ARCHAEOMAGNETIC INTENSITY IN FINLAND DURING THE LAST 6400 YEARS: PROBLEMS IN MEASUREMENT TECHNIQUES, DATING ERRORS OR EVIDENCES FOR A NON-DIPOLE FIELD?

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Abstract

Archaeomagnetic intensity in Finland has been determined for the past 6400 years with the Thellier technique of bricks, potsherds and baked clays. The normalized intensity shows an increase from ~4360 BC to the maximum at AD 500–AD 900, after which it decreases to the present value. The peak at AD 500–AD 900 is not a consequence of the applied Thellier technique since we are able to reproduce the known field values in the laboratory, and some of the bricks yield values which are in broad agreement with the observatory data. We have shown that variations in grain size of the magnetic carriers, cooling rate, fabrik or magnetic refraction are unlikely to cause systematic errors in intensity larger than ten percent. Previously we have demonstrated that the high intensity at AD 500 in Finland can be modelled by a non-dipole field producing enhanced latitude-normalized values at higher latitudes (Finland) and relatively weaker fields at lower latitudes (Bulgaria), and that extrapolation of the present field (IGRF 1990) back in time shows similar behaviour. However, the new Bulgarian smoothed archaeointensity curve by Daly and Le Goff (1996) shows a maximum in Bulgarian curve at ~AD 630 (i.e., 130 years later than in Finland) and another maximum at AD 950 (i.e., 50 years later than in Finland), and the new relative intensity data of Finnish lake sediments (Saarinen, 1996) reveals a peak at ~AD 870 corresponding roughly with the second maximum. These new curves are somewhat controversial but they cast doubt on the previous datings of the Finnish archaeomagnetic materials of the first millennia AD. Here we show that a better match of the Finnish and Bulgarian intensity data with the Finnish lake sediment data can be obtained if the Finnish ages of the first millennium are slightly younger than previously thought. However, the Finnish intensities are still significantly higher than the coeval Bulgarian intensities so that a non-dipole field enhancement may have also been operative.

1. Introduction

During the past decades the intensity of the magnetic field of the Earth has been measured for the last millennia in several countries using archaeological artifacts (see Pesonen et al., 1995 and references therein). These measurements have led to the construction of the global geomagnetic intensity curve for the last 10 000 years (McElhinny and Senanayke, 1982), showing a gradual increase in normalized field intensity from 8000 BC to ~AD 0 and then a decrease during the past 2 000 years. The global curve has been calculated by data from sites in low to moderate latitudes (± 10°–± 50°), with the majority from the northern hemisphere. Due to the averaging the *global* intensity curve reflects changes in the main dipole and does not allow observation of the more rapidly varying nondipole field (Liritzis and Kovacheva, 1992). Therefore, more emphasis has recently been given to the study of *regional* archaeointensity (B_a) curves since they allow investigation of important aspects of the field, e.g. (i) drift of the nondipole field (Liritzis and Lagios, 1993), (ii) detection of periods of rapid intensity changes (Liritzis and Kovacheva, 1992), (iii) ratio of the nondipole field to the dipole field (Yang et al., 1993) and (iv) dependency of B_a on latitude when the main dipole contribution is removed (Evans, 1987; Pesonen et al., 1993, 1995). If such features can be traced from the regional B_a curves they give new constraints for models of the geomagnetic field and also for the dynamo theories behind the models. A debate, however, has been ongoing on whether the differences in regional intensity curves are real (i.e., of geomagnetic origin) or whether they are artifacts of the laboratory techniques used to determine the intensity (Walton, 1987; Aitken et al., 1991), due to dating errors (Pesonen and Leino, 1997; this work) or due to some unexplained extraterrestrial cause (Pesonen and Leino, 1996). Clearly, more reliable intensity determinations on well-dated archaeological samples from various regions are required for solving these problems. The area of Finland satisfies these requirements since it occupies high northern latitudes (60° N–70° N), dated archaeological material is available and the Palaeomagnetic Laboratory of the Geological Survey of Finland (GSF) has the technical facilities for undertaking B_a determinations with various techniques (Leino, 1979; Pesonen et al., 1995).

In this paper we study further the archaeointensity curve for Finland from the last 6400 years (Pesonen et al., 1995) and compare it with two recently published intensity curves of coeval period, (1) the smoothed Bulgarian intensity curve by Daly and Le Goff (1996) and the relative intensity curve of varve-counted sediments of the lake Pohjajärvi in Finland (Saarinen, 1996). First we shortly review the evidences from various laboratory experiments to eliminate explanations other than dating errors or geomagnetic field variations for the B_a/B_0 in Finland. With the new data in focus, we propose that some of the previous mismatches in intensity curves between Finland and Bulgaria can perhaps partly be explained in terms of dating errors.

