ELSEVIER

Physics of the Earth and Planetary Interiors 134 (2002) 203–211

PHYSICS OF THE EARTH AND PLANETARY INTERIORS

www.elsevier.com/locate/pepi

On archeomagnetic secular variation curves and archeomagnetic dating

Maxime Le Goff [a,*], Yves Gallet [a], Agnès Genevey [a], Nicolas Warmé [b,a]

[a] *Laboratoire de Paléomagnétisme, Institut de Physique du Globe de Paris, Paris, France*
[b] *Institut National de Recherches Archeologiques Preventives, Antenne Centre, Ile-de-France, Paris, France*

Received 24 June 2002; received in revised form 2 September 2002; accepted 9 September 2002

Abstract

Secular variation (SV) of the Earth's magnetic field can be used for dating purposes by comparing archeomagnetic directions of unknown ages with a well-dated reference curve. In this study, we propose a dating technique based on the statistics of McFadden and McElhinny [Geophys. J. Int. 103 (1990) 725] for testing the hypothesis that two Fisherian distributions of individual directions share a common mean direction. The statistics are adapted to test the degree of compatibility between one individual Fisherian mean direction and a reference curve constructed using the bivariate extension of the Fisher distribution. Furthermore, as the density of the data which define the archeomagnetic reference curve varies in time, we suggest that one computes the mean directions with moving windows of varying duration, where both the window widths and the time shifts between successive mean directions are fixed when a minimum threshold density of data is reached within each time interval. In our paper, we apply this new procedure to the French archeomagnetic data set.

Keywords: Archeomagnetism; Secular variation; Bivariate statistics; Archeomagnetic dating

1. Introduction

The Earth's magnetic field varies in direction and intensity over time scales spanning less than one second to more than 100 million years (e.g. Courtillot and Le Mouël, 1988; Merrill et al., 1996). Variations ranging from a few tens of years to a few millennia, which are thought to be generated by non-dipole field components acting in the geodynamo, are referred to as geomagnetic secular variation (SV). The time range needed to effectively model secular variation is greater than that provided by historical observations alone, which describe at best the directional magnetic variations over the past four centuries (e.g. Alexandrescu et al., 1997; Jackson et al., 2000). On the other hand, the time range covered by paleomagnetism is much longer (several tens of thousands of years and longer), however, the fidelity of the secular variation record defined by paleomagnetic methods is limited both by large time gaps and dating. Archeomagnetism, paleomagnetic techniques applied to well-dated archeological human artefacts, is an ideal approach to characterize secular variation during the Holocene. Archeomagnetic secular variation (mainly directional) curves have been established for different regions around the world (Fig. 1; i.e. Great Britain, France, Bulgaria, Ukraine, southwestern North America) which cover, except for Bulgaria, only the last

* Corresponding author. Tel.: +33-1-45-11-41-84; fax: +33-1-45-11-41-90.
E-mail address: legoff@ipgp.jussieu.fr (M. Le Goff).

