GREEK ARCHAEOMAGNETIC INTENSITIES: SOME ASPECTS OF RELIABILITY AND GEOPHYSICAL IMPLICATIONS

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(Received 3 July, 1989)

Abstract. Archaeointensity results from Greece for the last 2000 yr have been obtained using thermal and alternating field (AF) demagnetisation techniques. Most of the samples consisted of tiles and bricks derived from Byzantine churches which were epigraphically dated. The accuracy of the dating of the samples (to within a few years) and the comparison of the two techniques for measuring geomagnetic intensity combine to provide a good basis from which to derive meaningful conclusions – i.e. (i) About 70% of the archaeointensity measurements, made by the two methods, were highly compatible, differing less than ±7% from their mean. In 60% of the cases, the AF technique yielded higher palaeointensity results than that for thermal demagnetization. The results for the thermal and AF techniques are discussed in accordance with reliability criteria and attention is drawn to the reliability of archaeointensity data in general. (ii) An overall similarity of the intensity trend was observed for the last 400 years between the AF, the thermal demagnetization and a modelled intensity curve derived from the spherical harmonic coefficients since AD 1600. (iii) A decrease of intensity amounting to 40% is noted in the new data for the period since AD 400, and (iv) a non-dipole disturbance was noted at around AD 1300 in southern Greece, where the intensity changed by about 30% within a period of 30 years or so.

Introduction

The archaeomagnetic intensity of ceramics, kilns, bricks, tiles and well-fired clays can reveal interesting aspects of diverse problems which can be directly related to the earth's magnetic field, its secular variation and dating (Creer and Tucholka, 1983).

As the magnetic field is a vector quantity, archaeointensity measurements (along with palaeointensities) are potentially as useful as palaeodirections.

The new palaeo- and archaeo-intensity data could pinpoint or reinforce significant events in the Earth's history. Therefore, the reliability of these and ensuing data must be ensured.

Here we report on some aspects of the archaeointensity measurements acquired by both the thermal and AF demagnetization techniques (Thellier and Thellier, 1959; Shaw, 1974), for bricks and tiles from Greek Byzantine monasteries. These are then compared to a modelled field. The geophysical implications of the new intensity data for Greece during the last 2000 yr are discussed.

1. The Material

The samples taken from Byzantine churches by the author were obtained from the traditional brick and tile masonry. A plastic hammer was used to dislodge samples which were generally of few cm^2 in size. Some samples were quite easily

Earth, Moon, and Planets **47**: 1–13, 1989.

