An investigation of the intensity of the geomagnetic field during roman times using magnetically anisotropic bricks and tiles

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Objekttyp: **Article**

Zeitschrift: **Archives des sciences et compte rendu des séances de la Société**

Band (Jahr): **37 (1984)**

Heft 3

PDF erstellt am: **22.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-740545

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Arch. Sc. Genève	Vol. 37	Fasc. 3	pp. 359-373	1984

Séance du 1er mars 1984

AN INVESTIGATION OF THE INTENSITY OF THE GEOMAGNETIC FIELD DURING ROMAN TIMES USING MAGNETICALLY ANISOTROPIC BRICKS AND TILES *

BY

Ronald John VEITCH, Ian George HEDLEY and **Jean-Jacques WAGNER** **

SUMMARY

Samples of tiles and bricks from three Roman archaeological sites, Vindonissa (Brugg, Argovie, Switzerland), Quarantus (Palaja, Aude, France) and the Graufesenque (Millau, Aveyron, France), have been used to determine the intensity of the geomagnetic field during the Roman period. The analyses were carried out using the "zero-field" version of the Thellier-Thellier method.

The experimentally derived intensities have been corrected for the magnetic anisotropy of the baked clay. The correction factor is calculated from the thermoremanence susceptibility tensor.

Although the experimental results for the Graufesenque are poor the other two sites yield good palaointensities; 69 ± 8 μT for Vindonissa and 74 ± 3 μT for Quarantus, adjusted to the latitude of Bern. These results confirm that the average value of the geomagnetic field was some 50% greater than the present intensity.

RÉSUMÉ

Des tuiles et des briques provenant de trois sites romains, Vindonissa (Brugg, Argovie, Suisse), Quarantus (Palaja, Aude, France) et la Graufesenque (Millau, Aveyron, France), ont été utilisées pour la détermination de l'intensité du champ magnétique à l'époque romaine. Cette détermination se fait par une variante dite du « champ nul » de la méthode de Thellier-Thellier.

L'intensité expérimentale a été corrigée pour tenir compte de l'anisotropie magnétique du matériau. Le taux de la correction est déduit du tenseur de la susceptibilité de la thermo-remanence.

Les résultats expérimentaux ne sont pas satisfaisants pour la Graufesenque, par contre ils sont de bonne qualité pour Vindonissa et Quarantus. Ces deux derniers sites donnent des intensités rapportées à Berne de 69 ± 8 μT et 74 ± 3 μT. Ces résultats confirment que la valeur moyenne de l'intensité du champ à cette époque était supérieure de 50% à celle que nous avons de nos jours.

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* Séance du 1er mars 1984, communication présentée sous le titre « Sur l'intensité du champ magnétique terrestre à l'époque romaine ».

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INTRODUCTION

Our knowledge of the past intensity of the earth's magnetic field from direct measurements is limited to the last two centuries. The first relative measurement of field intensity at Geneva for example was carried out in 1804 by Biot using an oscillating magnetic needle (Balmer, 1956, p. 501).

For earlier data one is obliged to use indirect methods based on the analysis of the thermoremanent magnetization of dated lava flows and archaeological baked clays.

The history of the variations of the intensity of the geomagnetic field is important for several geophysical reasons. Firstly, to help theoreticians refine their models of the dynamo in the earth's outer core which is thought to be responsible for the generation of the main field. Secondly, sufficient data are now available (McElhinny and Senanayake, 1982) to show that important changes in intensity have taken place during the last few thousand years. Such changes are known to affect the rate of production of the radioactive isotope C^{14} in the upper atmosphere and so indirectly influence dates obtained by the radiocarbon method.

Last but not least, although the variations in the intensity are slower than those in the direction of the geomagnetic field, the establishment of a master curve of intensity versus time is of some importance as an aid to the dating of baked archaeological artefacts. For the determination of the ancient field intensity using baked clays it is not necessary that the sample has remained undisturbed since its last firing so that a wide range of material, which would be unsuitable for a directional study, is available for palaeointensity studies. In particular pottery, which is an archaeologically abundant material and is also capable of being well dated by archaeologists, can be used.

Nevertheless, it is necessary to known the geographic co-ordinates of the workshop where the pottery was made. Fortunately, despite the considerable displacement of ancient pottery from kiln to archaeological site (sometimes hundreds of kilometres), provenance studies enable the area of production of pottery to be localised (Lemoine *et al.* 1982).

AIMS

The present study is a first step of an investigation of the variations of the geomagnetic field intensity during the Roman period, using bricks and tiles from ovens which had already yielded good directional results.

This time interval is of interest because of the richness of archaeological material which constitutes a source of well dated samples and also because of the surprisingly large and rapid changes in the field intensity indicated by previous studies

(Walton, 1979; Shaw, 1974, 1979). However, the agreement between these different data sets is poor. Clearly more and better data are called for with well defined rejection criteria for eliminating spurious results (Aitken, 1983). Aitken has shown that the magnetic anisotropy of ceramics cannot be ignored in intensity studies; and as the tiles and bricks of which ovens are built are often markedly anisotropic we too have made allowance for this.

SAMPLES

Three kilns each from a different archaeological site were chosen. Three samples were selected from a tile kiln at Quarantus, Palaja, near Carcassone (Aude) France [QRT]. It should be pointed out that this is not the same kiln which was sampled by Thellier (1981) and given as No. 27 in his list. The kiln was built of large pale coloured bricks (~ 20 × 10 × 10 cm) and its age is situated between 20 BC to AD 20 (M. Passelac, personal communication).