0031-9201/02/$ – see front matter
PII: S0031-9201(02)00161-9

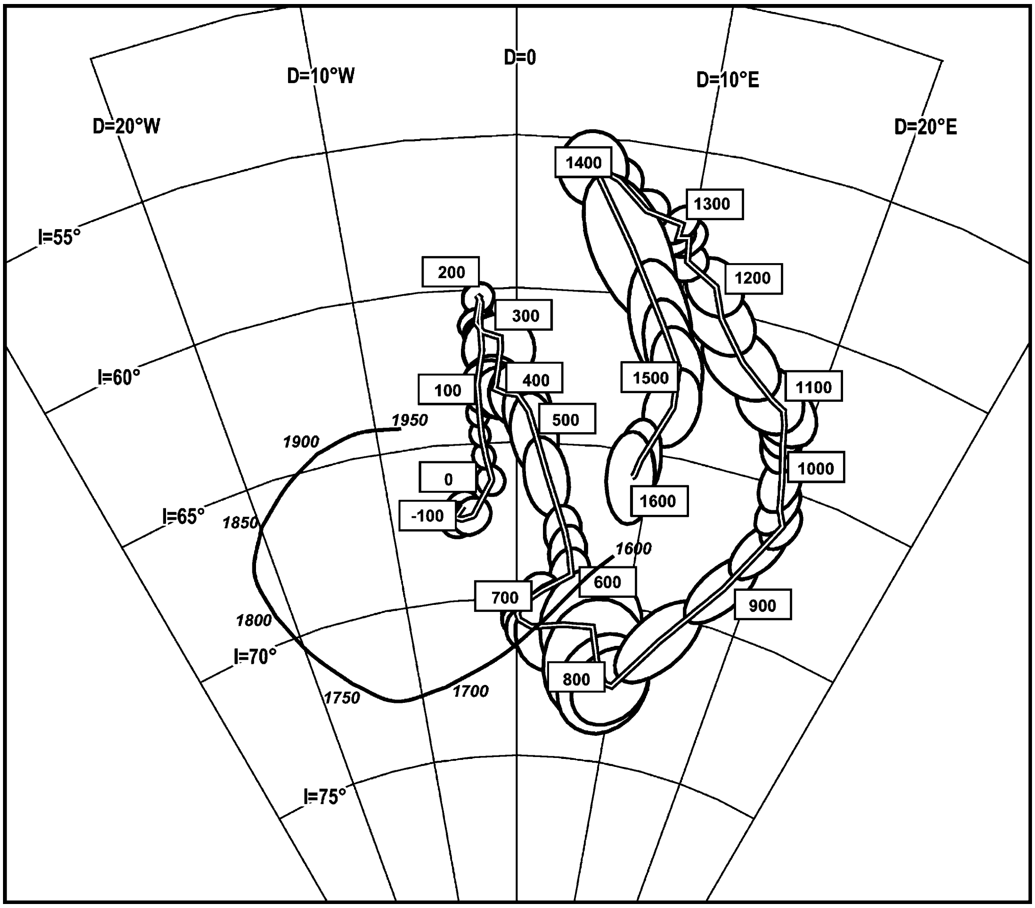

Fig. 1. Directional variation of the Earth's magnetic field in France during the last 2000 years (after Bucur, 1994 and Daly and Le Goff, 1996). Mean directions were computed using the bivariate Fisher statistics and considering moving windows of 80 years shifted every 25 years. All directions were reduced to Paris. The thick solid line indicates the secular variation curve from direct measurements between 1600 and 1950 A.D. as compiled by Thellier (1981) and also Bucur (1994).

2–3 millennia (e.g. Thellier, 1981; Clark et al., 1988; Kovacheva, 1992; Bucur, 1994; Sternberg and McGuire, 1990; Gallet et al., 2002; for synthesis, see Daly and Le Goff, 1996). Directional curves are usually constructed by averaging individual archeomagnetic results over time intervals of fixed duration (on the order of 100 years), shifted by a certain time step through the entire period documented by the data. The reliability (and the precision) of these curves depends on several parameters, such as the number of data, their time distribution, the precision of the individual archeomagnetic directions, the dating precision of the studied archeological structures, etc.

Once an archeomagnetic curve is established for a given region, it can then be used as a dating tool. This dating technique, which has often been used in France for archeological purposes (e.g. Menessier-Jouannet et al., 1995; Lanos et al., 1999), relies heavily on statistical methods to test the degree of compatibility between an individual mean direction obtained from the studied archeological structure with the reference secular variation curve. Up to now, the most elaborate method combines the probability densities obtained separately from the declination and inclination data (e.g. Lanos, 2001). In this paper, we present a new procedure to construct reference archeomagnetic SV curves which further allows us to use a spherical approach to derive statistically-constrained ages for undated archeomagnetic directions.

2. A modified procedure to construct archeomagnetic SV curves

Archeomagnetic SV curves are constructed from well-dated archeomagnetic directions which are selected based on quality criteria such as the measurement procedure, the number of analyzed samples and the dispersion of the magnetic directions obtained per archeological structure. In the case of archeological structures fired in situ (principally domestic or pottery kilns and hearths), each datum R_i is described by a mean direction (D_i, I_i) estimated from a number N_i of individual directions (i.e. at the sample level) and characterized by the dispersion Fisher parameter k_i (Fisher, 1953). To this mean direction is assigned an age interval T_i (usually a rectangular probability distribution) derived from archeological and/or historical constraints or from isotopic methods. We report in Fig. 2, the age intervals of the mean directions selected for France by Bucur (1994) for the period 0–1600 A.D. ($N = 110$). The number of available data and their associated time intervals critically depend on our knowledge of French history. In particular, the numerous data obtained for the Roman period are precisely dated, with typical age brackets of ∼50 years or less, while data available for the High Middle Age, between ∼500 and ∼1000 A.D., are scarce and relatively poorly dated with age brackets often larger than 100 years. The nature of this distribution varies according to the cultural and/or historical background of particular geographical areas.

It is also worth pointing out that all mean directions (D_i, I_i) obtained from a large area, a country or a region, such as western Europe, must be reduced to a single site, and Shuey et al. (1970) demonstrated that transferring the directions via virtual geomagnetic poles (Irving, 1964) was the most efficient reduction method (see also Noel and Batt, 1990).

