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Three millennia of directional variation of the Earth's magnetic field in western Europe as revealed by archeological artefacts

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Abstract

Directional secular variation of the geomagnetic field over the last 2000 years has been defined in western Europe from numerous archeomagnetic studies. However, the number of archeomagnetic results for older periods is much more limited. For this reason, we present new data obtained from fired archeological structures found in two French sites (Loupiac and Aspiran) dated within the first millennium B.C. (latest Bronze-earliest Iron Age transition, ∼850–700 B.C. and Iron Age, ∼525–475 B.C., respectively). From a compilation of archeomagnetic results from western Europe (Great Britain, Italy and France) and northern Africa (Tunisia), we propose a directional secular variation curve for western Europe that covers the entire first millennium B.C. This curve exhibits a large clockwise motion with rapid changes during the first half of the millennium, while the last four centuries B.C. are characterized by weak variations. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Archeomagnetism; Secular variation; Western Europe

1. Introduction

Emile thellier first initiated archeomagnetic studies in France more than 60 years ago (Thellier, 1938). His pioneering work led to a detailed geomagnetic directional secular variation curve in France covering the last two millennia (Thellier, 1981). More recently, this curve was completed and extended to the last 21 centuries with a set of 120 directional results generally obtained from well-dated kilns (Bucur, 1994). Depending on the time periods, the observed directional fluctuations are more or less large and rapid, reaching differences up to ∼15° in inclination between the 9th and the 14th centuries, and ∼40° in declination between the 11th and the 19th centuries (Fig. 1). This behavior is of interest for analyzing the secular variation in geomagnetic field both at local and global scales (Daly and Le Goff, 1996; Hongre et al., 1998; Constable et al., 2000). The reference curve shown in Fig. 1 is also commonly used as a dating tool for archeological purposes.

In order to contribute to secular variation studies, we present in this paper six new archeomagnetic results from France dated of the first millennium B.C. Together with a compilation of data obtained from Great Britain, France, Italy and Tunisia, these results allow the establishment of a preliminary archeomagnetic directional curve covering the entire first millennium B.C. valid for western Europe.

2. Acquisition of new archeomagnetic data

Samples were collected from two archeological sites in southern France: (1) from the so-called Combe Nègre area near the village of Loupiac (Latitude =

