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Secular variation of the geomagnetic dipole during the past 2000 years

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[1] We have constructed a very simple model of a time-varying geocentric dipole based on the archeomagnetic records obtained at four widely separated sites on the globe for the past 2 ka. The predictions of the model in terms of directional variations have been tested against actual archeomagnetic data from 12 sites distributed over the globe. They were also compared with the Hongre et al. (1998) time-varying spherical harmonic model and with the CALS7K-2 model by Korte et al. (2005). We find that the misfits between the predictions of our simple dipole model and the data are equivalent to those of the spherical harmonic models for the European sites and not strikingly larger for the rest of the world. Many discrepancies can be accounted for by uncertainties inherent to the archeomagnetic records, which, along with the small number and poor geographical distribution of sites, leads us to conclude that the present state of the database does not allow the extraction of secular variations described by terms going beyond degree 2. It appears also that dipole tilt could be responsible for the main part of the secular variation associated with time constants exceeding 10^2 years. In a second step, we used the paleointensity records contained in the same database to construct the curve depicting the variations of the true dipole moment. The present decrease of the dipole did not begin prior to 1000 years ago, and the dipole was actually increasing from 0 until A.D. 500. The dipole moment of CALS7K is lower than the present estimate, probably due to large repartition of energy to higher harmonics to minimize the misfit between the inversion and the data. The tilt and strength of the dipole can predict the dipole field at any site and were used to derive the contribution of the nondipole field to values of paleointensity at Paris during the past 2 ka. The results show that the "archeomagnetic jerks" are associated with various configurations depending on the phase relationship between the nondipolar and dipolar parts of the field.

Components: 7862 words, 12 figures, 1 table.

Keywords: secular variation; archeomagnetism; paleomagnetism; dipole field; nondipole field.

Index Terms: 1522 Geomagnetism and Paleomagnetism: Paleomagnetic secular variation; 1521 Geomagnetism and Paleomagnetism: Paleointensity; 1532 Geomagnetism and Paleomagnetism: Reference fields: regional, global.

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1. Introduction

[2] Recent satellite measurements have considerably improved our ability to model and identify the components of the Earth's magnetic field. However, despite high-quality satellite vector data which produce remarkable snapshot images of the field, the time interval explored so far remains too short to bear significantly on our ability to describe and understand field changes for longer than decadal time constants [*Hulot et al.*, 2002; *Olsen et al.*, 2006]. Historical data sets are our only source of information about main field evolution for the past four centuries. This evolution has been monitored with the help of magnetic observatories, complemented for earlier periods by measurements by mariners and by magnetic surveys [*Jackson et al.*, 2000]. These data sets provide invaluable information about the past behavior of the geomagnetic field. However, even in this case, field description is limited by the sparse geographic distribution of magnetic observatories and sometimes by the quality of the records [*Alexandrescu et al.*, 1997]. The absence of historical observation of field intensity prior to 1840 prevents from direct estimates of field strength. *Hulot et al.* [1997] demonstrated that directional data can still be used to recover robust information about the field geometry. In their analysis of the historical period, *Hulot and LeMouël* [1994] found that the typical time constants of individual spherical harmonic components are on the order of 500 years for the equatorial dipole (g_1^1, h_1^1) and less for other higher-degree terms, whereas axial dipole (g_1^0) changes are slower. Thus particularly relevant in this context is the time frame of the past few millennia. Studies of this interval provide the link between long-term (>10^3 years) field changes that are believed to be essentially governed by the dipolar field and centennial variations that are usually associated with the evolution of nondipole components. In this time interval, information about field variations is given only by archeomagnetic artifacts or paleomagnetic materials. Using a first detailed compilation of archeomagnetic data by *Daly and LeGoff* [1996] complemented by sediment data from Argentina and New Zealand and by lava flows from Hawaii and Sicily, *Hongre et al.* [1998] investigated the first time-varying low-degree spherical harmonic model of the field between 0 and 1700 A.D. up to degree 3 order 3 Gauss coefficients, the maximum degree that was estimated to be resolvable 10 years ago with the available database using synthetic tests. *Johnson and Constable* [1995], derived a time-averaged model from a combination of lacustrine and archeomagnetic data for the past 3000 years. Similar exercises were extended over time periods as long as 5 Ma [*McElhinny et al.*, 1996; *Kelly and Gubbins*, 1997; *Kono*, 1997; *Carlut and Courtillot*, 1998]. There is now a large number of archeomagnetic records. On the basis of a selection of 24 time series (12 regional composite archeomagnetic curves and 12 lake sediment records) and axial dipole constraints, *Korte and Constable* [2003] produced a first continuous spherical harmonic model (CALS3K-1) for the past 3 millennia (from 1000 B.C. to 1800 A.D.). A more detailed database which also includes a compilation of all intensity data [*Korte et al.*, 2005] was subsequently assembled and extended to the past 7 millennia by A. Genevey. *Korte and Constable* [2005a] used this database to calculate an inverse model extended to degree ten, thus to degrees that are not expected to be resolved with the available data. They used a regularization technique to determine the model with minimum structure which fits the data to within a certain accuracy. The aim was to find as much structure as required to fit the data but also to avoid giving too much weight to less reliable records (see *Korte and Constable* [2005a] for a thorough description of their modeling method). Korte and Constable tested their model predictions against the field variations recorded at several sites and concluded that it provides good fits.

[3] Several limitations inherent to this approach have been thoroughly discussed by *Korte and Constable* [2005a]. The first one is that sediments and archeomagnetic and volcanic materials acquire their magnetization over strikingly different characteristic durations. The deposition rates of the lake sediments involved in the database vary roughly between 10 and 100 cm/ka, and resolution of these records cannot be expected to be better than 100–200 years in the most optimistic cases. Uncertainties in dating and also truncation of certain records over a limited time interval are other limitations which generate mismatches between records of the same features at different locations [*Guyodo and Valet*, 1999; *Valet*, 2003]. This is particularly true for records from lake sediments which are subject to large variations in deposition rate.

[4] Archeomagnetic records are more appropriate to resolve fast field changes. However, the most critical factor is linked to the number of sites and above all to their geographical distribution which is far from being global [*Korte et al.*, 2005]. Almost

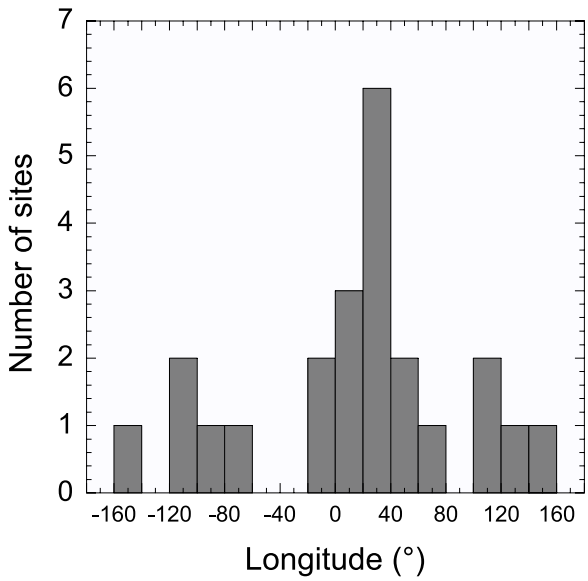

Figure 1. Distribution in longitude of all archeomagnetic and volcanic sites contained in the database.

no area is documented with a spatial resolution better than a few thousand kilometers and the archeomagnetic data set is heavily biased by European sites as shown by the histogram of site longitudes in Figure 1 with only 1 or even 0 records in twelve of its 18 bins. This imposes severe limitations on global models aimed at describing field evolution and more specifically their harmonic content. For these reasons, in parallel to studies attempting a detailed description of the field, it is important to investigate the role of the very first harmonics (i.e., primarily the dipolar terms) in the secular variation of the field.