Different methods have been developed to construct mean archeomagnetic SV curves (for a discussion, see Batt, 1997). Following Daly and Le Goff (1996), we consider here a method which computes weighted vectorial mean directions through successive time intervals A_j. The mean directions are estimated using the bivariate extension of the Fisher statistics (Le Goff, 1990; Le Goff et al., 1992). For a given interval A_j, the weighting $W_{i,j}$ attributed to each R_i is simply given by the proportion of the time T_i contained in the interval A_j, with $W_{i,j} = 1$ when T_i is entirely contained in A_j, and $W_{i,j} = 0$ when there is no overlapping fraction between T_i and A_j. We thus obtain a succession of ovals M_j characterized by a mean direction (D_j, I_j), a weight $W_j = \Sigma W_{i,j}$, a weighted number of samples $N_j = \Sigma N_i W_{i,j}$, a Fisher parameter k_j and the bivariate dispersion parameters $k_{x,j}$ and $k_{y,j}$ with the elongation direction Ω_j of the ellipse. In the present case, Ω_j yields an estimate of the

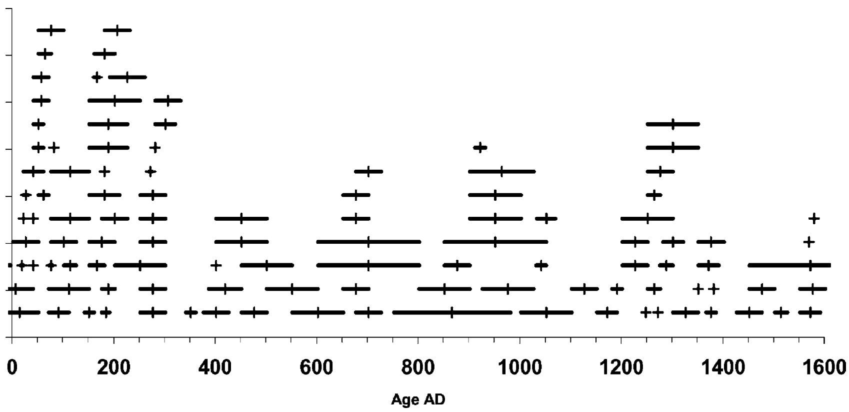

Fig. 2. Age distribution of the French archeomagnetic results selected by Bucur (1994) for the 0–1600 A.D. period.

