Available online at www.sciencedirect.com

SCIENCE DIRECT

EPSL

Earth and Planetary Science Letters 214 (2003) 237–242

www.elsevier.com/locate/epsl

On the possible occurrence of 'archaeomagnetic jerks' in the geomagnetic field over the past three millennia

Yves Gallet [a,*], Agnès Genevey [a,b], Vincent Courtillot [a]

[a] Laboratoire de Paléomagnétisme, UMR 7577, Institut de Physique du Globe de Paris, 4 Place Jussieu, 75252 Paris Cedex 05, France
[b] Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0220, USA

Received 1 April 2003; received in revised form 18 June 2003; accepted 25 June 2003

Abstract

Archaeomagnetism can provide a high-resolution full-vector description of the Earth's magnetic field for the past several thousand years. We analyse the bulk of archaeomagnetic data (both direction and intensity) obtained recently in Western Europe and the Eastern Mediterranean covering the past three millennia. We demonstrate a remarkable coincidence between sharp cusps in geomagnetic field direction and intensity maxima (two clear ones at ~AD 200 and 1400; two presently less well constrained at ~800 BC and AD 800). These sharp changes may constitute a new feature of geomagnetic secular variation ('archaeomagnetic jerks') with time characteristics intermediate between 'geomagnetic jerks' and 'magnetic excursions'.

Keywords: archaeomagnetism; secular variation; jerks; Western Europe; Middle East

1. Introduction

A major interest of archaeomagnetism is to provide a high-resolution full-vector description of the Earth's magnetic field over the past several thousand years, including the temporal behaviour of its dipole and non-dipole components [1–3]. This clearly cannot be expected from palaeomagnetic studies of series of lava flows, because of the episodic nature of lava emplacement and radiometric age uncertainties. Continuous high-resolution sedimentary records may appear much more promising (e.g. [4,5]), but we still understand insufficiently the link between sedimentation processes and magnetic acquisition. Archaeomagnetism, i.e. the study of remanent magnetisation of historically dated artefacts, remains our prime source of information over these millennial and centennial time scales. Unfortunately, no complete archaeomagnetic description of geomagnetic secular variation (SV) satisfying currently required standards has yet been obtained for any single region at the millennium scale. This is even the case in regions boasting a long and rich cultural past, such as the Middle East, China, Central and western South America or Western Europe. In some cases, only directional data exist in sufficient amount (and quality) to provide a relatively continuous record over the past few mil-

* Corresponding author. Tel.: +33-1-44-27-24-32; Fax: +33-1-44-27-74-63.
E-mail address: gallet@ipgp.jussieu.fr (Y. Gallet).

0012-821X/03/$ – see front matter
doi:10.1016/S0012-821X(03)00362-5

lennia [6]; in others, only (or mostly) archaeointensity results are available (e.g. China, Middle East, South America [7–9]). Moreover, most archaeointensity data sets from different regions display a large dispersion, which often prevents a consistent description of intensity variations [10]. This scatter likely reflects differences in experimental procedure and the insufficient reliability of many archaeointensity data, particularly those obtained more than 20 years ago [10–12].

In this study, we analyse the bulk of archaeomagnetic data (both direction and intensity) covering the last three millennia obtained recently in Western Europe and the Eastern Mediterranean [10,11,13,14], which show evidence for a remarkable coincidence between sharp cusps in geomagnetic field direction and intensity maxima: two clear ones at ∼AD 200 and AD 1400 and two presently less well constrained at ∼800 BC and AD 800. These rather sharp changes may constitute a new feature of geomagnetic SV (‘archaeomagnetic jerks’) with time characteristics intermediate between ‘geomagnetic jerks’ and ‘magnetic excursions’.

2. New archaeomagnetic data from France and Syria

New directional data have been acquired from fired hearths and pottery kilns in France, archaeologically dated to the first millennium BC [13]. Combining these data with previous archaeomagnetic results from Western Europe, we have constructed a composite smoothed directional SV curve, encompassing the entire first millennium BC. Together with the curve of Bucur [15], which spans the last two millennia and is in very good agreement with the curve derived from South Italian volcanics [16], we now have a 3000-yr-long continuous directional curve valid at least for Western and Central Europe (Fig. 1a). This curve displays large directional changes extending over ∼18° in inclination and up to ∼50° in declination.