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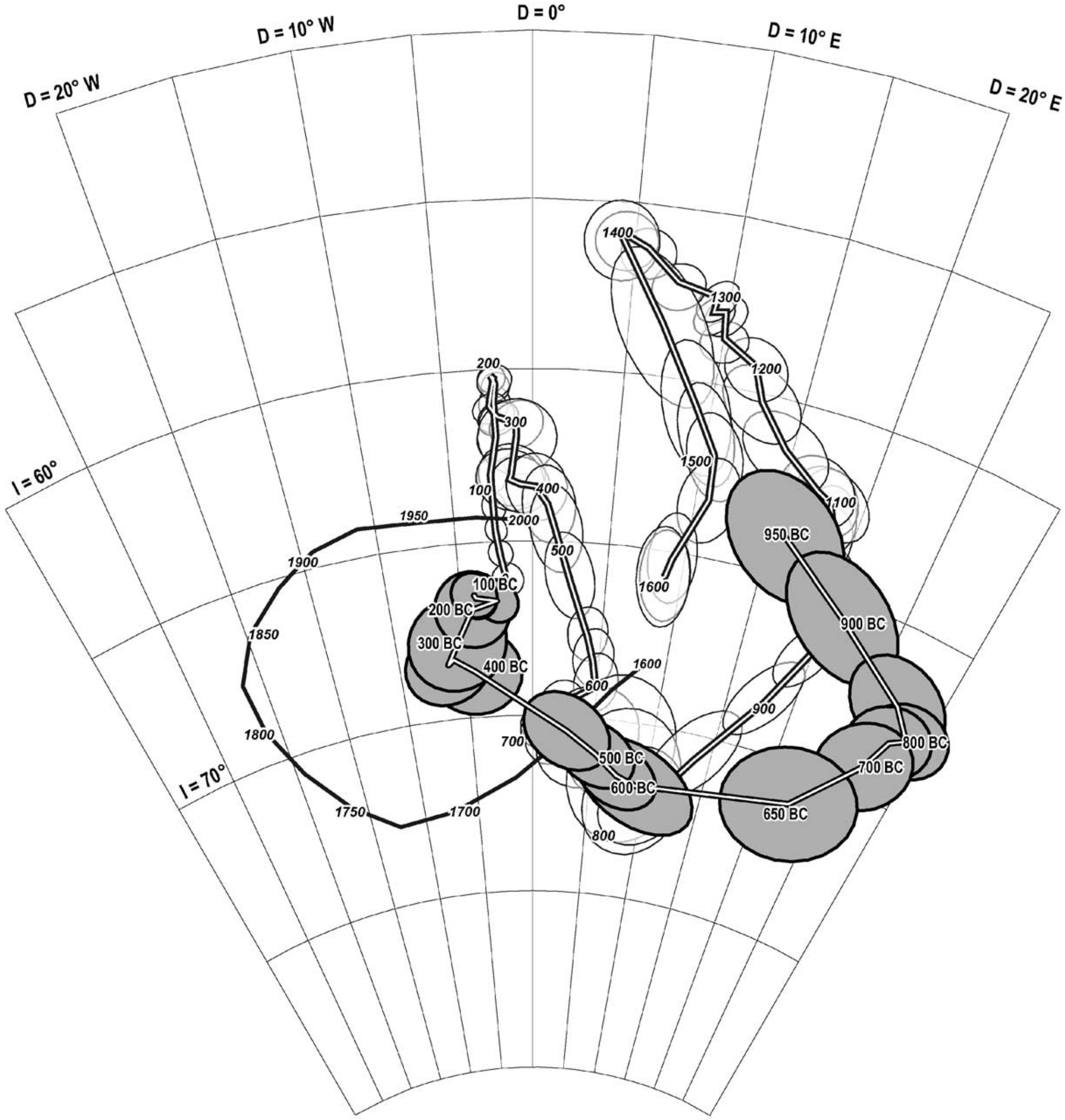

Fig. 1. Directional variations of the Earth's magnetic field in France over the last three millennia (all data were reduced to Paris). The curve spanning the last two millennia (white ovals) was established by Bucur (1994) using sliding windows of 80 years shifted every 25 years. Mean directions were computed with bivariate statistics (Le Goff, 1990; Le Goff et al., 1992). The new curve established for the first millennium B.C.(shaded ovals) was computed using sliding windows of 160 years with steps of 50 years.

44.9°N, Longitude = 1.5°E), close to the city of Souillac (Lot), and (2) from Aspiran, in the Mas de Pascal area (Latitude = 43.6°N, Longitude = 3.6°E), close to Montpellier. Excavations at Loupiac revealed a rich occupation layer of the late Bronze-earliest Iron Age boundary (Final Bronze IIIB-Hallstatt C age: 850–700 B.C.; Prodéo et al., in press). Several hearths were discovered, four of which we sampled for archeomagnetism. Three of them (Loupiac #01, #03, #16) had a baked clay aureole from which the samples were collected. Note that the Loupiac #03 structure was perturbed after its last use by the emplacement of a post that made a hole in the hearth. The age of these structures is archeologically well constrained, in particular by the findings of numerous age-diagnostic ceramics (Prodéo et al., in press). Two pottery kilns, having diameters of ~1.5 m, were found in Aspiran (AFR6186 and AFR6416; Pezin et al., in preparation). Their age, between 525 and 475 B.C., was ascertained by the typology of ceramics found in the field (Ugolini and Pezin, personal communication; Pezin et al., in preparation).