The second site was the large kiln at the Graufesenque, near Millau (Aveyron) France [GRA], an important centre for the production of *terra sigillata* (Samian ware) from the 1st to the middle of the 3rd century. Although built largely using blocks of pink sandstone some tiles and bricks were used in its construction and one sample from a tile [GRA 1.7.6] and another from a brick [GRA 1.10.4] were selected for the intensity measurements. The kiln was used between AD 80 and 120 (Vernhet, 1981) so the latter date would represent the "magnetic age" recorded by the baked clay.

A lime kiln at Königsfelden, in the military camp of Vindonissa, Brugg (Argovie) Switzerland [VND] was chosen as the third site. This imposing kiln some 3 m in diameter was constructed with tiles and three of these were used in the present study. Unfortunately the exact period during which the kiln was used in unknown: it could be within the interval AD 260-400 but the period AD 20-101 is not ruled out (Martin Hartmann, personal communication).

EXPERIMENTAL DETAIL

All the samples were in the form of ⌀ 25.5 × 23.5 mm cylinders cut from the original tiles or bricks. The remanent magnetizations of all the samples were measured with a DIGICO balanced fluxgate spinner magnetometer (Molyneux, 1971).

The heating and cooling steps were carried out in a apparatus built in Geneva for the thermal demagnetization of rock samples in palaeomagnetic studies.

The non-magnetic oven equiped with a bifilar nichrome heating element sheathed in stainless steel (Pyrotenax, Hebburn, Tyne and Wear, England) was situated in a cylindrical Mumetal shield. The temperature of the oven was regulated by a CRL 405 control unit (Control and Readout Ltd. Worthing, West Sussex, England) with the sensor, a Chrome/Alumel thermocouple, placed in the inner ceramic tube of the oven. Up to eight samples could be thermally treated at the same time.

Cooling was carried out in an adjacent cooling tube with a forced draught of air from an electric fan. The ambient field for "zero field" cooling was less than 10 nano Tesla. (In the S.I. system, 1 nano Tesla (nT) $= 10^{-3}$ micro Tesla (μT) $= 10^{-9}$ Tesla (T) $\equiv 10^{-5}$ Gauss in the *cgs* system). A coil wound on the cylindrical cooling tube enabled a magnetic field to be applied for the thermal remagnetization steps.

PALAEOINTENSITY METHOD

Given that the samples of tile and brick, by cooling from a high temperature in the past geomagnetic field, have acquired a *t*hermo*r*emanent *m*agnetization (TRM) the obvious way to determine the strength of this ancient field is to reproduce exactly the same magnetization in the laboratory. The field applied in the laboratory would then be taken to be equal that which had originally magnetized the sample, with the proviso that no changes had taken place in the sample between or during the two processes of magnetization. It is impractical to apply exactly the same field to the sample as was present in the past, but it turns out, that in fields of the order of 100 μT or less, the magnetization is proportional to the applied field. We can then write

$$(1) \qquad F_a = F_{lab} \cdot M_a/M_{lab}$$

Where F_a is the ancient field, F_{lab} the laboratory field, M_a the *n*atural *r*emanent *m*agnetization (NRM) of the sample, and M_{lab} is the remanent magnetization produced in the laboratory.

Deriving F_a from this expression alone, would use only one data point (the NRM), and would take no account of possible secondary components of magnetization acquired by the sample during its long exposure to the earth's field after cooling (viscous magnetization) or acquired during sampling or on later handling.

Thellier and Thellier (1959) developed the standard method of palaeointensity determination, which takes account of these difficulties, and provides a check on any chemical changes occuring in the samples during laboratory heating. In their method the samples are progressively remagnetized by heating to increasing temperatures.

If the *p*artial *t*hermo*r*emanent *m*agnetizations (PTRM's) acquired over each temperature interval are independent (Thellier, 1941), then equation (1) can be extended

$$F_a = F_{lab} \frac{M_\theta}{M_{lab_\theta}} \tag{2}$$

M_θ is the PTRM lost on cooling from temperature θ in zero field. M_{lab_θ} is the PTRM gained on cooling from θ in laboratory field F_{lab}.

We have used the "zero field" variant (Nagata *et al.*, 1963) of the Thellier-Thellier technique, in which two heatings are carried out to each temperature, the first of the coolings being in zero field and the second in F_{lab}. The sequence of measurements can be conveniently represented on an Arai plot (Nagata *et al.*, 1963) in which the NRM remaining after each heating is plotted against the PTRM gained on cooling from the same temperature.

Secondary components of magnerization, or chemical changes in the samples, can appear as non-linearities in the Arai plot. So this method of determination provides a built in check on the reliability of the intensity determination.

F_{lab} was a field of 60 μT applied along the cylindrical axis of the sample. This value was chosen as being close to the expected ancient field. The present magnetic field is Switzerland is about 46 μT. The samples were heated in stages from 150 to 590° C, at which temperature any magnetite grains should be completely remagnetized.

After the Arai plot has been drawn and a first estimate of the ancient field intensity derived from it further calculation is required to make various corrections to the result. Here, we consider the effect of sample anisotropy and the sample cooling rate on the derived field intensity and then apply a correction to adjust values from geographically separated sites to a common latitude.