2. Sampling sites and age data

The Finnish intensity curve is based on 23 samples from 19 archaeological sites in south-western Finland. The sites are listed in Table 1 and the datings in Table 2. Three types of sample were used: bricks, potsherds and baked clays, the majority (80%) being bricks. Four methods were used to assign the ages for the samples (see details in Pesonen et al., 1995). *(i)* Most ages were obtained from the archaeologists using standard archaeological criteria of typology and styles (M. Hiekkanen, pers. commun., 1985, 1994; C. Carpelan, pers. commun., 1993; P. Erämetsä, pers. commun., 1994; Hiekkanen, 1994). The errors are of the order of ± 25– ± 100 years and are estimates. In a few cases the ages rely on calibrated ^{14}C dates obtained from carbon-containing materials from stratigraphically controlled levels at the excavation sites (Sonninen et al., 1989). *(ii)* Accurate ages for some bricks can be obtained by investigation of church archives (Hiekkanen, 1988, Leino and Pesonen, 1994). *(iii)* Some bricks were dated with the thermoluminescence technique (TL), Table 2 (H. Jungner, pers. commun., 1993. The TL ages have standard errors of ± 50 years. We note here that the TL ages do not always agree with the archaeological ages; in some cases they are ~50–100 years younger than the latter (Table 2). A few of the TL ages are obviously too young when compared with archaelogical ages due to restorations or fires. *(iv)* A precise and accurate age has been obtained for some bricks since they have been stamped with

Table 1. Archaeomagnetic field intensities in Finland

#	site	S	symbol	material	Lat.	Long.	age	meth.	n	VADM±σ	B_a/B_0±σ
1.	Helsinki building	18	HE-T	brick	60.1	24.9	1906	a	1	5.9 ± 0.2	0.81 ± 0.03
2.	Kastelholma Castle	3	KL-T	brick	60.3	20.1	1905 ± 15	a	1	6.4 ± 0.1	0.87 ± 0.01
3.	Fiskars Museum	17	FI-T	stamped brick	60.1	23.5	1829	a	1	7.2 ± 0.2	0.99 ± 0.03
4.	Porvoo Church	7	PK-T	brick	60.4	25.7	1730 ± 25	a	1	8.2 ± 0.4	1.13 ± 0.05
5.	Espoo Church	4	EK-T	brick	60.2	24.6	1694	a	2	7.1 ± 0.4	0.97 ± 0.05
6.	Kastelholma Castle	3	KL-T	brick	60.3	20.1	1600 ± 50	a,TL	4	9.4 ± 0.5	1.29 ± 0.07
7.	Tyrvää Church	9	TK-T	brick	61.4	21.9	1525 ± 15	a	1	8.9 ± 0.8	1.22 ± 0.11
8.	Renko Church	10	RK-T	brick	60.9	24.3	1520 ± 10	a	4	8.8 ± 0.5	1.22 ± 0.07
9.	Lohja Church	6	LK-T	brick	60.3	24.1	1490 ± 50	TL	1	8.8 ± 0.5	1.25 ± 0.07
10.	Kastelholma Castle	3	KL-T	brick	60.3	20.1	1490 ± 60	a,TL, ^{14}C	3	9.8 ± 0.1	1.34 ± 0.01
11.	Espoo Church	4	EK-T	brick	60.2	24.6	1490 ± 5	a,TL	5	9.1 ± 0.3	1.25 ± 0.04
12.	Hämeenlinna Castle	1	HL-T	brick	61.0	24.4	1485 ± 15	a	4	8.9 ± 0.1	1.22 ± 0.01
13.	Kirkkonummi Church	5	KK-T	brick	60.1	24.4	1475 ± 25	a	4	9.7 ± 0.3	1.33 ± 0.04
14.	Kastelholma Castle	3	KL-T	brick	60.3	20.1	1450 ± 50	a,TL, ^{14}C	3	10.8 ± 0.3	1.48 ± 0.04
15.	Karjaa	15	KA-R	potsherd	60.1	23.7	900 ± 100	a	1	13.7 ± 0.6	1.88 ± 0.08
16.	Maalahti	11	MA-R	potsherd	63.0	21.6	500 ± 100	a	2	14.2 ± 0.5	1.97 ± 0.07
17.	Valkeakoski	16	VA-R	potsherd	61.3	24.1	500 ± 100	a	2	15.1 ± 0.6	2.07 ± 0.09
18.	Lempäälä	19	LU-R	potsherd	61.3	23.7	500 ± 100	a	2	12.6 ± 0.9	1.73 ± 0.13
19.	Nousiainen	14	NO-R	baked clay	60.6	22.0	–250 ± 250	a	1	10.9 ± 0.1	1.50 ± 0.01
20.	Espoo	4	ES-R	potsherd	60.2	24.6	–500 ± 200	a	1	12.3 ± 0.3	1.69 ± 0.04
21.	Halikko	8	HA-R	potsherd	60.6	23.1	2000 ± 100	a	1	8.6 ± 0.6	1.19 ± 0.08
22.	Kastelholma	3	KH-R	potsherd	60.3	20.1	2780 ± 150	a	2	5.9 ± 0.4	0.81 ± 0.05
23.	Kurikka	12	KU-R	potsherd	62.6	22.4	–4360	a,^{14}C	1	4.1 ± 0.2	0.56 ± 0.02

#	number of entry
site, S, symbol	sampling sites and site numbers (= S) refer to Fig. 1. No reliable results were obtained from site 2 (= Suomenlinna Castle, see Section 9). Results from self-made bricks (AD 1987) refer to Site 13 (= Katila Brick Factory) and are not included (see Fig. 10). Abbreviations for symbols: first two letters refer to site (e.g., HE = Helsinki) and the last letter denotes type of material, T = brick and R = potsherd or baked earth, respectively
Lat., Long.	latitude (° N), longitude (° E) of the site
age	age (+ = AD, – = BC), errors are estimates. For sources, see text (Section 2.2)
meth.	method used in dating: a, archaeological, TL, thermoluminescence, ^{14}C, radiocarbon (calibrated)
n	number of specimens
VADM ± σ	Virtual Axial Dipole Moment (10^{22} Am^2) ± weighted standard error of the mean, with weighting according to quality factor q (see text)
B_a/B_o ± σ	archaeointensity (B_a) normalised to present magnetic field intensity (B_o) at the site, errors as for VADM