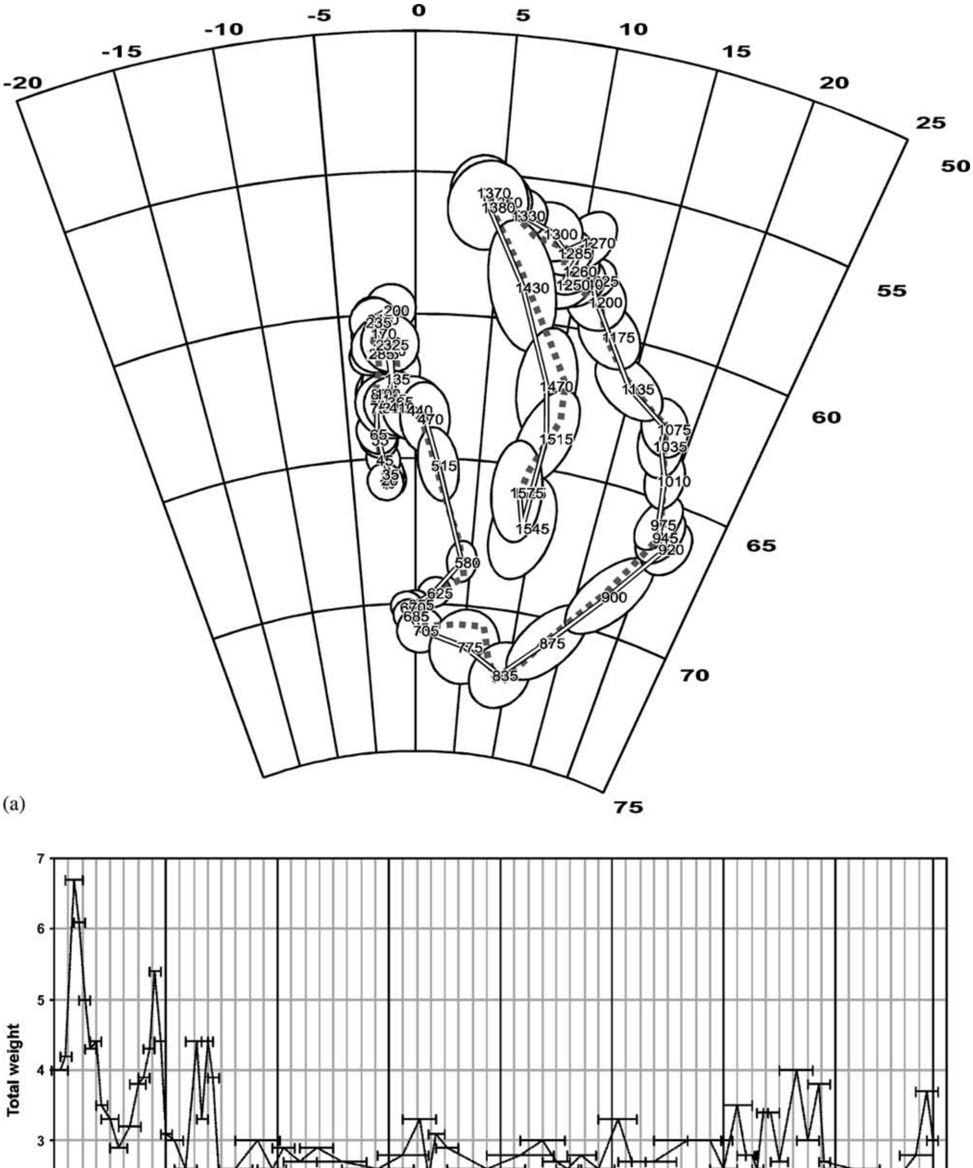

Fig. 3. French archeomagnetic secular variation curve during the last 2 millennia constructed using the bivariate Fisher statistics, over moving windows of varying durations (a). The width of each window and the time shift between two successive mean directions are fixed when a certain density of individual data given by the weight W_j is reached for one time interval (in the present case $W_j = 2.5$). For comparison, the curve constructed using moving windows of fixed duration (80 years) shifted every 25 years is also indicated by dashed lines. All directions were reduced to Paris. (b) Weight and duration of each time window between 0 and 1600 A.D. considering the threshold value of $W_j = 2.5$.

overall direction of the secular variation during the time interval A_j.

For drawing the French SV curve during the past 2000 years, Bucur (1994) and Daly and Le Goff (1996) considered sliding windows of 80 years shifted every 25 years. The choice of the window width was essentially constrained by the density of available data R_i over the time. Although this choice was somewhat arbitrary, it was however made to recover at short time scale a similar regularity in the geomagnetic directional variations that have been observed over the last three centuries from direct field measurements. As R_i are inhomogeneously distributed in time, whereas the window widths are kept constant, the derived SV curve does not possess the same robustness through time. As a consequence, fixing the window width, which necessarily relies on a compromise between the density of available R_i during magnetically well-documented and poorly-documented periods, is not a satisfactory approach when the resulting SV curve is used for dating purposes. It indeed amounts to a penalization of the precision of an archeomagnetic dating if the true age of the archeological structure to be dated is during a magnetically well-documented period, and on the contrary, likely an over-estimate of the reliability of an archeomagnetic dating if the true age lies during a magnetically poorly-documented period. This difficulty can be circumvented if the window widths of the averaged SV curve are chosen as a function of the density of data contained within each A_j. In the present case, this is possible by increasing the duration of each A_j from a short duration until a minimum value of W_j is reached in the window (note that this corresponds to a simplified version of the nearest neighbor method which adapts the smoothing to the local density of data; e.g. Silverman, 1986).

An example of this procedure is shown in Fig. 3a with a reasonable threshold value $W_j = 2.5$, and we report in Fig. 3b the distribution of the A_j periods and their weight W_j. We use a minimum window width of 20 years and a minimum overlapping step between two successive A_j being half of the duration of the first (i.e. older) window. The new archeomagnetic SV curve is not significantly different from the one previously obtained using moving windows of fixed duration but note that the nodes have different ages (Fig. 3a).

3. Determining archeomagnetic ages

Deriving an archeomagnetic age from an undated archeological structure supposes that this latter presents similar characteristics to the structures used for determining the reference secular variation curve. This concerns both the type of archeological structures (including the type of magnetic remanence) and the statistical nature of the archeomagnetic results (i.e. the confidence angles must have approximately the same size). The statistics used below are again those of Fisher (1953) and their bivariate extension (Le Goff, 1990; Le Goff et al., 1992). We will also consider the test of rejection previously developed by McFadden and McElhinny (1990) (and references herein) for testing the hypothesis that two Fisherian distributions of individual directions share a common mean direction.

