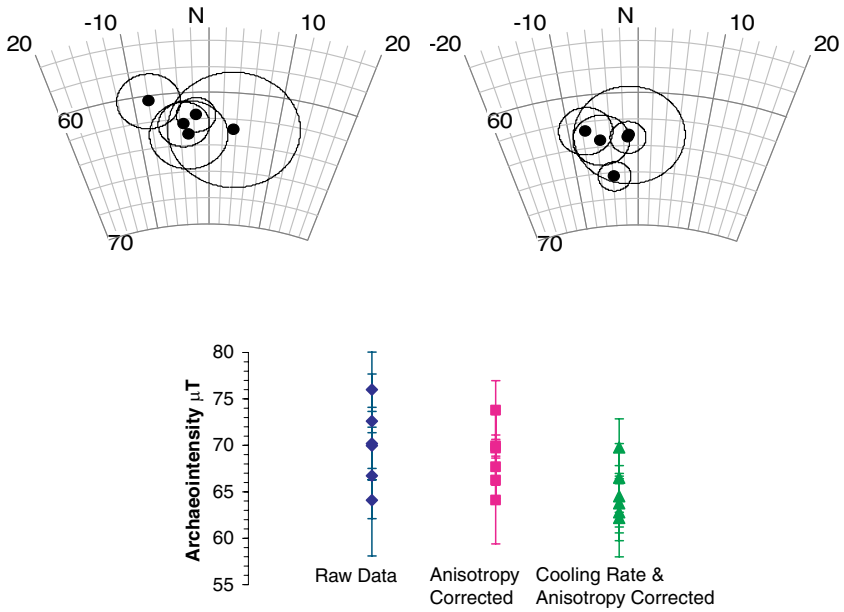



**Figure 5.** Mean results. (a) and (b) stereographic projection of the mean directions of the kilns with (a) before and (b) after anisotropy correction. (c) Archaeointensity results before correction (raw data), after anisotropy correction and after anisotropy and cooling rate correction for the 5 kilns and set of amphorae.

## RESULTS

### Remanence results

All results at the individual sample level are given in Table S1 of the Supplementary Material. All samples, bar one, are dominated by a single component of remanence and NRM/TRM diagrams that exhibit ideal behaviour (Fig. 3). A small viscous component of magnetisation is present in some cases which is always removed by 200°C. Sample 15 from kiln E has an unstable direction that does not trend to the origin and, therefore, this sample was rejected from further consideration. The near perfect success rate demonstrates

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the samples' stability to heating and suitability for archaeointensity experiments. There is no evidence for any multi domain grain behaviour as curvature in the NRM/TRM plots is not seen. Histograms of some of the quality parameters for the 124 samples are shown in Fig. 4. The mean fraction of NRM used to calculate the archaeointensity (f) is 85 per cent and the mean quality parameter as defined by Coe *et al.* (1978) (q) is 63 whilst for the directions the mean maximum angular deviation (MAD) is 2.7° and the mean deviation angle (DANG) is 0.9°.

One sample from kiln A gave an anomalous direction (sample 16), however the archaeointensity is in line with the other samples from the kiln. It is therefore, likely that the brick had moved since it was last fired or that an error in orientation occurred. It is not however possible to prove this so sample A16 was rejected when calculating the kiln mean intensity as well as when calculating the mean direction. Similarly, two samples from kiln D gave directions that do not cluster with the other samples from the kiln. Sample D05 was taken from a brick lying on edge so it is likely it had moved since its last firing. For sample D03 however there was no obvious reason for the different direction. As for sample A16, the intensities of these samples are in line with the rest of the samples from their kiln but they were not included in the mean intensity calculation (however it makes no difference to the mean intensity if they are included or not) as well as being excluded from kiln mean direction calculations.

Mean accepted results for the kilns and the amphorae are given in the first part of Table 1 and are shown in Figs 5(a) and (c). The mean directions are not significantly different from each other with all the $\alpha_{95}$ confidence circles overlapping. The mean inclination ranges from 60° to 63° and the mean declination from −8° to +4°. Kiln mean archaeointensity results range between 64 μT (kiln C) and 76 μT (kiln A) with the archaeointensity of the amphorae (which has the better constrained age) within this range at 70 μT. The mean archaeointensities are not significantly different from each other (the error bounds overlap) apart from kiln A and kiln C.