2. Data and Model

[5] The database used in the recent CALSK models [*Korte and Constable*, 2003, 2005a, 2005b] can be classified in two groups, data from sediments and those from archeomagnetic material and some lava flows. Taking advantage of this exhaustive compilation, we can attempt a comparison between the two kinds of records and evaluate their reproducibility at several locations, provided that the sites involved in the comparison are close enough to each other, say separated by less than 1000 km. We have identified eight cases which met this requirement and have plotted their inclination records in Figure 2. Data from top of the sedimentary cores being frequently affected by coring must be taken with caution. The most significant comparison based on proximity of sites is allowed by the Big Island of Hawaii which incorporates studies of ^{14}C dated lava flows from the Mauna Loa, Kilauea and Hualalei volcanoes [*Mankinen and Champion*, 1993; *Hagstrum and Champion*, 1994, 1995, 2002] and a detailed sedimentary record from Lake Waiau [*Peng and King*, 1992] at the summit of Mauna Loa. The Japanese sites which include the Lake Biwa record [*Ali et al.*, 1999] also enter this category, but they have lower resolution. Overall, there is considerably more dispersion in the archeomagnetic data than in the sedimentary records, which is somehow expected due to their time resolution and to smearing of field changes by the sedimentary recording processes. However, we note that smoothing of the archeomagnetic (or volcanic) data almost never reconciles the two kinds of records, with the exception of Hawaii (and even in that case, sediments from Lake Waiau appear to have a slightly lower mean inclination than the volcanics). Apart from problems linked to resolution, there are other discrepancies between the two data sets. The mean inclinations of the two French lacustrine records disagree with each other by about ten degrees and do not really match the archeomagnetic curve despite similar pattern. The pairs of records from England, or from Australia, do not overlap at all, as is also the case for half of the northwestern American data. Several causes can generate the observed discrepancies in the sediments. Mechanical perturbations of the sediment or remagnetization can be induced by coring, particularly for this young period which is recorded in the upper part of the cores. Flattening of inclinations is also frequently observed in sediments (which is probably the case for Lake Waiau and Lac d'Annecy). Last, distortion is inevitably introduced by constructing the time-depth correlation which depends on variations in deposition rate that can be quite large in lake deposits, e.g., at Lac du Bourget [*Hogg*, 1978], Lake Waiau [*Peng and King*, 1992], Fish Lake [*Verosub et al.*, 1986]. Alternately, dating uncertainties in archeological ages are sometimes difficult to evaluate so that the amount of stretching or compression that can be applied to sedimentary records to improve the match with archeomagnetic data is not straightforward. For these reasons, we prefer to rely on a single data set. We consider that the acquisition process of thermoremanent magnetization in volcanic and archeomagnetic materials is more appropriate to record the detailed features of the field with good accuracy over a period as short as 2 ka, and thus restrain our analysis to these records. We will deal first with inclinations which

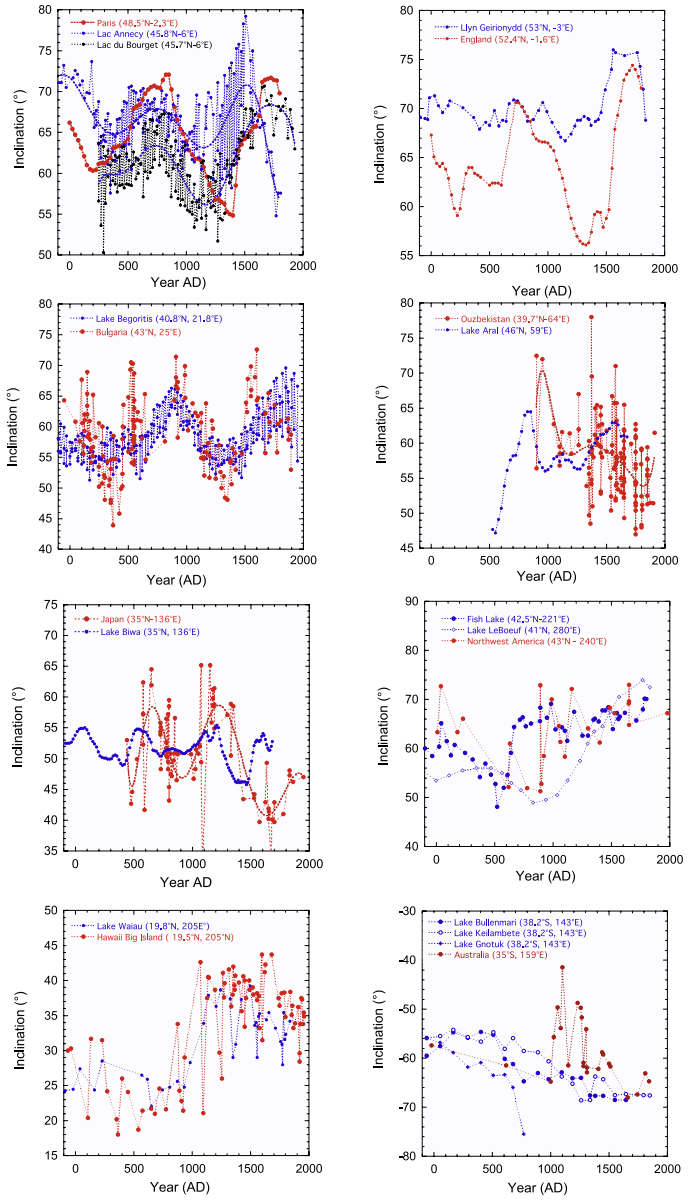

Figure 2. Comparison of lake sediments with archeomagnetic (and some volcanic) high-resolution records obtained from very close by sites. The Paris record is extracted from the *Daly and LeGoff* [1996] database.

retain a large part of the signal of secular variation and then with the full directional changes.

[6] Successive studies conducted on volcanic sequences from the Big Island of Hawaii provide an exceptional data set, with a ^{14}C age for each lava flow. In Figure 3a we compare the inclination variations recorded during the past 2 ka at Hawaii and in northwest America [*Hagstrum and Champion*, 2002]. The two data sets display very similar, if not identical variations when the error bars are taken in consideration. It is also striking that the inclinations changes recorded at Hawaii are almost anticorrelated to those reported for the same period at Paris [*Daly and LeGoff*, 1996] (Figure 3b). The two sites being almost longitudinally antipodal, this suggests that these changes could be dominantly driven by the tilt of the dipole. Last, we show in Figure 3c that the inclination changes recorded from sites as different as northwest America, Ukraine and France are also quite consistent with each other after being transferred and plotted at the latitude of Paris. This observation strengthens the hypothesis that variations with this amplitude and wavelength are likely largely governed by the dipole. Thus the first model which should be tested appears to be a simple time-varying geocentric dipole.