Table 2. Some TL datings of bricks from Finland

				age (AD)		
S	code	site	type of material	archaeological	TL	stamp year
4	E	Espoo Church	construction brick	1490 ± 5	1540 ± 50	–
4	E	Espoo Church	construction brick	1490 ± 5	1520 ± 50	–
4	E	Espoo Church	altar brick	1400 ± 15	1740 + 50	–
5	K	Kirkkonummi Church	pilaster brick	1300–1400	1540 ± 50	–
5	K	Kirkkonummi Church	brick	1300–1400	1770 ± 50	–
6	L	Lohja Church	ceiling groin brick	1510 ± 10	1490 ± 50	–
10	R	Renko Church	floor brick	1520 ± 10	1520 ± 50	–
10	R	Renko Church	ceiling groin brick	1520 ± 10	1580 ± 50	–
2	S	Suomenlinna Castle	stamped brick	1847	1830 ± 50	1847

S	site number refer to Table 1
code	see symbols in Table 1
age	TL-measurements by Vagn Mejdahl at Risö Research Institute, University of Århus (Denmark), see Table 1 (H. Jungner, pers. commun, 1993)

the brick-making year (Table 1; see examples in Leino and Pesonen, 1994). We note here that confidence in the TL ages was obtained since a stamped brick of Suomenlinna Castle (Site 2) of age AD 1847 gave a TL age of 1 830 ± 50 years which lies within the error limits of the true (stamp) age (Table. 2).

3. Determinations of Ba at GSF

A full description of the techniques and laboratory instruments used at the Paleomagnetic Laboratory of GSF are described in Leino (1979), Leino and Pesonen (1994) and Pesonen et al. (1995). The B_a technique used was the Coe variant of the Thellier technique (Coe, 1967; Leino, 1979) combined with the graphical-plotting method of Arai (Nagata et al., 1963). Partial thermoremanent magnetization (PTRM)-checks (Coe, 1967) were occasionally but not systematically done to detect physicochemical alterations during the course of Thellier runs. The applied B_L was in the range 48–52 μT, close to B_o in southern Finland (Pesonen et al., 1995). B_a was obtained from the slope (k) of the Arai-line; $B_a = -kB_L$). We used a modification of the least-squares technique of Coe et al. (1978) in fitting the best line and in calculating k and its standard deviation (Leino and Pesonen, 1994). Each Thellier run is also ranked with the quality factor (q) as described in Leino and Pesonen (1994): the higher is the q-value the more reliable is result. The other acceptance criteria concerning non-ideal Thellier behaviour, PTRM checks and mineral alteration effects are more subjective and are discussed in Leino and Pesonen (1994). Approximately 70% of the samples yielded reliable intensities. Causes of failure are described in Leino and Pesonen (1994).

4. Results

4.1. Previous data

Results of the typical archaeointensity plots are shown in Pesonen et al. (1995) and only a few examples are presented here. Most of the Arai-plots were linear over only part of the temperature range applied. Figs. 1 and 2 show examples of accepted B_a

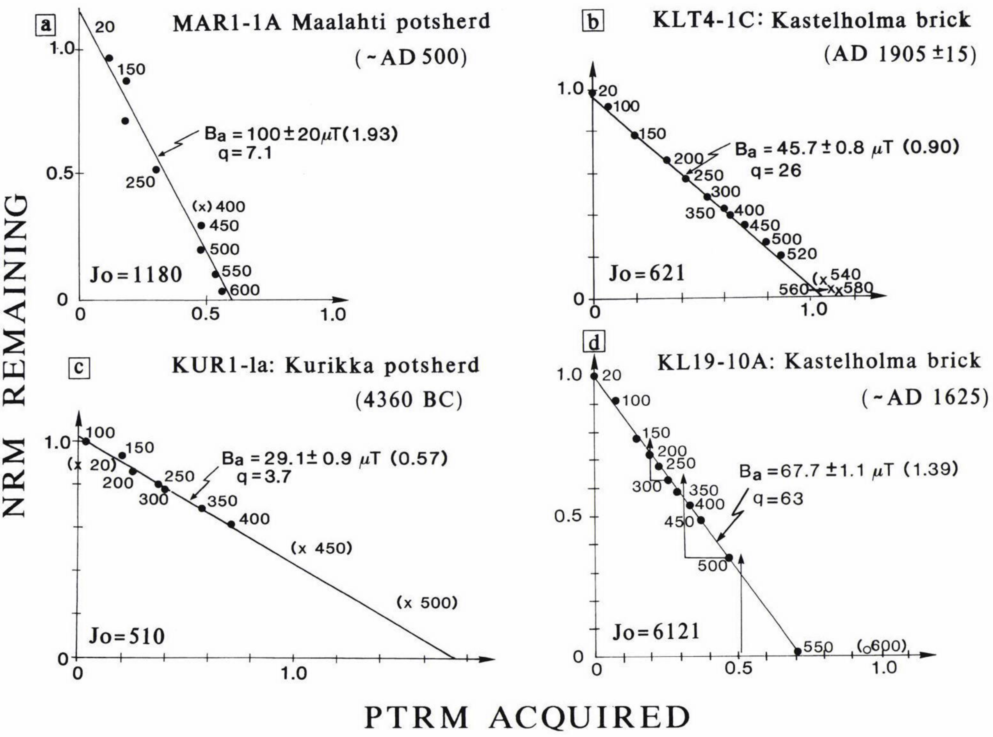

Fig. 1. Four examples of B_a determinations with Thellier technique of bricks and potsherds from Finland. All results (a–d) are plotted as NRM remaining vs. PTRM acquired plots (PNRM vs. PTRM). B_a is given in mT. Errors are standard deviations obtained from weighted least-squares line-fittings. B_a/B_o values are in parentheses. The quality factors (q) of each line (Coe et al., 1978) are also given. PTRM checks (arrows) were performed for specimen in (d). Dot (cross) denote an accepted (rejected) data point, respectively. J_o denotes the original NRM intensity in mAm^{-1}.

