On the use of Archeology in Geomagnetism, and vice-versa: Recent developments in Archeomagnetism

Sur l'utilisation de l'Archéologie en Géomagnétisme et vice versa: Développements récents en Archéomagnétisme

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Abstract

Archeomagnetism allows one to recover the temporal evolution in direction and in intensity of the Earth's magnetic field over the past few millennia, mainly from the magnetic property analyses of archeological materials which were baked during their manufacturing or their use. Its applications concern both Geomagnetism, with an increasingly precise description of the behavior and origin of the geomagnetic field, and Archeology, because a secular variation curve can be used as a dating tool. Recent archeomagnetic results also suggest a connection between the geomagnetic field and climate during the Holocene period. In addition to these aspects, we further present the acquisition of two new archeointensity data obtained from potsherds found in the Etruscan site of La Castellina (Italy) and in Vanves (France), respectively dated to the VIIth century BC and to the IXth century AD.

Résumé

L'archéomagnétisme est une discipline qui permet de retracer l'évolution temporelle en direction et en intensité du champ magnétique terrestre au travers des derniers millénaires, principalement à partir de l'analyse des propriétés magnétiques des matériaux archéologiques

ayant subi une cuisson au moment de leur fabrication ou de leur utilisation. Ses applications sont tournées à la fois vers le géomagnétisme, avec une description toujours plus précise du comportement et de l'origine du champ géomagnétique, et vers l'archéologie, car une courbe régionale de variation séculaire peut être utilisée comme outil de datation. Des résultats archéomagnétiques récents suggèrent également une connexion entre le champ géomagnétique et le climat durant l'Holocène. Outre ces aspects, nous présentons l'acquisition de deux nouvelles valeurs d'archéointensité obtenues à partir de fragments de poteries échantillonnés sur le site Etrusque de La Castellina (Italie) et à Vanves (France), datés respectivement du VIIe siècle av. J.-C. et du IXe siècle ap. J.-C.

1. Introduction

Irregular in space and time, the directional and intensity variations of the geomagnetic field measured at the Earth's surface illuminate the magneto-hydrodynamic processes acting in the outer core, principally made of liquid iron at depths between ~2900 km and ~5150 km, which generate the main geomagnetic field (e.g. Merrill et al., 1996). These variations include both the temporal evolution of the dipole and non-dipole parts of the geomagnetic field, which respectively represent ~90% and ~10% of the total field of internal origin measured at the Earth's surface. They are relatively well determined for the past four centuries thanks to direct geomagnetic measurements, i.e. directly obtained from instruments, acquired in a few land-observatories, as well as by ancient mariners aboard ships, and much more recently (since the eighties) from satellites (e.g. Jackson et al., 2000; Hulot et al., 2002; Jonkers et al., 2003). These measurements have provided a rather complete coverage of the magnetic field components at the Earth's surface, making it possible to recover the evolution of iron flow pattern at the core's surface (Figure 1; e.g. Jackson et al., 2000; Hulot et al., 2002). Before ~1600 AD, only indirect geomagnetic field measurements obtained from the analysis of the remanent magnetization of rocks and archeological materials offer the possibility to extend our knowledge of geomagnetic secular variation beyond historical geomagnetism. In this respect, recent efforts have been accomplished in better constraining the global evolution of the Earth's magnetic field over the past few millennia, using a large compilation of archeomagnetic data (Daly and le Goff, 1996; Hongre et al., 1998; Korte and Constable, 2005; Korte et al., 2005).

At the crossing of archeology, rock magnetism and geomagnetism, archeomagnetism is a domain of research which relies on the analysis of the magnetic properties of archeological material having undergone a firing at the time of their manufacturing or their use. The materials that contain iron oxides (principally magnetite) then acquired a stable thermoremanent magnetization, whose direction is parallel to the one of the geomagnetic field at the time and place of the cooling following the firing and whose intensity is proportional to the same ambient field (for a synthesis see in Dunlop and Ozdemir, 1996). When dated, the archeomagnetic study of in-place structures such as pottery and domestic kilns of different ages allows one to recover the evolution in direction and intensity of the geomagnetic field for a given region (e.g. Thellier, 1981; Lanos et al., 1999). In contrast, objects displaced from the place where they were originally fired (in unknown position), such as pottery, bricks or tiles, most often display only information on the ancient geomagnetic field intensity (e.g. Thellier and Thellier, 1959). In some cases, however, hypotheses can be made on the position of those objects inside the kilns during their firing, which then allows one to determine ancient geomagnetic inclinations (e.g. Lanos, 1987). Archeomagnetism is therefore continuously benefiting from our increasingly historical and archeological knowledge of the ancient civilizations that have succeeded through the millennia in different parts of the world.