ANISOTROPY CORRECTION

The previous discussion is inadequate if the strength of the laboratory TRM is dependent on the direction in which the magnetic field is applied. When some preferential orientation of the magnetic grains in the sample causes this to be the case, then, unless the laboratory field is applied to the sample in exactly the same orientation as was the ancient field, there will be some error in the derived ancient intensity. The importance of this error depends on the degree of anisotropy of the sample, and on the relative orientations of the laboratory and ancient fields with respect to this anisotropy.

Aitken *et al.* (1981) describe a method of correction particular to their apparatus, whilst we have used another approach suitable for our equipment.

As our samples are drilled cores, it is most convenient to magnetize them along their cylindrical (z-axis), or in the $x-y$ plane, but troublesome to mount them at intermediate angles (the orientation of the applied magnetic field being fixed by the

As our samples are drilled cores, it is most convenient to magnetize them along their cylindrical (z-axis), or in the x-y plane, but troublesome to mount them at intermediate angles (the orientation of the applied magnetic field being fixed by the geometry of the thermal demagnetization equipment). In consequence, the laboratory TRM's could not applied parallel to the NRM's, and an anisotropy correction was applied as follows:

First we can consider the usual magnetic susceptibility of an anisotropic material. In the low field limit the induced magnetization is linearly proportional to the applied field and the two are related by the initial susceptibility tensor κ_{ij}.

$$\begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} \kappa_{11} & \kappa_{12} & \kappa_{13} \\ \kappa_{21} & \kappa_{22} & \kappa_{23} \\ \kappa_{31} & \kappa_{32} & \kappa_{33} \end{bmatrix} \begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix} \tag{3}$$

where H_1, H_2 and H_3 are the components of the applied field along the x, y and z axes and M_1, M_2 and M_3 are the corresponding components of the magnetization $\mathbf{M}$, and $\kappa_{ij} = \kappa_{ji}$ (for $i \neq j$).

Equation (3) is written more conveniently as $M_j = \kappa_{ij} H_i$.

A TRM susceptibility κ_{ij}^{TR} may be defined by analogy; $M_j^{TR} = \kappa_{ij}^{TR} H_j$.

In our experiments, the κ^{TR} terms were found experimentally by giving TRM's to the samples with the field aligned along each axis in turn. For example, a field H_2 along the y-axis of the sample produces a TRM with components $\kappa_{12}^{TR} H_2$, $\kappa_{22}^{TR} H_2$, $\kappa_{32}^{TR} H_2$.

TABLE 1.

Magnitudes and directions of the principal initial susceptibilities and the principal TRM susceptibilities (S.I. units).

	Principal components of initial susceptibility									Principal components of TRM susceptibility								
Sample name (see text)	κ ($\times 10^{-3}$)	Dec deg.	Inc deg.	κ ($\times 10^{-3}$)	Dec deg.	Inc deg.	κ ($\times 10^{-3}$)	Dec deg.	Inc deg.	κ^{TR} ($\times 10^{-3}$)	Dec deg.	Inc deg.	κ^{TR} ($\times 10^{-3}$)	Dec deg.	Inc deg.	κ^{TR} ($\times 10^{-3}$)	Dec deg.	Inc deg.
VND 01.12.02	12.0	334	4	12.2	244	-6	10.5	28	-83	205.	308	3	187	218	-6	158	14	-84
VND 01.16.04	1.27	346	-1	1.27	257	12	1.14	251	-78	6.35	316	0	5.99	227	43	5.82	226	-47
VND 01.17.03	24.1	312	12	23.7	221	4	20.8	293	-78	105	292	17	98.8	205	-10	83.6	325	-70
QRT 03.02.01	13.3	144	71	13.5	244	3	13.1	335	19	117	287	0	110	197	26	108	13	64
QRT 11.03.02	18.2	110	9	17.9	11	43	17.5	29	-45	124	117	-23	121	47	39	111	5	-42
QRT 18.02.01	13.5	73	-6	13.3	155	51	13.2	348	38	81.4	89	25	76.3	204	42	71.5	338	38
GRA 01.07.06	0.476	6	23	0.474	289	-29	0.471	63	-52	14.1	343	9	13.6	254	-8	12.2	25	-77
GRA 01.10.04	1.99	114	5	1.98	22	18	1.91	38	-71	2.93	117	3	2.62	28	-3	2.41	156	-86

Table 1. Magnitudes and directions of the principal initial susceptibilities and the principal TRM susceptibilities (S.I. units).

The matrix of the measured susceptibility terms should be symmetrical, but because each measurement is subject to some error, this condition is not exactly satisfied. The best fitting diagonal matrix is given by replacing the off diagonal terms κ^{TR}_{ij} $(i \neq j)$ with $(\kappa^{TR}_{ij} + \kappa^{TR}_{ji})/2$ (see Nye (1957), chapter 9, for a treatment of the least squares fitting of a tensor to experimental data). Making TRM experiments with more than three orientations would improve the determination of the TRM susceptibility tensor. The magnitudes and directions of the principal TRM susceptibilities are listed in table 1, together with the initial susceptibilities measured by a Digico Magnetic Anisotropy Delineator. There is a general agreement in the orientations of the principal axes of these two susceptibilities, apart from when the anisotropy is very small.

