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Archaeomagnetic secular variation in the UK during the past 4000 years and its application to archaeomagnetic dating

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Abstract

This paper examines the limitations and deficiencies of the current British archaeomagnetic calibration curve and applies several mathematical approaches in an attempt to produce an improved secular variation curve for the UK for use in archaeomagnetic dating. The dataset compiled is the most complete available in the UK, incorporating published results, PhD theses and unpublished laboratory reports. It comprises 620 archaeomagnetic (directional) data and 238 direct observations of the geomagnetic field, and includes all relevant information available about the site, the archaeomagnetic direction and the archaeological age. A thorough examination of the data was performed to assess their quality and reliability. Various techniques were employed in order to use the data to construct a secular variation (SV) record: moving window with averaging and median, as well as Bayesian statistical modelling. The SV reference curve obtained for the past 4000 years is very similar to that from France, most differences occurring during the early medieval period (or Dark Ages). Two examples of dating of archaeological structures, medieval and pre-Roman, are presented based on the new SV curve for the UK and the implications for archaeomagnetic dating are discussed.

Keywords: Archaeomagnetic dating; Secular variation; UK; Database; Moving window; Spline modelling; Bayesian statistics

1. Introduction

The principal role of archaeology is to reconstruct and explain how people lived in the past and it is particularly important to establish the time frame within which cultural changes have occurred. Over the past few decades scientific dating techniques, such as archaeomagnetic dating, have become increasingly important in the accurate determination of archaeological chronologies (Aitken, 1999). Archaeomagnetism involves the comparison of the archaeomagnetic direction and/or intensity, determined by laboratory measurements of samples from artefacts or archaeological features, with the known secular variation record (calibration curve) of changes in the Earth's magnetic field over archaeological timescales. Thus, to ensure the accuracy of archaeomagnetic dating, a robust and detailed secular variation record has to be established for this purpose. However, the Earth's magnetic field changes spatially as well as temporally; consequently, the archaeomagnetic dating calibration must be performed using relatively local data. It has been shown that data from within an

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area of 500 km radius can be used in the same calibration curve without introducing significant errors (Shuey et al., 1970; Tarling, 1989; Noël and Batt, 1990). The data comprised direct historical observations of the geomagnetic field and indirect measurements derived archaeomagnetically from features dated by other independent methods, and they are all mathematically relocated to a central location.

The construction of a calibration curve depends on finding well-dated material with a stable remanent magnetisation, a task that can be very difficult and depends heavily on local conditions and cultural development. Thus, the procedure can prove to be both laborious and slow, even impossible for time spans with limited cultural remains (e.g. the dark ages in Britain). The first attempt to present a master curve for Britain was made by Cook and Belshé (1958) based on direct observations and archaeomagnetic measurements on Roman and later medieval fired structures. Following from this work, Aitken (1970) published a secular variation curve for the years 50–350 A.D. and 1000–1600 A.D., identifying the problem of the lack of structures for the Dark Ages (350–800 A.D.). Clark et al. (1988) augmented the data base of calibration material and were able to produce a continuous calibration curve covering the entire period from 1000 B.C. to 1975 A.D. Although more recent attempts have been made to improve the UK archaeomagnetic calibration curve using more objective methods to assess the data (Batt, 1997; Tarling and Dobson, 1995) the version most commonly used remains that produced by Clark et al., perhaps because the subsequent curves have offered no significant improvement in dating. None of the curves cited incorporate archaeomagnetic intensity measurements for Britain, due to the relative paucity of such data.

2. The present situation

As previously mentioned, the master curve used until today for archaeomagnetic dating studies was the one produced by Clark et al. (1988). It is typically represented as two continuous curves on a Bauer plot (Bauer, 1895, 1896); one corresponding to 1000 B.C. to 600 A.D. and one for 600–1975 A.D. (Fig. 1), and was constructed using archaeomagnetic measurements from 92 fired structures, over 200 direct observations of the geomagnetic field (Malin and Bullard, 1981) and magnetic direction measurements from lake sediments (Turner and Thompson, 1979, 1981, 1982). All data were relocated to Meriden (52.43°N, 1.64°W) as described above. This curve was the best possible, given the numerical tools and archaeomagnetic techniques available at the time, and it has been used to good effect in numerous archaeomagnetic dating studies. However, several problems can be identified with the methodology of its construction when considering its applicability to a more extensive dataset. These include (a) interpolation between data points was by subjective freehand drawing, (b) individual data points are not represented, (c) no assessment or representation of uncertainties (errors) in the calibration curve is provided, (d) extensive interpolation was required in some periods (e.g. early medieval), and (e) calibration of an archaeomagnetic direction using the curve must be done by visual comparison. Moreover, in some periods the shape of the curve has been strongly influenced by the lake sediment data curve. More recent research suggests that there are many difficulties with comparing archaeomagnetic measurements on fired materials with sedimentary palaeomagnetic records (e.g. Gallet et al., 2002). For example a similar shift in declinations was observed by Gallet et al. (2002) when comparing the