determinations of this work. Fig. 1a is an example of a potsherd of Maalahti (Site 16, AD 500) in which all data points (except 400° C) fulfil the reliability criteria of line-fitting. Fig. 1b shows an example (Kastelholma brick, AD 1905) of non-ideal behaviour at high temperatures caused by physicochemical changes during repeated heatings of the Thellier run: high-temperature points (540–580° C) were rejected from analysis. Possible causes of nonlinearity at low temperatures are often caused by viscous remanent magnetization (VRM) (e.g. Kurikka potsherd, 4360 BC, Fig. 1c). PTRM checks were occasionally used to verify that no physicochemical changes have occured during the temperature interval used for analysis; Fig. 1d (Kastelholma brick, AD 1625) is an example.

Fig. 2a shows an example of a Thellier determination on dated bricks where the "absolute" date is seen as a stamp "AD 1829" on the brick (Leino and Pesonen, 1994). This sample yielded a reliable B_a with moderately high q-value (19.3). The B_a for this dated brick (50.4 ± 1.6 μT) is close to the present field (B_a/B_o = 0.99) and in good agreement with the value (~50.2 μT) of the intensity curve of Nurmijärvi Observatory curve for this time (Pesonen et al., 1995). The sample RU1-1a (Fig. 2b) is from a potsherd at Lempäälä (Site 19) of age AD 500 ± 50 (Carpelan, pers. commun., 1993) and yields a high Ba (97 ± 8 μT) in good agreement with the previous high values (~100

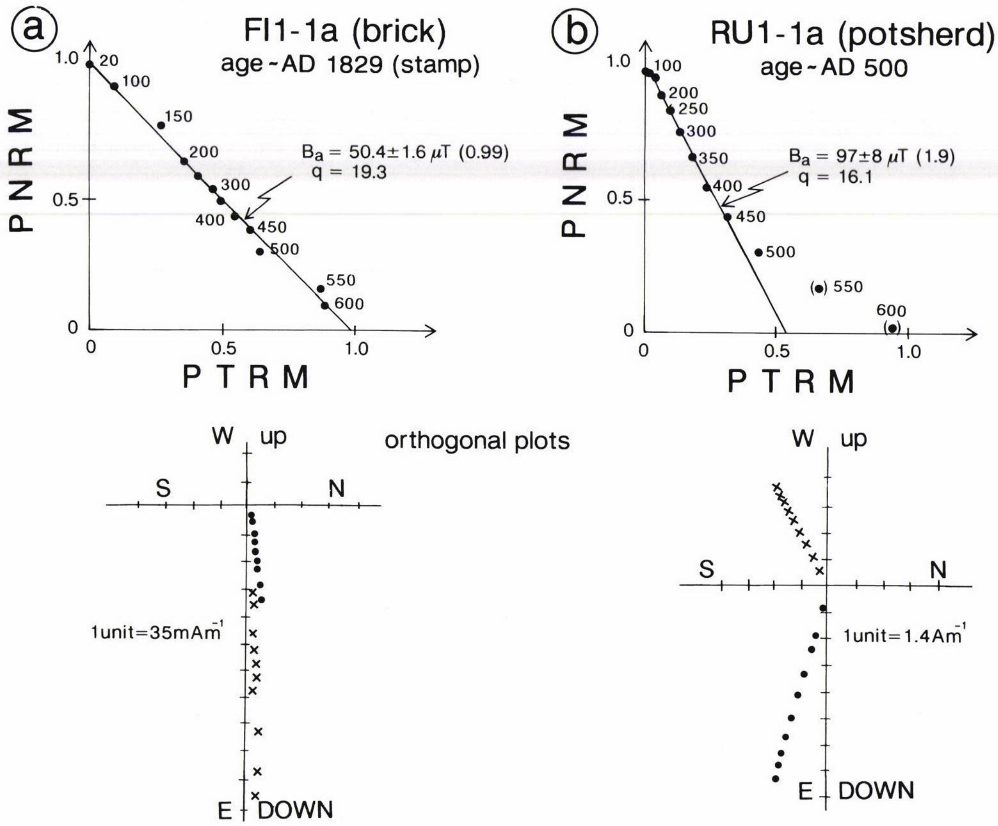

Fig. 2. Two more examples of B_a determinations. (a) specimen FI1-1a (Fiskars brick) with stamp "AD 1829" (Table 1), (b) specimen RU1-1a (Lempäälä potsherd), age ~AD 500. *Up*: Thellier plots, *Down*: Orthogonal diagrams for NRM directions, where cross (dot) denote horizontal (vertical) projections, respectively. Note univectorial behaviour (straight lines converging to origin).