From the TRM susceptibility tensor we are able to derive a palaeointensity anisotropy correction factor. First, knowing the direction of the NRM, one solves for the direction of the ancient magnetic field.

$$(4) \qquad \mathbf{h} = \frac{\kappa^{TR^{-1}}\mathbf{M}}{|\kappa^{TR^{-1}}\mathbf{M}|} \qquad \mathbf{h} \text{ is unit vector in direction of ancient field}$$

Then, the correction factor *f.* is the ratio of the intensity of TRM produced by unit field along the *z*-axis (for which the Arai plots were constructed) and a field parallel to **h**.

$$(5) \qquad \mathrm{f} = \frac{|\kappa^{TR}\mathbf{k}|}{|\kappa^{TR}\mathbf{h}|} \qquad \mathbf{k} \text{ is unit vector along } z\text{-axis}$$

The directions of the NRM in sample coordinates are given in colums 3 to 5 of table 2.

TABLE 2.

Ancient field intensities derived from Arai plots, with the values corrected for sample anisotropy and site latitude.

Sample name (see text)	Date	NRM Direction (sample co-ords.) Dec deg	Inc. deg	Anisotropy correction factor	Intensity from Arai plot μT	Intensity after anisotropy correction μT	Site mean μT	Corrected to Bern latitude 47^{c} μT
VND 01.12.02	AD 260 to AD 400	108	75	0.99	73	72	69 ± 8	69±8
VND 01.16.02		5	56	1.00	60	60		
VND 01.17.03		16	60	0.95	78	74		
QRT 03.02.01	20 BC to AD 20	146	64	0.98	71	70	71 ± 3	74±3
QRT 11.03.02		139	62	1.03	67	69		
QRT 18.02.01		265	69	1.02	73	74		
GRA 01.07.06	AD 120	70	55	0.96				
GRA 01.10.04		31	49	0.95				

Table 2. Ancient field intensities derived from Arai plots, with the values corrected for sample anisotropy and site latitude.

f is seen to range from 0.95 to 1.02 for different samples. It is therefore a small, but significant, correction factor.

COOLING RATE EFFECT

Cooling time from the highest temperature was of the order of an hour. As this is an order faster than the cooling of the sample when it was part of the kiln there will be an error in the derived field intensity (Fox and Aitken, 1980).

Aitken (1983) reported the result of a trial experiment in which a number of samples were magnetized by cooling over a period of two days (considered a typical time for the cooling of a kiln) in a known field. Intensity determinations carried out using laboratory cooling times of five minutes and four hours yielded overestimates of the magnetizing field of 11% and 3% respectively. Our cooling time of one hour may therefore lead to values of the ancient field which are about 5% too high. With our present equipment we are unable to vary the cooling rate to investigate this effect.

LATITUDE CORRECTION

As the value of the geomagnetic field varies with the latitude of the site of observation it is important to take this into account when comparing data from different sites. We have reduced our data to a common latitude of 47° (that of Bern, the Swiss federal capital). A latitude of 46° was chosen by Shaw (1979) for his data for baked clay from France and Italy.

The following relationship for the variation of the field intensity F with latitude λ for an axial dipole

$$F = \frac{\mu_o P}{4\pi r^3}(4\text{-}3\ \cos^2\lambda)^{\frac{1}{2}} \tag{6}$$

was used. P is the geomagnetic dipole moment, r is the geocentric distance of the site, and μ_o is the permeability of free space.

In the case of the site Quarantus this correction is some 4%.

RESULTS

The Arai plots of eight samples are given in figures 1 to 8. In each case they give acceptable straight line fits (the derived ancient field intensity and its standard deviation, calculated from the least squares straight line fit to all of the points, are given on each diagram).

After making the anisotropy correction (see table 2), it can be seen that the sets of samples from Vindonissa and Quarantus give consistent ancient fields of 68 ± 8 μT and 71 ± 3 μT respectively, although the cooling rate affect which we have discussed suggests that these values may be as much as 5% too large. No conclusion could be drawn from the widely differing Graufesenque results.

In comparison with other published data for this time interval (figure 9) the two acceptable results from the present study fit in well and are in agreement with the concensus that the earth's magnetic field was some 50% stronger than at present.

However, further detailed study is needed with the application of reliability criteria to verify the claim that rapid variations of the field were a feature of Roman times (Shaw, 1979).

The quality of these first results shows that the Geneva thermal demagnetizer is well suited to the determination of palaeointensities and we intend to continue this study using ceramics as well as tiles and bricks so as to allow a detailed coverage of the whole of the Roman period.

ACKNOWLEDGEMENTS

We are grateful to the Swiss National Research Foundation (F.N.R.S.) for financial support (project No. 1.606-0.82). We would also like to thank the archaeologists who made this study possible by kindly allowing samples to be taken from their sites. In particular Dr. Martin Hartmann, Reinhard Maag (Vindonissa), Michel Passelac (Quarantus) and Alain Vernhet (Graufesenque). Stephan Bratschi, Anne-Catherine Castella and Patrick Moinat carried out the initial magnetic measurements. Victor Cornut and Ricardo Stouvenel helped with coring the samples, whilst Jacqueline Berthoud typed the text and Pierre Zbinden drew the diagrams.