The use of McFadden and McElhinny (1990) test for archeomagnetic dating (hereafter referred to as the M&M test) was first suggested by Sternberg and McGuire (1990). We will use it here in two different ways. First by considering the critical angle γ_c at which the mean direction U obtained from an undated structure can be considered different from the mean directions M_j at the confidence level $1 - p$ (usually at 95%):

$$\cos \gamma_{cj} = 1 - \mathcal{A}_j \left[\left(\frac{1}{p} \right)^{1/(N-2)} - 1 \right] \qquad (1)$$

with

$$\mathcal{A}_j = \frac{(N - \mathcal{R}_j - \mathcal{R}_U)(\mathcal{R}_j + \mathcal{R}_U)}{\mathcal{R}_j \mathcal{R}_U} \qquad (2)$$

(see Eq. 15 in McFadden and McElhinny, 1990) with the following parameters, $N = N_j + N_U$ where N_j is the weighted sample number in the window A_j and N_U is the number of individual directions obtained from the undated structure. $\mathcal{R}_j$ and $\mathcal{R}_U$ are respectively derived from the number of directions N_j and N_U and from the Fisher parameters k_j and k_U, with

$$k = \frac{N - 1}{N - R} \qquad (3)$$

In the opposite way, the M&M test can be used as a rejection test since we can estimate the probability p (in %) of making an error if an undated archeomag-

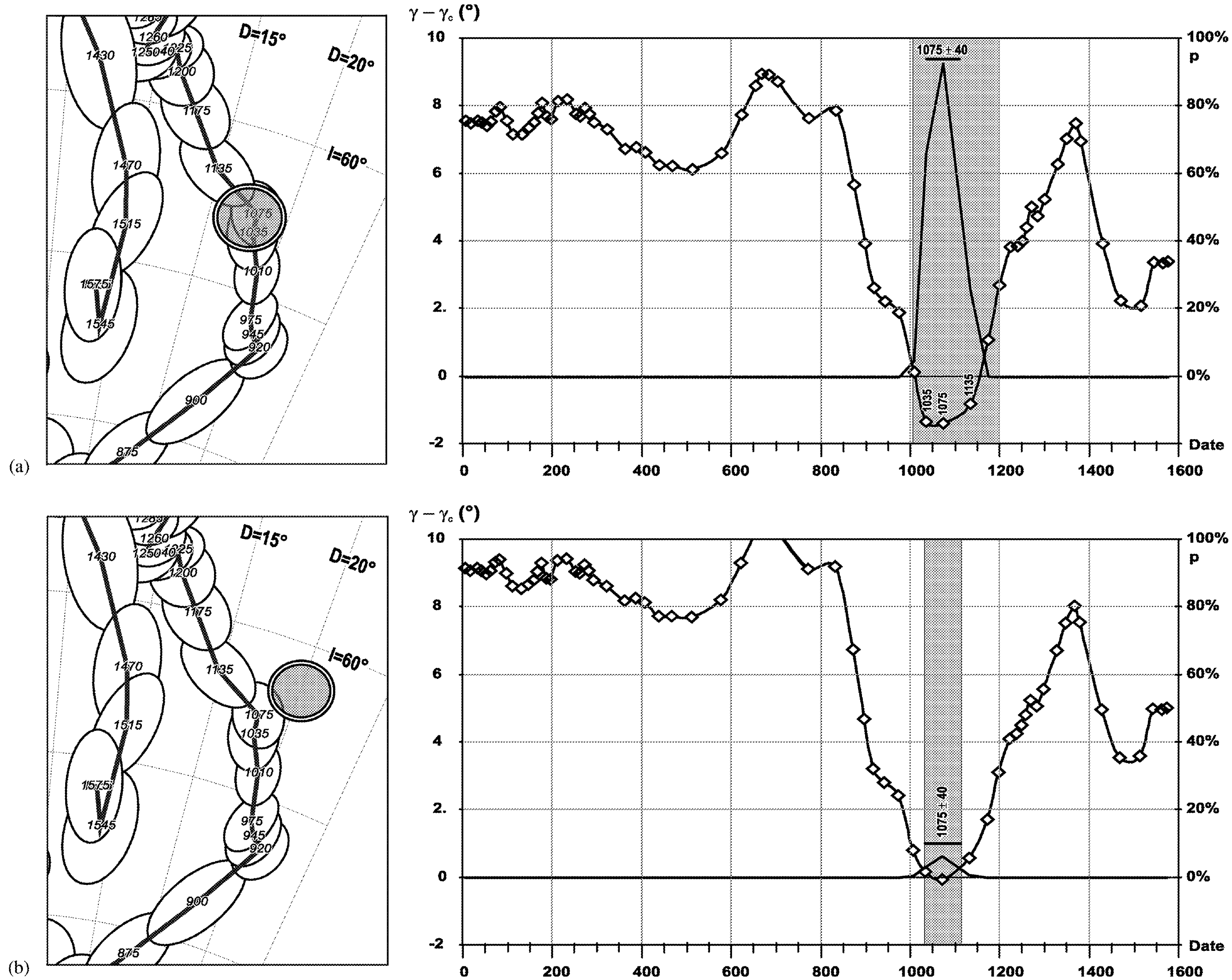

Fig. 4. Two synthetic examples of archeomagnetic dating using the French SV curve constructed with moving windows of varying durations (with $W_j = 2.5$). In the first case (a), perfect agreement exists between the undated direction and a portion of the reference curve, while the agreement is not as good in the second example (b). We obtain roughly the same archeomagnetic date interval (thick horizontal line) for the two cases, but the probability curves illustrate the higher reliability of the first dating.