The archeological structures were sampled using the procedure described in Thellier (1981) and

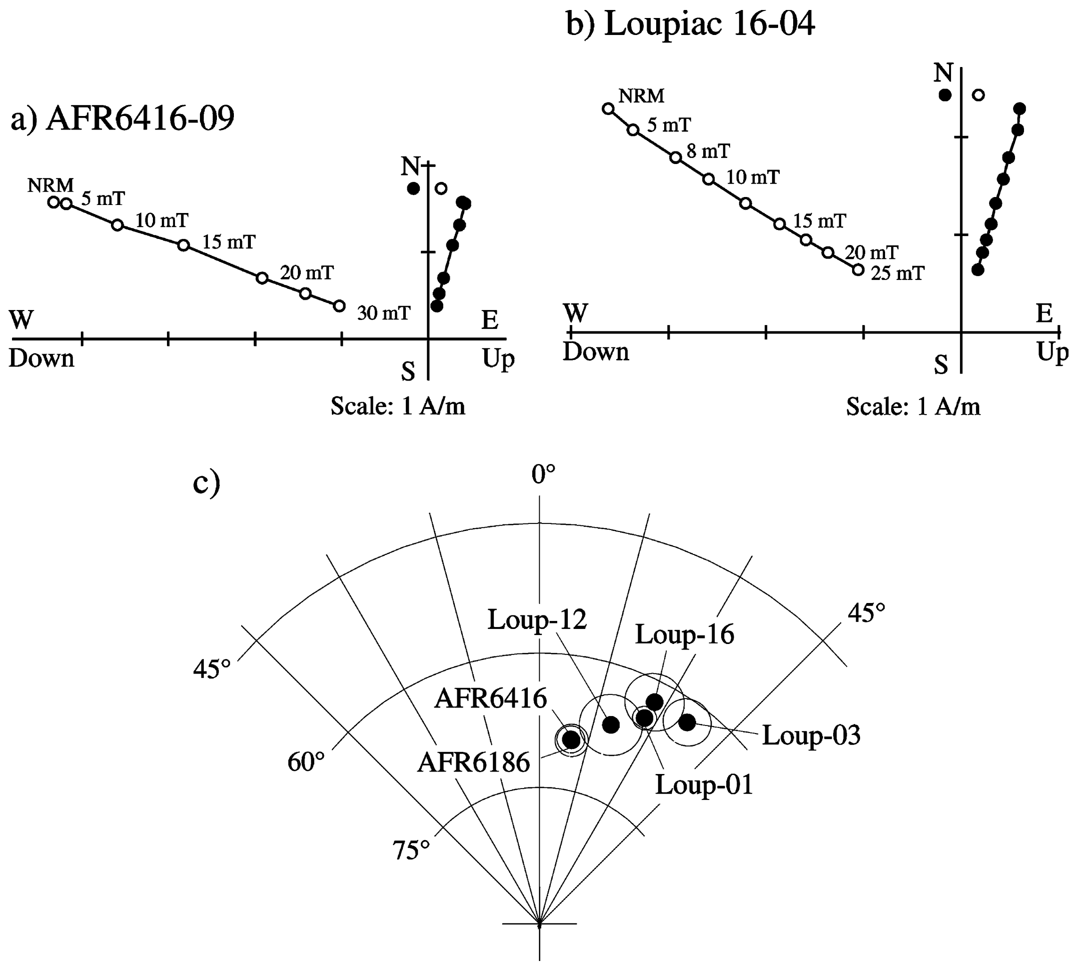

Fig. 2. Archeomagnetic results obtained from Aspiran and Loupiac. Orthogonal vector diagrams obtained after AF demagnetization of one sample from Aspiran (a) and Loupiac (b). The closed (open) symbols refer to the horizontal (vertical) plane. (c) Equal-area projection of the mean archeomagnetic directions obtained from each structure (AFR for Aspiran, Loup for Loupiac). Closed symbols refer to directions in the lower hemisphere.

Table 1
Archeomagnetic results obtained from Aspiran and Loupiac

Structures	N	Visc. (%)	Dec. (°)	Inc. (°)	k	α_{95}(°)
Aspiran (43.62°N, 3.58°E)						
AFR 6186	17	2.6	9.9	69.5	398.1	1.8
AFR 6416	13	2.7	9.6	69.4	728.0	1.5
Loupiac (44.91°N, 1.48°E)						
Loup-01	14	6.5	27.0	64.5	888.7	1.3
Loup-03	14	2.2	36.2	62.4	241.6	2.6
Loup-12	9	11.8	19.7	66.7	236.0	3.4
Loup-16	17	3.4	27.4	62.4	122.6	3.2

Visc., viscosity; Inc., inclination; Dec., declination; α_{95}, 95% dispersion angle of the Fisherian distribution.