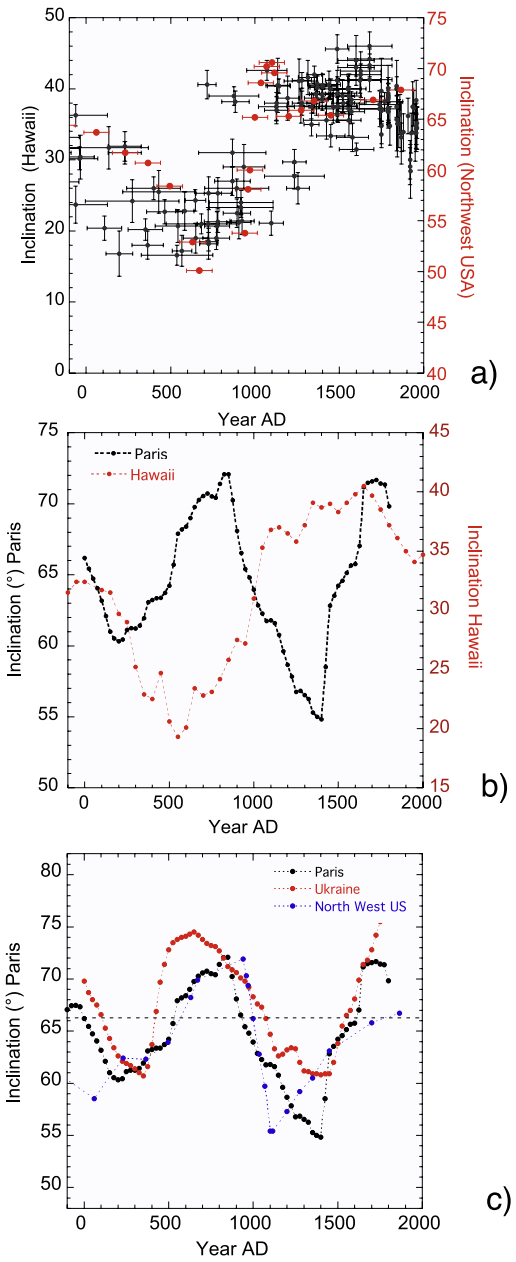

Figure 3. Comparison between the inclination records obtained from widely separated sites. (a) Between Hawaii and northwestern America, (b) between Hawaii and Paris (France), which are almost antipodal in longitude, and (c) between Paris, Ukraine, and the NW U.S. sites at Paris latitude (thus under the assumption that the mean inclinations would be controlled by an axial dipole).

[7] At this stage we do not consider any paleointensity record and thus deal with unit vectors. We can thus follow a standard "paleomagnetic" approach and calculate the successive mean Virtual Geomagnetic Pole (VGP) positions for a selection of sites at the surface of the Earth. The criteria for selecting the most reliable records can always be matter of discussion. We rely on sites that provide records for all periods with continuous temporal resolution, reasonably low dispersion between successive data points and few errors on dating. We also need to consider sites sufficiently far away from each other for better coverage. We find that records from Hawaii, western USA, France and probably Ukraine satisfy these requirements and can thus be used with relatively good confidence, although their levels of quality are different. Despite large uncertainties we have added the data from Japan which is an important location because it fills a critical geographical gap. About half of the archeomagnetic sites provide field records prior to 2000 years B.P., but with a much lower density of data points than these after 2 ka, hence insufficient resolution. This period remains in our view poorly constrained, and therefore analysis has been limited to the past 2000 years.

3. Model Predictions at Archeomagnetic Sites

[8] We computed the mean dipoles first from three sites only (Paris, Japan, Hawaii) using the Paleo-Mac software [*Cogné*, 2003], then from four sites (Paris, Ukraine, Japan, northwestern USA) and finally five sites (Paris, Ukraine, Japan, northwestern USA, Hawaii). In order to preserve the good temporal resolution inherent in these records, the data were linearly interpolated at constant intervals of 25 years and the dipole estimates were calculated accordingly. As outlined by *Korte et al.* [2005], coverage of the southern hemisphere is very sparse (with data from Australia) and no detailed record can be used with good confidence for this exercise. This is evidently a strong limitation to the present study, but it is also the case for all models produced so far. A dipole can be defined in principle from two locations only, so that additional sites, which are in principle redundant, actually allow us to test the robustness of the estimate. In Figure 4 we show the evolution of the VGP latitudes as a function of time for the three estimates and also display the predictions of the GUFM model for the historical period [*Jackson et al.*, 2000]. There is no statistically significant difference between any of the three curves and the agreement with GUFM is quite satisfactory. Because the dipole obtained from four sites provides a reasonable longitudinal coverage (but evidently without sites in the southern hemisphere), we prefer to use this calculation

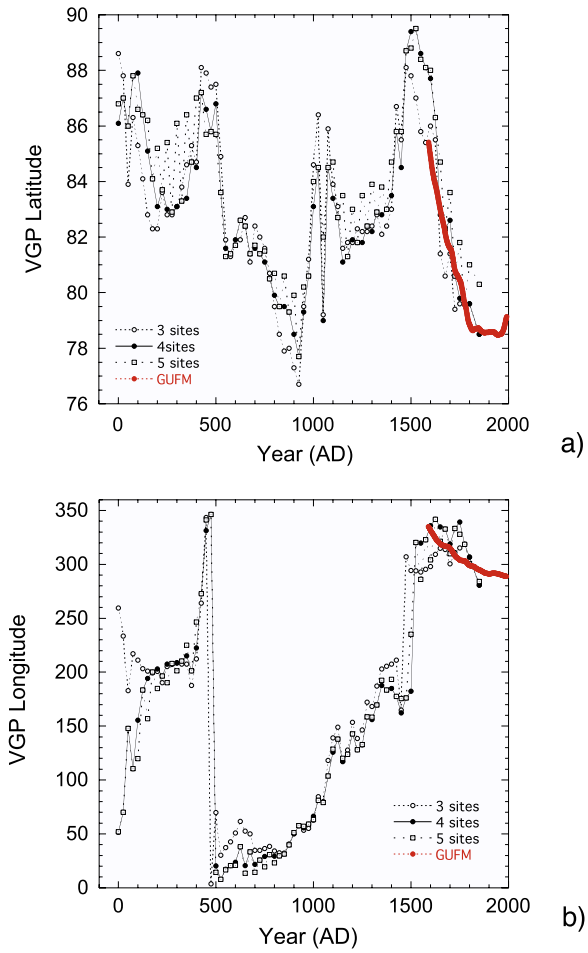

Figure 4. Evolution of the north VGP position in latitude and longitude as a function of time for three possible dipoles calculated using the directions recorded at 3, 4, and 5 sites, respectively. Their evolution is compared with the VGP positions calculated from the GUFM dipole [*Jackson et al.*, 2000] derived from historical measurements.

as our reference "dipole fit," but any curve can be used as well.

[9] The next step is to calculate the directions predicted by our simple dipole model at each archeomagnetic site and to test them against the data. Given the sparsity of data points in many records (sometimes even the absence of declination) and frequent poor resolution of dating, we restrict the comparison to 12 sites (listed in Table 1) that we consider as the best documented ones and are sufficiently spaced from each other to preserve as much geographical coverage as possible. In Figure 5, we compare the evolution of inclination predicted at these 12 sites with the corresponding records. Also shown for comparison are the predictions at the same sites of the *Hongre et al.* [1998] and CALS7K [*Korte et al.*, 2005] models. In order to estimate the importance of the uncertainties inherent to the data, we plot the inclinations with their associated errors. When available the uncertainties of the ages are also shown. A first observation is that the fit of the dipole and *Hongre et al.* [1998] models are quite satisfactory and sometimes can even be better than the CALS7K model for the Eurasian sites. Most discrepancies at these sites occur for periods characterized by very low inclinations (e.g., 300–500 years A.D. for Bulgaria and 1300–1500 for Paris and Bulgaria). Note also that southern Europe does not have any data between 500 and 900 years A.D., so the difference between the models for this period cannot be tested. Similarly, the Australian data set being very poorly constrained, it is not surprising that the three models exhibit very different predictions. The predictions of CALS7K are closer to the data and slightly above those of *Hongre et al.* [1998] at the other sites, but this is not always very significant, especially when the uncertainties of the data are taken into consideration. A typical example is Japan which is characterized by very large dispersion of the directions within some intervals (e.g., between 700 and 800 years A.D.). The Hawaiian site does not match the dipole fit between 0 and 400 years A.D., but we can argue that this oldest part of the record is considerably less documented and shows significant scatter. The dipole model fits rather well with the northwestern American data considering their large dispersion, while the records from Meso America are not simulated correctly by any of the three models. Also in Figure 5 are shown the results for Uzbekistan and China which were selected for their eastern location despite the lack of declination records. In both cases the data exhibit large dispersion so that preference cannot be given to any model.