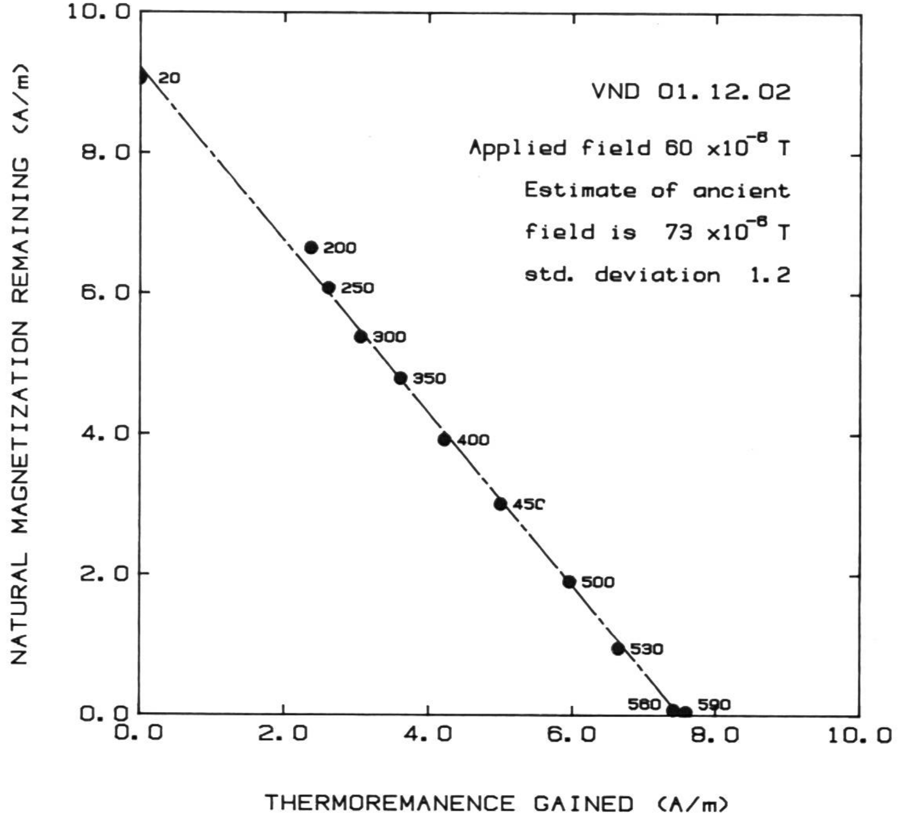

FIG. 1.

Arai plot of the NRM remaining after heating the sample and then cooling in zero magnetic field, against the magnetization gained on reheating to the same temperature and then cooling in an applied field of 60 μT. The points are labelled with the temperature to which the sample was heated. In each case the field was applied along the cylindrical z-axis of the sample.

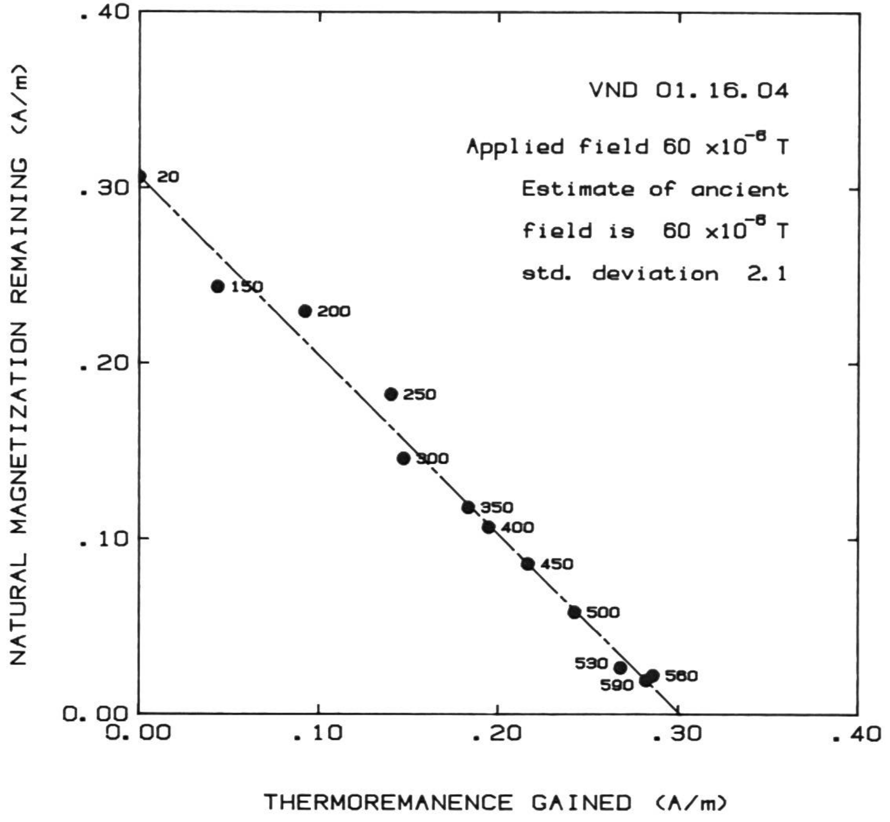

FIG. 2.

Same as for Figure 1.