We have also computed changes in curvature of directional drift during the past three millennia, after slightly smoothing the composite curve in

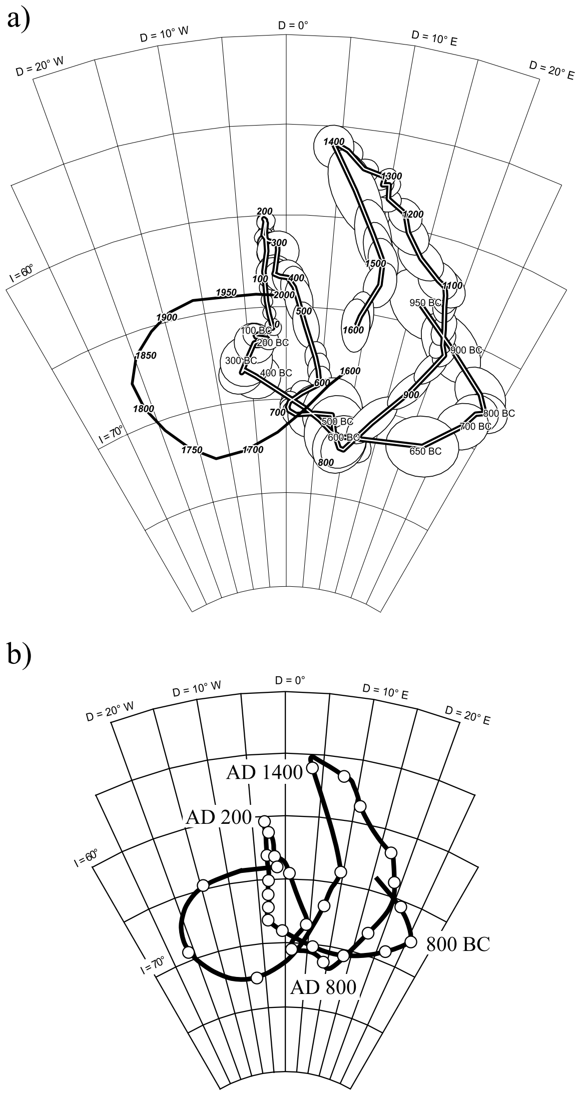

Fig. 1. Directional variations of the geomagnetic field in Western Europe during the last three millennia inferred from archaeomagnetic data [13,15]. (a) The mean directions are computed using bivariate statistics over time intervals of 160 yr shifted every 50 yr during the first millennium BC [13] and over time intervals of 80 yr shifted every 25 yr for the last two millennia [15]. All data were reduced to Paris. (b) Same, smoothed in order to average out some scattered directions. A different smoothing was applied to data prior to and following AD 0, which do not have the same time resolution and reliability. For the most recent and best-constrained part, a running mean was estimated every 25 yr, averaging three successive directions; a Stineman function was adjusted to the older part (‘Kaleidagraph’ software).

Fig. 1a in order to eliminate spurious effects due to locally scattered directions (Fig. 1b). Two major directional cusps (or hairpins) occur at ~AD 200 and AD 1400 (Fig. 2a). A third, less important change is observed at ~AD 800. Despite lesser resolution, a fourth sharp change in direction is seen around 800 BC.

We also obtained new intensity results from archaeologically dated potsherds and brick fragments, which allow us to recover geomagnetic field intensity variations during most of the past two millennia in Western Europe [14] and during the past eight millennia in Mesopotamia [10]. These results were derived using the Thellier and Thellier [17] method modified by Coe [18]. The raw archaeointensity data were corrected for both the anisotropy of thermoremanent magnetisation (TRM) acquired while the archaeological materials were moulded into shape [19] and the cooling rate dependence of TRM acquisition [20]. Data reliability is strengthened by the use of stringent selection criteria, aimed at ensuring the reliability of intensity determinations both at the potsherd or brick-fragment level (two samples per fragment) and at the dated-site level (at least three independent fragments per site). Archaeointensity data satisfying the same quality criteria have also recently been obtained by Chauvin et al. [11] for the Roman period. The ages of most of the latter data were constrained using the archaeomagnetic (direction) dating technique but relying on a now superseded reference (inclination-only) variation curve [21,22]. We therefore used the well-accepted reference curve of Bucur [15] together with the archaeomagnetic dating procedure described in Le Goff et al. [23], which takes into account the full directional information of the archaeomagnetic directions. To reduce age uncertainties, we retained only those results (11 out of 22) for which age intervals assigned by archaeologists (i.e. defined from the archaeological contexts) were smaller than 200 yr and for which archaeological and archaeomagnetic age intervals overlapped, at least in part. All data from France are plotted in Fig. 2b. Comparisons between the data sets from France and Syria in the time interval where they overlap [24], but also from Greece, Bulgaria, Georgia, Egypt and Central Asia [7,10,