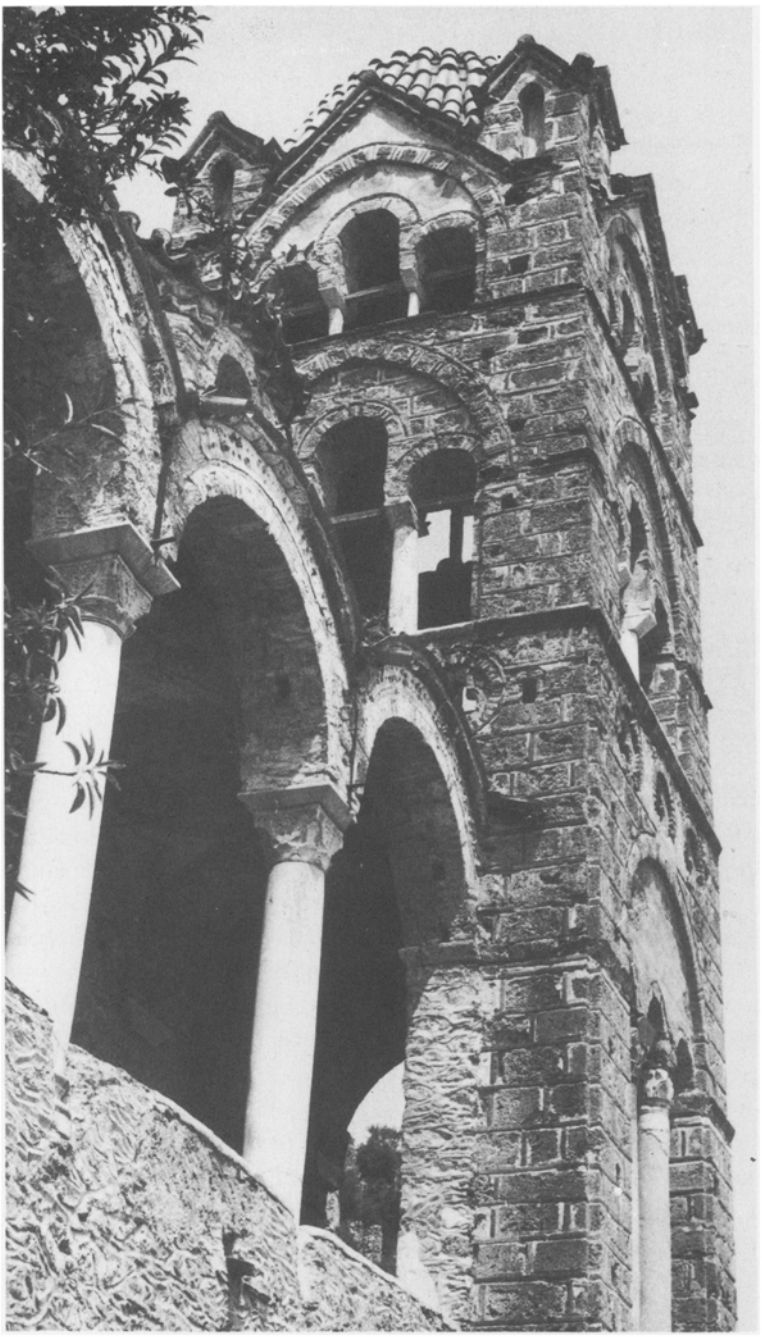

Fig. 1. Pantanassa Church, Mystras, South of Peloponese, Greece dated by epigraphy to AD 1428. Ceramic bricks and/or large tiles were used as decorative or building materials. They were made at most a year prior to the church construction. The sampling was carried out on such materials from outside as well as inside the church.

dislodged by hand. Where Byzantine vases were sampled, an impregnated diamond driller was used to obtain it. Vases could be accurately dated from their style. Churches were dated by epigraphy, as the date of construction or completion of the building was usually carved above the entrance to the church (Fig. 1).

Where epigraphy was absent, the churches could be dated accurately by architects or historians. Their advice was also sought in choosing the original part of the building for sampling, thus avoiding more modern additions.

2. The Measurements

In order to introduce the reader to the present work, the measurement procedures, based on Prof. Aitken's admirable efforts, are described.

Archaeomagnetic intensity determinations, using different techniques on samples from bricks and tiles from Greek monasteries are reported (see Aitken *et al.* 1988 for a complete presentation of the results). The samples were well dated from epigraphy. The measurements were performed by Prof. Aitken and his team at Oxford with a SQUID cryogenic magnetometer using a modified version of the Thellier technique (Aitken *et al.* 1983) consisting of a pair of heatings at each temperature step (the steps being at 50° degree intervals from 150° to 600 °C), each heating being followed by measurement at room temperature; the first in a known laboratory field F^L and the second in zero field F^0. The equation of the determination of the Earth's magnetic field in pottery baked in antiquity is given by:

$$F^A = (M^A/M^L)F^L\,, \tag{1}$$

where F^A is the intensity of the magnetic field in ancient times, F^L is the intensity of the applied magnetic field in the laboratory, M^A is the thermoremanent moment in ancient times, and M^L is the acquired magnetic moment after reheating in a known laboratory field. The well-known double heating technique introduced by Thellier and Thellier (1959) was modified initially by Walton (1977) and was later adopted by Oxford laboratory (Aitken *et al.*, 1981, 1983). This technique was further modified by the same laboratory (Aitken, 1983; Aitken *et al.*, 1986). Equation (1) due to Walton's modification based on the particlar experimental setting of SQUID I, in Oxford, is now expressed as:

$$F^A \cos\theta = F^L_V\,, \tag{2}$$

where θ is the angle defined by the sample's ancient magnetization and the vertical (stalk axis), F^A is in the ancient geomagnetic field, assuming that the sample is magneticallly isotropic and its demagnetizing factor is negligible, and F^L_V is the oven magnetic field which partly satisfies Equation (2). The ancient field value before correction for cooling-rate effect and anisotropy is given by Equation (3)