μT) from Maalahti (Site 11, Fig. 1a) and Valkeakoski (Site 16, Table 1), also of age ~AD 500. This sample, however, shows mineral alterations at ≥ 500° C. We feel, however, that the intensity estimate of the interval of 20–500° C is acceptable since the NRM direction remains univectorial up to 600° C (Fig. 2b, lower) and there are no drastic susceptibility changes during the heating cycles. Moreover, another specimen of this sample also yielded comparable intensity results further supporting the high field intensity in Finland during ~AD 500 (Pesonen and Leino, 1993).

4.2. The Ba for Finland: the last 6 400 years

A total of 23 accepted B_a determinations were obtained from the last 6 400-years. All individual specimen B_a determinations with error bars, temperature intervals and q-factors are listed in LEINO and PESONEN (1994). To allow the Finnish data (from high latitudes) to be compared with data from lower geographic latitudes (e.g. Bulgaria) we calculated the mean B_a/B_o-values, where the normalization is done with B_o of IGRF 1980 (Nevanlinna et al., 1983). These data along with the corresponding mean VADMs are summarized in Table 1. When B_a/B_o-values are used the first-order re-

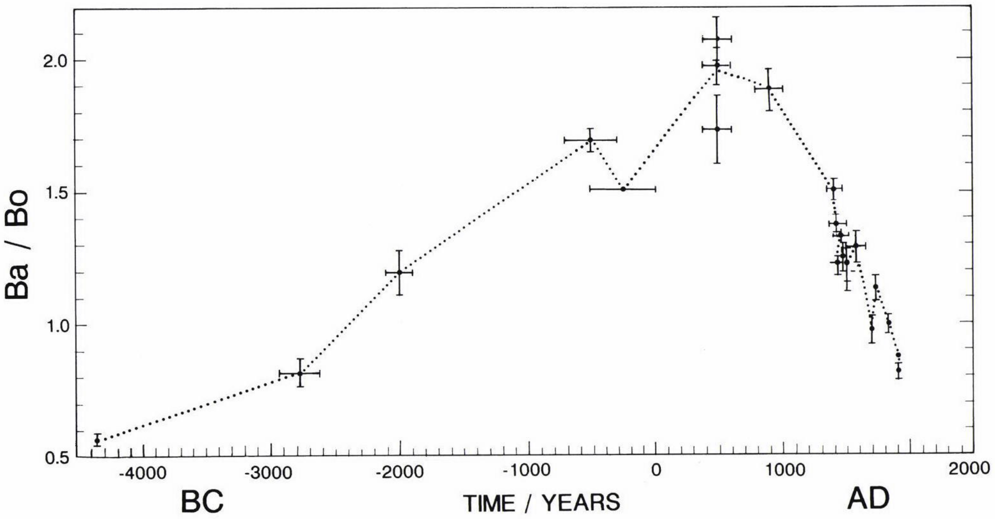

Fig. 3. Ba/B0 curve for Finland for the last 6400 years based on 23 average values of Table 1. Error bars of Ba/Bo are standard errors of mean and those for ages are arcahaeological estimates. (See Pesonen et al., 1995).

moval of the latitudinal dependence of the field due to the Axial Geocentric Dipole (AGD) has been done. The B_a/B_o curve of Finnish data (mean values with standard errors of the means) is plotted in Fig. 3. This curve, although still data-sparse during the time span, shows an overall trend towards increasing intensity during 4400 BC – AD 500 after which the intensity decreases to B_o in Finland. The most striking feature in Fig. 3 is the very high values of the B_a/B_o in Finland at about AD 500 (Pesonen et al., 1993; 1995). Inspection of a typical Thellier runs of the potteries of which the high B_a values are obtained (Fig.1a, Fig. 2b), however, shows that the determinations are acceptable with q values of 7.1 and 16.1 and data spanning from 20–600° C. Since there are high B_a from three separate localities (Sites 11,16 and 19) we believe that the high B_a/B_o in Finland at ~AD 500 is well established. We remind here in passing that the datings (AD 500) are not radiometric nor TL-dates, however, and we return to this point later in Chapter 5.

In Fig.4 we plotted the B_a/B_o curves from Bulgaria (Lat. 43° N, Long.22° E; Kovacheva and Kanarchev, 1986), and Japan (Lat. 37.5° N, Long.136° E; Sakai and Hirooka, 1986) together with the Finnish curve. The more rapid intensity variations in the Bulgarian and Japanese curves are due to larger amounts of data and thus of better time resolution. Two main observations can be seen. *(i)* All curves show the broad "global" type of field change: B_a/B_o increases gradually from ~4000 BC to ~300 BC – AD 1000 after which it begins to decrease towards the present intensity. *(ii)* The Finnish curve reveals a pronounced maximum ($B_a/B_o \sim 1.9$) at about AD 500 while the Japanese curve shows a broad, slightly increased plateau and the Bulgarian curve a broad minimun at that time. The lack of a distinct peak in the Japanese curve at AD 500 can simply be due to the westward-drifting field since the longitudinal difference between Japan and Finland is ~114°. In fact, a feature probably corresponding to the Finnish maximum may be the minor peak in the Japanese curve at AD 250 (Fig. 4) implying a