[10] In order to provide a quantitative estimate of the misfit of the models to the data we compared the angular deviations between each data point with the predicted value of each model at the 12 sites described previously. Evaluation of misfit between model and data is usually achieved using the root mean square (RMS) misfit. In the absence of intensity, a representation of the angular deviations of unit vectors provide a direct indication and a clear picture which is as significant as the RMS with the advantage of being directly related to the directions. These angular deviations are shown as a function of time in Figure 6 for the 12 sites (keeping in mind that the two records from Uzbe-

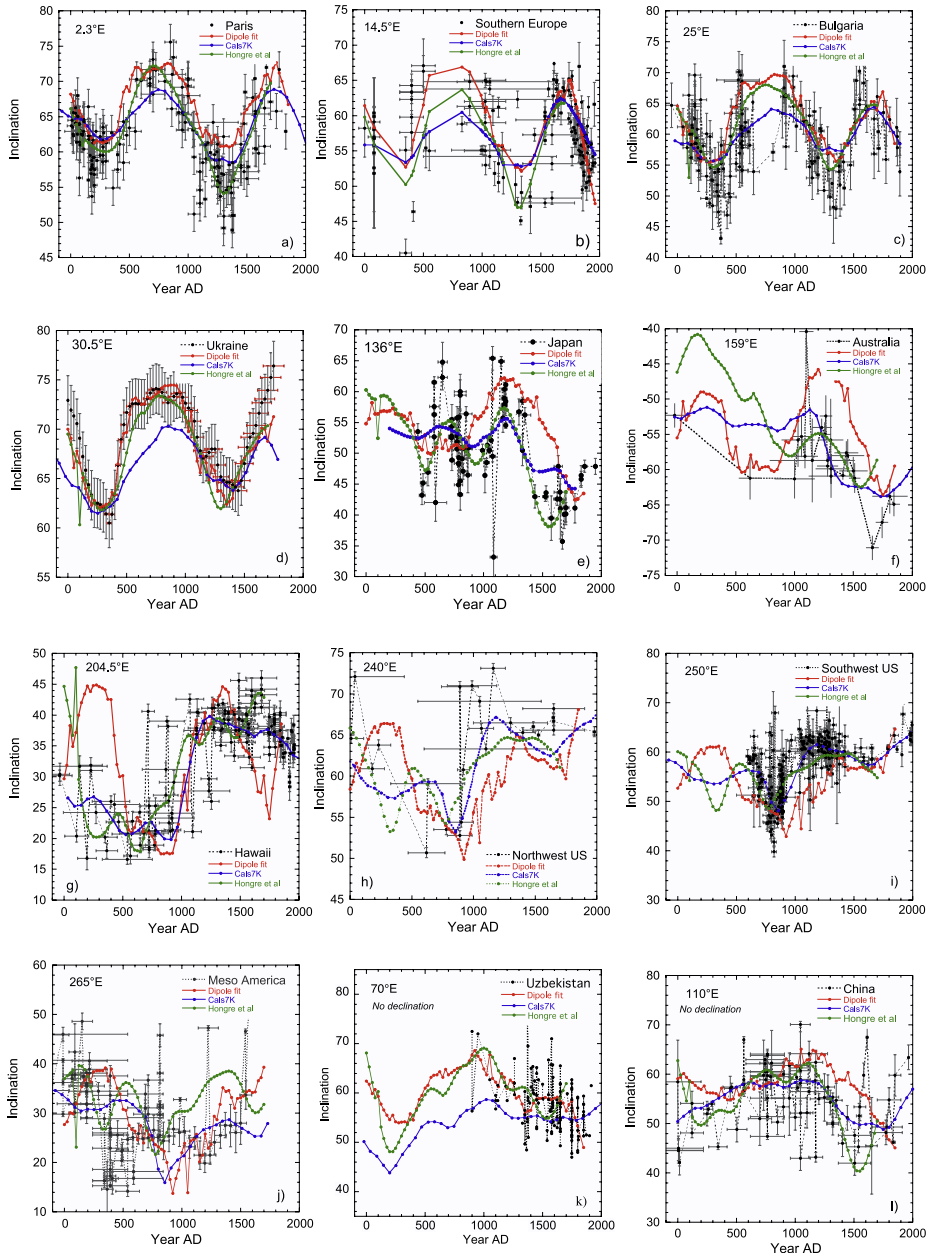

Figure 5. Fit between the predicted inclination changes derived from the present simple dipole model and the archeomagnetic records at 12 different sites selected for their quality, resolution, and geographic distribution. The results are plotted as a function of time at each site and compared with the predictions of the CALS7K [*Korte and Constable*, 2005a] and *Hongre et al.* [1998] models.

kistan and China did not incorporate declination values). As expected from Figure 5, the three models fit equivalently the Eurasian sites, whereas the predictions of the harmonic models appear to be closer to the data for the rest of the world. We also note that in all cases the angular deviations are frequently characterized by similar patterns, which indicates that most discrepancies result from differences in amplitude rather than in shape. In other words, similarities between the three models would be mostly linked to the dipole.

[11] In Figure 7 and Table 1, we report the mean value of the angular deviations obtained for the three models at the 12 studied locations as a function of site longitude. Note that these estimates do not take any uncertainty in consideration, which would evidently reduce the misfits. The mean values of all deviations are 6.9 ± 2.7° for the dipole