$$F^A = F^L_V(1+f)\cos\theta\,, \tag{3}$$

where f is the negative of the slope of the line obtained by plotting M^L_V (the

vertical component of the sample's moment at each step) after remagnetization, versus M_V^0, the moment remaining at each step, after the subsequent demagnetization at zero field. Both these produce a plot illustrating that the modified Thellier technique works well. The lack of linearity (usually apparent at the extremes of the line) means mineral or chemical change within the matrix of the sample. The general equation which satisfies these abovementioned conditions is given by Equation (3). When the remanent magnetization is different in direction from the field, then an effect is produced due to the anisotropy. Equation (3) then becomes

$$F^A \cos\theta = c\, F_V^t(1+f)\,, \tag{4}$$

where c is the combined effect of $m(=M^V/M_V^{V+H})$ (where, M^V is the moment emplaced by a vertical field in magnitude to the vertical component of the inclined field and M_V^{V+H} is the vertical component emplaced by the 'sufficiently close' inclined field (quotation by Aitken *et al.*, 1981, p. 57)) and $u(=\cos\theta_1/\cos\theta_2)$ where θ_1, θ_2, are the angles to the vertical of the applied field and its resulting demagnetization in the remagnetizing procedure that gave a direction sufficiently close to M^A). The Equation (4) values are corrected for cooling-rate (Fox and Aitken, 1980) and for distortion of internal fields (Aitken *et al.*, 1981). Confirmatory checks were made on some samples as described by Kono (1978).

For an intensity determination to be deemed reliable, we require that the Arai plot should show a linear portion extending over a substantial fraction of the demagnetization range. An intensity determination was accepted as having good reliability (Grade 1 or 2) only if it satisfied the criteria described by Aitken *et al.* (1983). In fact, the principal criteria, that the results for a core must satisfy, in order to be regarded as having good reliability, class A (or B^+), are described in Aitken *et al.* (1983); while the sample itself was given a grading on the following basis; Grade 1 (Excellent), Grade 2 (Good), Grade 3 (Poor), Grade 4 (Bad), Grade 5 (Ignore) (Aitken *et al.*, 1986).

In the alternative demagnetization technique (Shaw, 1974) alterating field (AF) demagnetization is employed. By this means the ratio of natural remanent magnetization (NRM) to thermoremanent magnetization (TRM) can be obtained for different parts of the coersivity spectrum. Also, after AF demagnetization of the NRM and before any heating takes place, the sample is given an anhysteretic remanent magnetization (ARM) by subjecting it to a strong AF (of 200 mT) and applied a weak DC field (of the order of 0.1 mT). The steps in this technique, include; measurement NRM and repeat with AF demagnetization for increasing maximum field; emplace ARM and measure it; emplace TRM by heating (say, T =700°C) measure TRM and repeat measurement after each step of AF demagnetization, emplace another ARM as above, measure it e.t.c

A difficulty with Shaw technique is that, unlike Thellier, it is not possible to separate out the component of magnetization acquired from a partial heating that took place after the original firing. In some other cases the decision whether or not to use the origin of the NRM–TRM plots as a data point is crucial for the

TABLE I

Intensity data for Thellier and Shaw techniques, their grades, their deviations and ratios (obtained by the Oxford team and presented in Aitken *et al.*, 1989).