## Anisotropy of TRM

Sample 01 from kiln D did not pass the alteration check during the TRM anisotropy experiment (50 per cent difference). Three other samples also failed the alteration check, sample 13 from kiln E (24 per cent difference) and amphorae samples 271 and 272 (23 and 29 per cent difference, respectively). The anisotropy of TRM results for all samples with a successful alteration check ($N = 121$) are shown in Fig. 6 and given in Table S2 of the Supplementary Material. The mean degree of TRM anisotropy (defined as the ratio of the maximum and minimum axes of the TRM anisotropy tensor $K_{max}/K_{min}$) is 1.21 (1.16) for the kilns (amphorae) (Fig. 6a). If the clay platelets become aligned during manufacture along the plane of flattening then the easy plane of magnetisation ($K_{max}$) will be in this plane. All the brick samples from the kilns were drilled perpendicular to the top of the brick, hence perpendicular to the plane of flattening (apart from sample 05 from kiln D which was drilled parallel to the top of the brick). Thus the $Z$ axis in core coordinates would correspond to the hard direction of magnetisation ($K_{min}$) and the easy axis would be in the $XY$ plane (for D05 $K_{min}$ will be in the $XY$ plane) if the above scenario were true. Stereoplots showing the maximum, intermediate and easy directions of magnetisation in core coordinates are plotted in Fig. 6(b). Whilst the results for individual samples are somewhat scattered it can be seen that for all the kilns the mean $K_{min}$ is close to the $Z$ axis indicating that the easy direction of magnetisation is on average in the plane of flattening

**Table 1.** Overall results for the 5 kilns and the set of amphorae before and after correction for anisotropy and cooling rate.

| | Raw data | | | | | | | | Anisotropy corrected | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | N | Inc° | Dec° | $\alpha_{95}$ | $k$ | F μT | σF | σF/F (per cent) | 2 se | N | Inc° | Dec° | $\alpha_{95}$ | $k$ | F μT | σF | σF/F (per cent) | $F_{crc}$ μT | $\sigma F_{crc}$ | σF/F (per cent) | 2 se | VDM $\times 10^{22}$ A m$^2$ | VADM |
| Kiln A | 21 | 61.7 | −1.7 | 1.3 | 643.8 | 76.0 | 4.1 | 5.3 | 1.8 | 21 | 63.4 | −1.4 | 1.2 | 722.8 | 73.8 | 3.2 | 4.3 | 69.8 | 3.1 | 4.4 | 1.3 | 11.43 | 11.72 |
| Kiln B | 24 | 62.4 | −3.5 | 1.7 | 316.9 | 72.6 | 5.1 | 7.0 | 2.1 | 24 | 66.3 | −3.8 | 1.1 | 753.9 | 69.7 | 4.0 | 5.7 | 66.5 | 3.7 | 5.6 | 1.5 | 10.48 | 11.17 |
| Kiln C | 15 | 63.2 | −2.9 | 2.6 | 211.5 | 64.1 | 6.0 | 9.4 | 3.1 | 15 | 63.5 | −5.4 | 1.9 | 419.7 | 64.1 | 4.7 | 7.4 | 62.2 | 4.2 | 6.8 | 2.2 | 10.17 | 10.45 |
| Kiln D | 6 | 62.8 | 3.7 | 4.4 | 234.6 | 66.7 | 4.6 | 6.9 | 3.8 | 5 | 63.2 | −1.2 | 3.7 | 386.5 | 66.3 | 2.4 | 3.6 | 62.8 | 3.1 | 4.9 | 2.7 | 10.30 | 10.55 |
| Kiln E | 16 | 60.4 | −8.0 | 2.1 | 305.8 | 70.0 | 3.7 | 5.3 | 1.8 | 15 | 62.7 | −7.5 | 1.8 | 471.2 | 67.7 | 3.4 | 5.1 | 64.5 | 3.3 | 5.1 | 1.7 | 10.66 | 10.84 |
| Amphorae | 39 | | | | | 70.2 | 3.9 | 5.6 | 1.2 | 37 | | | | | 69.9 | 3.4 | 4.8 | 63.8 | 3.2 | 5.0 | 1.1 | | 10.71 |

$N$ is the number of samples, Inc and Dec are the mean direction with the $\alpha_{95}$ confidence angle and the precision parameter k. F is the mean archaeointensity, σF the standard deviation and 2se the 95 per cent confidence limit (2 standard errors of the mean). $F_{crc}$ and $\sigma F_{crc}$ are the cooling rate and anisotropy corrected archaeointensity and standard deviation, respectively. VDM and VADM are the virtual dipole moment and the virtual axial dipole moment.