In addition to the acquisition of new archeointensity data from Western Europe dated back to the VIIth century BC and to the IXth century AD reported in this study, the main objective of the present article is to show that the applications of archeomagnetism are not restricted to the domain of geomagnetism, but also now concern archeological, climate and environmental sciences.

2. Directional geomagnetic variations as a dating tool in France

There has been in France a long tradition of archeomagnetic studies first initiated by Emile Thellier (Thellier, 1938, 1981). The patient (and on-going) analysis of numerous archeologically well-dated burnt structures (pottery, domestic and lime kilns) has led to the construction of a rather detailed directional secular variation curve spanning the past two millennia (Thellier, 1981; Bucur, 1994) and also, but with a lower time resolution because of a smaller number of available data, the first millennium BC (Figure 2; Gallet et al., 2002). This curve exhibits large fluctuations with, for instance, differences reaching ~40° in declination between ~1100 AD and ~1800 AD and ~15° in inclination between 800 AD and ~1400 AD. It turns out that the nature of these variations provides a dating tool for archeological purposes. Indeed, the comparison between an archeomagnetic direction obtained from a structure of unknown age and the “known” (or reference) directional variation curve makes it possible to derive dating constraints whose accuracy depends on the reliability and precision firstly of the reference curve, and secondly of the archeomagnetic direction to be dated. In favorable cases, i.e. when the directional changes are large and rapid such as during the Middle Ages (Figure 2), the archeomagnetic dating precision at 95% can be as good as ~50 years (e.g. Lanos et al., 1999; Le Goff et al., 2002). This technique is in particular very efficient in France when applied for constraining the age of the last use of numerous domestic kilns excavated in many agricultural settlements of the Ile-de-France region dated to the High Middle Ages, a time interval for which chronological data are often imprecise (Warmé, 2003). In contrast, the situation is less favorable for the Roman period characterized by a relatively tight loop in geomagnetic directions, preventing a good precision in archeomagnetic dating (although the reference curve is well known for the first centuries AD and even if the archeomagnetic direction to be dated is precisely determined). It is worth pointing out that this archeomagnetic method is also efficient for the dating or identification of volcanic deposits. It was largely used for this purpose on the volcanoes from Southern Italy, providing invaluable information on the eruptive frequency of those volcanoes over centennial and millennial time scales (e.g. Tanguy et al., 2003; 2007).