		Thellier		Shaw			
Date	Site	$F^A(\mu T)$	Gr[a]	$F^A(\mu T)$	Gr	%Dev[b]	R[c]
1275 ± 25	Volos[d]	43.6	1	49.1	B^+	−5.9	0.89
1285 ± 1	Krokees	59.1	2	54.1	B^+	4.6	1.09
		62.13	3	56.8	B^-	4.5	1.09
1290 ± 1	Myrtia.	68.3	2	57.2	B^+	8.8	1.19
		61.6	2	56.3	A^-	4.5	1.09
		62.5	3T	71.6	B^+	−6.7	0.87
		61.2	3	66.1	B^+	−3.8	0.92
1303 ± 9	Thess.	53.1	2	57.2	A^+	−3.8	0.93
		58.7	2	38.7	B?	17	1.52
1305 ± 15	Thess.	53.3	1	56.7	A^-	−3.0	0.94
		52.9	3	47.5	C^+	5.4	1.11
		58.2	3	62.4	A^-	−3-5	0-93
1314 ± 19	Desfina	62.6	2	66	A^-	−2.6	0.95
		57.9	2	59.1	B^+	−1.0	0.98
		61.9	2	46.4	B^+	14.3	1.33
		60.1	2	61.0	B^+	+0.7	0.98
1315 ± 15	Thess.	48.7	1	72.2	C^+	−19.4	0.67
1428 ± 1	Mystras	49.4	3T	42.9	B^+	7.0	1.15
		54.5	3T				
		53.2	2				
1431 ± 1	Geraki	46.6	2	47.4	A^-	−0.8	0.98
		44.9	2	54.1	A^-	−9.3	0.83
		48.7	2	49.2	B^-	−0.5	0.99
1508 ± 1	Athos	45.9	2	41.2	A^-	−1.5	0.97
		46.8	3T	53.7	A^-	−5-6	0.89
1535 ± 5	Athos	47	1	41.3	A^-	6.4	1.14
		52.8	2				
		51.4	3				
1615 ± 5	Laconia	50.5	3	69.73	B^-	−16	0.72
		61.7	3	65.26	B^+	−2.7	0.94
		54.9	3T	73.75	B^+	−12.7	0.74
1640 ± 1	Chrysafa	60.7	3	54.92	B^+	5.0	1.10
		46.1	2	58.94	B^-	−12.2	0.78
1767 ± 1	Athos	40.8	3	35.80	B^-	6.5	1.14
Average						−0.34	0.99
Standard dev.						8.8	0.18
Std. error mean						1.5	0.03

[a] Gr for Grade.

[b] %Dev: Mean intensity = (Thellier + Shaw)/2 ± % deviation from their mean value. (−) is for higher Shaw's results.

[c] R: Ratio of Thellier to Shaw.

[d] Geraki, Mystras, Krokees, Myrtia, Laconia, Chrysafa is for South Greece (36.8° N, 22° E), Thess. for Thessalonica, Athos the holy mountain in the Chalkidiki peninsula is for north Greece (39.5°–41°): Desfina is Central–South Greece and Volos, Central–North.