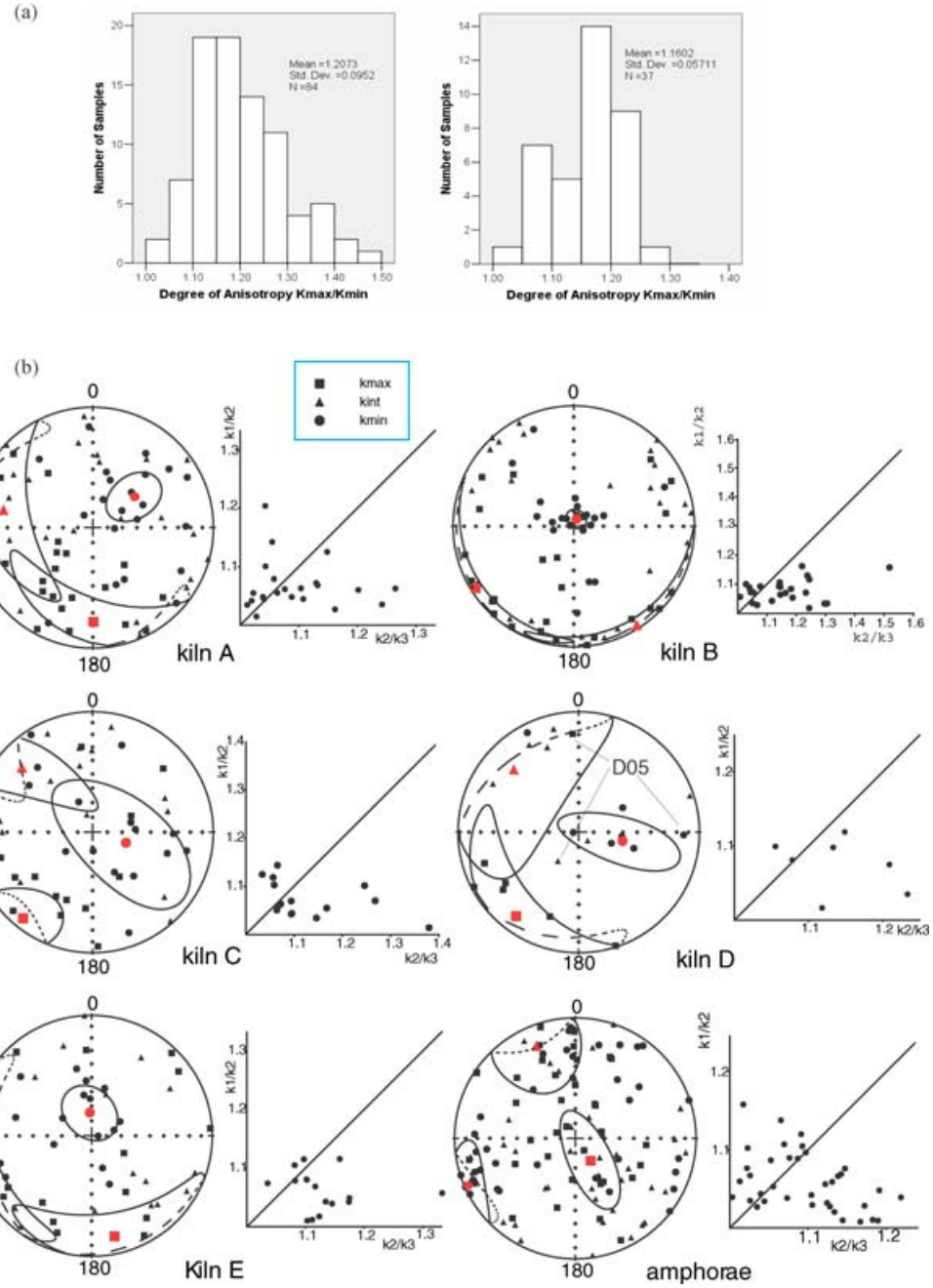



**Figure 6.** Anisotropy results (a) Histograms showing the degree of anisotropy (b) stereo plots of the principal axes of the anisotropy tensor and Flinn diagrams of lineation ($K_{max}/K_{int}$) and foliation ($K_{int}/K_{min}$) per kiln and for the amphorae. Also shown on the stereoplots are the mean values (larger red symbols) and the confidence circles. For kiln D results for sample D05 are indicated and these were not included in the calculation of the kiln mean anisotropy tensor.

for these bricks. This is most pronounced for the samples from kiln B. Consistent with this, sample D05 has its $K_{min}$ in the *XY* plane. The majority (73 per cent) of the kiln samples plot in the oblate portion of the Flinn diagram indicating the predominance of magnetic foliation (Fig. 6b).