Bucur (1994). Large plaster cap oriented samples (~1 dm^3) were collected from each structure. These samples were adjusted and plastered in 12 cm-side moulds in the laboratory, and their magnetization was measured with a rotating inductometer specially designed for large samples (Le Goff, 1975).

A viscosity test was first performed for each sample to establish a magnetic viscosity index defined by the ratio of viscous remanent magnetization (VRM) to the primary thermoremanent magnetization (TRM) (Thellier and Thellier, 1959). Only those samples having a magnetic viscosity index <15% were retained for further analyses, because otherwise the heating of the samples was likely not sufficient enough to allow an accurate record of the Earth's magnetic field. In order to preserve the high precision of the sample orientations made in the field, the magnetic components were isolated by alternating field (AF) treatment using a coil also constructed for large samples.

Demagnetization first removed a soft component, likely a small VRM, in very low fields up to ~5 mT (Fig. 2a and b). Thereafter, higher fields clearly isolated a single component which decays toward the origin of the orthogonal projections. AFs of less than ~30 mT, sometimes less than ~20 mT, were sufficient to remove about 75% of the total (NRM) magnetization. We consider that this component, which is probably carried by magnetite as commonly observed in archeological fired materials (Jordanova et al., 1997), was acquired during the last heating–cooling of the structures. For each structure, the magnetic directions are relatively well clustered (Fig. 2c; Table 1), with clustering being largely dependent on the preservation of the structures. The two well-defined ($\alpha_{95} < 2°$) mean directions obtained from Aspiran are identical at the 95% confidence level (McFadden and McElhinny, 1990; $\gamma = 0.2°$, $\gamma c = 2.4°$), which likely indicates that both kilns were in use at the same time. In contrast, the results obtained from Loupiac are more dispersed (Fig. 2c), which argues for different blocking times of magnetization and thus, for slightly different ages.

3. Selection of western European data

Many archeomagnetic results obtained by different workers were either never published or published in journals of limited distribution and/or internal reports. Thanks to a compilation recently performed by Tarling (1999), we have summarized the data obtained for the first millennium B.C. from Great Britain and Italy, the nearest countries to France where data of that age are available (25 and 10 data points, respectively). Other results reported in Table 2 were also obtained from France by Thellier (1981; 2 data points), Bucur (1994; 7 data points) and Moutmir (1995, 7 points). In addition, we have considered two directions obtained by Thellier (1981) from the Punic kilns sampled in Carthage (Tunisia; note that the distance between southern France and northern Africa is similar to the distance between France and southern Italy).

Altogether, the results form a very inhomogeneous data set involving different sampling methods and different magnetic analysis procedures. Concerning the latter, Tarling (1999) defined quality categories between 0 and 5 for taking into account the demagnetization treatments applied to the samples. These

Table 2
Compilation of archeomagnetic results of the first millennium B.C. obtained from France by Thellier (1981); Bucur (1994); Moutmir (1995)