netic direction is assumed different from any mean direction M_j distant by the angle γ_j, with

$$p_j = \left[\frac{\mathcal{A}_j}{\mathcal{A}_j + 1 - \cos\gamma_j}\right]^{N-2} \qquad (4)$$

We next have to adapt the M&M test because the mean direction isolated from one undated archeological structure, while it is assumed to be Fisherian, is compared to directions computed from the bivariate statistics which are not Fisherian. This can be made by simply considering values of k_j for the direction M_j intermediate between $k_{x,j}$ and $k_{y,j}$ and computed in the direction δ_j of the great circle joining the mean directions M_j and U, with

$$k_j = k_{y,j}\cos^2(\delta_j - \Omega_j) + k_{x,j}\sin^2(\delta_j - \Omega_j) \qquad (5)$$

The critical angle γ_c as defined by Eq. (1) and computed between U and the successive M_j therefore allows the determination of an archeomagnetic age interval. To (partly) avoid the ambiguity which results from the fact that a direction U very close to the reference SV curve will tend to provide an age interval apparently less precise than a direction marginally in agreement with the reference curve, it is necessary to define this archeomagnetic age interval from the entire durations of the different windows A_j for which the associated M_j yield a positive M&M test. In a second step, the probability curve defined by Eq. (4) is useful to classify better the agreement within the time interval previously determined. To illustrate this point, we reported in Fig. 4, two synthetic examples of archeomagnetic dating. The first undated archeomagnetic direction was chosen in perfect agreement with a portion of the reference SV curve (Fig. 4a), and the second more distant from the curve (Fig. 4b). We observe that the second archeomagnetic age interval deduced by the critical angle γ_c is more precise than for the first direction, but the probability curves, with values reaching ∼95% in the first case and only ∼5% in the second, clearly indicate that the first dating is by far more reliable than the second one.

4. Discussion

We present below a typical example of archeomagnetic dating applying the method described in our study. We sampled in 1999, a pottery kiln near the village of Lassy (kiln #3 in the La Renarde area; latitude: 49.10°N, longitude: 02.43°E), about 30 km to the north of Paris (Guadagnin, 2000). There, 18 large plaster cap-oriented samples were collected using the procedure perfected by Thellier (1981) and Bucur (1994). The magnetization of these samples was measured with a rotating inductometer specially designed for big samples (Le Goff, 1975). Following Thellier and Thellier (1959) and Thellier (1981), the directional results were selected on the basis of magnetic viscosity experiments. Only those samples having a magnetic viscosity index, as defined by the ratio of viscous remanent magnetization (VRM) to thermoremanent magnetization (TRM), lower than 5% were considered for the computation of a mean archeomagnetic direction. Many studies carried out in the Paleomagnetic laboratory in Saint Maur indeed showed that this simple, but stringent, selection criterion was efficient to isolate, after vectorial subtraction of the VRM, a reliable direction of the original TRM acquired during the last use of the sampled archeological structures (Thellier, 1981). We obtained the mean direction: $D = 19.2^\circ$, $I = 65.1^\circ$, $k = 1659$, $\alpha_{95} = 1.3^\circ$ and $N = 9$. This direction was first reduced to Paris ($D = 19.1^\circ$, $I = 64.9^\circ$) before comparing it to the reference French archeomagnetic SV curve. The modified version of the M&M test allows us to define an archeomagnetic age interval between ∼915 and ∼1065 A.D. (Fig. 5). The probability curve further indicates that the more probable age lies in the middle of this interval, around 1010 ± 35 A.D. This archeomagnetic result is in good agreement with other archeological time constraints available for this kiln (second half of the 10th century; Guadagnin, 2000). These latter constraints essentially rely on the typology of ceramics found in the kiln itself and also inside two other kilns discovered in the same area (kilns #1 and #2; Guadagnin, 2000).

This example, therefore, illustrates the potential of archeomagnetism in western Europe for archeological dating. Of course, this potential (and the interest) of the archeomagnetic dating technique strongly depends on the nature of the geomagnetic directional variations. In western Europe, the Roman period which is characterized by variations of small amplitude, is not favorable to obtain precise archeomagnetic dating, in particular in comparison with other time constraints often available for this archeologically well-documented period.