For the amphorae samples the TRM anisotropy results indicate that on average the mean easy direction of magnetisation ($K_{max}$) is along the *Z* axis (core coordinates) (Fig. 6b). All cores were drilled vertically into the narrow base of the amphora (Fig. 1). From visual inspection of the cores it appears that during manufacture the clay was spiralled around the vertical direction. It is likely that the clay would have been stretched during manufacture and that on average the stretching plane would be along the vertical.

The individual sample results corrected for anisotropy of TRM are given in Table S3 of the Supplementary Material. Application of the correction to the kilns generally results in a decrease in the archaeointensity. This is to be expected as the applied laboratory field was placed in the *Z* direction (core coordinates) which corresponds to the hard direction of magnetisation in many cases. Similarly for the amphorae the application of the correction factor increases the individual archaeointensities in many cases. The corrected mean results per kiln and for the amphorae are given in the right hand

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part of Table 1 and in Figs 5(b) and (c). The application of the TRM anisotropy correction reduces the scatter in both the directions and the intensity as seen by the reduction in $\alpha_{95}$, an increase in $k$, and a decrease in the percentage standard deviation of the intensity for each kiln. The percentage standard deviation of the amphorae intensity also reduces slightly after the correction.

The TRM anisotropy corrected mean directions of the kilns are better clustered than before the correction. The direction for kiln B no longer overlaps with the directions from kiln A or kiln E, consistent with stratigraphical information that kiln B is older than kiln A. There is a corresponding small reduction in the scatter between kiln mean archaeointensities. The mean archaeointensity for kiln B remains within the range of the other kilns.

Thus, the significance of TRM anisotropy for these samples and the necessity of carrying out the anisotropy of TRM correction has been clearly demonstrated.

### Cooling rate correction

The cooling rate correction $T_{cor}$ and the associated reproducibility check $T_{check}$ are plotted in Fig. 7. $T_{cor}$, $T_{check}$ and the individual cooling rate corrected archaeointensities are listed in Table S3 of the Supplementary Material. In all cases $T_{cor}$ is positive as is predicted for assemblages of SD particles (e.g. Dodson & McClelland-Brown 1980; Halgedahl *et al.* 1980). $T_{cor}$ varies between 0 and 10 per cent for the kilns and between 4 and 15 per cent for the amphorae. The reproducibility check $T_{check}$ ranges from $-8$ to $+1$ per cent with the vast majority of the samples having $T_{check}$ less than zero [indicating the final fast cooling remanence (T4) was less than the previous fast cooling remanence step (T2)]. It is thought that this most likely results from alteration occurring at some point after T2. It can be seen in the Curie curves (Fig. 2b) that whilst reproducibility of heating and cooling curves is good, the cooling curve is always below the heating curve suggesting that if alteration were to occur during the cooling rate experiment it would result in a reduction of magnetisation consistent with a negative $T_{check}$. It is not known at what point after T2 the alteration occurred but it is reasonable to assume that a negative check due to alteration implies that the cooling rate correction $T_{cor}$ will be a minimum estimate.

$T_{check}$ is typically less than 5 per cent but it is interesting to note that the samples that have the largest (negative) $T_{check}$ have the higher $T_{cor}$ values and are mainly amphorae samples. The amphorae samples can also be distinguished from the kiln samples in terms of their hysteresis parameters (Fig. 2a). Fig. 8 shows $T_{cor}$ plotted against some of the measured rock magnetic parameters. Whilst there is no obvious correlation between $T_{cor}$ and Curie temperature (nor IRM, or individual hysteresis parameters) there does appear to be two groups of behaviour seen in the plot of the ratio of saturation remanence to saturation magnetisation ($M_{rs}/M_s$) against $T_{cor}$. The kiln data generally has lower $T_{cor}$ and higher $M_{rs}/M_s$ whilst the amphorae data has higher $T_{cor}$ and lower $M_{rs}/M_s$. Lower $M_{rs}/M_s$ suggests that the amphorae could be more MD like than the kilns (however there is no direct evidence for any MD remanence behaviour). If MD grains are present and a pTRM as opposed to a full TRM is imparted then high temperature pTRM tails may influence the results giving an overestimate of $T_{cor}$ and a negative $T_{check}$. The cooling rate experiments were carried out 5–15°C higher than the final heating temperature used in the Thellier experiment and only a few percent at most of remanence remained in some samples. It is however possible that in some cases a full TRM was not imparted. To avoid the possible influence of pTRM tails from MD grains, should they be present, in future it would be preferable (alteration permitting) to ensure that the cooling rate experiments are carried out on full TRMs as opposed to pTRMs.