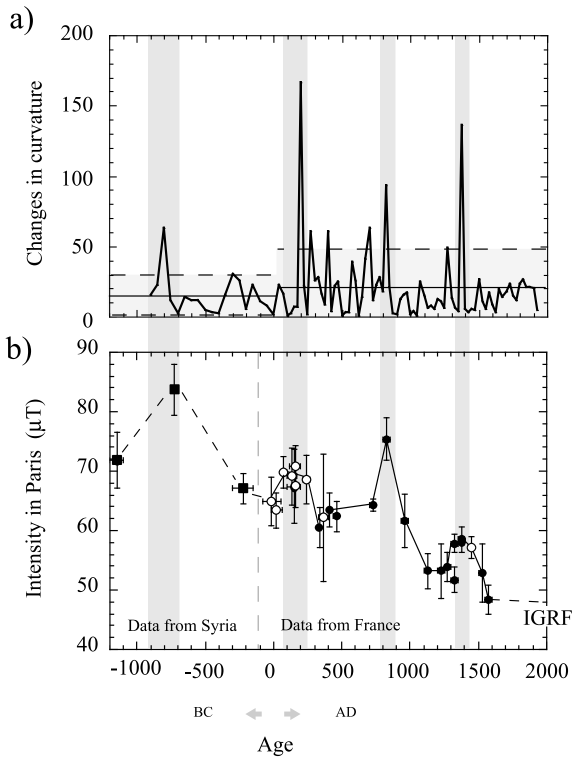

Fig. 2. (a) Changes in curvature of the smoothed directional drift curve of Fig. 1a. The means and variances of the curvature values are given separately for the 1000 BC–AD 0 and AD 0–AD 2000 parts of the curve, which have different time resolutions. The largest peak in the older part and three largest peaks in the younger part coincide with cusps in magnetic field directional drift and sharp intensity maxima of panel b (shaded bands). (b) Archaeointensity variation curve in Europe and the Middle East during the last 3000 yr. The intensity curve is constructed using the data obtained from Syria [10] (transferred to the latitude of Paris; squares), a selection of results obtained in France by Chauvin et al. [11] for the Roman period (open circles), and data obtained from French potsherds by Genevey and Gallet [14] (closed symbols). See text for discussion.

25–28], suggest that during the past few millennia geomagnetic field intensity fluctuations were largely consistent over a vast region extending at least from the Western Mediterranean to Central Asia (~50° in longitude). There is particularly clear evidence for a strong intensity maximum during the first millennium BC. For this reason, due to the lack of archaeointensity data from Western Europe in this time interval, we also plotted in Fig. 2b the results obtained from

Syria during the first millennium BC, after reducing them to the latitude of Paris (our reference site).

3. Discussion

Fig. 2b shows an overall decreasing trend with the occurrence of several intensity maxima. Two are defined by relatively numerous data at ~AD 200 and AD 1400, whereas two other maxima with larger amplitudes, at ~750 BC and AD 800, are less well constrained in France so far (Fig. 2b). We note that the two best-defined intensity maxima coincide in time with the two sharpest directional cusps seen in Fig. 2a, whereas coincidence of the other two maxima with the other two major directional changes is suggested, though it still requires further confirmation. Additional data should also clarify whether the directional cusps occur at the time when intensity starts to decrease, as appears to be indicated in Figs. 1 and 2.