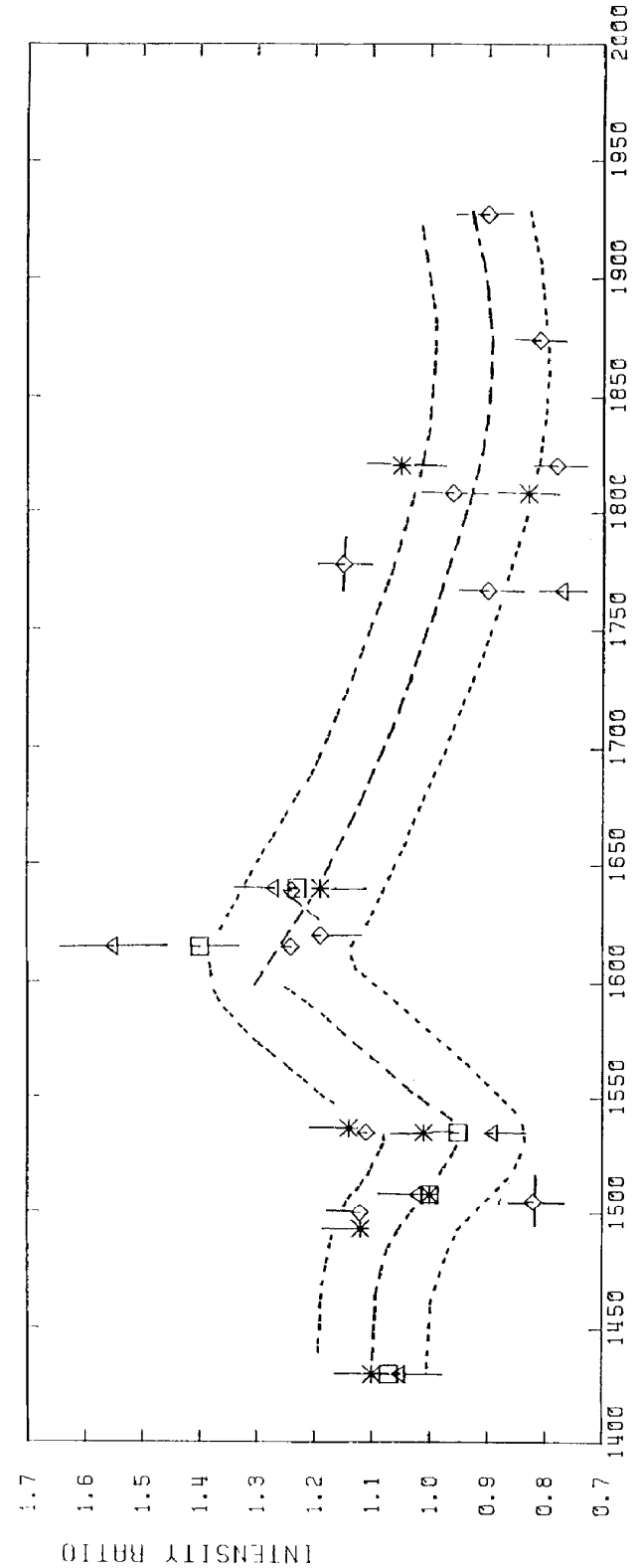

Fig. 2. Archaeointensity ratios F^A/F^D compared with the modelled geomagnetic field (fourth degree and order) from Barraclough (1974) and Thompson and Barraclough (1982), for 40° N, 20° E (dashed line) since 1600 AD following the prediction. (*) is for Thellier (1, 2), (◇) is for Thellier (3+) (□) for Thellier (1, 2) + Shaw (A, B) and (△) for Shaw (A, B), techniques and associated significance criteria. Note that the 10% confidence band includes nearly all points, in a free-hand fit.