The calculated cooling rate correction is variable for each kiln and the set of amphorae demonstrating the necessity of carrying out the correction at a sample, as opposed to a site, level. After correcting for cooling rate the mean archaeointensity reduces by 3 per cent for kiln C, 5 per cent for the other kilns and there is an 8 per cent reduction for the amphorae (Table 1 and Fig. 5c). Whilst the scatter in intensity results for each kiln and the amphorae does not significantly change (standard deviation about the mean 4–7 per cent), the variation between the mean archaeointensity results is reduced. The corrected archaeointensities range from 62 to 70 μT with the amphora corrected archaeointensity now closer to the lower end of this range at 64 μT. The archaeointensity for kiln B is the second highest (behind kiln A) but it is not significantly different from any of the other kilns or the amphorae.

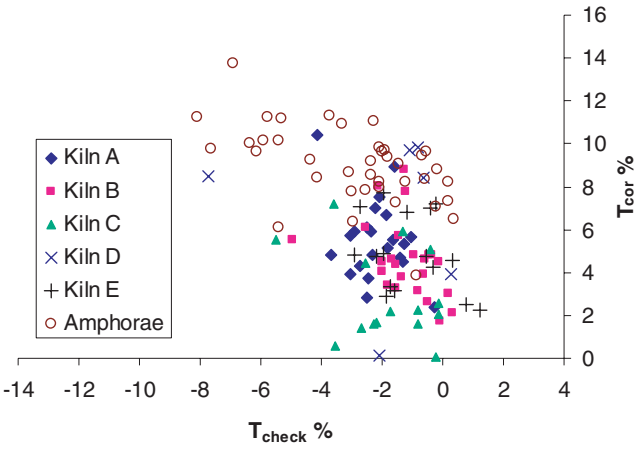



**Figure 7.** Cooling rate correction $T_{cor}$ plotted versus the reproducibility check $T_{check}$.

## DISCUSSION AND COMPARISON TO OTHER DATA

### Directions

The directional results can be compared to the secular variation curves for France (in this case data from Gallet *et al.* 2002 treated with Bayesian modelling Lanos 2004) and Italy (Tema *et al.* 2006) by relocating these results to Paris (48.9°N 2.3°E 1000 km away) and Viterbo (42.45°N 12.03°E 70 km away), respectively (Fig. 9). The relocation error will be less when relocating to Viterbo as opposed to Paris as the kilns are located within the same geographic area as the data used to construct the master curve (e.g. see Schnepp & Lanos 2006). However, the Italian curve is only a preliminary curve containing few data points and a large error envelope. Additionally, the archaeomagnetic directions used have not all been corrected for anisotropy and as demonstrated in this study and also in Tema *et al.* (2006) this is certainly necessary for brick samples. The French curve whilst well constrained after 100 BC is also not well constrained prior to 100 BC. From Fig. 9 it can be seen that within error the directional results from the kilns agree with both the French and Italian curves [they also agree with the Hungarian SV curve (Marton & Ferencz 2006) which is closer than the French curve (800 km away)]. Inclination varies much more than declination

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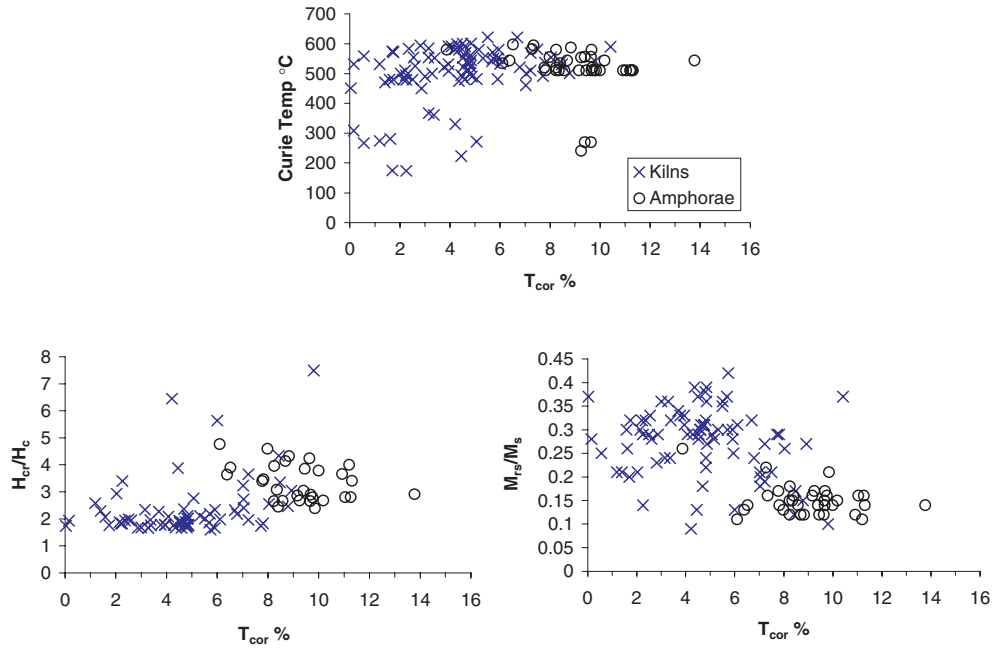