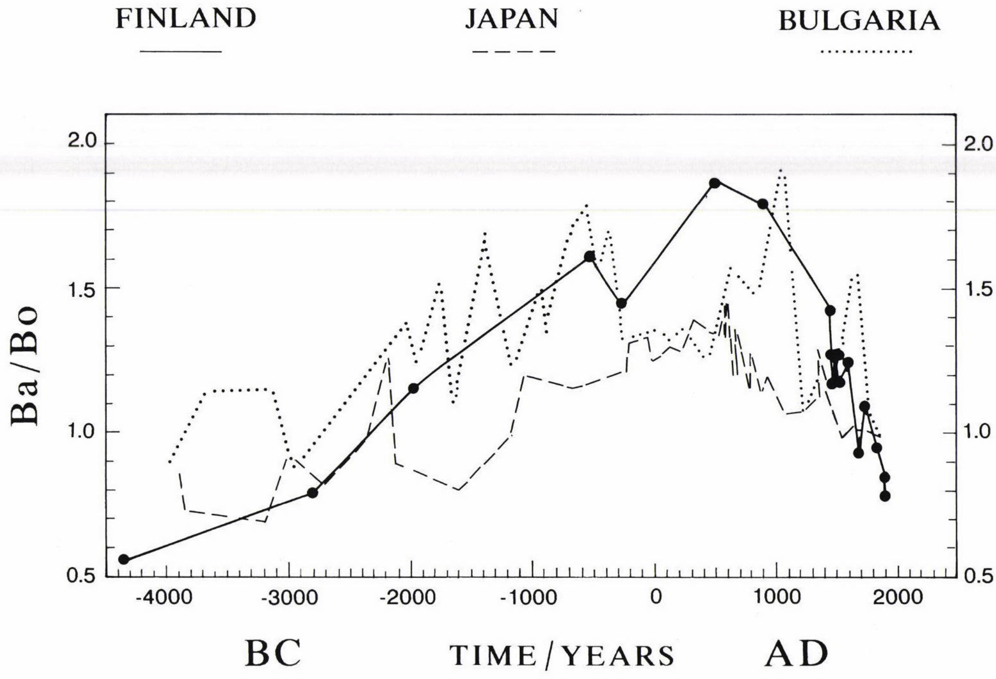

Fig. 4. Comparison of three B_a/B_0 curves for last 6400 years. Solid line = Finland (Lat. = 61° N, Long. = 22° E; Pesonen et al., 1995), dotted line = Bulgaria (Lat. = 43° N, Long. = 22° E), data from Kovacheva and Kanarchev (1986); dashed line = Japan (Lat. = 37.5° N, Long.=136° E), data from Sakai and Hirooka (1986).

westward drift rate of 0.45° /year (see also Lirirzis and Lagious, 1993). The Bulgarian curve shows two maxima, one smaller at ~AD 700 and one larger at ~AD 1100. We return in Chapter 5 to this point when we discuss of the new Bulgarian intensity data by Daly and Le Goff (1996) along with lake sediment intensity data from Finland (Saarinen, 1996).

4.3. Origin of high Ba?

Before accepting that the high B_a/B_0 at ~AD 500 are caused by rapid increase of the geomagnetic field in Finland we investigated other causes as an explanation for intensity anomalies and for the scatter in intensity curves. These include: (i) grain size, (ii) cooling rate, (iii) fabric anisotropy, (iv) shape anisotropy, (v) applied B_a techniques (e.g. geometry), and (vi) dating errors (see Aitken et al., 1991; Walton, 1987; Yang et al., 1993). In our previous articles (Leino and Pesonen, 1994; Pesonen et al., 1995) we have shown that causes (i) to (v) cannot explain the high field at AD 500 in Finland since the errors caused by these causes are less than 10% and generally less than 3%, and the *same* errors should also be present in regional (e.g., Bulgarian) curves. Therefore the most likely explanation for the high peak at AD 500 in Finland is related to either to errors in datings or to a true latitudinally dependent non-dipole field enhancement. The latter explanation has been thoroughly presented in Pesonen et al. (1995). Here we look a new possibility that there is an age problem in the Finnish data of AD 500–AD 900.