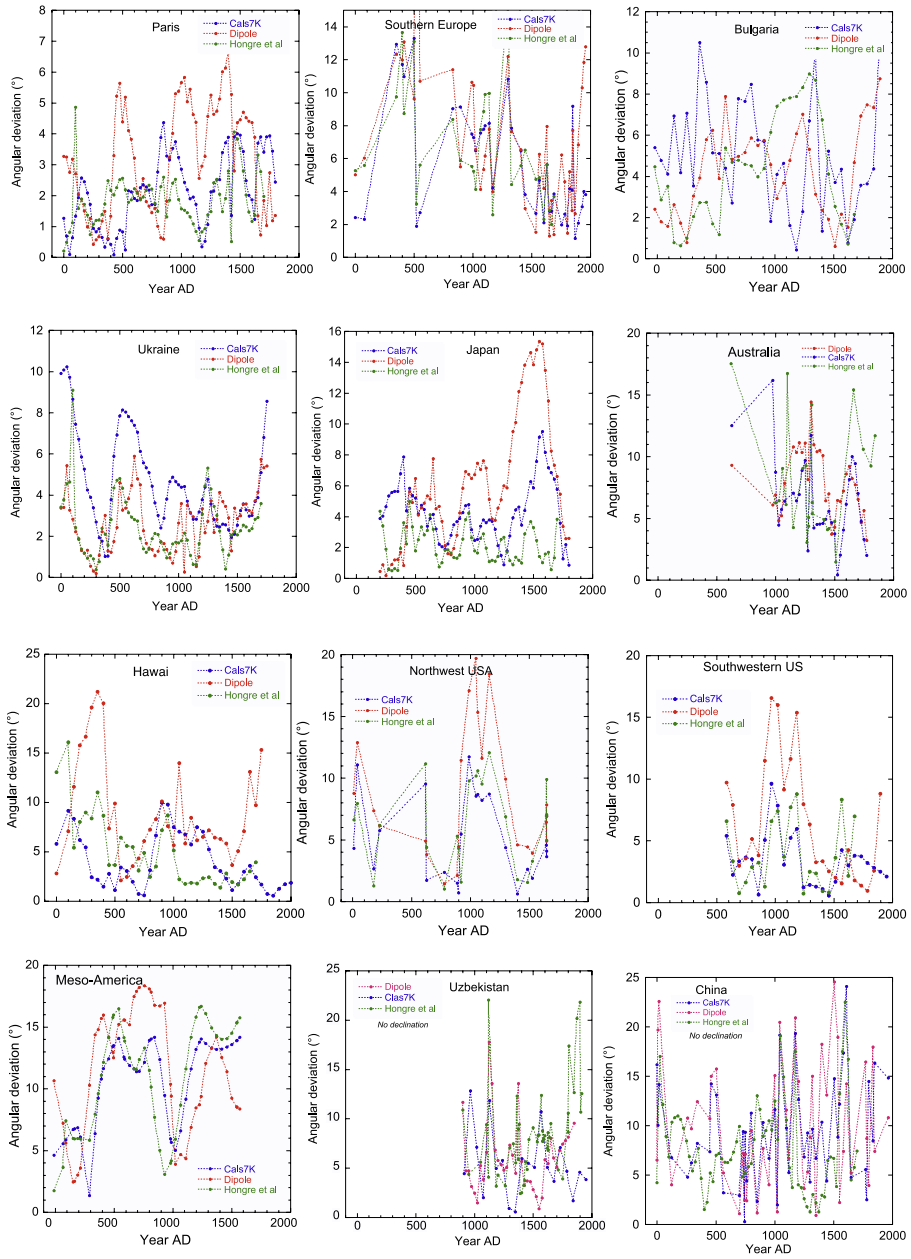

Figure 6. The angular deviation between the predicted directions and the original data as a function of time indicates the misfit between the dipole, the CALS7K model [*Korte and Constable*, 2005a], and the *Hongre et al.* [1998] model at 12 sites.

fit, 5.6 ± 2.8° for *Hongre et al.* [1998] and 5.5 ± 2.4° for the CALS7K model. Given the error bars the differences between the different models are not statistically significant. The plot in Figure 7 also confirms that the three models are equally consistent with records from the Eurasian hemisphere, while the rest-of-the-world records are in better agreement with CALS7K. We note that this difference in behavior could also be amplified by noisier data and large temporal discontinuities in sampling resolution in the Pacific than in the Eurasian hemisphere. We note also that the error bars associated with the misfits between models and data are large and significantly overlap. Thus despite its potential resolution, the CALS7K spherical harmonic model does not provide strikingly better fits than a single time-varying dipole.

[12] However, this does not indicate in any manner that the dipole would drive all variations and that

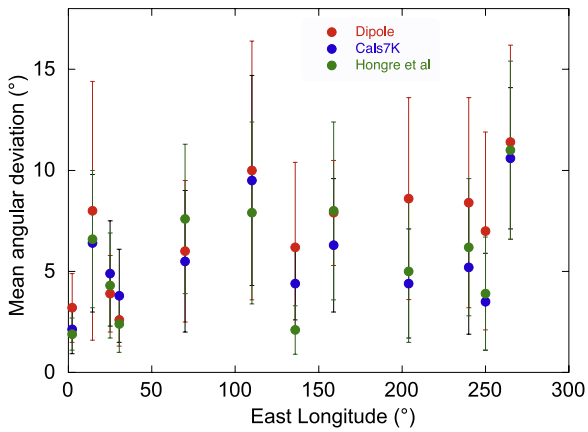

Figure 7. Mean angular deviations between each model and the original data (as shown in Figure 6) calculated for 12 sites as a function of their longitude.

other harmonic terms must be excluded. In Figure 8, we show the changes predicted by the dipole derived from the spherical harmonic models for six of the sites around the globe. It is interesting that they are frequently very different from the present results. They mostly do not fit the individual records and are even sometimes not sensitive to large amplitude changes. We see it as a consequence of the inversion procedure which probably gave too much importance to degree 2, 3 and 4 harmonics, particularly in the case of CALS7K. In addition to the weak number of sites, their distribution can affect the orthogonal relationship between the spherical harmonics and thus repartition of energy between each term. Perhaps this must be invoked also to account for the fact that the dipole from CALS7K does not match better the original records. This observation leads us to wonder how far terms of high degree are really useful in this case. Apart from the dipole, the other significant term which obviously plays a role is the quadrupole which would likely improve our fit as testified by the results of *Hongre et al.* [1998], but we must be aware that this model was not constructed on exactly the same database. We consider that even for degree 3 terms, which require at least 15 sites, the database (which contains only 23 sites, some probably largely unreliable) is likely not appropriate given the limitations described above. For these reasons, we think that the present state of the database does not allow the extraction of significant information going further than variations associated with the tilt of the dipole, to which we hopefully can attempt to add quadrupole terms although the absence of sites in the southern hemisphere is another limiting factor.

4. Dipole Field Intensity

4.1. Time Averaging of Dipole Moments

[13] The next step is to determine the evolution of the dipole strength over the same time interval. The archeomagnetic intensity database [*Korte et al.*, 2005] incorporates very few directions so that paleointensity and direction must be analyzed separately to extract the evolution of the dipole. In this case, paleomagnetists make the assumption that the field originates from an axial geocentric dipole. They calculate the moment of the hypothetic axial geocentric dipole that would produce the measured field intensity at the site latitude and is referred as the virtual axial dipole moment (VADM). If directions are present, it is assumed that the inclination deviation from the value of the axial dipole at the site latitude reflects the tilt of the dipole. The calculation of the virtual dipole moment (VDM) incorporates the equatorial dipole and thus provides an estimate of the total dipole moment. However, determinations of absolute paleointensity from volcanic or archeological material represent a spot reading of total field intensity at a given site, so that both VADM and VDM calculations do not take into account the nondipole field components. For example, varying and standing nondipole components have clearly been present in Europe during the last century. If we calculate the VDMs derived from the observatory records over the past century, we find very

Table 1. Averaged Values of the Angular Deviation Between the Archeomagnetic and Paleomagnetic Data and Predictions of the Models at the 12 Sites Considered in This Study

Site	Lat., °N/ Long., °E	Dipole	sd	Cals	sd	Hongre	sd
Paris	48.9/2.30	3.2	1.7	2.1	1.2	1.9	0.8
South Europe	39.5/14.5	8.0	6.4	6.4	3.4	6.6	3.4
Bulgaria	43.0/25.0	3.9	1.9	4.9	2.6	4.3	2.6
Ukraine	50.4/30.5	2.6	1.3	3.8	2.3	2.4	1.4
Uzbekistan	40.0/70	6.0	3.5	5.5	3.5	7.6	3.7
China	38.0/110	10.0	6.4	9.5	5.2	7.9	4.5
Japan	35.0/136	6.2	4.2	4.4	1.8	2.1	1.2
Australia	−35/159	7.9	2.6	6.3	3.3	8.0	4.4
Hawaii	19.4/204	8.6	5.0	4.4	2.7	5.0	3.5
NW U.S.	43.0/240	8.4	5.2	5.2	3.3	6.2	3.4
SW U.S.	37.0/250	7.0	4.9	3.5	2.4	3.9	2.8
Méso Am.	18.0/265	11.4	4.8	10.6	3.5	11.0	4.4