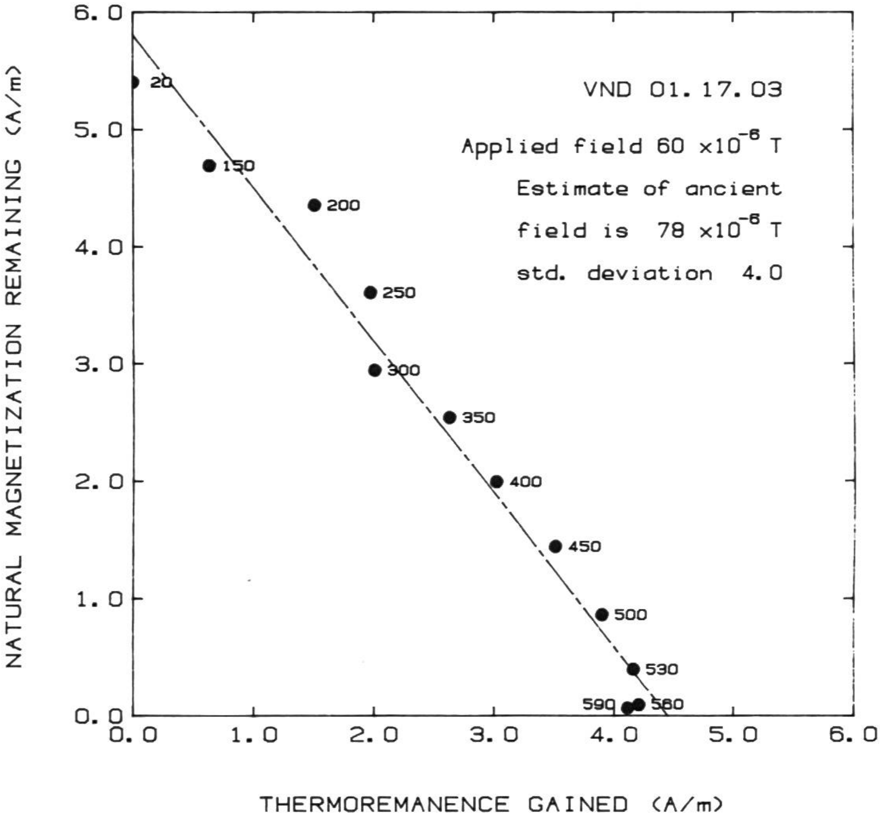

FIG. 3.

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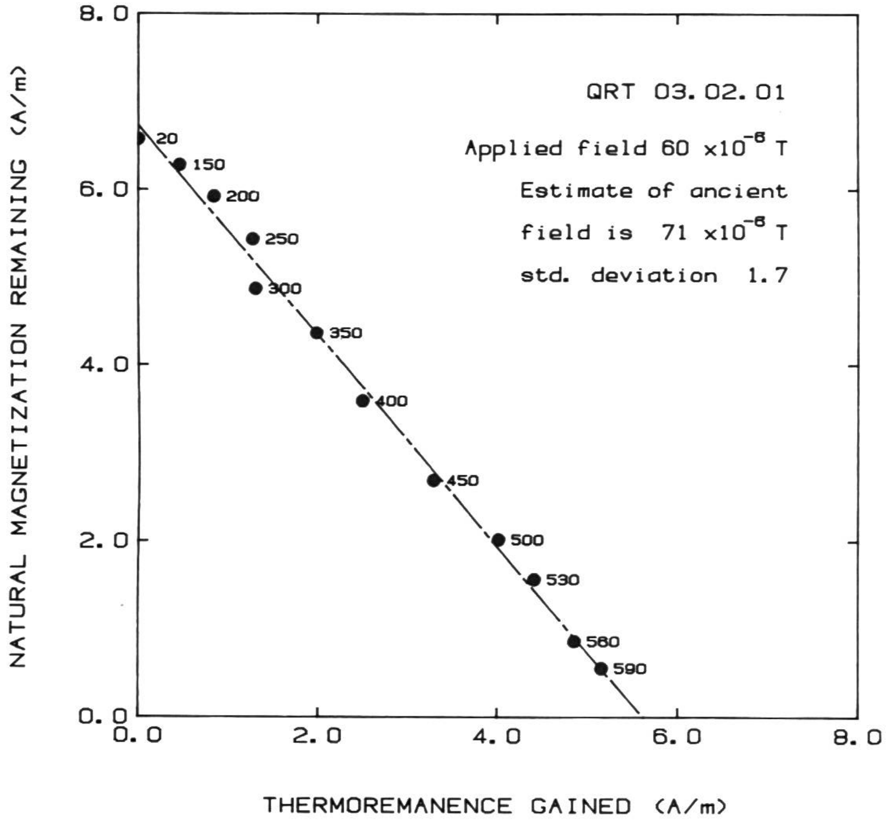

FIG. 4.

Same as for Figure 1.