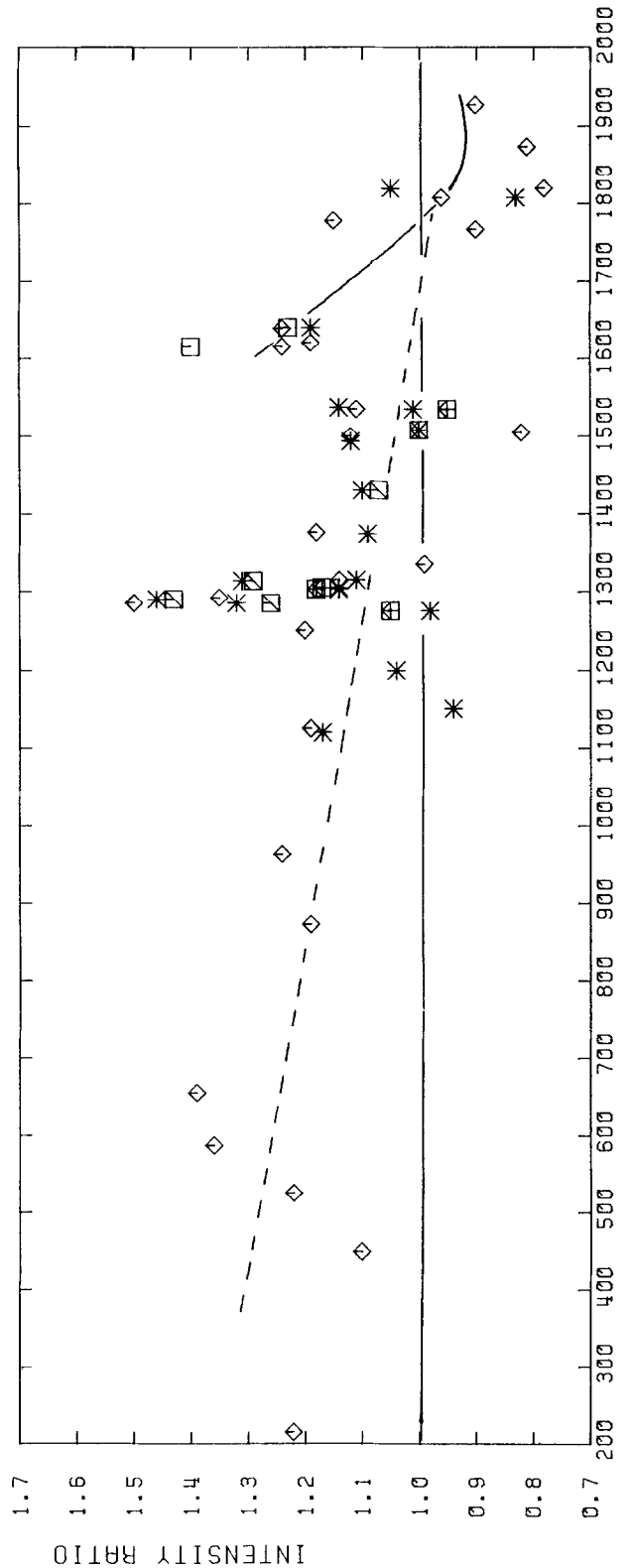

Fig. 3. As per Figure 1 (⊞) is for Thellier (1, 2) and Shaw (A, B), for North of Greece, and (⊠) for Thellier (1, 2) + Shaw (A, B) for South of Greece. The north and south Greek data are important in c. 1300 AD, in other periods they are displayed as (◇), (∗) or (□). The F^D of the different latitudes in the Greek sites was 4% for a maximum latitude difference, $\Delta\lambda = 3.5°$ (37–40.5° N). Note the modelled curve (solid line) and the intensity decrease (dashed line) for the last 2000 yr (see text).

estimation of the intensity as the original firing may have not reached Curie point or grains beyond the range of the AF are unchecked by the ARM monitoring. The accuracy of the intensity results obtained by the Thellier or Shaw technique has been questioned by Walton (1987), who maintains that a straight line (Arai plot) is no guarantee of reliability. Both techniques provide, according to Walton, a fictious magnetic moment due to mineral alteration.

This is because the processes of mineral alteration due to heating in the laboratory and the magnetization proceed in parallel and are difficult to separate with the linearity test.

Walton proposes a technique for measuring magnetic moments with a SQUID. The contradistinction, with the Oxford Group, is on the other hand, strongly based on satisfactory results using the modified Thellier technique and occasionally, the Shaw technique and following certain imposed criteria. A discussion on these is given in Aitken *et al.* (1985, 1986), Walton (1987, 1983, 1985, 1986), Aitken (1983), RG (1988).

The present results (which are of grades 1, 2, 3 and 3T for Theiller, and $A^{\pm}$ and $B^{\pm}$ for Shaw) have been normalised to the present axial dipole field value F^D of moment $M = 8 \times 10^{22}\,\mathrm{Am}^2$. They are listed in Table I and plotted with error bars in Figures (2, 3). A discussion of the reliability of these recent results is made and some geophysical implications are remarked.

3. Estimation of Historic Geomagnetic Field

The field intensity for lat 40° N, long 20° E was determined (R. Thompson, pers. comm.) by extrapolation of the recent decrease of the axial dipole intensity in combination with the spherical harmonic coefficients by Barraclough (1974) and by Thompson and Barraclough (1982). These values, normalized to the present axial dipole field intensity (F^D) are presented in Figure 2 and joined by a dashed line.

4. Discussion of Data Obtained by Thellier and Shaw Techniques

From Table I it is noted that the intensities made by the Thellier and Shaw techniques differ by amounts which vary from zero to ±20%. Out of 32 pairs, 47% fall within $<\pm 5\%$, 25% fall within ±5–7% and 28% within >7%. This agreement refers to their percentage deviations from their mean, as these percentages are of the order of standard errors of the intensity determinations. In 60% of the pairs the results using Shaw technique are higher than those using Thellier technique. On average their ratio is almost one, but, with a standard deviation of 1 ± 0.18. The standard deviation of the percentage variation from the mean is ±8.8%

Rejection of results in the previous work (Aitken *et al.*, 1988) means a poorer grading that 2, on the basis of the reliability criteria by which the samples were

placed on a scale of 1–5, although rejected samples placed in grade 3 follow the geneal trend of those in grades 1 and 2, but there is more scatter (Figures 2, 3).

It is interesting to note the overall similarity in the trend (Thellier's, Shaw's results and modelled field), within the stipulated errors (Figure 2). Certainly the modelled intensity is non-linear earlier than 1600AD and the expression for the time-dependence of g_1^0, is no longer valid. Nevertheless, the archaeomagnetic results (Aitken *et al.*, 1988) can be used in the future as reference points for extending the spherical harmonic model (SHM) of the geomagnetic field to a good approximation for earlier periods.