Reference	Site	Lat.	Long.	Max.	Min.	Dec. (°)	Inc. (°)	α_{95}	N	k
Thellier (1981)	Frejus Piece	43.5	6.8	−40	−40	−6.4	64.3	1.2	8	1629
Thellier (1981)	Limoux II F2	43.1	2.3	−20	−5	−0.1	62.0	2.1	7	625
Bucur (1994)	St Blaise	43.5	5.0	−575	−550	0.5	65.6	0.9	11	2355
Bucur (1994)	Sainte Florence	44.8	0.0	−325	−275	−2.8	66.4	2.2	11	386
Bucur (1994)	Aiguillon F4	44.3	0.3	−120	−80	2.6	64.1	0.8	19	1607
Bucur (1994)	Aiguillon F1 + F2 + F3	44.3	0.3	−120	−80	−2.4	62.4	0.5	45	1825
Bucur (1994)	Montans 4	43.9	1.8	−100	−80	−2.6	63.5	1.0	11	1696
Bucur (1994)	Petit et Grand Lezat	46.0	3.3	−100	−50	−7.9	65.7	1.5	10	931
Bucur (1994)	Lagruere	44.4	0.2	−80	−40	−3.7	62.9	0.9	14	1797
Moutmir (1995)	Marlenheim	48.6	7.5	−1000	−900	18.0	64.6	1.6	11	704
Moutmir (1995)	Gannat	46.2	3.3	−850	−700	14.0	65.1	2.9	10	237
Moutmir (1995)	Lignat	45.8	3.3	−850	−700	29.4	67.7	2.4	24	146
Moutmir (1995)	Mairy	49.0	5.0	−800	−700	23.3	69.4	1.9	11	449
Moutmir (1995)	Issoire 1	45.5	3.3	−750	−250	21.6	69.1	1.4	21	961
Moutmir (1995)	Issoire 2	45.5	3.3	−700	−600	22.0	73.0	1.6	8	483
Moutmir (1995)	Herblay	49.0	2.2	−530	−430	10.4	71.1	2.7	9	295

Lat., latitude; Long., longitude; Max., maximum; Min., minimum; Inc., inclination; Dec., declination; α_{95}, 95% dispersion angle of the Fisherian distribution.

treatments are indeed highly variable depending on the studies with in some cases no demagnetization (category "0") and in others demagnetization at one thermal or AF step or, but rarely, complete demagnetization allowing vectorial analyses to isolate the archeomagnetic directions. Data obtained from France by Bucur (1994) and Thellier (1981) were systematically considered in the weakest category, but we think that the quality of these data is better than classified by Tarling (1999). We recall that French results met several stringent quality criteria defined by Thellier (1981): (1) the high precision in orientation of the samples in the field obtained by collecting only large samples coupled with a high precision of magnetization measurements which leads to direction fidelity better than 0.5° (Tanguy, 1990; Tanguy et al., 1999); (2) the retained results have a low viscosity index (<10% in all cases, and <5% in 80% of cases), which is an efficient method to detect structures having suffered insufficient heating or chemical alteration since their last time of use; (3) only mean archeomagnetic directions defined by a small dispersion were considered (93% of the data reported by Bucur have Fisher k parameters >500, and 95% of the results have $\alpha_{95} <$ 2.5°), allowing the rejection of structures which could have been perturbed by mechanical deformations during their burying or their excavation. We further note that the magnetization isolated from each individual sample was corrected by vectorial subtraction for the small VRM component (Thellier, 1981).

Considering the previous ambiguity in defining the quality factor and the relatively small number of data presently available data for western Europe (59), we restricted the data set by rejecting mean directions with $\alpha_{95} > 5°$ ($N = 7$). The geographical and age distributions of the retained data are shown in Fig. 4. The ages are concentrated within three dominant periods: the first century B.C., between the sixth and third centuries B.C. (more or less during the recent—or second—Iron Age which corresponds to the La Tène period in Gaul and to the first half of the Roman Republic period in Italy), and ~700–850 B.C. (latest Bronze—earliest Iron Age boundary). We also remark that the old—or first—Iron Age (also called the Hallstatt period) is poorly defined by very few data, in particular during the seventh century.

4. Establishment of a smoothed directional curve

The data available for the 1000 B.C.–0 period are mainly located in three areas: the southern Great Britain, the southern part of France, and regions more to the south including southern Italy, Sicily and northern Tunisia (Fig. 3). This dispersed site distribution requires us to reduce all results to a common site.