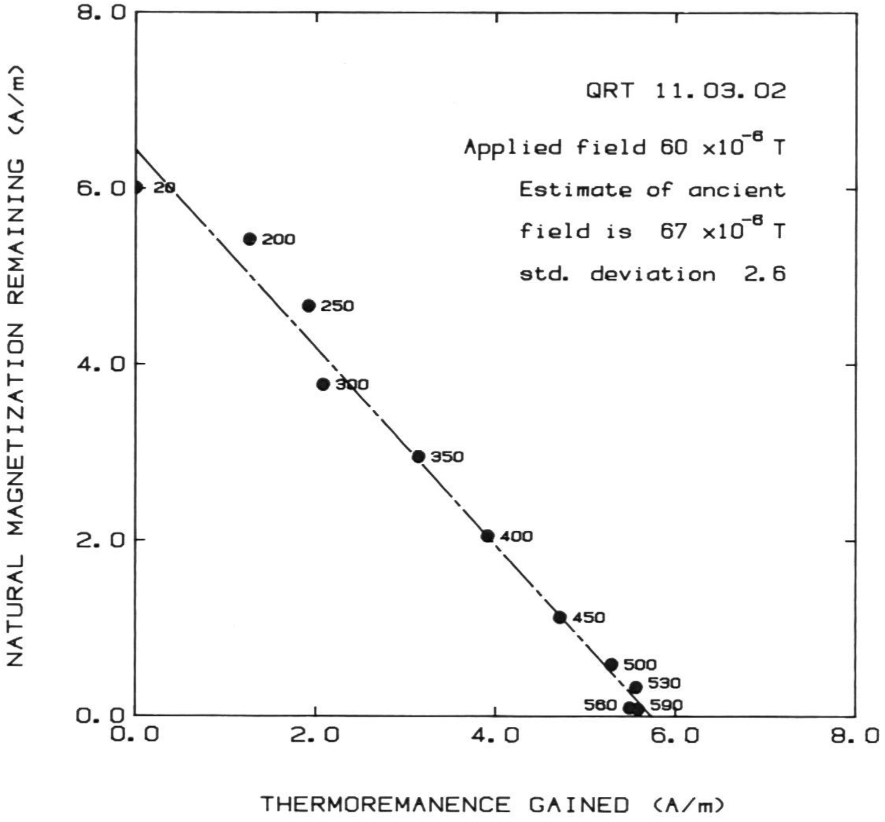

FIG. 5.

Same as for Figure 1.

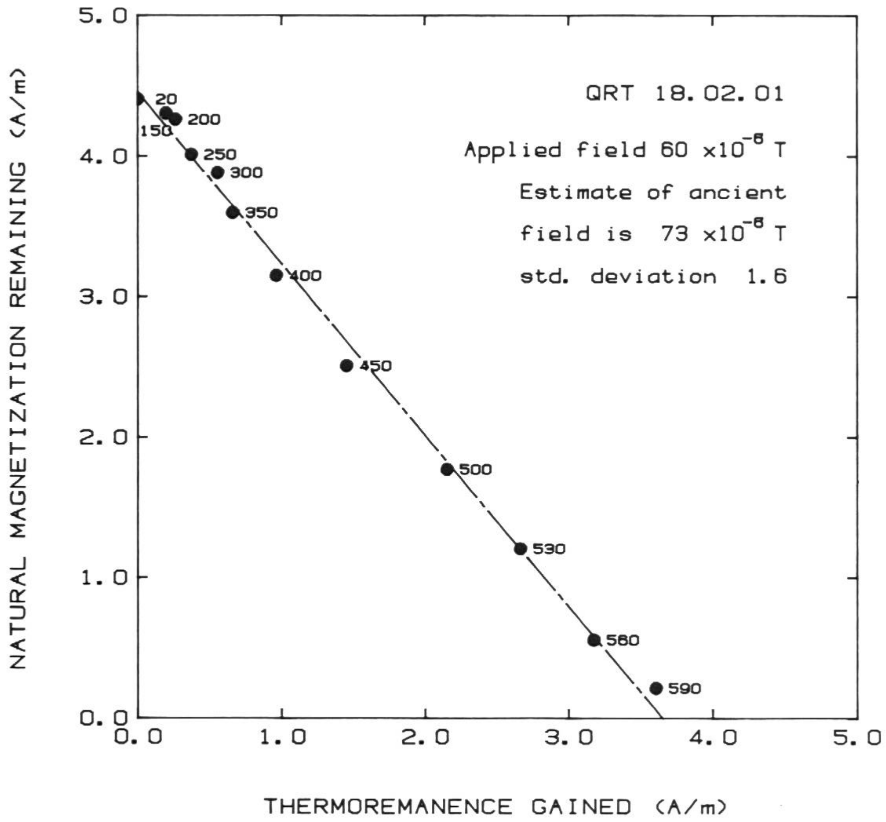

FIG. 6.

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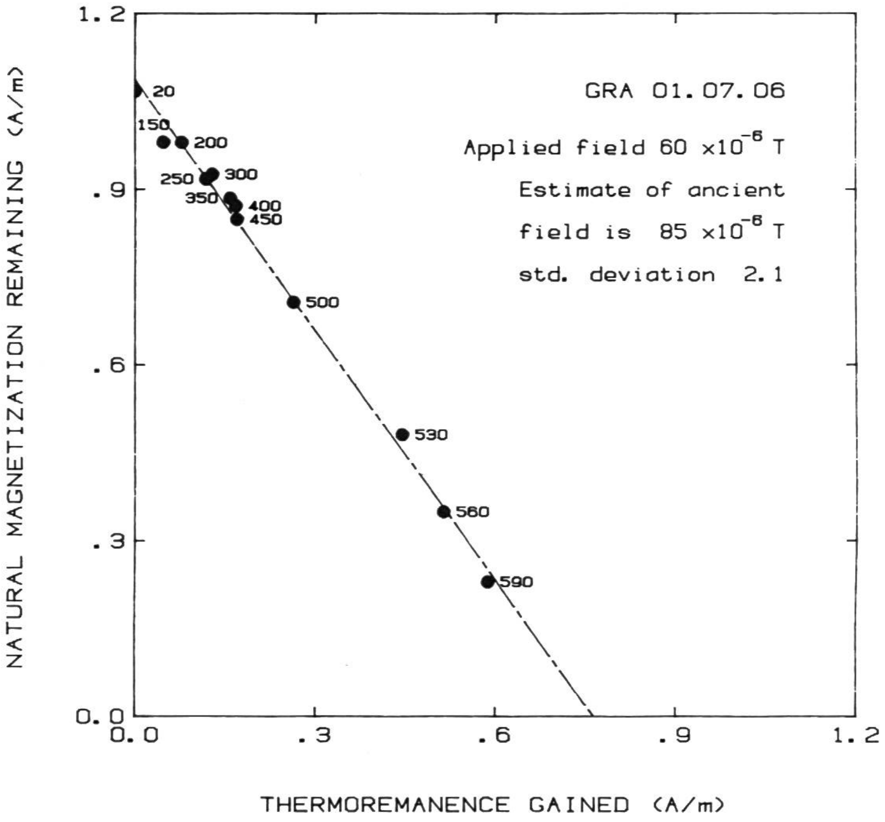

FIG. 7.