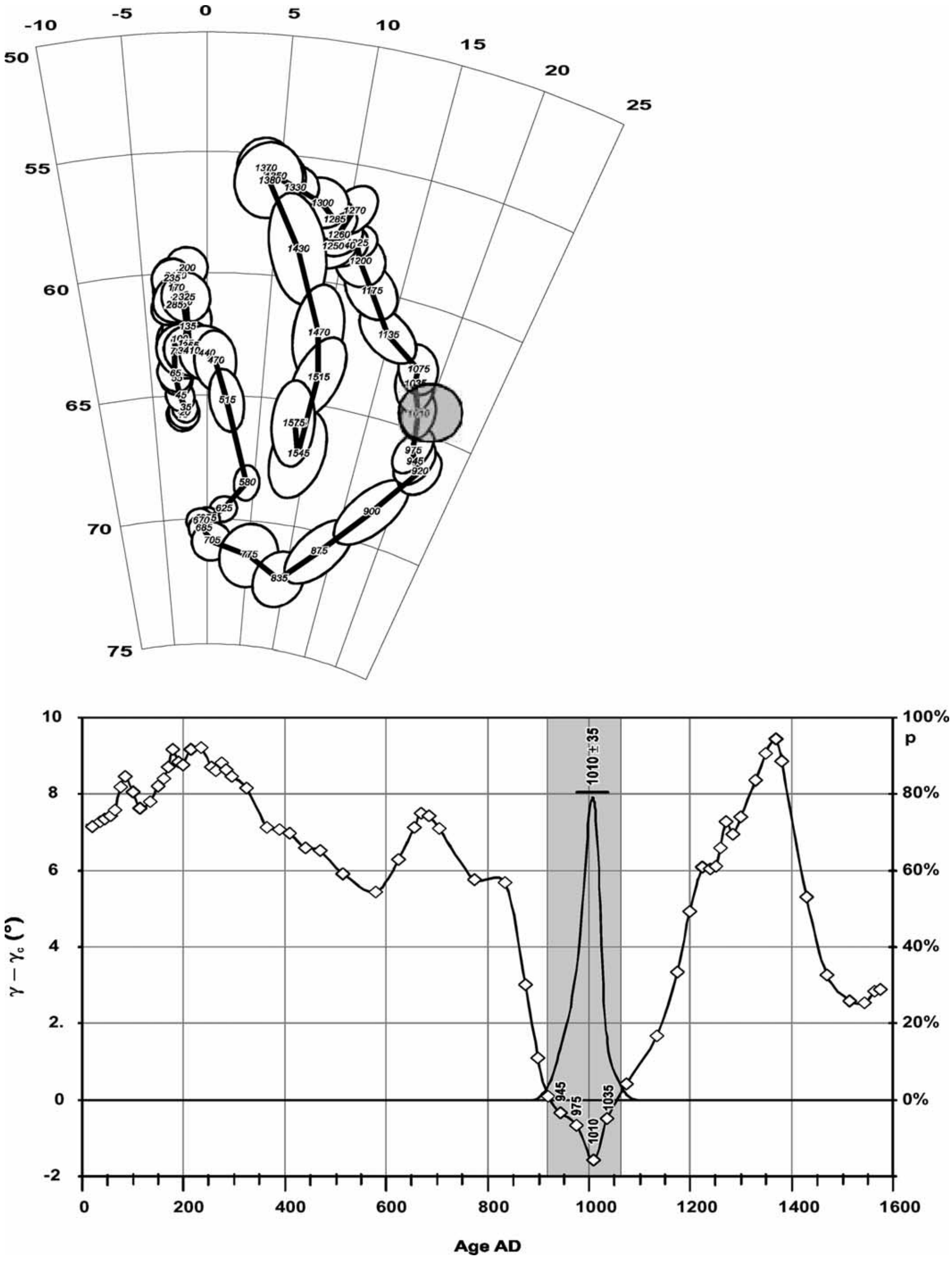

Fig. 5. Archeomagnetic dating of a pottery kiln found in Lassy, to the north of Paris (Guadagnin, 2000). The archeomagnetic age interval derived from our dating method is between ∼915 and ∼1065 A.D. with a more probable age during the middle of this interval, around 1010 ± 35 A.D.

In contrast, the High Middle Age (∼500 to ∼1000 A.D.) and all the Middle Age, showing much larger directional variations, are more favorable, with the possibility to obtain relatively short archeomagnetic age intervals. In parallel to this application of archeomagnetic measurements, we highlight the need for additional well-dated archeomagnetic directions to define better the reference archeomagnetic SV curve.

Note that the program used in this study is available upon request.

Acknowledgements

We thank R. Enkin and S. Gilder for helpful comments on the manuscript, and M. Fuller and R. Butler who reviewed the paper. This is IPGP contribution no. 1843 and CNRS-INSU contribution no. 320.