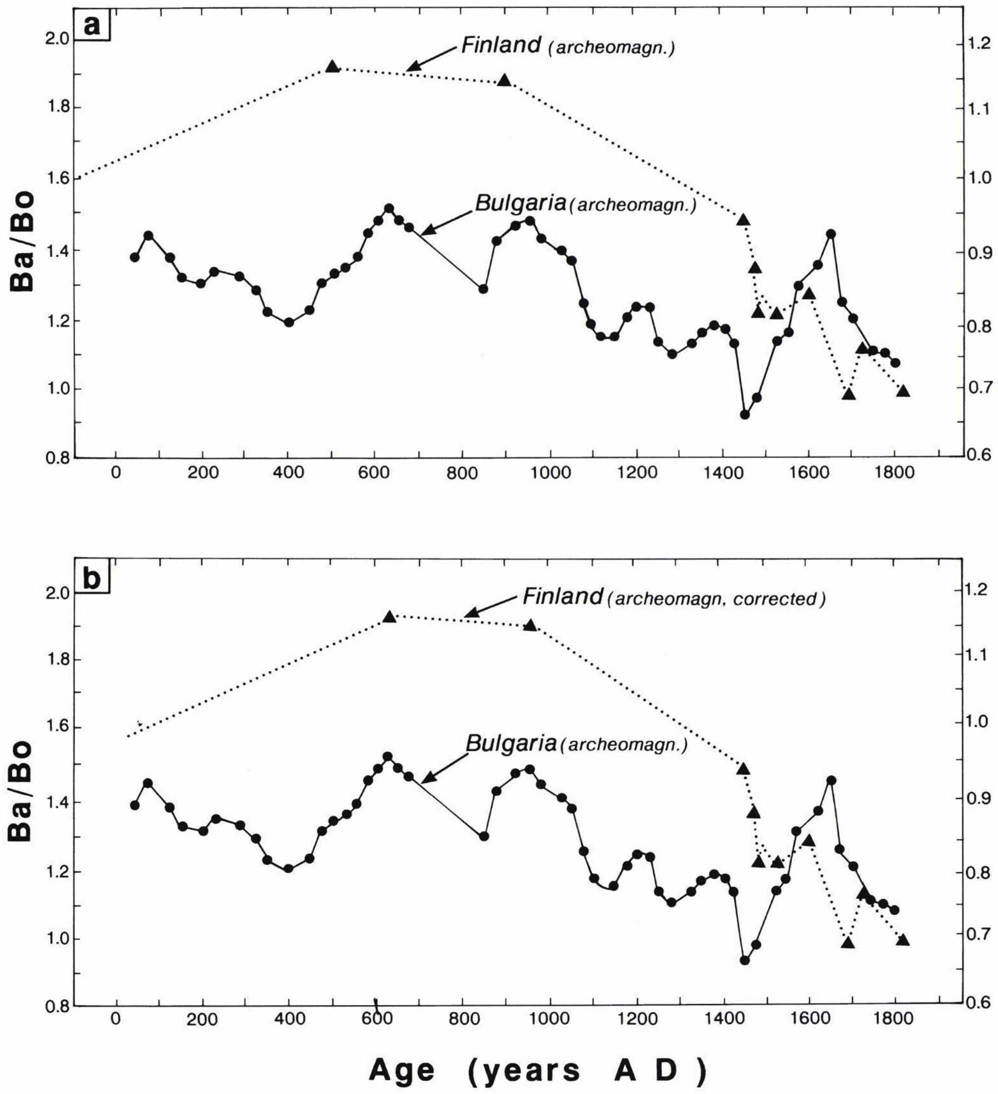

Fig. 5. (a) Comparison of the Finnish (dotted line, same as in Fig.4) and the new smoothed Bulgarian B_a/B_0 curve (solid line) by Daly and LeGoff (1996) from the past 2 000 years. (b) same curves as in (a) but now the Finnish data at AD 500 (AD 900) are shifted to be somewhat younger at AD 630 (AD 930) to obtain a better match with the Bulgarian curve (see text).

5. Comparison with new intensity curves

Two new magnetic field intensity curves have recently been published. Daly and Le Goff (1996) has presented a mathematically smoothed and homogeneous Bulgarian archaeointensity curve based on Kovacheva's data (see e.g., Kovacheva, 1980; Kovacheva and Kanarchev, 1986). On the other hand Saarinen (1996) has presented a well dated relative intensity curve of Pohjanjärvi lake sediments, where the dating is based on varve-countings. In Fig. 5a we have plotted the Finnish archaeointensity curve