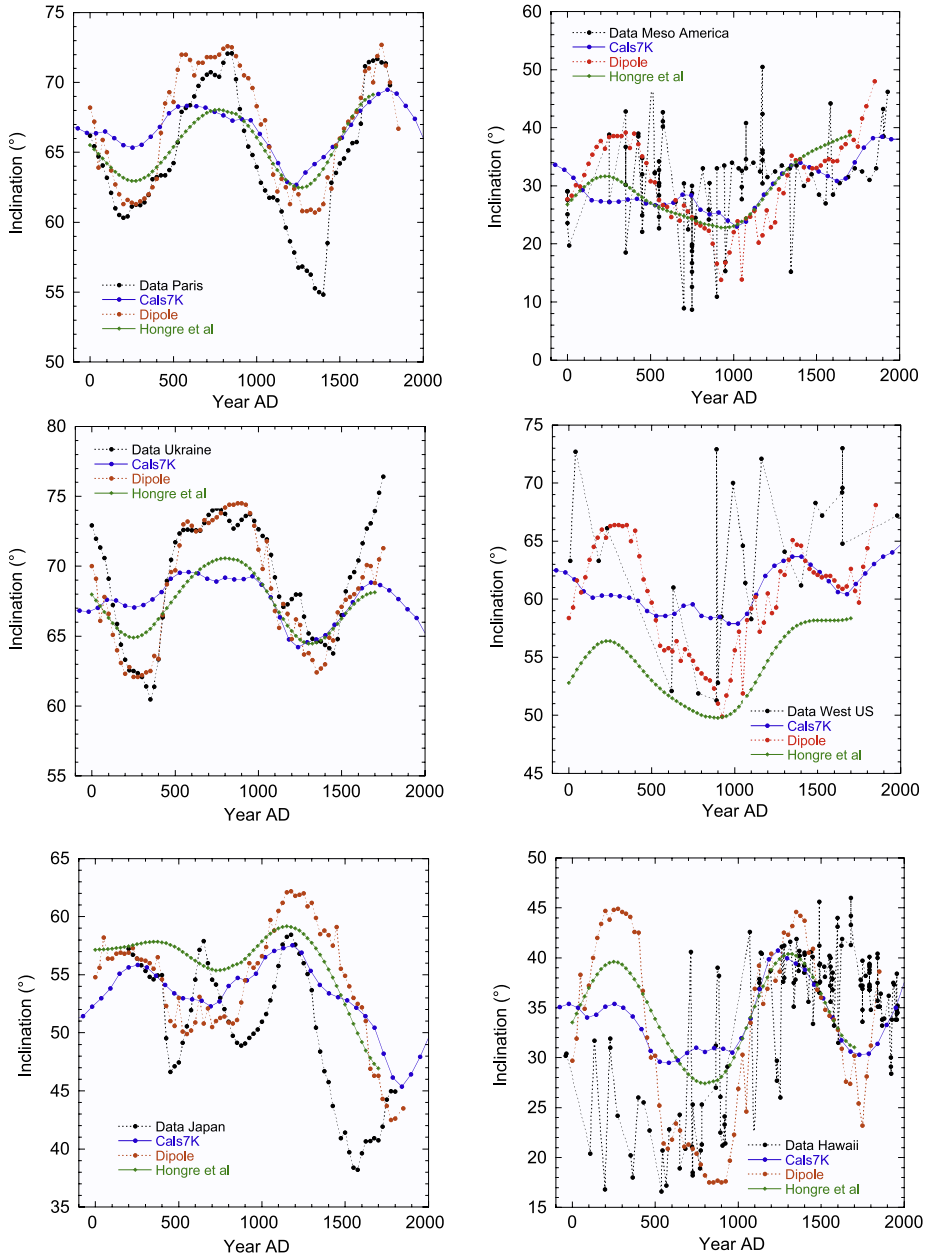

Figure 8. Predicted inclination changes derived from the present simple dipole model and the dipole changes of the CALS7K [*Korte et al.*, 2005] and *Hongre et al.* [1998] models tested against the inclination variations recorded at 6 sites.

contrasting results, some of them indicating an increasing moment over the past 50 ka which is opposite to the overall decrease derived from global analysis. Time-averaging global intensity values over several hundred years should cancel out the nondipole components and the VDM and VADM should thus provide correct determinations of the true averaged dipole and axial dipole moments. This brings us back to the importance of geographical site distribution, even in order to extract the contribution of a term with degree as low as the axial dipole.

[14] We used the succession of virtual axial dipole moments (VADM) and averaged all values within 100 year long rectangular windows in order to remove short-term fluctuations linked to nondipole components but also to any source of noise. This calculation should provide a close estimate of the axial dipole moment. We will thus refer here to

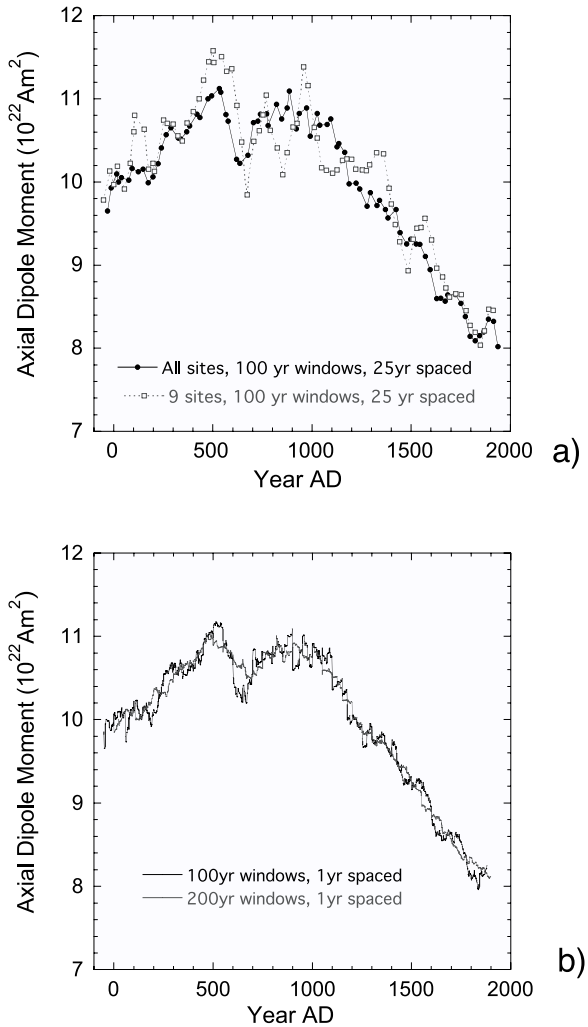

Figure 9. Estimates of the axial dipole moment as a function of time derived from different time-averaged windows of archeomagnetic VADMs.

axial dipole moment, and not to the usual definition of "virtual" dipole moment, which relies on the total field intensity measured at a single site and thus incorporates nondipole and equatorial dipole contributions. *Korte and Constable* [2005b] consider that this assumption cannot be validated even with averaging of VADMs over time windows as large as 500 or 1000 years. They reported that the existing estimates of either VADMs or VDMs were both systematically higher than the geomagnetic dipole moment based on spherical harmonic analysis (CALS7K model) for the time period 5000 BC to 1950 A.D. (15). Data quality and unremoved contributions of the nondipole field would be responsible for this situation. We will see below that a large part of the discrepancy could actually be attributed to the dipole value derived from the CALS7K model [*Korte and Constable*, 2005b]. A second important reason would be the existence of geographical biases in sampling. *Korte and Constable* [2005b] noticed that there is a strong latitudinal dependence in the average VADM for the present field. They show that the mean VADMs and/or VDMs derived from the GUFM model [*Jackson et al.*, 2000] at equatorial latitudes are larger by almost 10^{22} Am^2 than those measured at 40°S, which would be linked to the nonzonal South Atlantic anomaly. *Korte and Constable* [2005b] infer that 400 years are not long enough to completely average out the asymmetry. We note that the largest deviations from the mean GUFM dipole moment given by CALS7K [*Korte and Constable*, 2005b] are observed at equatorial and mid-equatorial latitudes of the northern hemisphere, which are almost devoid of archeomagnetic sites. In fact, the archeomagnetic database described by *Korte et al.* [2005] contains 9 sites with latitudes between 40 and 50°N which thus show negligible deviation from the expected dipole strength. Five sites lie below 40°N and 5 others above 50°N so that their respective deviations should more or less cancel each other. Only 3 sites at similar latitudes between 17.5 and 19.5°N could contribute some positive deviation and the last one in the southern hemisphere would have a negative contribution. We thus consider that these deviations should not drastically affect the results and certainly cannot account for the differences between these various estimates of the dipole moments. More regrettable is the lack of additional sites in the southern hemisphere, but such a deficiency has more consequences for spherical analysis than for determining only the dipole.