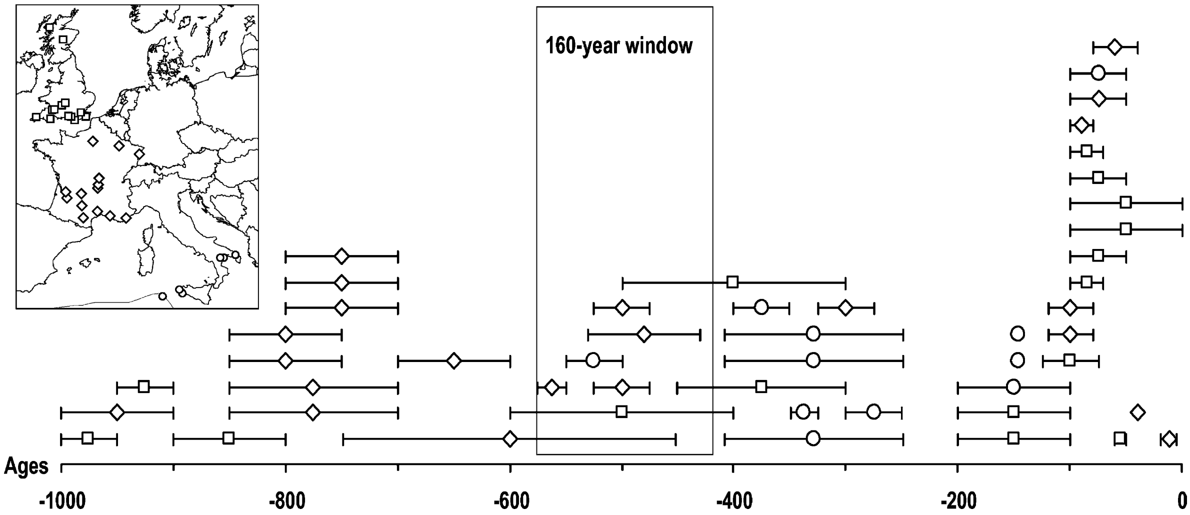

Fig. 3. Site and age distribution of the directions compiled to establish the directional secular variation curve in western Europe during the first millennium B.C. The open dots, open diamonds and open squares indicate data obtained from southernmost regions (southern Italy, Sicily and Tunisia), France and Great Britain, respectively.

Following Bucur (1994), we opted for Paris which lies roughly in the middle of the distribution (48.9°N, 2.3°E). The reduction was performed using virtual geomagnetic poles (VGP; Shuey et al., 1970; Bucur, 1994). We, however, acknowledge that VGPs still introduce some errors (a geographically more restricted distribution would of course have been preferable). To roughly estimate these errors, we compared the present directions at the different sites of our data set, as derived from the International Geomagnetic Reference Field of 2000 and then transferred to Paris via VGPs, to the true magnetic direction in Paris. We found that the angular distances between all pairs of directions slightly exceed 2° in a very few cases (those from the southernmost regions), and are <1° in 70% of the cases. These values are clearly in the lower bound of the intra-site angular error of the directions (α_{95}). Furthermore, a significant bias produced by the VGP method in mean direction computations appears unlikely since no long-lasting time interval within the 1000 B.C.–0 period is defined only by data obtained from a single region lying far away from Paris.

The secular variation curve was computed using the sliding window technique described by Bucur (1994) and Daly and Le Goff (1996). The computations were carried out using the bivariate extension of the Fisherian statistic (Fisher, 1953) developed by Le Goff (1990) and Le Goff et al. (1992) in order to take into account the fact that individual directions (i.e. obtained at the site level) within certain time intervals are likely elongated (non-Fisherian) distributions because of the secular variation path during these periods. The individual directions, whose ages are defined between two age limits, were weighted depending on the proportion of their age brackets contained within the considered time intervals. We computed several curves using sliding windows of different durations (in all cases >100 years), which demonstrated the stability of the directional path upon smoothing. The first millennium B.C. curve shown in Fig. 1 was obtained using sliding windows of 160 years shifted every 50 years, which reasonably reflects the resolution allowed by the present data set (Table 3). For comparison, we note that the curve established for the last two millennia was computed using sliding windows of 80 years with steps of 25 years (Bucur, 1994). Only three results, clearly discordant with respect to the other data contained within the same time interval, were rejected from mean direction computations (British data with reference #35, #51 and #93 by Tarling, 1999).

The western European directional secular variation curve exhibits a large clockwise movement during the first millennium B.C., with rapid changes during the

Table 3
Mean archeomagnetic directions in western Europe during the first millennium B.C.