However limited, the current database emphasises the irregular character of SV at the ~100-yr scale. A rough description of archaeomagnetic SV could be that of 500–1000-yr-long periods of smooth SV separated by ~100-yr-long 'archaeomagnetic jerks'. It is interesting to confront our observations with SV models based on a global database [1–3], which can be used to predict the directional changes expected at our reference site. This is shown in Fig. 3a for the SV model of Korte and Constable [3], which spans the past three millennia. We see that the model provides a quite reasonable first-order fit, though some important features differ in phase or amplitude. The data used in this modelling have a time resolution and a spatial coverage that makes higher-degree terms rather uncertain (this is emphasised by differences between three available models [1–3]). We expect that the lower-degree terms (i.e. the dipole) are the most robust. Fig. 3b shows the directional changes expected at our reference site when only these dipolar terms are included. The range of amplitudes of changes in declination and inclination are underpredicted by a factor ~2–3. However, the overall shape and features are again

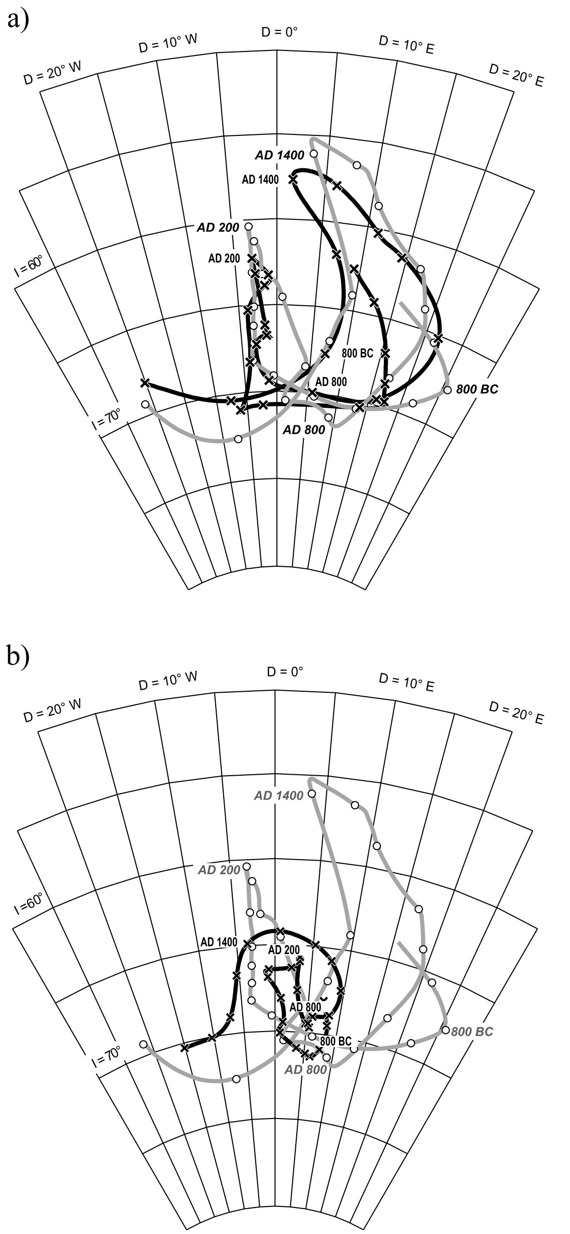

Fig. 3. (a) The directions (in black) expected at our reference site ($\lambda = 48.9°N$, $\varphi = 2.3°E$) based on the SV model of Korte and Constable [3]. The axial dipole intensity is assumed to have remained constant. The model includes terms up to degree and order 10 from 1000 BC to AD 1800. (b) Same as panel a, but only the dipole ($n = 1$) terms are included. Our European directional SV curve is also shown in grey for comparison for the same period (see text).

reasonably similar to the first order. It is particularly intriguing that the main features (cusps and loops) of the SV curve predicted by the models when all terms up to degree 10 are used are so similar to those found when only the dipole is retained.

This leaves us with several open questions. Is the relation between intensity maxima and directional cusps a general characteristic of short-term geomagnetic field variations? Are the 'archaeomagnetic jerks' only of regional significance? Concerning the latter question, a first look at Fig. 3a,b might seem to indicate a positive answer. However, the similarity in shape of European SV with that predicted from changes in the (global) equatorial dipole alone (Fig. 3b) may suggest an alternative interpretation. Time uncertainties, smoothing and poor data distribution adversely affect higher-degree terms (quadrupole and beyond) in global models and we cannot exclude the possibility that the archaeomagnetic jerks could actually be global features: the regional European curves of Figs. 1a and 2b would then have more of a global character than could have been expected at first.