[15] Despite uneven site distribution, we assume that long-term nondipolar features should be considerably attenuated over 100 years and even more over 200 years windows (2) (Figure 9a). This assumption is reinforced by the fact that the curve derived from a database limited to the nine best documented sites (Caucasus, Japan, North America, South America, Bulgaria, China, France, Uzbekistan, Russia) with relatively good geographical distribution is quite similar to the one obtained from the complete set of 12 sites (Figure 9b). We verified the consistency of the results obtained after treatments using different windows (100, 200 and 400 years) spaced at different intervals (one point every 25 years or with the initial time distribution of the data).

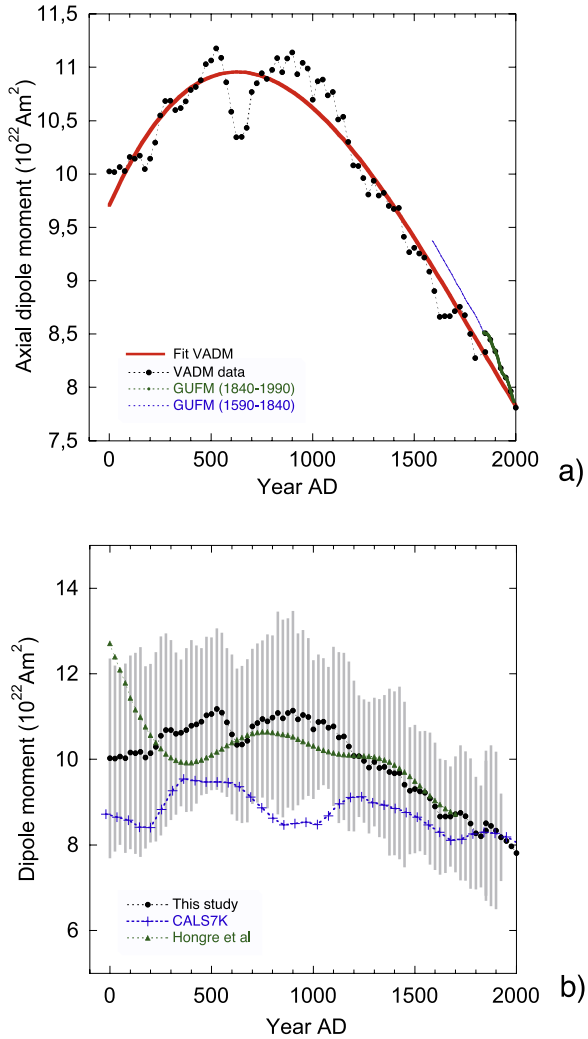

Figure 10. (a) Time-averaged VADMs over 100 year long moving windows (black dots). Persistent nondipolar features were removed using a simple polynomial fit and provide our best estimate of the axial dipole moment. (b) Mean dipole moments (see text) and their standard deviations within each time-averaged window. The mean dipole moment derived from CALS7K [*Korte and Constable*, 2005b] is shown for comparison (blue crosses).Vertical scale is larger than in Figure 10a to show the standard deviation.

4.2. Dipole Strength Over the Past 2 ka

[16] We selected the curve obtained using 100 year windows with one point every 25 years (but any other could have been used as well) as a first approximation of the dipole variations. Despite this treatment, we note that some small amplitude oscillations persist. We have mentioned previously that such oscillations could either be due to nondipole fields or equally result from persisting noise in the signal. For this reason, we prefer to remove these small wavelengths by a polynomial fit of order 3. The results shown in Figure 10a are interpreted as our best approximation of the axial dipole moment during this period. They are not in contradiction with the previously published composite curves [*McElhinny and Senanayake*, 1982; *Thouveny et al.*, 1993; *Yang et al.*, 2000] but they were obtained with higher resolution and from a recent updated database. We find a confirmation that the axial dipole has been decreasing with almost constant slope to first order since A.D. 900, but that it was actually increasing prior to A.D. 500–600. The variations of GUFM derived from the historical measurements (after A.D. 1840) (Figure 10a) are consistent with our estimate. As already mentioned, the axial dipole moments of GUFM [*Jackson et al.*, 2000] for the previous 250 years were not obtained from direct measurements, but constrained by extrapolation of the axial dipole evolution. Therefore they cannot be used for testing the suitability of the archeomagnetic intensity models. We simply mention that they increase drastically, similar to (actually even stronger than) the present results, yet *Gubbins et al.* [2006] recently concluded that the dipole was nearly constant from 1590 to 1840. Although being subject to uncertainties, the overall consistency between these data sets does not fit with the concept that the dipole moments derived from VADMs or VDMs would be systematically stronger than the true dipole moment [*Korte and Constable*, 2005b]. Overall, the evolution of CALS7K dipole moments (Figure 10b) is significantly different from the present curve, as well as from *Hongre et al.* [1998] predictions, with a much smaller decrease since A.D. 1000. As a consequence, prior to this period, the CALS7K moments are systematically lower and almost outside the error bars of the present results. The difference between the slope of CALS7K with respect to the other two curves can be retraced until A.D. 1960 and was actually noticed by *Korte and Constable* [2005b] for the historical period. On the basis of the limits imposed by the dispersion of the data, it is certainly delicate to determine whether this change is significant on a decadal timescale. However, it is puzzling that the overall pattern of CALS7K is so much different from the other two curves over the 0–1700 ka interval, and that the CALS7K moments lie almost outside the range of the archeomagnetic measurements (Figure 10b), which incorporate measurements uncertainties and nondipole effects. For this reason and following our analysis of the directions, we confirm our suspicion that too little power was given to the dipole in the spherical harmonic analysis of the CALS7K model.