**Figure 8.** Rock magnetic parameters Curie temperature, the ratio of coercivity of remanence to coercivity $H_{cr}/H_c$ and the ratio of the remanent saturation magnetisation to the saturation magnetisation $M_{rs}/M_s$ plotted against the cooling rate correction $T_{cor}$.

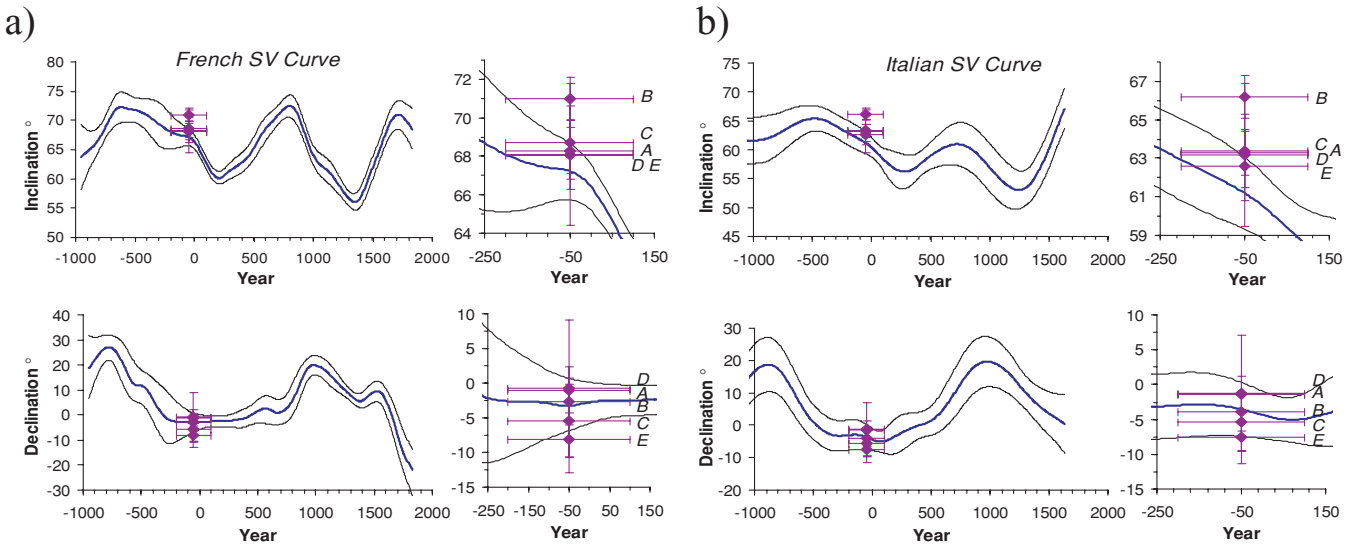



**Figure 9.** Secular variation curves (heavy line) with 95 per cent confidence error bands (thin lines) and the data from this study (diamonds) for (a) France (Gallet *et al.* 2002; Lanos 2004) (all data relocated to Paris) and (b) Italy (Tema *et al.* 2006) (all data relocated to Viterbo). Kilns are labelled in the expanded scale plots.

over the time period of interest with steeper inclinations indicating older ages. Kiln B has the steepest inclination and thus could be inferred to be the oldest kiln, which is consistent with the stratigraphical interpretation that kiln B is older than kiln A. Comparing the inclination results with the French and Italian curves suggests that the kilns are towards the older part of the archaeologically given age. Due to the uncertainties in the current secular variation master curves for Italy and France it is not possible at present to refine the ages of the kilns using archaeomagnetic dating (using the software RENDATE (Lanos 2004; http://www.meteo.be/CPG/aarch.net/download_en.html) the age intervals at the 95 per cent confidence level are from 237 to 661 yr). Instead, using the archaeological given age (−200 to +100 AD), the archaeomagnetic directions from the kilns should be used to augment the Italian secular variation master curve.