We present below an example of archeomagnetic dating obtained from a lime kiln excavated in a rock shelter called La Fanfarline, close to the small city of Orgon in southeastern France (Figure 3a). Two uppermost Paleolithic (Alleröd time interval) and one Mesolithic occupation layers were identified at this location. These prehistoric layers were strongly perturbed by a late occupation dated to the High Middle Age (Carolingian period) marked by three pits containing very few datable potsherds (Brochier and Livache, 2004). One lime kiln was also, surprisingly, found in the La Fanfarline rock shelter, whose dating was totally unknown. Seventeen large samples were collected using the plaster cap method described in Thellier (1981) and precisely oriented towards the magnetic North and the geographic North (using a sun compass for the latter orientation). After preparation in the laboratory, the magnetization of standard 12 cm-side samples was measured using a rotating inductometer specially designed for the large size of the samples. Following the Thellier's methodology involving a stringent viscosity test, only the results obtained from the samples having a magnetic viscosity index (defined by the ratio of viscous remanent magnetization to thermoremanent magnetization) of less than 5% were retained for the computation of the mean -ancient- thermoremanent magnetization direction (for more details on the method, see in Thellier, 1981 or Bucur, 1994). In the case of the studied burnt structure, the individual directions obtained from only 10 samples were further considered (mean viscosity index of 3.1% -note that 2 samples were also rejected because of their weak magnetization). These directions give a mean direction (Declination, 8.1°; Inclination, 57.1° at the site; Figure 3b) precisely defined with a Fisher parameter of 1911 (α_{95}=1.0°). The comparison between this archeomagnetic direction and the reference directional archeomagnetic database available in France was made using the method described in Le Goff et al. (2002). This method aims at testing the compatibility between a Fisherian direction, the one to be dated, and a reference directional variation curve constructed with the help of sliding windows of varying duration, whose durations are principally fixed following the changing density of available "reference" data over the time, and whose successive mean directions are computed using the bivariate extension of the Fisher distribution (Le Goff, 1990; see also in Lanos et al., 2005 for a different method based on the Bayesian approach for drawing the directional variation curve) (Figure 3b). An archeomagnetic age interval is then determined using a modified version of the McFadden and McElhinny (1990) test developed for testing the compatibility at 95% between two Fisherian directions: this amounts to comparing the angular distance (γ) between the direction of unknown age and each of the directions from the reference directional variation curve with a critical distance (γ_c) defined at the confidence level of 95% (Figure 3c). We obtain for the kiln of La Fanfarline an archeomagnetic dating at 95% between 1380 AD and 1510 AD. Le Goff et al. (2002) further proposed to use the compatibility test above as a rejection test in order to estimate the probability p (in %) of making an error if the direction of unknown age was considered different from one dated mean direction. In that case, the parameter p can be used to define a more probable age within the archeomagnetic age interval previously determined. This allows us to find a more probable age around 1470 AD for this kiln (Figure 3c). Since our archeomagnetic study carried out in 2003, a radiocarbon age was obtained from charcoals found in the La Fanfarline kiln (J.E. Brochier, personal communication). The calibrated age, between 1440 AD and 1637 AD (at 2σ; ref.#LY12917), is consistent with our archeomagnetic dating. Combining both the archeomagnetic and radiocarbon age constraints further allows one to reduce the time interval to between 1440 AD and 1510 AD, which is again in very good agreement with our most probable archeomagnetic date of around 1470 AD.

It is worth mentioning that archeomagnetism constitutes an evolutionary dating method: this means that the continued acquisition of new well-dated and well-determined archeomagnetic directions will help to better constrain the reliability and the time resolution of the reference directional variation curve, and this will give the possibility to obtain more accurate and precise archeomagnetic dating (including the revision of previously proposed archeomagnetic dating).

3. New methodological progress in the determination of ancient geomagnetic field intensities

In order to complement the description of the Earth's magnetic field in Western Europe over the past few millennia, an effort is underway to determine geomagnetic field intensity variations (e.g. Chauvin et al., 2000; Genevey and Gallet, 2002; Gallet et al., 2005; Gomez-Paccard et al., 2006). From an experimental point of view, these determinations are much more complex than those dealing with geomagnetic directions. This is the reason why our knowledge on geomagnetic field intensity variations is at present still fragmentary and the results sometimes strongly debated (e.g. Gallet et al., 2005; Gomez-Paccard et al., 2008; Genevey et al., 2009).

It is beyond the scope of this paper to make a precise description of the various experimental methods used for "archeointensity" determinations (e.g. Tauxe and Yamazaki, 2007; Genevey et al., 2008). We briefly recall here the very general principle derived from the works of Néel (e.g. 1949) and Thellier and Thellier (1959). The thermo-remanent magnetization (TRM) of a baked clay fragment that can be measured in the laboratory is related to the ancient geomagnetic field intensity at the time and place of its original firing by a proportionality factor which depends on the intrinsic magnetic properties of the studied fragment (nature, quantity and size of the magnetic grains). To recover the ancient field intensity, most protocols derived from the Thellier and Thellier (1959) method are based on gradually thermally replacing the old magnetization, the Natural Remanent Magnetization or NRM supposed to be a pure TRM, by a new magnetization acquired in the laboratory in known field (intensity and direction) conditions (a laboratory TRM). The ancient magnetic field intensity is then obtained from the ratio between the NRM and the TRM multiplied by the intensity of the field applied while acquiring the laboratory-TRM. This is however valid only if the magnetic mineralogy of the analyzed fragment is well adapted to such a technique, i.e. principally if the magnetization is carried by magnetite in the range of single or pseudo-single domain sizes and if no alteration occurs during the thermal treatment. Those conditions are very stringent and many refinements in the intensity protocols have been developed in order to efficiently recognize the presence of multi-domain grains and to detect alteration of the magnetic mineralogy leading to the rejection of the samples (e.g. Leonhardt et al., 2004; Yu et al., 2004). Furthermore, the intensity values derived in this way may be biased by two effects induced one by the anisotropy of TRM due to the stretching of the clay paste during the manufacturing of the artifacts and the other by the cooling rate dependence of TRM acquisition (e.g. Chauvin et al., 2000; Genevey et al., 2008).