The new geomagnetic events have time characteristics intermediate between geomagnetic jerks (~ 1 yr [29,30]) and excursions or reversals ($\sim 10^3$ yr [31]). At present, deciphering their origin is difficult but some interesting constraints could be obtained by determining more precisely geomagnetic field behaviour during the first millennium BC. In addition to the intriguing directional kink seen from the SV model around 300 BC (Fig. 3a), but which is not yet linked to an intensity maximum, several data sets obtained in the northern hemisphere from lake and marine sediments and from archaeological structures show strong and sudden departure from dipolar directions around the 8th century BC. This departure may reflect a very brief excursional event [32,33] that could have been smoothed out in the Western European curve [13]. In any case, the suggestion that there exist archaeomagnetic jerks begs for confirmation, and we emphasise the need for an 'observatory approach' to gather a detailed and complete high-quality archaeomagnetic description of SV at a few distant sites.

Acknowledgements

This is IPGP contribution No. 1920 and INSU-CNRS No. 346. We thank Gauthier Hulot, Maxime Le Goff and Jean-Louis le Mouël for useful comments and discussions. We are also grateful to M. McElhinny, S. Banerjee and R. Merrill for constructive reviews of the manuscript.*[BARD]*

References

[1] L. Hongre, G. Hulot, A. Khokhlov, An analysis of the geomagnetic field over the past 2000 years, Phys. Earth Planet. Inter. 106 (1998) 311–335.
[2] C. Constable, C. Johnson, S. Lund, Global geomagnetic field models for the past 3000 yeras: transient or permanent flux lobes?, Philos. Trans. R. Soc. London 358 (2000) 99–1008.
[3] M. Korte, C. Constable, Continuous global geomagnetic field models for the past 3000 years, Phys. Earth Planet. Inter. (2003) in press.
[4] I. Snowball, P. Sandgren, Geomagnetic field variations in northern Sweden during the Holocene quantified from varved lake sediments and their implications for cosmogenic nuclide production rates, Holocene 12 (2002) 517–530.
[5] G. St-Onge, J. Stoner, C. Hillaire-Marcel, Holocene paleomagnetic records from the St. Lawrence Estuary, eastern Canada: centennial- to millennial-scale geomagnetic modulation of cosmogenic isotopes, Earth Planet. Sci. Lett. 209 (2003) 113–130.
[6] L. Daly, M. Le Goff, An updated and homogeneous world secular variation data base. 1. Smoothing of the archaeomagnetic results, Phys. Earth Planet. Inter. 93 (1996) 159–190.
[7] M. Aitken, A. Allsop, G. Bussell, M. Winter, Geomagnetic intensity variation during the last 4000 years, Phys. Earth Planet. Inter. 56 (1989) 49–58.
[8] S. Yang, J. Shaw, Q. Wei, Tracking a non dipole geomagnetic anomaly using new archaeointensity results from north-east China, Geophys. J. Int. 115 (1993) 1189–1196.
[9] S. Yang, J. Shaw, T. Rolph, Archaeointensity studies of Peruvian pottery - from 1200 B.C. to 1800 A.D, J. Geomagn. Geoelectr. 45 (1993) 1193–1207.
[10] A. Genevey, Y. Gallet, J. Margueron, Eight thousand years of geomagnetic field intensity variations in the Eastern Mediterranean, J. Geophys. Res. 108 (2003) 2228, doi: 10.1029/2001JB001612.
[11] A. Chauvin, Y. Garcia, P. Lanos, F. Laubenheimer, Palaeointensity of the geomagnetic field recovered on archaeomagnetic sites from France, Phys. Earth Planet. Inter. 120 (2000) 111–136.