Age BC	N_{si}	W_{si}	W_{sa}	Inc.	Dec.	α_{95}	α_x	α_y	Ω
950	4	3.3	40.1	63.8	15.8	2.1	1.4	2.1	136.1
900	8	4.2	64.3	65.5	20.9	1.9	1.3	2.1	130.2
850	10	5.5	91.2	67.2	26.8	1.4	1.2	1.6	122.2
800	9	7.0	111.4	68.0	28.5	1.2	1.1	1.2	86.5
750	10	7.2	104.4	68.3	27.4	1.1	1.1	1.2	67.1
700	9	5.3	70.1	69.2	26.5	1.3	1.2	1.4	40.4
650	9	3.2	39.6	71.0	22.3	1.7	1.6	1.9	73.1
600	8	3.6	41.7	71.7	9.1	1.4	1.1	1.8	118.9
550	9	6.2	78.8	71.5	7.4	1.0	0.9	1.2	117.9
500	9	6.8	86.5	70.9	5.4	1.0	0.9	1.2	121.5
450	12	7.0	87.4	70.3	2.9	1.2	1.0	1.3	127.5
400	13	6.6	76.6	68.6	−4.2	1.3	1.2	1.3	107.9
350	10	7.9	86.5	68.2	−5.7	1.1	1.0	1.2	48.4
300	9	7.0	75.5	68.4	−6.2	1.2	1.1	1.2	53.2
250	11	5.0	53.5	67.8	−5.3	1.4	1.3	1.4	43.4
200	11	5.8	58.7	66.7	−2.1	1.1	1.1	1.2	121.5
150	18	14.3	195.4	66.6	−1.6	0.6	0.6	0.7	138.0
100	20	19.0	257.2	66.5	−3.2	0.6	0.6	0.6	138.5
50	19	16.9	235.5	66.4	−3.9	0.6	0.6	0.7	141.8

All directions, reduced to Paris, are obtained using sliding windows of 160 years shifted every 50 years. Columns (left to right): mean age of the 160-year window; N_{si}, number of sites in the window; W_{si}, weight relative to sites; W_{sa}, weight relative to samples; Inc., inclination; Dec., declination; α_{95}, 95% dispersion angle of the Fisherian distribution; α_x, α_y 95% dispersion angles of the ellipse of the bivariate statistic; Ω, angle between the elongation direction of the confidence ellipse and the mean meridian.

first half of the millennium marked by variations of ~30° in declination between ~800 and 400 B.C. and of ~10° in inclination between ~1000 and 600 B.C. In contrast, the last four centuries B.C. are characterized by weak fluctuations (Fig. 1). Fig. 1 shows that during the last three millennia the geomagnetic field varied up to ~50° in declination (between ~800 and 1800 A.D.). Such large fluctuations are clearly favorable for using the geomagnetic secular variation in western Europe to constrain the age of fired archeological structures, except during the Roman period (including the last few centuries B.C.) characterized by limited changes in direction. In particular, archeomagnetism appears to be a powerful dating method for the Hallstatt period which is marked by large atmospheric C14 fluctuations (mainly between 800 and 500 B.C.) that hamper good precision in radiocarbon dating (Pearson et al., 1986).

Finally, we compared the archeomagnetic curve over the last 3000 years with continuous secular variation records obtained from lake sediments in Great Britain (Fig. 4, Turner and Thompson, 1981, 1982). The same trends are observed in the two data sets, although there are some discrepancies in the amplitude of the variations and in the age of the geomagnetic features. The differences mainly concern the declinations, with a relatively constant and systematic shift of ~10° between the two records from 1000 B.C. to ~1000 A.D. (Fig. 4a), which might indicate a problem in azimutal reorientation of the sediments. The agreement is better in inclination, which argues against noticeable flattening of the studied sediments due to compaction. However, discrepancies exist in inclination at the beginning of the first millennium B.C., the archeomagnetic curve showing more pronounced variations (Fig. 4b). We tentatively suggest an erroneous age calibration of the sediments around the second millennium and the beginning of the first millennium B.C., a time interval which could be over represented in the master curve proposed by Turner and Thompson (1982). Although we recognize the great potential to use both archeomagnetic and well-dated and oriented sedimentary results to determine the detailed and continuous signature of geomagnetic secular variation, as previously attempted by Clark et al. (1988), such combination is not yet possible in western Europe.