To improve the above methodology and also to make easier the archeointensity determinations, Le Goff and Gallet (2004) have developed a new vibrating sample magnetometer called the Triaxe. This instrument allows the simultaneous measurements of the three components of the magnetization vector carried in a small (1 cm-height; 1 cm-diameter) cylindrical sample, where the sample can be heated (up to 680°C) and submitted to a magnetic field in any direction and intensity up to ~200 μT (Figure 4). Unlike most classic methods which involve magnetization measurements at room temperature (i.e. after successive heating and cooling of the studied samples), the Triaxe magnetometer therefore allows us to perform magnetization measurements at high temperatures. The potential applications of this magnetometer concern the study of rock magnetism in general, but the key application we have developed so far concerns the establishment of a new fully automated and fast (~two hour long) archeointensity routine, which takes into account both TRM anisotropy and cooling rate effects. Numerous comparative tests between results obtained using the Triaxe and several other widely used versions of the classic Thellier and Thellier (1959) method (for instance Aitken's or Coe's versions or the so-called IZZI version; Yu et al., 2004) have demonstrated the efficiency of the former procedure (Gallet and Le Goff, 2006; Gallet et al., 2006; 2008; Genevey et al., 2009).

4. Acquisition of new archeointensity results from Western Europe

To better illustrate the Triaxe methodology and the recent efforts which have been made to construct a reliable geomagnetic field intensity variation curve in Western Europe over the past few millennia, we report below the acquisition of two new sets of archeointensity data from Italy and from France, dated respectively to the VIIth century BC and to the IXth century AD.

A collection of ten pottery fragments was sampled from the archeological site of La Castellina del Marangone, ~4.5 km south of Civitavecchia and ~66 km to the north-west of Rome (Italy). This site occupies a hill, ~130 m in height, near the seashore. Excavations have shown that it was continuously inhabited from the Bronze Age to the Hellinistic period (XIVth to IIIth century BC). During the Etruscan period, La Castellina had a remarkable position, midway between the two major cities of Tarquinia and Cerveteri, which greatly favored its commercial importance for regional and sea trading. Our potsherds were collected from one single occupation layer on the oriental terrace area (Gran-Aymerich, 2006) and they all correspond to a fine pottery characterized by a very distinctive decor with painted fish or bird, well dated to the middle of the VIIth century (layer 7, orientalising period, ~670-630 BC; Martelli, 2000; Gran-Aymerich, 2003).

Another group of fragments was sampled in the city of Vanves, located on the southwestern periphery of Paris (France). Six pottery kilns were excavated in 2004 (Gaudray street; work managed by X. Peixoto, Institut National de la Recherche Archéologique Préventive). When abandoned, these kilns were used as dumps and filled by thousands of potsherds covering the VIth-IXth century period. The fragments were collected from kiln #1050 which delivered a large and homogeneous collection of potsherds with a fine or semi-fine clay paste and, based on their typology, dated to the first half of the IXth century (Lefèvre, 2007).