### Intensity

At present there is only a very limited amount of archaeointensity data from Italy however there are many archaeointensity data for Greece. An archaeointensity secular variation curve for the Aegean area has recently been constructed (De Marco *et al.* 2007) which combines new and previously published data. In order to reduce the considerable scatter seen in the data (which is of variable quality) individual raw data points were weighted according to the criteria of Chauvin *et al.* (2000) which takes in to account experimental method, number of samples used per site and type of material. The

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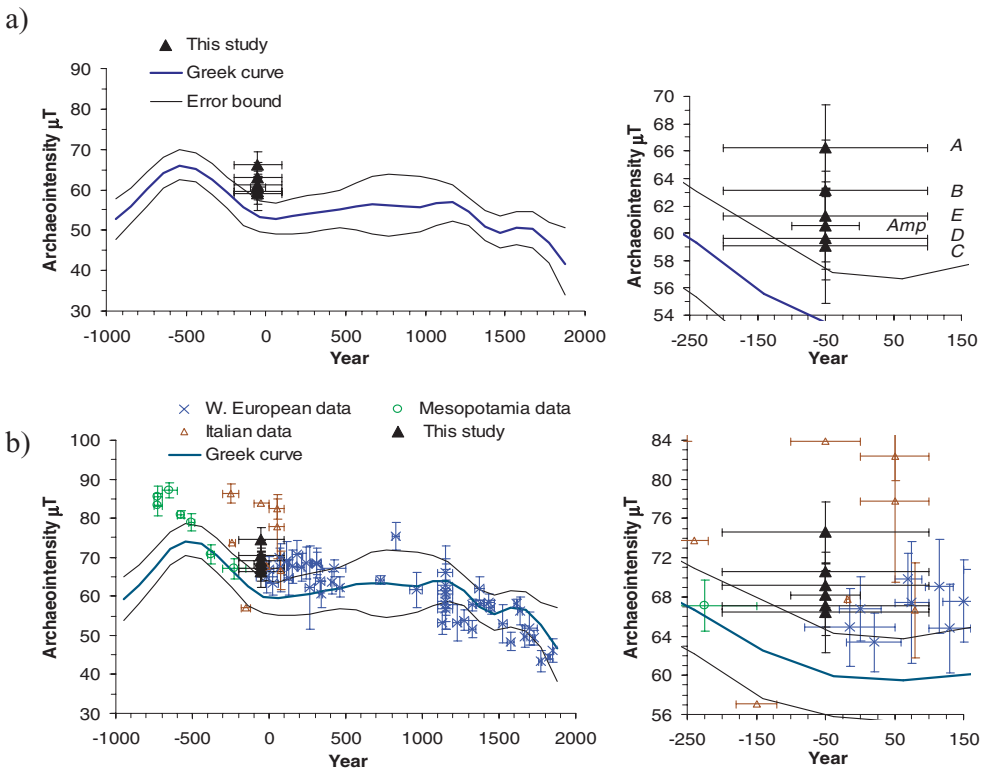



**Figure 10.** Archaeointensity results from this study (a) relocated to Athens and compared to the Greek SV curve with 95 per cent confidence band (De Marco *et al.* 2007) and (b) compared to previously published Italian data (Evans 1986, 1991; Hedley & Wagner 1991), Western European data (Chauvin *et al.* 2000; Genevey & Gallet 2002; Gallet *et al.* 2005; Gómez-Paccard *et al.* 2006), data from Mesopotamia (Gallet *et al.* 2006) and the Greek SV curve (all data relocated to Paris) for the last 3000 yr. Kilns and amphorae are labelled in the expanded scale plot in (a).

weighted archaeointensity data were then treated using the hierarchical Bayesian modelling technique of Lanos (2004). The De Marco *et al.* Greek archaeointensity curve with 95 per cent confidence bounds from 1000 BC to present is shown in Fig. 10(a) along with the Albinia archaeointensity results relocated to Athens (37.97°N, 500 km latitudinal distance away). Kiln A which gives the highest archaeointensity estimate does not fall within the error bounds of the Greek curve at the 95 per cent confidence level but the archaeointensity results for the other four kilns and the amphorae do. Comparison to the curve suggests that the kilns and amphorae may be nearer the older half of their archaeological age consistent with the inclination data. However contrary to the inclination data there is no suggestion that kiln B is older than kiln A, in fact, the opposite seems to be true as the higher intensity corresponds with older ages and kiln A has the highest intensity.