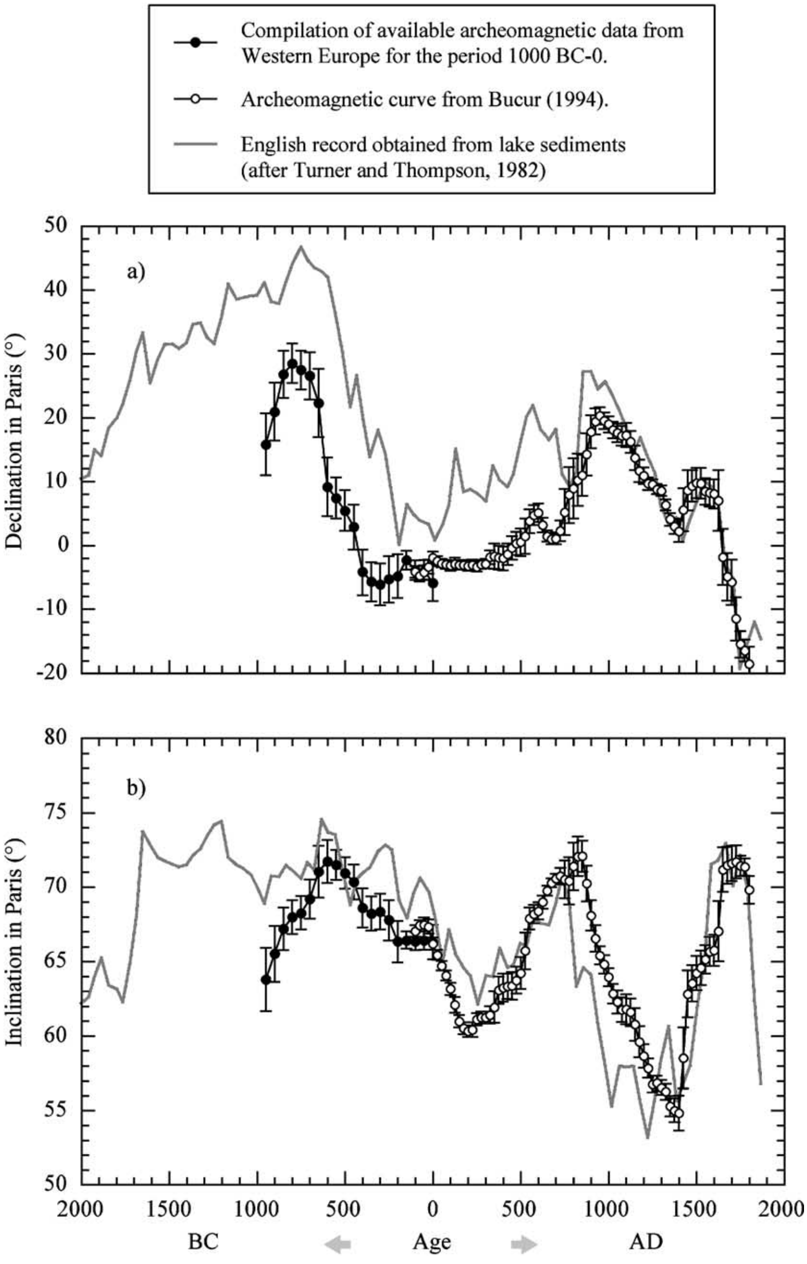

Fig. 4. Comparison between archeomagnetic and lacustrine declinations (a) and inclinations (b) obtained from Great Britain over the last 4000 years (after Turner and Thompson, 1982). All results were reduced to Paris.

The archeomagnetic data presented here further define the directional secular variation of the geomagnetic field in western Europe over the first millennium B.C. Together with previous analyses, this study provides a detailed record of the secular variation in this region over the three last millenia. Archeointensity results are now required to fully describe the geomagnetic field which may test the link between direction and intensity changes as found by Genevey and Gallet (in press) for the last 2000 years.

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