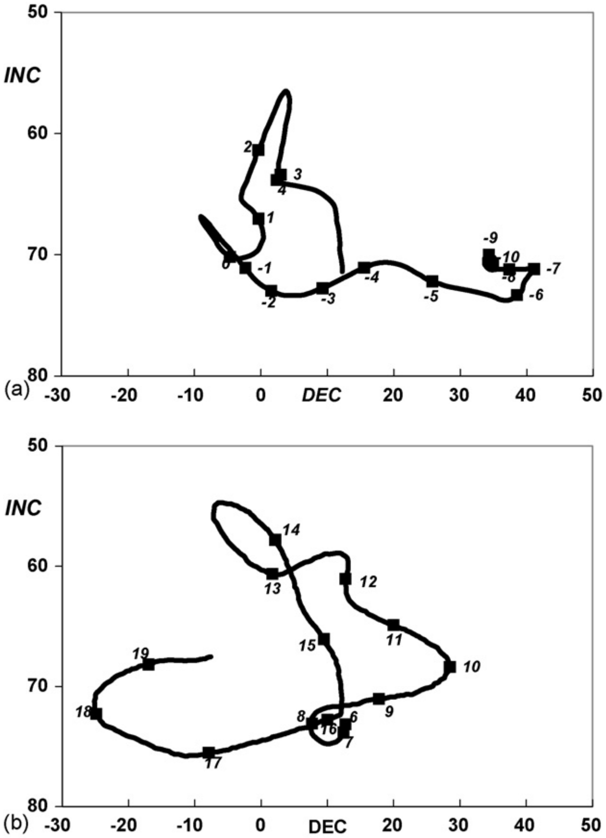

Fig. 1. The British archaeomagnetic calibration curve proposed by Clark et al. (1988). The data have been normalized to Meriden, for the time span of (a) 1000 B.C. to 600 A.D., and (b) 600–1975 A.D. Figures are in hundreds of years B.C. (−) and A.D. Inclinations were corrected for estimated effects of refraction, usually <2–3°.

data of Turner and Thompson (1979, 1981, 1982) with archaeomagnetic measurements from western Europe. Another issue that has to be taken into account is the magnetic refraction correction applied by Clark et al. (1988) to the thermoremanent directions incorporated in his dataset. In order to correct for the possible distortion of the magnetizing field within the material sampled (Aitken and Hawley, 1971), Clark et al. (1988) added 2.4° to the inclinations of floor samples, thus shifting parts of the curve towards higher inclinations.

Apart from the problems evident with the existing curve, there are several other issues that have to be addressed. Archaeomagnetism has become a routine dating technique in recent years and this in conjunction with more sophisticated and refined laboratory equipment has led to the accumulation of many new and accurate data not incorporated into the evaluation of the calibration curve. Furthermore, the widespread availability of increasingly powerful computers now allows more complex statistical analyses to be carried out on large data sets. It is thus timely to reassess the UK archaeomagnetic calibration curve in the light of these developments. All existing data must be taken into account and an objective treatment should be adopted allowing an assessment of the errors involved in the construction of the calibration curve. The motivating factor should be to obtain an accurate tool for dating rather than simply drawing a calibration curve.

3. Database

The database constructed contains the existing directional results covering the entire historic and prehistoric period in the UK; the oldest feature present dates back to 4000 B.C. Moreover, archaeomagnetic results with no independent date have also been included, to allow for their future use should independent dating evidence comes to light. The dataset presented includes 858 determinations, comprising 238 direct historical observations of the geomagnetic field (Malin and Bullard, 1981) and 620 archaeomagnetic measurements from dated fired structures. Those data were obtained from published papers, several PhD theses, English Heritage Ancient Monuments Laboratory reports and unpublished laboratory reports. The data of Clark et al. (1988) have been quoted as published, since the purpose of this work is to produce an updated secular variation record of all available archaeomagnetic determinations, rather than re-evaluate published work (a detailed discussion on error assessment of fired material observations can be found in Tarling and Dobson, 1995). Moreover, due to the large number of fired structures (620) the floor features with magnetic refraction correction applied are unlikely to bias the new UK calibration curve. The structure of this local database has been organised mainly following discussions and suggestions during the Third Annual Meeting of the AARCH (Archaeomagnetic Applications for the Rescue of Cultural Heritage) research training network (Madrid, 2005). Results are given for each feature separately, for which the mean direction has been provided: a 'site' being 'a volume of material that can be considered to have been magnetised at the same time' (Tarling, 1983).

Site information includes the latitude and longitude (western longitude defined as negative) of each site, along with the locality name and the country. The type of the archaeological structure is defined (kiln, hearth, brick, other baked clay, etc.) and each site is assigned an identification number (ARC001 or GEO001, etc., for archaeomagnetic or geomagnetic data correspondingly) for future reference. Archaeomagnetic information includes the measured archaeomagnetic direction, comprising the inclination and the declination. It is emphasised that uncorrected directions are given, to allow for global use and future relocation to different geographical locations. Several statistical parameters are included, to allow an estimation of the accuracy of the data. These are the number of samples (N), the angular estimate of 95% probability (α_{95}, Fisher, 1953) and the precision parameter (k), the latter being calculated from the data provided. Where direct observations are involved, the number of samples was arbitrarily assigned as 1, the precision parameter to 99999, and the α_{95} to 0.5° to account for possible instrumental errors. Information is also given regarding the remanence magnetisation type (thermoremanent, viscous, etc.), the demagnetisation technique (thermal, alternating field or microwave) and the corrections, if any, that have been applied (cooling rate, anisotropy). No data were eliminated from the database due to low precision or inadequate treatment; they are left for any future user's assessment. Dating information: the mean age of the feature is given (Tm), as well as its lower (T1) and upper (T2) limits, along with information about the dating method employed (archaeological evidence, radiocarbon, etc.). For the geomagnetic observatory data T1 corresponds to the year the data refer to, while T2 is the following year. Finally, in the field REF a number is given, indicating the corresponding detailed reference information, provided in a separate file.

Due to space limitations only the data used in the calibration curve calculations are provided in Appendix B. Complete data table providing further information for each site will be uploaded in MAGIC database and is available from authors upon request.