The only previously published archaeointensity data obtained from Italian archaeological material are two studies by Evans (1986, 1991) and part of a study by Hedley & Wagner (1991). Evans used the Shaw technique (Shaw 1974) without correction for anisotropy of TRM or cooling rate correction on four kilns; one aged 79 AD, two 1st century AD and one 3rd century BC in age. Hedley & Wagner used the Coe version of the Thellier technique (Coe 1967) without systematic pTRM checks, but did carry out anisotropy correction on four potsherds (two 1st century BC, one 2nd century BC and one 3rd century BC). The Western European archaeointensity data that includes anisotropy and cooling rate correction are mainly from France (Chauvin *et al.* 2000; Genevey & Gallet 2002; Gallet *et al.* 2005) with a few data from Spain (Gómez-Paccard *et al.* 2006). This data set covers the last 2000 yr but not further back in time. A high quality data set from Mesopotamia (Gallet *et al.* 2006, and references therein) covers earlier times and from comparisons of various data sets of variable quality from different locations it appears that geomagnetic intensity variations are generally consistent from the Western Mediterranean to Central Asia (Gallet *et al.* 2003). To allow a comparison of all these data sets for the last 3000 yr intensities have been relocated to Paris and are plotted in Fig. 10(b). It can be seen that the results from this study are broadly consistent with the other high quality data as well as the Greek SV curve. The previously published Italian data is scattered with four data points giving much higher archaeointensities than the other data. This is most likely due to the fact that no cooling rate experiments were carried out along with older (less reliable) experimental protocols.

The spread of 8 μT seen between the mean kiln archaeointensities may well (at least in part) be explained by the kilns being different ages. However the directions are all very similar (apart from kiln B) plus the recent study of seven Spanish medieval contemporaneous kilns from the same archaeological site (Gómez-Paccard *et al.* 2006) found a similar spread in archaeointensity between individual kiln means. In fact, looking at Fig. 10(b) it appears that wherever there is more than one data point covering a particular time period, there is always a range of intensity values. This supports the conclusion of Gómez-Paccard *et al.* that it is necessary to have several archaeointensity determinations per century in order to reliably reconstruct archaeointensity variations and that the variation seen (5 per cent in this study) is probably an indication of the limitations of the experimental method and/or the samples. In an attempt to see if the magnetic mineralogy influenced the archaeointensity estimates in this study archaeointensity values were plotted against a

number of different rock magnetic properties however no correlations were found. Combining the results from the five kilns and the amphorae gives a mean archaeointensity of 64 ± 3 μT at Albinia (69 ± 3 μT at Paris) at their time of last heating which occurred during 200 BC–100 AD.

## CONCLUSIONS

In this study an intensive archaeomagnetic investigation of five kilns and a set of 39 amphorae from an Italian Roman amphorae workshop has been carried out. The classical Thellier method was used to obtain high quality directional and archaeointensity results. Anisotropy of TRM experiments indicate that anisotropy is significant for these samples and that an anisotropy correction is necessary. After correction, both the scatter for an individual kiln (the amphorae) is reduced and the scatter between kilns is also reduced for both the directions and the intensity. The cooling rate correction results in a reduction in individual intensities by 0–15 per cent. Whilst not reducing scatter in the mean archaeointensity results the correction does result in a reduction in the scatter between the kilns. As both the preliminary Italian and the French secular variation curves are not well constrained around the time of interest it is not possible to constrain the ages of the kilns using archaeomagnetic dating. Comparing the new directional results to the master curves however does indicate that the kilns may be towards the older part of the given archaeological age range. kiln B which has the steepest inclination may be older than kiln A as suggested by the stratigraphy. However the archaeointensity results for kiln B lie within the range found from the other kilns. The anisotropy and cooling rate corrected archaeointensity results range from 62 to 70 μT. The archaeointensity from the amphorae which have a better constrained age lie within the range of archaeointensities found for the kilns. The new archaeointensity data are consistent with the broad trends seen in the limited high quality Western European and Mesopotamian data sets and with the newly constructed archaeointensity SV curve for Greece. The variation in archaeointensity seen between the kilns (5 per cent) may be due to them being of differing ages however it is thought more likely to reflect the limitations of the experimental protocol and/or samples. This further supports the suggestion that a number of archaeointensity data per time interval are required to reliably determine the past variations of the geomagnetic field. Combining the results from the five kilns and the amphorae gives a mean archaeointensity of 64 ± 3 μT at Albinia (69 ± 3 μT at Paris) during 200 BC–100 AD.

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## SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article:

**Table S1.** Individual sample results before any corrections, * and italics indicates samples that have anomalous directions and hence were not included in the kiln mean calculation.

**Table S2.** Individual anisotropy results, * and italics indicates samples that have anomalous directions, and # and italics indicates samples that have anisotropy alteration check.

**Table S3.** Individual sample results after anisotropy and cooling rate correction, * and italics indicates samples that have anomalous directions, # and italics indicates samples that failed the anisotropy check and hence were not included in the kiln mean calculation.

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