References

Alexandrescu, M., Courtillot, V., Le Mouël, J.-L., 1997. High-resolution secular variation of the geomagnetic field in Western Europe over the last four centuries: comparison and integration of historical data from Paris and London. J. Geophys. Res. 102, 20245–20258.
Batt, C.M., 1997. The British archaeomagnetic calibration curve: an objective treatment. Archaeometry 39, 153–168.
Bucur, I., 1994. The direction of the terrestrial magnetic field in France during the last 21 centuries. Phys. Earth Planet. Int. 87, 95–109.
Clark, A., Tarling, D., Noël, M., 1988. Developments in archaeomagnetic dating in Great Britain. J. Archaeol. Sci. 15, 645–667.
Courtillot, V., Le Mouël, J.-L., 1988. Time variations of the Earth's magnetic field: from daily to secular. Ann. Rev. Earth Planet. Sci. 16, 389–476.
Daly, L., Le Goff, M., 1996. An updated and homogeneous world secular variation data base. 1. Smoothing of the archaeomagnetic results. Phys. Earth Planet. Int. 93, 159–190.
Fisher, R., 1953. Dispersion on a sphere. Proc. R. Soc. Lond. A217, 295–305.
Gallet, Y., Genevey, A., Le Goff, M., 2002. Three millennia of directional variation of the Earth's magnetic field in Western Europe as revealed by archeological artefacts. Phys. Earth Planet. Int. 131, 81–89.
Guadagnin, R., 2000. Fosses–Vallée de l'Ysieux, Mille ans de production céramique en Ile de France, vol. 1, Les données archéologiques et historiques, CRAM pub., 367 pp.
Irving, E., 1964. Paleomagnetism and its Application to Geological and Geophysical Problems. Wiley, New York.
Lanos, P., Kovacheva, M., Chauvin, A., 1999. Archaeomagnetism, methodology and applications: implementation and practice of the archaeomagnetic method in France and Bulgaria. Eur. J. Arch. 2 (3), 365–392.
Lanos, P., 2001. L'approche bayésienne en chronométrie: application à l'archéomagnétisme. XXIe rencontres internationales d'archéologie et d'histoire d'Antibes, APDCA eds.
Le Goff, M., 1975. Inductomètre à rotation continue pour la mesure des faibles aimantations rémanentes et induites en magnétisme des roches. Mém., Diplôme d'Ingénieur CNAM, Paris.
Le Goff, M., 1990. Lissage et limites d'incertitude des courbes de migration polaire: pondération des données et extension bivariante de la statistique de Fisher. C. R. Acad. Sci. Sér. II 311, 1191–1198.
Le Goff, M., Henry, B., Daly, L., 1992. Practical method for drawing a VGP path. Phys. Earth Planet. Int. 70, 201–204.
Jackson, A., Jonkers, A., Walker, M., 2000. Four centuries of geomagnetic secular variation from historical records. Philos. Trans. R. Soc. Lond. A358, 957–990.
Kovacheva, M., 1992. Updated archaeomagnetic results from Bulgaria: the last 2000 years. Phys. Earth Planet. Int. 70, 219–223.
McFadden, P., McElhinny, M., 1990. Classification of the reversal test in palaeomagnetism. Geophys. J. Int. 103, 725–729.
Menessier-Jouannet, C., Bucur, I., Evin, J., Lanos, P., Miallier, D., 1995. Convergence de la typologie de céramiques et de trois méthodes chronométriques pour la datation d'un four de potier à Lezoux (Puy-de-Dôme). Rev. Arch. 19, 37–47.
Merrill, R., McElhinny, M., McFadden, P., 1996. The Magnetic Field of the Earth, Paleomagnetism, the Core and the Deep Mantle. Academic Press, New York, 431 pp.
Noel, M., Batt, C., 1990. A method for correcting geographically separated remanence directions for the purpose of archaeomagnetic dating. Geophys. J. Int. 102, 753–756.
Shuey, R., Cole, E., Mikulich, M., 1970. Geographic correction of archaeomagnetic data. J. Geomagn. Geoelectr. 41, 485–489.
Silverman, B.W., 1986. Density Estimation for Statistics and Data Analysis. Chapman and Hall, London.
Sternberg, R., McGuire, R., 1990. Techniques for constructing secular variation curves and for interpreting archaeomagnetic dates. In: Eighmy, J., Sternberg, R. (Eds.), Archeomagnetic Dating. University Arizona, Tucson, pp. 109–134.
Thellier, E., Thellier, O., 1959. Sur l'intensité du champ magnétique terrestre, dans le passé historique et géologique. Ann. Geophys. 15, 285–376.
Thellier, E., 1981. Sur la direction du champ magnétique terrestre en France durant les deux derniers millénaires. Phys. Earth Planet. Int. 24, 89–132.