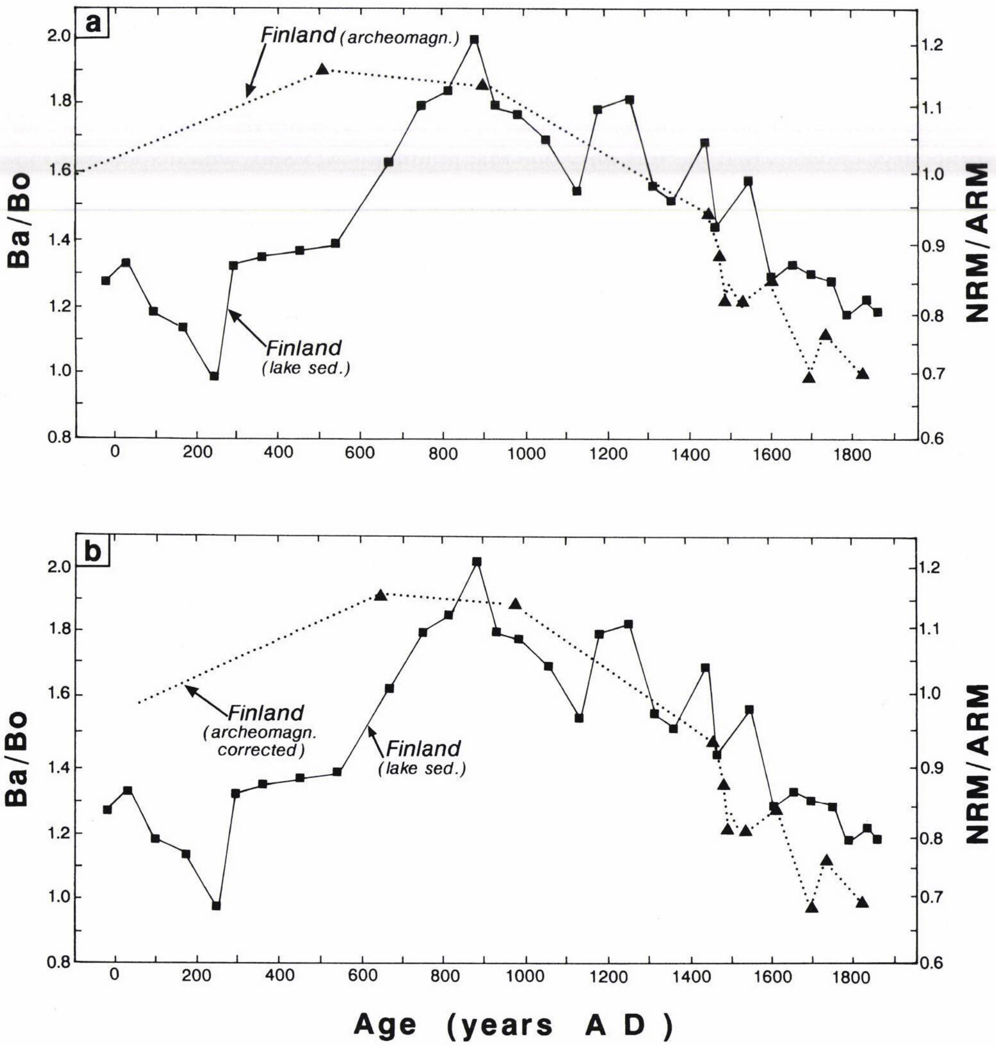

Fig. 6. (a) Comparison of the Finnish (dotted line, same as in Fig.4) archaeointensity B_a/B_0 curve with the new relative intensity curve of varve-dated lake sediments of the Lake Pohjajärvi, Finland (solid line; Saarinen, 1996) from the past 2 000 years. (b) same curves as in (a) but now the Finnish archaeointensity ages at AD 500 (AD 900) are shifted to be somewhat younger at AD 630 (AD930), respectively. Compare with Fig. 5 and see text.

(dashed line) together with the new smoothed Bulgarian curve (solid line) for the last two millennia AD. The data density of the latter curve is much higher than in the former curve so that detailed comparison is not worthwhile. However, some trends are clearly to be observed. First, one can notice that after ~AD 900 the two curves show a similar shape of decaying intensity but with the Finnish data having much higher intensities. We also notice that unlike in the previous Bulgarian curve (Fig.4) the new curve has a double maxima during the latter part of the first millennium, the first at AD 630 and the second one at AD 950. These peaks could now be the *same* ones as those in the Finnish curve at AD 500 and at AD 900, respectively, but appearing somewhat later in Bulgaria. Since Finland and Bulgaria lie roughly at the same longitude (22°E), and if we assume that the drift was due west rather than due north-south (see Pesonen et al., 1995), there is clearly a possibility that there are dating errors in either of the curves.

Inspection of the lake sediment intensity record of Lake Pohjajärvi, Finland (Fig.6a, solid curve) reveals that there is only one maximum at ~AD 880, which appears to in-between the two maxima of the corresponding archaeointensity curve (Fig.6a, dotted line). Thus, taking these new data together, we propose that the Finnish archaeological materials at AD 500 (Maalahti, Valkeakoski and Lempäälä) are younger by some 130 years (i.e., their age is AD 630), and that the objects of AD 900 (Karjaa potsherds) are younger by some 50 years (i.e., their age is AD 950). In Fig. 5b and 6b we have replotted the Finnish archaeomagnetic intensity curves by correcting their ages at these two data points, respectively, while keeping the Bulgarian archaeointensity curve and the Finnish lake sediment curves unchanged. We can notice a better agreement between the "corrected" Finnish and the Bulgarian archaeointensity curves and also with the Finnish lake sediment curve at least in a qualitative way. No mathematical correlation has yet been applied since the data densities in the three curves are drastically different. We further note that although the shape of the curves become more similar by allowing these age corrections, the Finnish and Bulgarian intensities still have different amplitudes, the Finnish archaeointensities being clearly higher. Since the major dipole effect has been removed by plotting normalized intensities, the amplitude variations could be due to the non-dipole field enhancement as described by Pesonen et al. (1995).

6. Conclusions

The main conclusions of this paper are as follows:

1. Variations in rock magnetic properties (e.g., grain size, cooling rate, fabric, magnetic refraction) or variations in the applied Thellier techniques have only a minor effect on B_a and these effects can be corrected for. These error sources are not capable to explain the high intensity value at AD 500–AD 900 as observed in Finnish archaeointensity curve. Moreover, these error sources are also present in the Bulgarian data which are uncorrected for rock magnetic variations.

2. The Finnish B_a/B_o curve shows a major field enhancement at AD 500–AD 900 which are not seen in other regional B_a/B_o curves from northern hemispheres, particularly in the previous Bulgarian curve of Kovacheva and Kanarchev (1986). Previously we have pointed out that a radial non-dipole field model can explain this enhancement of the field intensity at higher latitudes like in Finland. The present geomagnetic field also shows similar latitude dependent nondipole effects (Leino and Pesonen, 1994).

3. Recent lake sediment intensity data (Saarinen, 1996) and the new Bulgarian smoothed archaeointensity curve (Daly and Le Goff, 1996), however, show evidence of field maxima at ~AD 630 and at AD 950 thus somewhat later than in Finland. If these appear to be real there is a change that the Finnish age data at AD 500 are some 130 years, and the age data of AD 900 are some 50 years, too old, respectively. If an allowance for these age corrections is made for the Finnish archaeointensity data there is a better agreement between the Finnish and Bulgarian intensity curves including the lake sediment data. However, since the Finnish intensities (normalized by dipole effect) are much higher than the Bulgarian intensities, the non-dipole field effects of Pesonen et al. (1995) may still have been operative.

11. Acknowledgements

We are highly appreciative of the helpful collaboration of archaeologists Markus Hiekkanen from the National Board of Antiquity, Christian Carpelan and Högne Jungner of the Helsinki University. Sincere thanks are also due to Salme Nässling and Pirjo Jelkamäki for making the figures.

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