However, because the NRM measured in the laboratory will frequently not represent the total TRM acquired during the original firing due to various processes (e.g., weathering, chemical magnetization, viscous magnetization, mineralogical changes), it is safer to use more than one technique for the determination of ancient intensity. Our Figure 2 shows that the combined applied criteria for Thellier (Grades 1, 2) and Shaw's (A, B) techniques for these samples yield satisfactory estimates of the geomagnetic field intensity in comparison to the modelled curve within the errors. We note that Thellier grade 3 results are close to SHM curve. The latter is the case for the 1640, 1808, 1927 points (Figure 2). Also, two of the Thellier grades (1 or 2) in c. 1800 do not seem to be very compatible with the modelled curve too; but only within 2SD.

In fact the modelled curve is compatible with all the results to within a band of $\pm 10\%$; which could be less if the normalisation of the SHM curve was made on respective site latitude instead of on an average 40° N, 20° E point. Surprisingly, enough grade 3 data are included within this band. This gives the impression that grade 3 in some, only, materials provide good results compared with a reference value (here the SHM curve) and in some other materials, good grades do not provide compatible results with expected values (following, say, the trend in a short-time interval). We should, however, refer to the compatibility of Thellier results compared with observatory-based measurements, made on bricks from modern buildings and tile, pottery, brick from a kiln, where the F^A to modern field average was 0.97 ± 0.07. On the other hand the average value of the ratio Thellier to Shaw was 1.01 ± 0.10 out of 31 results, the high scatter being attributed to lower precision of the Shaw results (Aitken *et al.*, 1986). At present, however, it is safer to use grades 1, 2 of Thellier technique and grades A^{+-} of Shaw technique, according to stipulated criteria of reliability (Aitken *et al.*, 1983, 1986, 1985), anticipating an acceptable deviation in their intensity, only within their errors, as in Table I.

5. Geophysical Implications of the Greek Intensity Curve During the Last 2000 yr

Figure 3 shows all thc data from Greek churches, incorporating those of Figure 2.

The downgraded data (grade 3 plus) generally follow the variation of the more reliable results (grades 1 and 2).

There is a 40% decrease in the field intensity circa AD 400; this clearly represents a decrease in the main dipole field at a rate of 0.019 μT. Similar rates were estimated from recent Chinese data for the same period, (but with an allowance for longitude), (Wei Quing-Yun *et al.*, 1987). A similar broad trend was also found in Bulgaria by Kovacheva (1980), though the magnitude of these peaks are higher at AD c. 1100–1700. The peak we note at AD 1300 is not present in Kovacheva (1980) though the revised Bulgarian data (Kovacheva and Kanarchev, 1986) demonstrate a high scatter of approximately 40% which, when fitted with a spline, exhibits a peak at AD c. 1300, with a dip at AD c. 1500. This is similar to ours.

From AD c. 1850 onwards the magnetic field in Greece starts to increase again and this has continued until today.

During the last 1500 years or so, the field has decreased from 63 μT to around 37 μT.

During this period there appears rapid latitude dependent non-dipole field changes, one of which in AD 1300 reaches about 68 μT and lasts around 30-yr. Within this c. 30 years period, the average field values change by approximately 32%.

When we consider the intensity ratio for the Greek regional groups, we note that the average ratio for both the contemporary Laconian Byzantine churches (S. Greece) and the Macedonian Byzantine churches (N. Greece) represents a change in intensity of about 27% over 3.7 latitude, (Aitken *et al.*, 1989).

It is not yet known if, during such a long gradual decrease of the total magnetic moment short term variations would always occur.

This uncertainty is due to the poor dating resolution, the lack of finding samples within the desired chronological sequence and experimental inaccuracy.

Without preconceptions, we could explain the nature of our data in any of the following ways:

(i) by accepting the hypothesis of recurrent 'drastic variations', one could then start looking for models which describe periodic intensity variations which can be applied to earlier periods where similar behaviour of the main dipole field can be encountered, and

(ii) if stochastic processes are involved then two points may arise:

(a) that such localised drastic increases might act as triggering mechanisms which are related to the development of stronger turbulence. This subsequently leads to stronger fields (field increase from 1850 onwards), and

(b) that it is not possible to date or recognise archaeological-geological events within less than a 30-yr period if the dates attributed to the samples to be measured are not more precise, and

(iii) the scatter in the data may not be entirely of geomagnetic origin, but represent inaccuracy of the archaeo intensity measurements.