All collected fragments were subjected to rock magnetic experiments in order to first obtain information on the nature of their magnetic mineralogy and second to investigate the stability of this magnetic mineralogy during heating. Isothermal remanent magnetization (IRM) acquisition measurements indicate that the mineralogy of the Italian and the French sites behave in different ways. While magnetization reaches saturation in fields of ~0.2-0.3 T for all fragments from La Castellina, saturation is not always reached in fields up to 0.8 T for the samples from Vanves (Fig. 5a). For the latter, when IRM saturation is not reached, hysteresis measurements exhibit “wasp-waisted” shapes (Fig. 5b), which likely reflect the presence of two families of magnetic grains with significantly different magnetic coercivities (e.g. Dunlop and Ozdemir, 1996). In contrast, for all the samples showing IRM saturation at fields < 0.3T, the shape of the hysteresis loops is not constricted (Fig. 5c,d) and the hysteresis parameters lie in the pseudo-single domain range of magnetite (Day et al., 1977). These results indicate that the magnetization of our samples is mostly carried by minerals from the magnetite family but that hematite (i.e. a high-coercivity mineral) is also present in some fragments from Vanves. Such variety in magnetic mineralogy is reminiscent of that previously observed in other western European potsherds (e.g. Chauvin et al., 2000; Genevey and Gallet, 2002; Hill et al., 2007). We also systematically measured the temperature variations of the low-field magnetic susceptibility of each fragment between ~20°C and ~550°C using a KLY3-CS3 Kappabridge apparatus (Fig. 5e-h). In all cases, the thermomagnetic curves confirm that the magnetization is dominated by magnetite, perhaps sometimes with different titanium contents or different grain sizes, which would explain a rather “wavy” shape for some curves from La Castellina samples (Fig. 5e,f). The reversibility of the thermomagnetic curves acquired during heating (in red) and cooling (in blue) is a good marker of lack of alteration of the magnetic mineralogy during heating treatment. For this reason, we selected for our archeointensity experiments (i.e. inducing a heating of the samples) only the samples displaying a reversible susceptibility behavior. This led to the rejection of only one sample, which underlines the particularly favorable magnetic behavior of the analyzed fragments.

One sample from each selected fragment was analyzed using the Triaxe magnetometer. The automatic intensity procedure described in detail in Le Goff and Gallet (2004) involves 5 successive sequences of continuous measurements (hereafter numbered step#1 to step#5). It first consists of demagnetizing almost completely the NRM by heating in a zero-field the sample from a fixed low temperature T1, usually 150°C, up to a high temperature T2, chosen between 445°C and 525°C (step#1). The sample is next successively cooled down to T1 (step#2) and again heated to T2 (step#3) in order to measure the temperature variations of the spontaneous magnetization of the small magnetization fraction remaining blocked above T2. A laboratory TRM is then acquired by cooling the sample from T2 to T1 in a field of fixed intensity (Hlab), generally close to the expected ancient intensity, and whose direction is very precisely oriented along the original NRM direction (step#4). Finally, this new TRM is demagnetized up to T2 (step#5), before the sample is cooled down to room temperature. When the temperature is varying, magnetization measurements are continuously carried out every ~5°C (running temperature Ti between T1 and T2) providing different sequences of measurements numbered M1(T1≤Ti≤T2) to M5(T1≤Ti≤T2). At each temperature Ti, an intensity determination is obtained from the ratio R'(Ti) of the NRM fraction unblocked between T1 and Ti (Δ'1(Ti)) to the laboratory TRM fraction also unblocked between T1 and Ti (Δ'5(Ti)) multiplied by Hlab.

with Δ'1(Ti) = [M1(T1)-M1(Ti)] – [M3(T1)-M3(Ti)] (1)

and Δ'5(Ti) = [M5(T1)-M5(Ti)] – [M3(T1)-M3(Ti)] (2)

For each sample, a mean archeointensity value is derived by averaging the R'(Ti) data between T1 and T2 (see more details and discussion in Le Goff and Gallet, 2004).

Among the samples analyzed with the Triaxe, 6 from La Castellina and 11 from Vanves fulfilled the same selection (or quality) criteria as those defined by Gallet and Le Goff (2006) and further presented in Gallet et al. (2008) and Genevey et al. (2009). These results are reported in Figure 6 and Table 1. In this figure, each curve thus corresponds to the R'(Ti) data obtained from one sample between 150°C-250°C (=T1) and 445°C-525°C (=T2). Note that some curves from Vanves (Fig. 6b) are significantly scattered, principally in the low-temperature range, because the magnetization fractions considered for the R'(Ti) computations are small. However this noise does not contribute significantly to the mean R'(Ti) values averaged over the entire T1 and T2 temperature interval. The R'(Ti) curves in both sites are very consistent, which allows one to compute well-defined site mean intensity values (i.e. by averaging the different mean R'(Ti) data obtained at the sample level), with standard deviations of less than 5% of the corresponding mean. These new values, although of different ages, are close to 80μT, which is much higher than the intensity value currently prevailing in France and in Italy (~47μT today in Paris and ~45μT in Civitavecchia).