Same as for Figure 1.

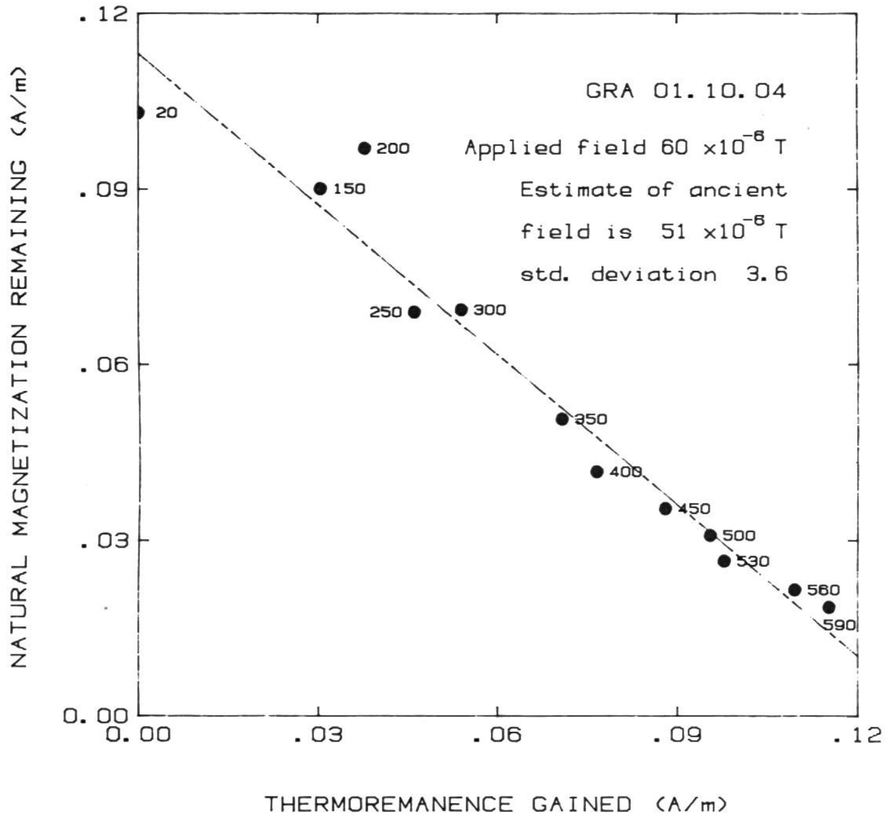

FIG. 8.

Same as for Figure 1.

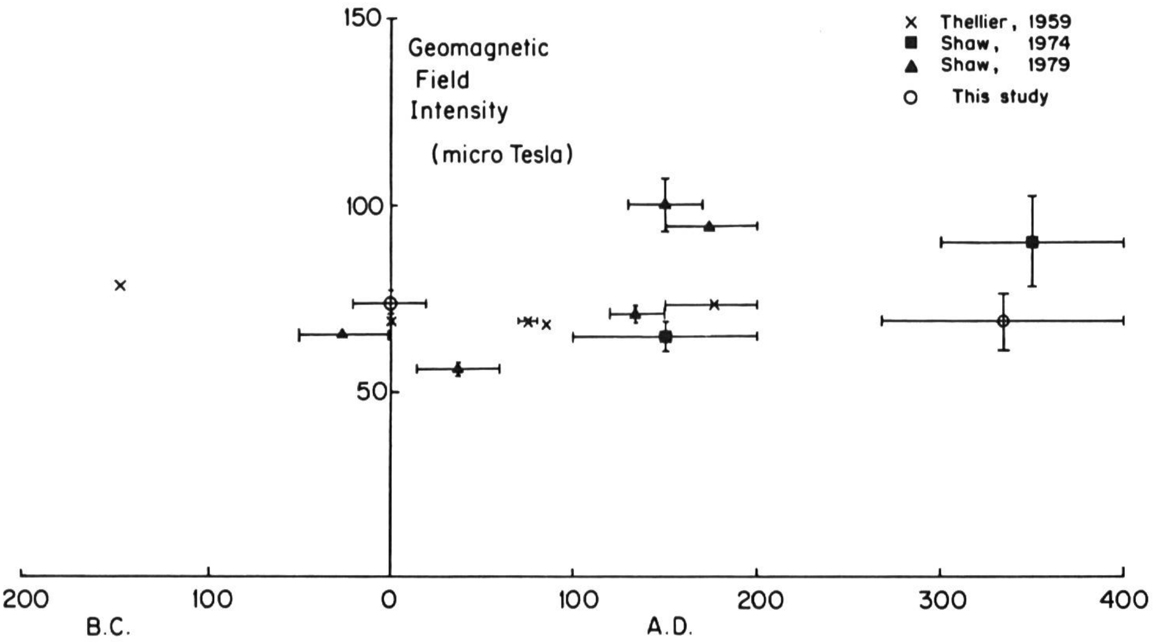

FIG. 9.

Intensity of the geomagnetic field for Western Europe during the Roman period. Data corrected to an inclination of 65° (Thellier) or a common latitude of 46° (Shaw). Our data are corrected to a latitude of 47°, that of Bern.

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