This is not the case for churches with epigraphy or for materials for which there is historical documentation. Point (b) above applies mainly to earlier periods in the archaeological record, where dating errors are within at least 100 yr or so.

A similar picture of field decrease occurred also during the period BC c. 1100

to BC c. 1800 in Crete and in Egypt–Mesopotamia (Aitken *et al.*, 1983). Similar, apparently, rapid archaeointensity changes have also been recorded by Games (1980) for Egypt and Sternberg (1988) for south-west America.

In the main non-dipole field, spatial dependence can not be ruled out, for these areas, and any attempt to smooth the data must be done with due caution.

The question of short-term fluctuations in the magnetic field is still unresolved. One possible resolution may be to examine the characteristic properties of secular variations, synthesized from simple computer models for homogeneous data from areas around the world. In this approach, the magnetic field sources in the outer core produce the main dipole and non-dipole fields in a variety of combinations, e.g., a drifted radial dipoles of fixed moment; drifting current-loop sources of fixed moment; oscillating of pulsating radial dipoles at fixed positions; spatial variation of SV due to a standing oscillating or pulsating source, or drifting sources of variable moment (Creer and Tucholka, 1983).

Regarding the drastic intensity change of about 30 yr in the Greek data, we should note that this may indeed be of truly geomagnetic origin.

The change at AD c. 1300 coincides with an anticlockwise to clockwise motion of the magnetic direction and this may imply the development of localised disturbances at the core-mantle boundary. It should also be recalled that interference between the growth and decay patterns of two or more standing sources may contribute to rotation of the geomagnetic vector. Thus, two or more geomagnetic sources which grow and then decay as they, say, drift west, would perhaps yield VGP paths which exhibit counter-clockwise loops, if the influence of the changing variations in their intensity were to outweigh the influence due to that of their movement.

The magnetic field is very complicated to interpret with any great accuracy. Regional studies of the field can only contribute to the elucidation of the associated problems.

A further problem associated with the geophysical interpretation of the palaeointensity results is that of normalisation. The F^D factor is an acceptable method based as it is on the assumption of the dipolar nature of the earth's field, but this is not true. It becomes pronounced, especially when the normalization is made on some sites which exhibit drastic localised disturbances.

All the above must be borne in mind before any attempt is made to draw conclusions. Our observations of possible drastic short term variations of the field are, at present, speculative and thus this phenomenon requires further investigation before it can be accepted with any confidence.

6. Discussion of the Greek Geomagnetic Intensities

Our evidence suggests the occurrence of rapid fluctuations in the geomagnetic field, but these can only be identified as being of geomagnetic origin when further data becomes available.

The Greek monasteries offer more data for testing the techniques of Thellier and Shaw in obtaining archaeomagnetic intensities and also for confirming short-term variations. The main advantage of the Greek material lies in the accuracy of the dating as samples were dated by epigraphy.

The present results exhibit interesting short-term features at around AD c.1300 and AD c.1630. On the whole, the archaeomagnetic intensity of the last 2000 years decreased till AD c.1800 after which it began to increase again.

From all the observations above, it is now clear that it will be necessary to revisit and thoroughly re-examine the cause of those intensity deviations which are of a magnitude greater that those associated with experimetnal errors. This really ought to be done before much new data accumulate as models, once formulated, are tenaciously adhered to, and can yield misleading rather than simply incomplete conclusions.

Therefore, given the weighty implications which intensity estimates can have, it is important to reconsider very carefully the different techniques for measuring palaeo- (archaeo-) intensity and be fully aware of their inherent failings.

The archaeointensity results for the Greek churches may offer one means of dating similar Byzantine churches which are devoid of epigraphy. Further work on these Greek churches and monasteries would be a worthy project from both the dating as well as the purely geomagnetic point of view.

Acknowledgements

I appreciate the help afforded to me by Prof. K. Creer and Dr R. Thompson in their useful discussions and I am thankful to Prof. R. Sternberg for further useful comments on the manuscript. Financial assistance for this work was obtained from the National Hellenic Research Foundation, The Royal Society of London, the Onassis Foundation and the British Council.

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