Figure 7 displays a synthesis of the archeointensity results dated to the past three millennia presently available from Western Europe, which meet modern selection criteria. For the past eight centuries, however, we report only the well-dated results obtained by Genevey et al. (2009) because this data set satisfies several consistency tests and because it reveals a smooth intensity evolution contrasting with the large scatter when all available results are considered (for a discussion see in Genevey et al., 2009). For comparison, we also report data previously obtained from the Middle East (Syria and Iran; Genevey et al., 2003; Gallet et al., 2006). Note that all results in Figure 7 were transferred to the latitude of Paris. Figure 7 clearly shows that the geomagnetic field intensity variations in Western Europe were large and rapid during the past 3000 years. The second half of the first millennium BC was marked by a significant intensity decrease of ~30% in three to four centuries. The new result from La Castellina helps to better define a strong intensity maximum during the beginning of the first millennium BC, with a value of ~90μT at the latitude of Paris around the VIIth-VIIIth century BC. Several data from the Middle East nicely confirm this evolution and allow one to draw more precisely the intensity decrease between ~600BC and ~200 BC. The end of the first millennium AD was also characterized by a distinctive intensity peak centered around the VIIIth-IXth century AD. In particular, the result from Vanves provides further evidence for this peak. We note that it is in very good agreement with another archeointensity value of the same age previously obtained from Saran (~90 km south of Paris) by Genevey and Gallet (2002). After the IXth century AD, there was a large decreasing trend, perhaps with a rate as high as ~7μT per century until the XIIth century AD. Furthermore, Gallet et al. (2005) and Genevey et al. (2009) have shown that the evolution of geomagnetic field intensity during the past millennium was not regular, with the occurrence of at least two intensity peaks during the XIVth century AD and around 1600 AD. Although sometimes still scattered, the current

Western European archeointensity database is improving rapidly. In this context, the acquisition of two new archeointensity results from La Castellina and Vanves contributes to this effort.

5. Archeomagnetism and "Archeoclimate": a missing link?

From their archeomagnetic investigation conducted in France and in the Middle East, Gallet et al. (2003; 2006) proposed the existence of a new type of geomagnetic event, which they propose to call "archeomagnetic jerks". Occurring over multi-decadal time scales, these events are characterized by sharp and rapid directional variations ("cusps") synchronous with intensity maxima. Over the past three millennia, such archeomagnetic jerks were detected at ~800 BC, ~200 AD, ~750-800 AD and ~1400 AD (Gallet et al., 2003). Snowball and Sandgren (2004) and Gallet et al. (2006) further reported the possible occurrence of three older archeomagnetic jerks at ~2700 BC, ~2200 BC and ~1600 BC. The origin of archeomagnetic jerks is currently under debate (e.g. Stoner et al., 2005; Dumberry and Finlay, 2007; Knudsen et al., 2008; Valet et al., 2008; Gallet et al., 2009). Using global archeomagnetic field models, Dumberry and Finlay (2007) have proposed to link archeomagnetic jerks with some dynamics at the core surface at mid to high lalitudes of the northern hemisphere. Using the same approach, Gallet et al. (2009) recently went one step further, showing that archeomagnetic jerks most probably correspond to periods of maximum geomagnetic field hemispheric asymmetry. During these periods, the geometry of the geomagnetic field appears best described by an eccentric dipole significantly displaced from the Earth's center. Gallet et al. (2009) further proposed to link these most eccentric events with the production and gathering of magnetic flux patches at the core-mantle boundary within preferential longitudes. Though first detected in French archeomagnetic records, the best documented archeomagnetic jerks discussed by Gallet et al. (2003) would therefore possess a global signature.