4. Mathematical modelling for directional data

The 620 archaeomagnetic measurements included in the database are widely distributed over England and Wales (Fig. 2). Very few data are still available for Scotland and Northern Ireland, although recent data from the Shetland Isles have expanded the area covered by the data set. Taking into account the spatial distribution of the sites, Meriden (52.43°N, 1.64°W) was chosen as an appropriate location for the geographical correction of the data although this is technically the central point for England and Wales alone; the relocation was performed using the 'conversion via pole method' (Shuey et al., 1970; Tarling, 1983, 1989; Noël and Batt, 1990). Data from northern France are not included in the data set at this stage, although they might be relevant for archaeomagnetic analyses on sites situated in southern Britain.

The data are initially presented in Bauer plots, separated in two subsets, one for the time span 1000 B.C. to 600 A.D. (Fig. 3a) and one for 600–1975 A.D. (Fig. 3b), to allow comparison with Clark's calibration curve. Statistical uncertainties in declination (D) and inclination (I) are shown. A visual examination of the figures reveals a very complex distribution of data points that requires further statistical treatment and mathematical modelling. Although archaeomagnetic data do not have a Gaussian distribution the most commonly employed statistical distribution is approximated by a bivariate normal distribution; therefore in all the calculations applied hereafter the unit sphere analogue of a normal distribution is adopted, namely the spherical (Fisher) distribution, along with the corresponding statistical treatment (Fisher, 1953).

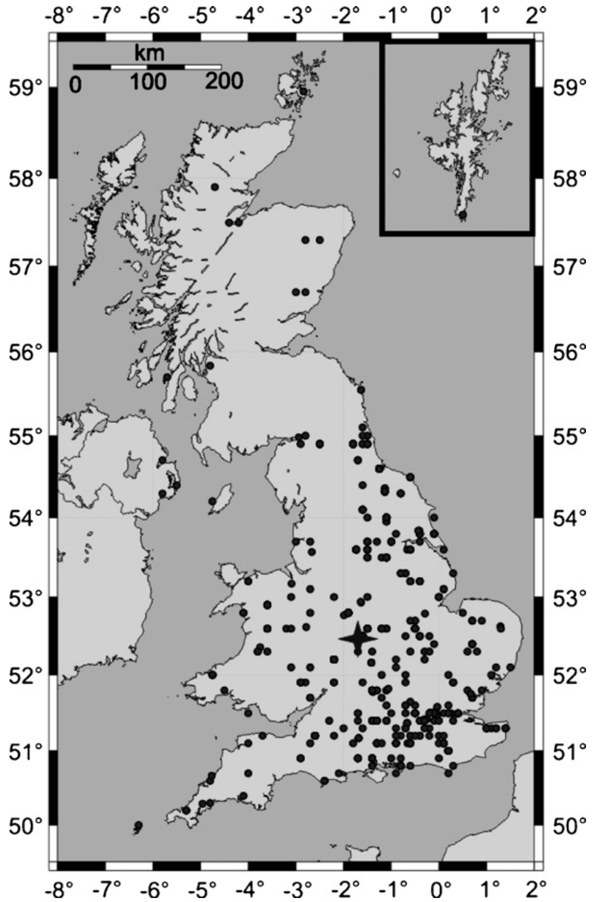

Fig. 2. Spatial distribution of sites in Britain. Dots represent site locations, while the star denotes Meriden (52.43°N, 1.64°W), to which all data have been relocated. The map was created using the GMT software (Wessel and Smith, 1991).

The difficulty encountered in every attempt to construct a secular variation record from archaeomagnetic measurements is that it is described by a relation of the form $(D, I) = f(t)$, where the dependent variable (direction) is bivariate, and where uncertainties exist in both the dependent and independent (time) variables. For the majority of the British data, the age of each feature is poorly constrained; only 141 features have age ranges less than 50 years (Fig. 4a) and 20% of the features have age ranges greater than 400 years. On the other hand, the calculated directions appear very precise with α_{95} being <4.0° for 68% of the features (Fig. 4b). Geomagnetic observatory data were excluded from the histograms in Fig. 4 to avoid biasing the results and giving a misleading impression of the precision of the available archaeomagnetic data.

4.1. Moving window

The sliding moving window technique (Sternberg, 1982), was first applied to fit a smooth line to the data, allowing the separation of the signal from the noise. The noise in this case is defined as all outliers, resulting from whatever errors (sampling/laboratory work, inadequate treatment, local conditions, etc.). Fisherian statistics were employed for averaging of directions within each window, each point being assigned a weight to account for uncertainties in both variables (Eighmy and Sternberg, 1990, and references therein). For the dependent variable the precision parameter K_{ij} is used, while for the independent variable the fractional overlap of the age range of the feature with the window was calculated, to account for the corresponding weight (P_{ij}) (Sternberg, 1989):

$$W_{ij} = P_{ij} K^{*}_{ij} \tag{1}$$

$$P_{ij} = \frac{d(\lfloor t_{ij1}, t_{ij2} \rfloor \cap [t_i - L/2, t_i + L/2])}{t_{ij2} - t_{ij1}} \tag{2}$$