[12] J. Bowles, J. Gee, J. Hildebrand, L. Tauxe, Archaeomagnetic intensity results from California and Ecuador: evaluation of regional data, Earth Planet. Sci. Lett. 203 (2002) 967–982.
[13] Y. Gallet, A. Genevey, M. Le Goff, Three millennia of directional variation of the Earth's magnetic field in western Europe as revealed by archaeological artefacts, Phys. Earth Planet. Inter. 131 (2002) 81–89.
[14] A. Genevey, Y. Gallet, Intensity of the geomagnetic field in Western Europe over the past 2000 years: New data from French ancient pottery, J. Geophys. Res. 107 (2002) 2285, doi: 10.1029/2001JB000701.
[15] I. Bucur, The direction of the terrestrial magnetic field in France, during the last 21 centuries, Phys. Earth Planet. Inter. 87 (1994) 95–109.
[16] J.-C. Tanguy, M. Le Goff, C. Principe, S. Arrighi, V. Chillemi, A. Paiotti, S. La Delfa, G. Patanè, Archaeomagnetic dating of Mediterranean volcanics of the last 2,100 years: validity and limits, Earth Planet. Sci. Lett. 211 (2003) 111–124.
[17] E. Thellier, O. Thellier, Sur l'intensité du champ magnétique terrestre dans le passé historique et géologique, Ann. Géophys. 15 (1959) 285–376.
[18] R. Coe, The determination of palaeointensities of the Earth's magnetic field with emphasis on mechanisms which could cause non-ideal behavior in Thellier's method, J. Geomagn. Geoelectr. 19 (1967) 157–179.
[19] J. Rogers, J. Fox, M. Aitken, Magnetic anisotropy in ancient pottery, Nature 277 (1979) 644–646.
[20] J. Fox, M. Aitken, Cooling-rate dependence of thermoremanent magnetisation, Nature 283 (1980) 462–463.
[21] P. Lanos, La datation archéomagnétique des matériaux de construction d'argile cuite, Apports chronologiques et technologiques, Gallia 47 (1990) 321–341.
[22] F. Laubenheimer, P. Lanos, Chronologie des fours de potiers de Sallèles d'Aude, Archéomagnétisme et Archéologie, 1st European Workshop on archaeological ceramics, Università degli studi di Roma 'La Sapienza', Dipartemento di Scienza della Terra, 1994, pp. 251–267.
[23] M. Le Goff, Y. Gallet, A. Genevey, N. Warmé, On archaeomagnetic secular variation curves and archaeomagnetic dating, Phys. Earth Planet. Inter. 134 (2002) 203–211.
[24] A. Genevey, Apport de l'archéomagnétisme à la connaissance du champ magnétique terrestre durant les derniers millénaires, Doctoral Thesis, Institut de Physique du Globe de Paris, 2002, 217 pp.
[25] M. Aitken, A. Allsop, G. Bussell, M. Winter, Geomagnetic intensity in Egypt and Western Asia during the second millennium BC, Nature 310 (1984) 305–306.
[26] I. Nachasova, K. Burakov, Change in intensity of the geomagnetic field in the second millenium BC in the territory of Georgia, Geomagn. Aeron. Engl. Transl. 27 (1987) 766–768.
[27] I. Nachasova, K. Burakov, The geomagnetic field intensity in Central Asia from 6000 to 3000 B.C., Izvestica, Engl. Transl. Phys. Solid Earth 36 (2000) 358–363.
[28] M. Kovacheva, Archaeomagnetic database from Bulgaria, Phys. Earth Planet. Inter. 102 (1997) 145–151.
[29] V. Courtillot, J. Ducruix, J.-L. Le Mouël, Sur une accélération récente de la variation séculaire du champ magnétique terrestre, C. R. Acad. Paris 287 (1978) 1095–1098.
[30] V. Courtillot, J.-L. Le Mouël, Time variations of the Earth's magnetic field: From daily to secular, Annu. Rev. Earth Planet. Sci. 16 (1988) 389–476.
[31] J.-P. Valet, L. Meynadier, Geomagnetic field intensity and reversals during the past four million years, Nature 336 (1993) 234–238.
[32] K. Burakov, I. Nachasova, Anomalous behaviour of the geomagnetic field in the first millennium BC, in: Geomagnetic Field in Quaternary, Postdam, 1990, pp. 135–138.
[33] O. Raspopov, V. Dergachev, E. Goos'kova, Ezekiel's vision: Visual evidence of Sterno-Etrussia geomagnetic excursion?, EOS Trans. AGU 84 (2003) 77.