The latter point is of special interest, as Gallet et al. (2005; 2006) have observed intriguing and repeated coincidences between archeomagnetic jerks and the occurrence of cooling events in western Europe over the past few millennia (Figure 8). This was, for instance, the case during the VIIIth century AD (Holzhauser, 1997; Holzhauser et al., 2005), and during the XIVth century AD with the occurrence of the first cooling episode of the Little Ice Age (e.g. Le Roy Ladurie, 2004). The repeated nature of these coincidences led us to propose some connection between the secular variation of the geomagnetic field and climatic changes over multi-decadal time scales. The physical mechanism that could link the two phenomena still remains uncertain, but Gallet et al. (2005) and Courtillot et al. (2007) suggested that the geomagnetic field variations of internal origin may modulate the cosmic ray flux interacting with the atmosphere. Based on the works of several authors focused on cosmic ray induced ionization of the atmosphere (e.g. Svensmark and Friss-Christensen, 1997; Marsh and Svensmark, 2000; Kovaltsov and Usoskin, 2007; Kirkby, 2007; Usoskin et al., 2008), it seems possible that such interaction produced significant changes in cloudiness, therefore modifying the radiation budget of the Earth and the temperatures at the Earth's surface (e.g. Gallet et al., 2005; Kovaltsov and Usoskin, 2007; Courtillot et al., 2007; Usoskin et al., 2008; Knudsen and Riisager, 2009). Although controversial (e.g. Bard and Delaygue, 2008; Courtillot et al., 2008), this scenario appears all the more plausible given that the archeomagnetic jerks indeed correspond to remarkable features in the global geometry of the Earth's magnetic field (Gallet et al., 2009). On another hand, results from the CLOUD (for "Cosmics Leaving OUtdoor Droplets") experiment, in which the conditions of interaction between the atmosphere and incoming high-energy particles will be simulated in a cloud chamber (e.g. Kirkby, 2007), should provide more physical and chemical constraints on the possible connection between cosmic rays and the production rate of clouds. Of course, the point here is not to reject the widely held view linking solar activity to climate variability over the past millennia (e.g. Bard and Frank, 2006), but to defend the idea that the geomagnetic field of internal origin may have an influence on atmospheric processes and climate that has been largely ignored until now. Moreover, Snowball and Muscheler (2007) recently emphasized the fact that, prior to 1600 AD, our still limited knowledge of dipole field moment evolution over centennial time scales is the "Achille's heel" of solar activity reconstructions derived from the geomagnetic-dependent past production rates of cosmogenic isotopes (^{14}C, ^{10}Be) in the Earth's atmosphere (see also St Onge et al., 2003). In any case, the possible connection between Earth (i.e. its geomagnetic field), Sun and Space (galactic cosmic ray flux) calls for the continuation of archeomagnetic studies in order to refine the description of geomagnetic field behavior over the past few millennia.

6. Discussion

6a. Archeointensity: a promising dating tool

Until very recently, directional variations of the Earth's magnetic field were the only available way to constrain the age of in-situ burnt structures, and sometimes of displaced materials for which hypotheses could be made regarding their position inside the kilns during firing (e.g. bricks and tiles; Lanos, 1987). However, the rapid development of archeointensity measurements in Europe over the past few years has allowed use of geomagnetic field intensity fluctuations as a dating tool. This should in particular offer the possibility to date all displaced baked materials commonly found in excavations, such as pottery, tile and brick fragments. For a given region, the efficiency of the method depends on the amplitude and rapidity of geomagnetic field intensity variations, and of course on our ability to make precise intensity determinations. Although the latter point is still debated, the consistency observed between archeointensity results dated to the same age is very satisfactory (see discussion in Genevey et al., 2009).

The new data presented in this paper, together with the previous results reported in Figure 7 clearly indicate that geomagnetic field intensity variations have been both large and rapid in Western Europe over at least the past three millennia, which is therefore favorable for obtaining precise age determination in this region. Such is in particular the case for the second half of the first millennium BC and the IXth-XIIth time interval, characterized in both cases by a significant intensity decrease. For those periods, archeointensity-based dating with a precision of a century or even less is a reasonable objective. The recent work of Genevey et al. (2009), focused on the past eight centuries, has further revealed the occurrence of two peaks in intensity during the XIVth century and around 1600 AD. Such an evolution would, for instance, make it possible to clearly distinguish fragments dated to the XVIth or XVIIth century from other fragments dated to the XVIIIth or XIXth century: a direct application would be, for example, the possible identification of fake ceramics. This curve also shows significantly different intensity values between the beginning and the end of both the XIVth and the XVIth centuries, which in the two cases may provide good chronological constraints. However, all these possibilities for dating should not make one forget the need for further acquisition of well-dated archeointensity data in order to refine the reference geomagnetic field intensity variation curve in Western Europe for the past few millennia.