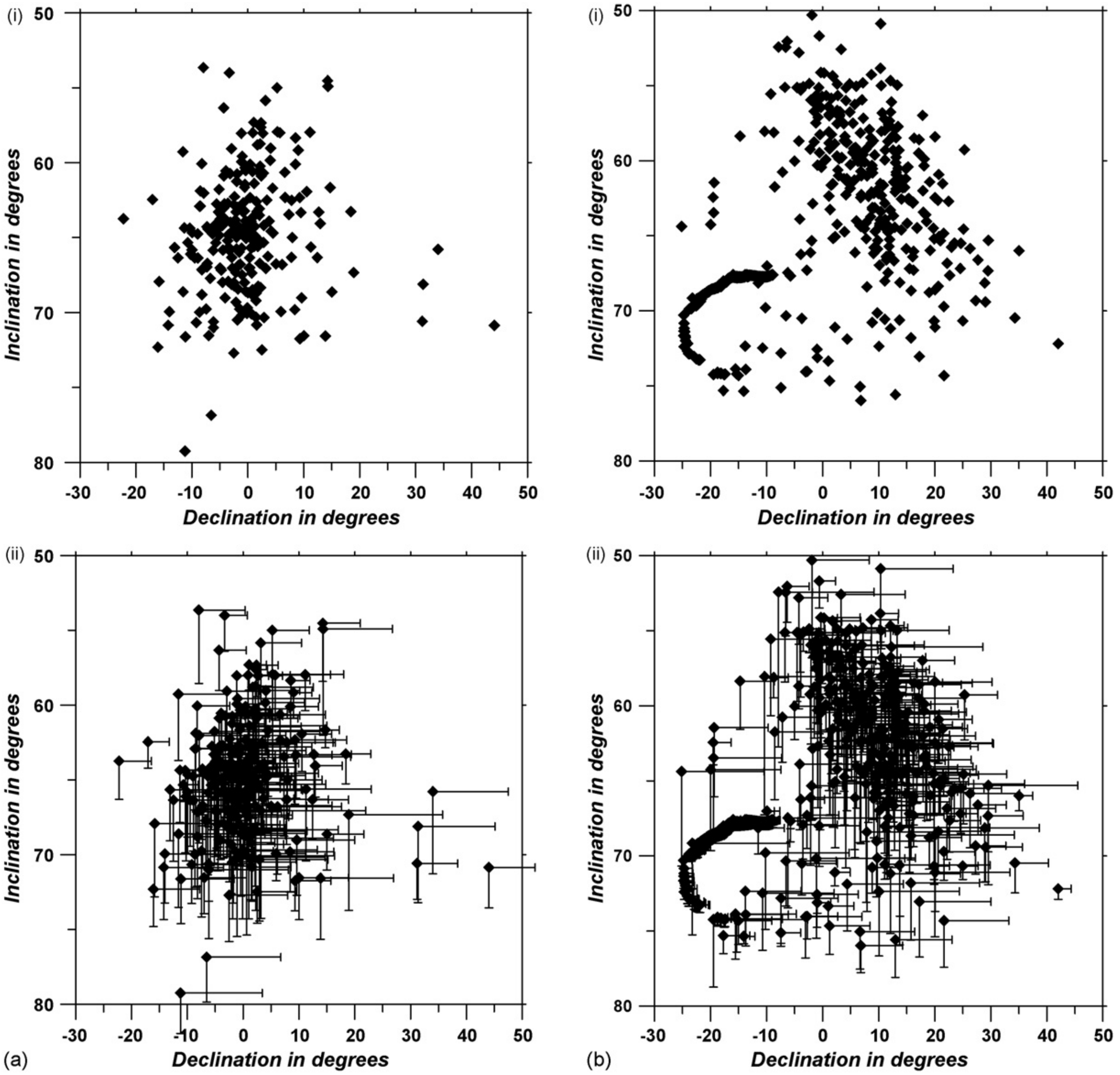

Fig. 3. Graphical representation of the compiled British dataset: (a) 2000 B.C. to 600 A.D. and (b) 600–2000 A.D. These are shown (i) without and (ii) with error bars. Diamonds represent data (values relocated to Meriden); error bars (95% confidence limit) are drawn only towards positive direction due to the large number of points.

where the distance $d([x, y]) = |x - y|$, t_i is the time expressed in the calendar (solar or sidereal) date system and L is the window length (Lanos et al., 2005).

In the specific case when $t_{ij} = t_i$, then $P_{ij} = 1$.

The total weight (W_{ij}) of the feature is the product of those two values. Due to the uneven temporal distribution of the data, with some periods almost lacking archaeomagnetic measurements, a variable window size was chosen. For the time periods of 2000 B.C. to 0 A.D. and 350–800 A.D., a window size of 150 years was applied, while for the time periods of 0–350 and 800–1950 A.D., window size was set to 40 years. Nevertheless, the choice was intuitive giving the best fitting and smoothing (Le Goff et al., 2002). In all cases window overlap was equal to half of the window size. The result from each window was assigned to the middle age value of the window. The moving window averages were plotted, along with the original data (Fig. 5).

An alternative approach was also implemented to better constrain the effect of outliers on the average for each window; the mean value of each window was substituted with the median value (Fig. 6). Though several abnormal peaks in the secular variation due to the presence of outliers are eliminated and the envelope appears

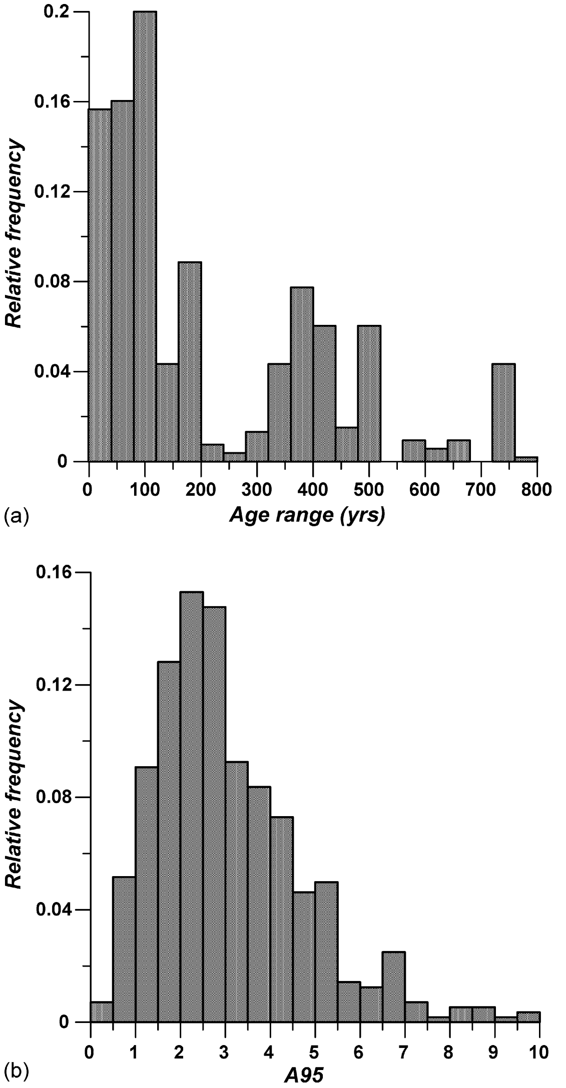

Fig. 4. Relative frequency histograms. (a) Age ranges; 36 features with age ranges greater than 800 years are not plotted. (b) Angular precision (α_{95}). Four features with α_{95} greater than 10.0° are not plotted.