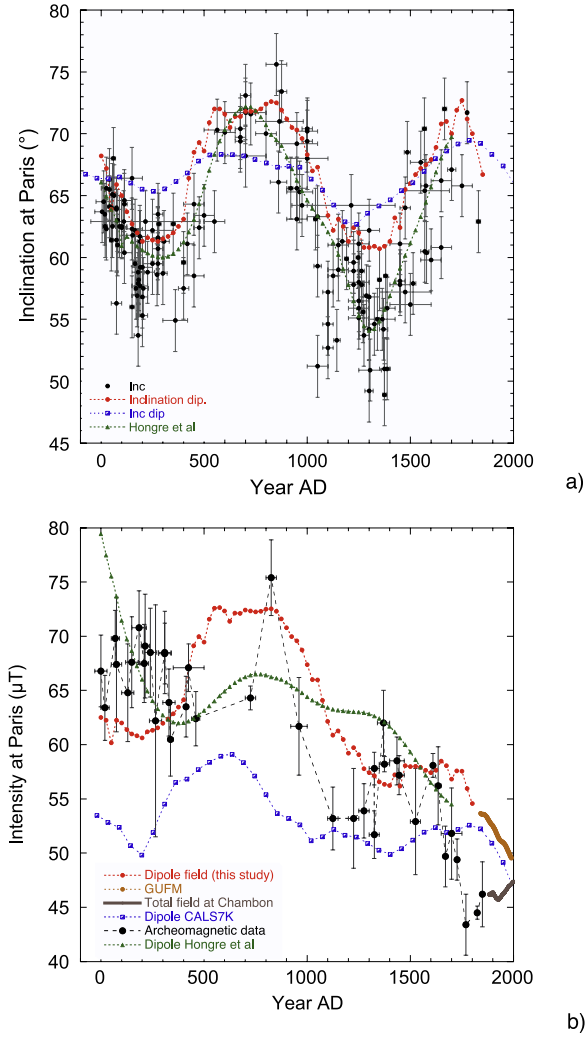

Figure 11. (a) Inclination variations of the dipole at Paris derived from the present model (red dots) and from CALS7K (blue crosses). Inclinations (back dots) from archeomagnetic artifacts at Paris. (b) Evolution of dipole field intensity at Paris obtained from the present results and from GUFM after 1840; changes in total field intensity (black dots) from the most recent archeomagnetic records [*Chauvin et al.*, 2000; *Genevey and Gallet*, 2002; *Gallet et al.*, 2003, 2005] and from observatory measurements (Chambon La Forêt) for the historical period. Dipole field intensity variations derived from CALS7K at Paris are plotted for comparison (blue crosses).

[17] Dipole field intensity at a given site for a given period can be calculated from knowledge of both the axial dipole moment and the geomagnetic pole position which indicates the tilt of the dipole with respect to the Earth's rotation axis. The evolution of the axial dipole moment over the last 2 ka has been shown in Figure 10a. The successive pole positions are given by the composite dipole described in the previous section. We can thus directly deduce the evolution of the dipole field intensity and direction at any site for the past 2 ka. In Figure 11a we show the inclination changes at Paris that are derived from the present dipole, from the dipoles obtained in CALS7K and by *Hongre et al.* [1998], and last the inclination of the total field given by the most recent archeomagnetic records. In Figure 11b, we plot the evolution of dipole field intensity derived from the three models and the evolution of total field intensity obtained from the most recent and detailed records from western Europe [*Chauvin et al.*, 2000; *Genevey and Gallet*, 2002; *Gallet et al.*, 2003]. As could be expected from Figure 10a, the dipole field calculated from GUFM [*Jackson et al.*, 2000] for the historical period is consistent with the archeomagnetic dipole. It is also noticeable that the quality of the archeomagnetic records is validated by the fact that the historical field intensity recorded from Chambon La Forêt extends the curve in a consistent manner.

[18] Several further considerations can be derived from Figure 11. A first remark is that, except for the last 200 years, the dipole field intensity predicted by CALS7K is much lower than the present dipole and consequently also than the total archeomagnetic field, sometimes by up to 30%. We wonder again how far this difference could be due to leakage of dipole energy to nondipole components. The dipole field variations derived from the present model display extrema at A.D. 800 and 1400 which are in coincidence with peaks in total field intensity referred as "archeomagnetic jerks" [*Genevey and Gallet*, 2002; *Gallet et al.*, 2003, 2005; *Courtillot et al.*, 2007]. This link with the dipole is not surprising since these periods were shown to coincide with sharp cusps in geomagnetic field direction [*Gallet et al.*, 2003, 2005] and thus induce a change in dipole field intensity at Paris. However, all three "jerks" in total field intensity (A.D. 200, 800 and 1400) appear to be characterized by different phase relationship between the evolution of the nondipole and the dipole field strength.

[19] We can provide a more quantitative picture of the residual nondipole field by removing the dipole component from the total field given by the archeomagnetic results in Figure 11b. Despite the absence of directions in the archeointensity records, the directional database [*Korte et al.*, 2005] contains a compilation of the successive field directions at Paris over the past 2 ka (see Figure 6a for

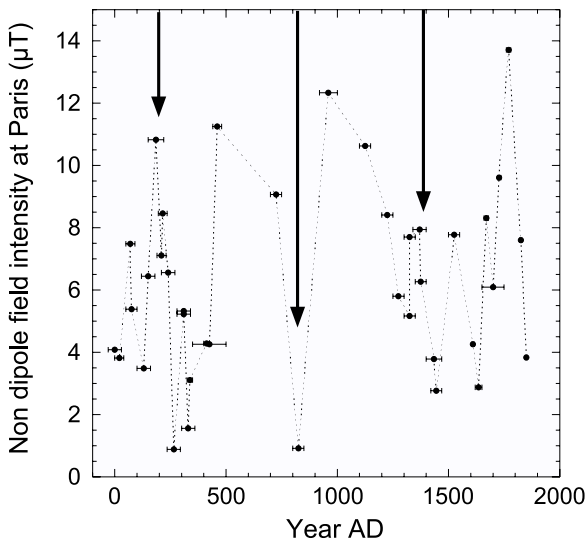

Figure 12. Evolution of the nondipole field intensity at Paris given by the modulus of the vector difference between total field and dipole field. Data are limited to the ages of the recent archeomagnetic records. The positions of the archeomagnetic jerks are indicated by arrows.

inclination) which can be interpolated to exactly the same age as each estimate of total field intensity shown in Figure 11b. Therefore, both total and dipole field vectors being constrained, the modulus of their vectorial difference depicts the evolution of the nondipole field intensity at Paris. The results plotted in Figure 12, which are necessarily restrained to the temporal coverage of the archeomagnetic results, show a series of fluctuations with more or less similar amplitudes varying between 5 and 10 μT. They indicate that the deviations between total and dipole field intensity at A.D. 200 and 1400 are not inconsistent since they lie within this range of variability. As expected the jerk reported for A.D. 200 is associated with rather strong nondipolar contribution. In contrast, A.D. 800 coincides with a very strong dipole and very weak nondipolar contribution, while A.D. 1400 can be seen as an intermediate situation. On the average, the nondipole field represents 10 ± 5% of the dipole, which agrees with the present field structure.

5. Conclusion

[20] We have shown that a simple model with only a geocentric dipole component can reasonably account for field variations recorded in the existing database for the past 2000 years. The predictions of the CALS7K model involving harmonics up to degree 10 are not strikingly better than those predicted by limiting the model to degree and order 3 as done by *Hongre et al.* [1998] or even to the dipole as done here. Given the many inaccuracies inherent to the database and also the number and the distribution of sites, we suggest that the present data remain too poor to go beyond the dipolar and maybe the quadrupolar terms in the description of the evolution of the harmonic content of the field. The present results indicate also that variations with typical time constants exceeding one hundred years would be largely governed by the dipole, which is consistent with previous estimates by *Hulot and LeMouël* [1994]. A direct consequence is that records of paleosecular variation with relatively low resolution could be more or less correlated on a global scale provided accurate age control can be obtained. This potential application could be explored for sedimentary records obtained for the same period from widely different areas. The present study has led us also to calculate a curve depicting the first order evolution of the dipole moment over the past 2 ka. The results are consistent with historical measurements and indicate that the dipole began its decrease 1000 years ago. The curve can thus be used to predict dipole field intensity at any location and offers potential for studies related to the evolution of the magnetosphere. As a direct application, we calculated the variations of dipole field intensity in Paris and extracted the contribution of the nondipole components from the archeomagnetic records of total field. It was thus possible to determine their respective importance in the successive field variations. We noticed that the archeomagnetic jerks do not share a common origin but result from different phase relationship between the dipolar and nondipolar field variations.

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