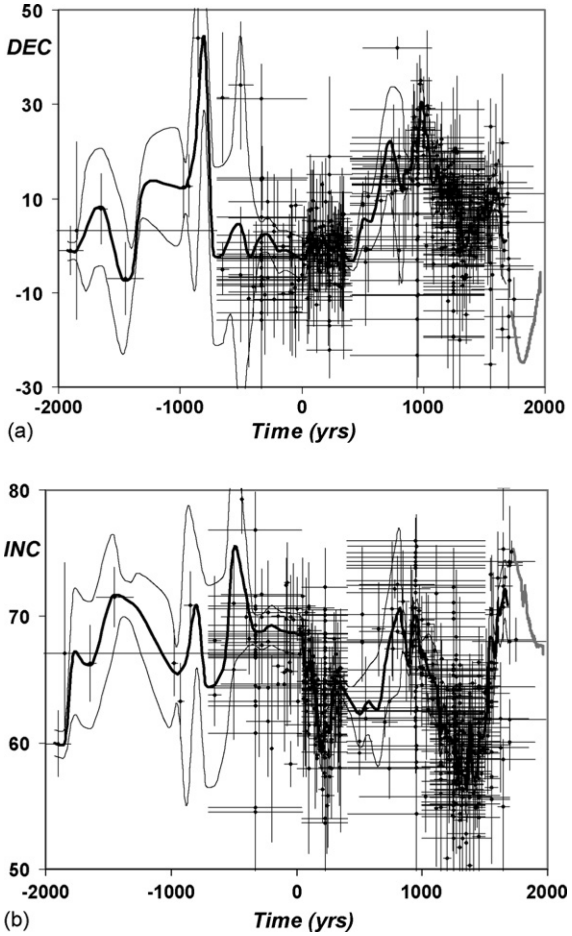

Fig. 5. Moving window smoothing for (a) declination, (b) inclination. Variable window widths were applied: 150 years for 2000 B.C. to 0 A.D. and 350–800 A.D., and 40 years for 0–350 and 800–1950 A.D. Diamonds represent the original data, error bars are shown (archaeological estimate for age and 95% confidence limit for direction); solid line corresponds to moving window average, while thin lines define the moving window envelope. The grey line after 1700 represents geomagnetic observatory values for the last 300 years (Malin and Bullard, 1981).

to be better defined, this method has the disadvantage of using unweighted data from a set of data with high uncertainties.

4.2. Spline modelling

A new statistical curve estimation method (Lanos, 2004) was also applied to the British dataset, however only declination and inclination values were used since intensity data are sparse. This smoothing technique is based on a Bayesian stochastic approach using penalized maximum likelihood for smoothing, and fitting time series which may carry errors of both date and measure. The main advantage of this technique is the *a posteriori* dating of original data. In particular, the dating of each *a priori* dated reference structure used for calibration curve building is *a posteriori* improved using the Bayesian calibration curve calculation. This bivariate algorithm fits a natural cubic spline (Champion et al., 1996) based on roughness penalty to declination, inclination and time simultaneously. The resultant mean curve was estimated and a functional envelope (error band) at 95% confidence level was obtained (Fig. 7). This means that the 'true' curve will lie somewhere inside the derived error band. Thus, any linear curve inside this error band (such as the broken line in Fig. 7) represents a solution, but is not the only possible one and not necessarily the most

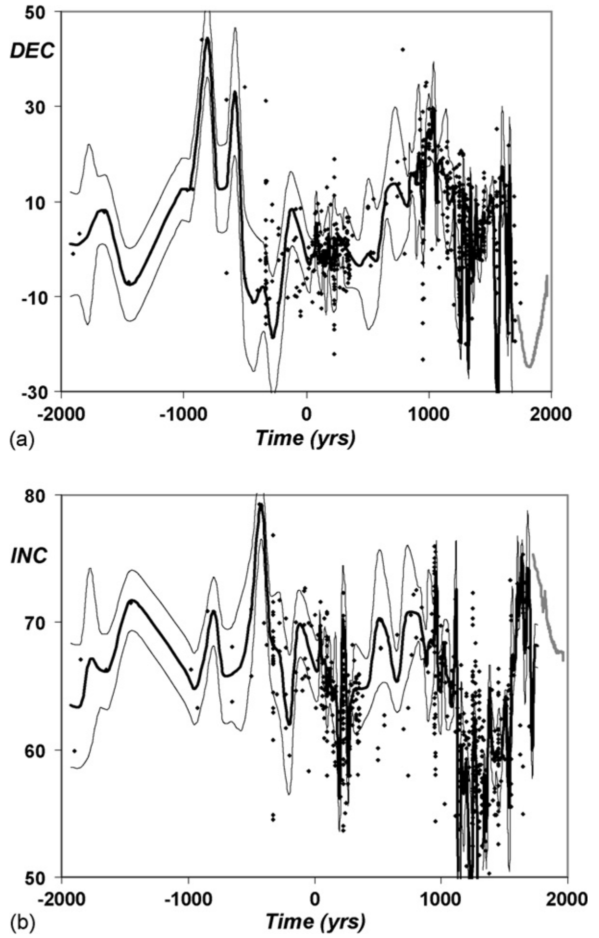

Fig. 6. Moving window smoothing with window median used instead of the average (same variable window widths) for (a) declination and (b) inclination. The median of each window is assigned to its middle position. Diamonds represent the original data; solid line corresponds to moving window median, while thin lines define the moving window envelope. The grey line after 1700 represents the geomagnetic observatory values for the last 300 years (Malin and Bullard, 1981).

probable. Thus, the Bayesian estimate, which includes all of the measurement, dating and stratigraphic information, is much more informative than the simple line curve, which in fact carries many restrictive and unstated assumptions.

5. Evaluation of the new UK curve

The secular variation reference curve that was produced by the above analysis for the UK for the past 4000 years is very similar to that for France compiled by Gallet et al. (2002) using the moving window approach (Fig. 8). The maximum and minimum values for declination and inclination appear at the same time, while small divergences can be attributed to the different technique implemented. Differences between the applied method and the moving average technique using bivariate statistics have been discussed by Lanos et al. (2005). The only significant differences are observed during the Dark Ages (600–800 A.D.) and can be attributed to the small number of data for the UK during those times. The curve has been drawn up to 1700 A.D. since, for the last three centuries direct observations of the geomagnetic field have been taken into account (Fig. 8, grey line). Although there is a numerical difference between the end of the curve, obtained by spline modelling, and the first observatory values, this can be attributed to a rapid change in the direction of the magnetic field during the early 17th century or to irregular marginal determination of the curve.

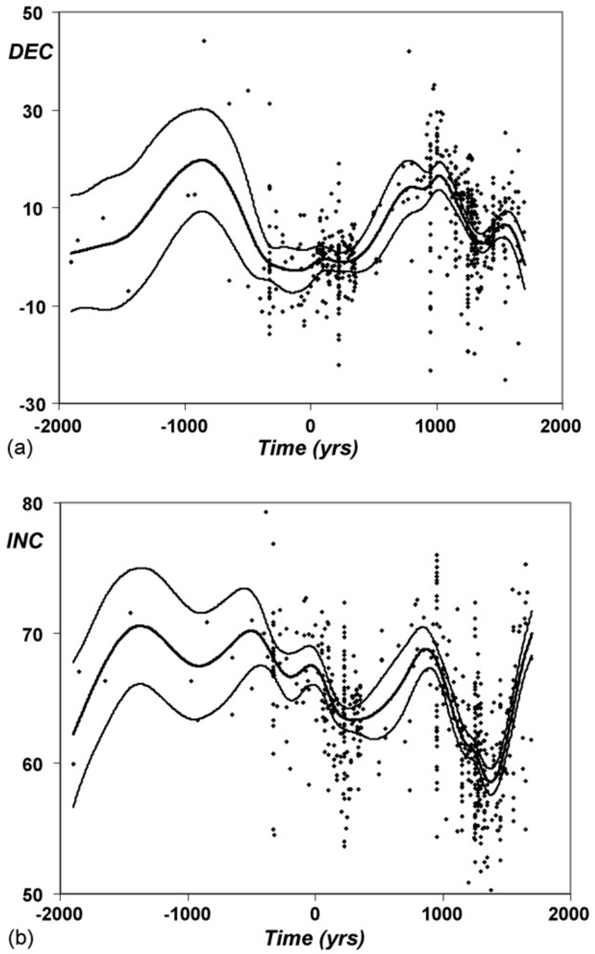

Fig. 7. Declination (a) and inclination (b) values plotted vs. time scale for the UK data set. All directions are relocated to the reference site of Meriden. Thick lines show the obtained secular variation reference curves surrounded by the 2σ error envelope (thin lines) as obtained from the Bayesian modelling.

When the new calibration curve is compared with that of Clark et al. (1988) several significant differences arise

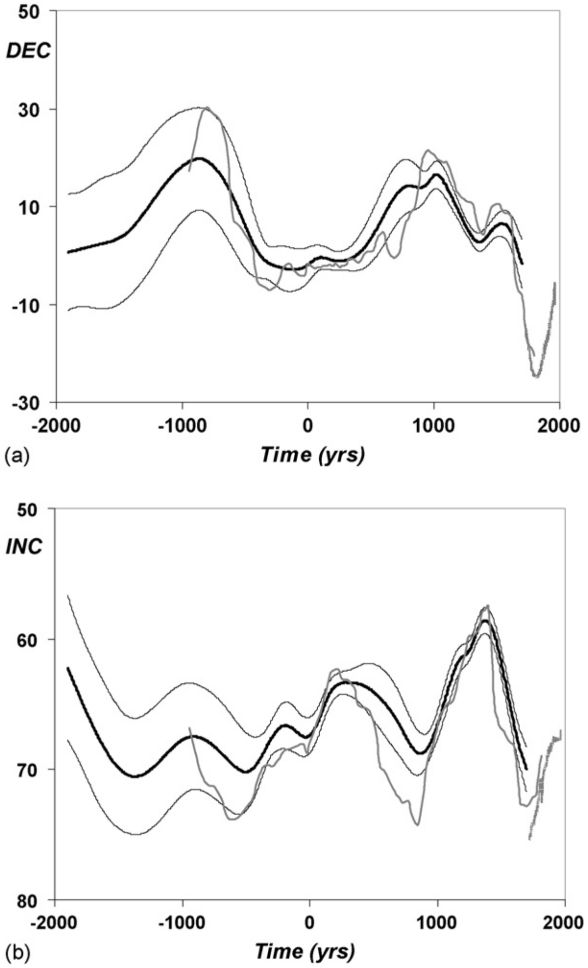

Fig. 8. Declination (a) and inclination (b) of the obtained by Bayesian modelling SV reference curves (as in Fig. 7). For comparison the French SV curve (Gallet et al., 2002) is shown with a line. Grey line after 1700 represents the geomagnetic observatory values for the last 300 years (Malin and Bullard, 1981).

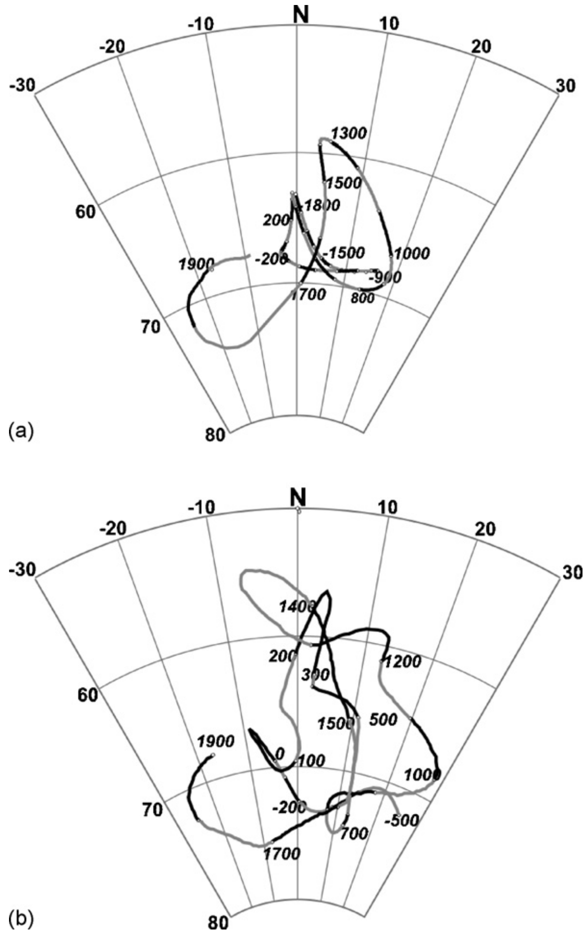

Fig. 9. Comparison between secular variation curve obtained by Bayesian statistical modelling (a), and the calibration curve produced by Clark et al. (1988) (b). Each black and grey segment of the curves represents a 100 years interval.

(Fig. 9). The latter seems to be greatly affected by a small number of points exhibiting extreme inclination values, and has been weighted to fit more those points rather than the majority of observations. Moreover, the lack of any error representation reduces the accuracy of dating, whilst the 95% envelope produced during spline modelling (not presented in Fig. 9 for graphical representation reasons) is a significant advantage of the new curve.

Korte and Constable (2003), using spherical harmonic basis functions, and based on a dataset of archaeomagnetic and palaeomagnetic directional data, and axial dipole constraints, developed a continuous global geomagnetic field model for the last three millennia, which was soon expanded to cover the last 7000 years (Korte and Constable, 2005). The British dataset of archaeomagnetic measurements was treated with version CALS7K.1 of their software, to estimate the applicability of spherical harmonics modelling to archaeomagnetic dating (Fig. 10). The model seems to fit the data well at times with an abundance of archaeomagnetic directions, but it is prone to abnormal behaviour when the data are sparse and outliers are present (e.g. the fifth century B.C.). Instances can also be observed where the data, and especially the declinations, were oversmoothed, e.g. pre-Roman and 800–1100 A.D. From the above it is concluded that while the geomagnetic field models are an excellent way to model the behaviour of the Earth's magnetic field on large scale, they do not have the accuracy needed for dating an archaeological structure. Thus, it is necessary to treat the data on a smaller scale using localised reference curves.

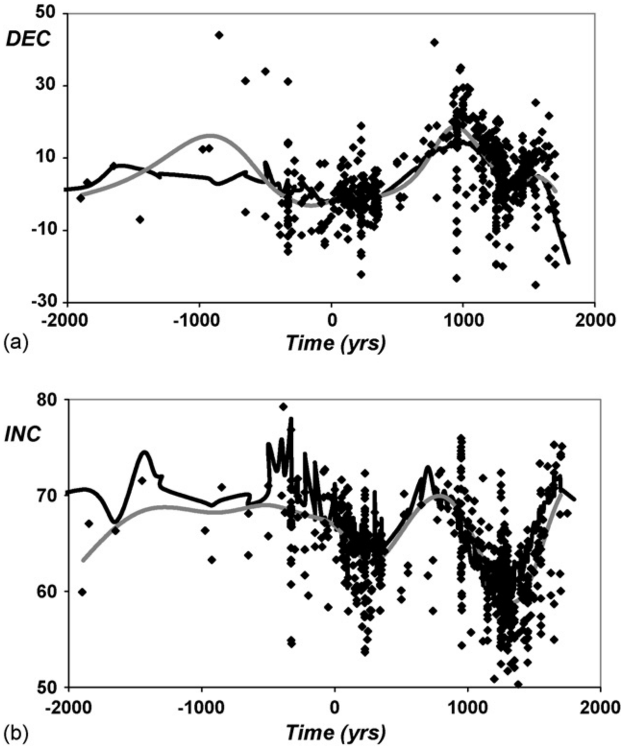

Fig. 10. Comparison between archaeomagnetic data (diamonds) and predictions of the geomagnetic field produced with model CALS7.1 of Korte and Constable (2005). Solid black line: (a) declination; (b) inclination. Grey line represents the secular variation UK curve obtained by Bayesian statistical modelling.

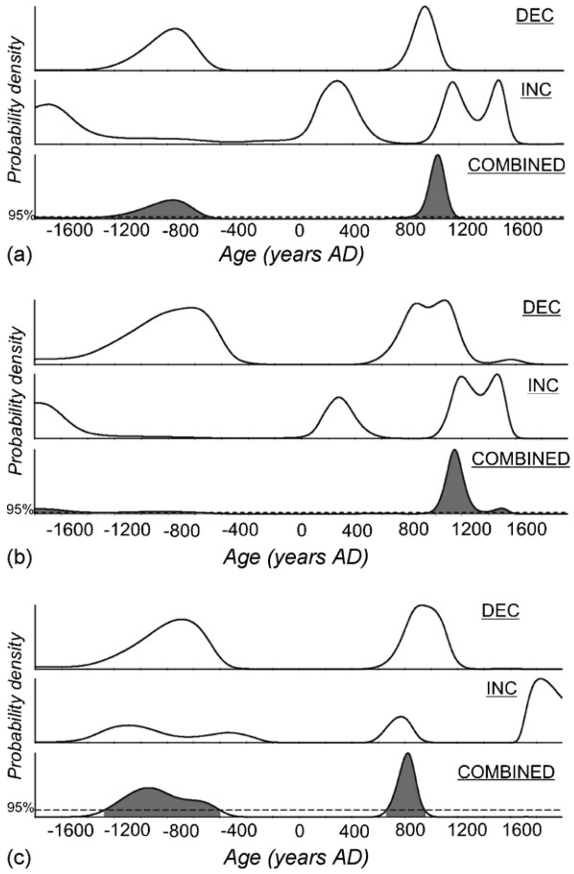

Fig. 11. Probability densities for dating of the structures: (a) EP02 – Exeter, (b) EP03 – Exeter, and (c) c.213 – Kingsdale. These were obtained from the reference curve with a 95% confidence. In each case independent dating for declination and inclination is presented as well as their combined probability (filled in grey).

6. Dating with the new UK reference curve

To assess the efficiency and accuracy of the approach described above, two examples of dating are considered. These recently determined archaeomagnetic directions have not been included in the calibration curve calculation, thus they can serve as an independent test set. The new UK calibration curve is used with *RenDate* software (Lanos, 2004), which based on the previously calculated curve produces a probability density distribution of possible dates for each geomagnetic field element of the feature under examination. The archaeomagnetic dating is obtained by combining all probability densities, in order to find the most probable solution.

The first example refers to archaeomagnetic directions determined during an urban rescue excavation at Princeshay, in the old town centre of Exeter (Winkler et al., 2006). Structure EP2 corresponds to a shapeless spot of burnt soil, while feature EP3 is most probably a fireplace located within a built structure. The city of Exeter was continuously populated since the Roman period and archaeological evidence at the site is inconclusive, thus it is not possible to date the site based solely on archaeological constraints. The dating intervals provided by *RenDate* software with 95% confidence are shown in Fig. 11(a) and (b). Although more than one possible time interval arises (feature EP02: −1467 to −682 and 839–1194; feature EP03: −2001 to −1570, −1390 to −787 and 958–1570), based on the lack of extensive occupation prior to the Romans any pre-Roman age can be eliminated. Consequently, both features are dated in the early medieval period (EP02: 839–1194, EP03: 958–1570), with EP02 being most probably the older one. However, the choice of the 95% confidence limit for dating intervals is arbitrary; while this increases the confidence level of the resultant date it reduces its precision. Should a smaller confidence limit be chosen, the dating intervals will have shorter time spans but it is possible for a number of alternative disconnected intervals to result. A comparison of the observed direction with the reference curve of Clark et al. (1988) produced no date as it does not intersect with the curve.

The second example comes from a feature thought to have been involved in heating, encountered during excavations of site at Kingsdale Head, North Yorkshire (Clelland and Batt, 2006). The resultant probability density distribution provides two possible dating intervals: one places the feature to the Bronze to Early Iron Age (−1477 to −600) and the second assigning the site with a Late Medieval age (661–952) (Fig. 11(c)). Archaeological evidence favours the latter as the site is possibly of Viking origin. However, both time intervals are poorly constrained; the reason for the low accuracy in this case is probably the small number of data points used for the construction of the secular variation curve for pre-Roman times and for the Dark Ages. The comparison of the observed direction with the curve of Clark et al. (1988) suggests the following possible dating intervals: −950 to −560, −510 to 300 and 1560–1600.

7. Conclusions

The archaeomagnetic database for the UK has been considerably enhanced with the collection of new data measured in the past decade and a thorough examination of all available data has been performed to estimate their accuracy and reliability. After an assessment of the various statistical treatments that have been developed to treat such data the one involving the Bayesian modelling was used to produce the new UK secular variation reference curve as it was considered the most effective in providing a quantitative evaluation of most of the errors involved. The British curve now extends back 4000 years and is in good agreement with the French SV curve of Gallet et al. (2002). This suggests that it can be used as an accurate tool for archaeomagnetic dating, with the accuracy depending on the quality of the direction to be dated (low α_{95}) and the width of the curve's envelope. Oversmoothing is an unavoidable problem during modelling and progress is being made towards minimizing such effects by slight modifications of the mathematical algorithms. It is interesting to note that the precision of the archaeomagnetic data used to produce the British SV curve is generally very good; the main errors remain in establishing the ages of the points that constrain the curve. The main priority is therefore to obtain further data from well dates sites.

A file of the data used for the curve calculation as well as data files of the presented curves can be requested via e-mail from the authors (izanan@geo.auth.gr, C.M.Batt@Bradford.ac.uk). It is intended that subsequent new archaeomagnetic observations will be incorporated into the international database MAGIC, enabling local secular variations to be compiled using, for example, the Rennes software packages. *RenDate* software can be downloaded from the AARCH website: http://www.meteo.be/CPG/aarch.net/frameset_en.html.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.pepi.2006.08.006.

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