There are several recent examples of archeomagnetic dating derived from geomagnetic field intensity variations (e.g. Kovacheva et al., 2004; Jordanova et al., 2004; Ben-Yosef et al., 2008). In particular, Ben-Yosef et al. (2008) took advantage of archeointensity data spanning the last few millennia BC now available from the Middle East to constrain the age of several poorly dated archeometallurgical sites. This approach, which relies on archeointensity determinations obtained from copper slag deposits, is promising, although the proposed ages do not seem definite because of the still limited time resolution of the “reference” archeointensity curve from the Middle East. At this stage, it is of interest to discuss further the comparison between reliable archeointensity data obtained from Western

Europe and from the Middle East. When concordant in age, the data appear very similar after reduction to the same geographic latitude using the approximation of a "simple" geocentric axial dipole. This indicates that, over the past few millennia, geomagnetic field intensity variations in Western Eurasia were strongly dominated by the dipole field component (or at least very low degree spherical harmonics), therefore offering the possibility to construct a composite reliable intensity variation curve that would integrate data obtained from different places over a large spatial area and concerning different civilizations, such as France, Italy, Greece, Bulgaria, Egypt or Mesopotamia (Genevey et al., 2008). We may, for instance, use Neolithic intensity data obtained from the Middle East to constrain the age of poorly dated potsherds found in Western Europe. Another consequence is also clear: the accuracy and the time resolution of the reference Western Eurasian intensity variation curve may be notably improved by selecting only the best dated groups of fragments available from the "richest" periods of the different concerned civilizations. Such careful selection of well-dated and reliable intensity results is however far from trivial (e.g. Genevey et al., 2008), but would doubtlessly increase the potential of (and the interest in) the archeointensity dating technique all over the Mediterranean area. Note that there is no other place in the world (neither South of North America, nor Africa or even China), where our knowledge of past regional geomagnetic field intensity fluctuations is presently good enough to currently use those variations for accurate dating.

6b. Archeomagnetism and ancient human societies

The influence of climate on the fate of ancient civilizations has been hotly debated for many years (see for instance deMenocal, 2001; Fagan, 2004; Issar and Zohar, 2004; Diamond, 2005). For many historians and archeologists, the risk, however, when correlating Holocene climate variability to human history, is to propose an over simplistic scenario in which anthropic actions on the evolution of civilizations are ignored. Moreover, obtaining evidence for a "collapse of civilization", a "cultural downturn" or even for a "civilization crisis" from highly fragmentary archeological records is not a trivial matter. Hence, Gallet and Genevey (2007) wrote with caution: "This potential influence, which serves as the foundation of 'climate determinism', can be viewed as the response of natural-resource-dependent, agricultural-based communities to climatically driven environmental changes. In some cases, these could have provoked major damage in economic and social organization of the societies, thus paving the way for political disintegration". And in fact, there are several examples in the literature in which major societal events were directly linked to climatic (drought) events: for instance in the Middle East, with the end of the Uruk civilization and the beginning of the Old Egyptian empire (end of the 4th millennium BC-beginning of the 3th millennium BC; e.g. Brooks, 2006) or the disappearance of the Akkadian empire and of the Old Egyptian empire around 2200 BC (e.g. Weiss et al., 2001; Cullen et al., 2000), and in Mesoamerica where the Classic Maya civilization was probably struck by different climate-related crises during the first millennium AD (e.g. Hodell et al., 1995; Haug et al., 2003). It is reasonable to believe that the social organization of some societies was particularly vulnerable to climate-induced environmental changes, in particular those living in semi-arid regions (Middle East) and in seasonal desert (Mesoamerica) where the water supply was most probably a critical factor in social and political stability. However, it is worth noting that the concept of "climate determinism", as first promoted by Huntington (1911) (see in Issar and Zohar, 2004), appears rather inappropriate, or at least too simplistic, because the reasons leading to the demise of well-organized societies were likely a complex combination of natural and human inter-related processes, though climate may have played the role of a catalyst.

Gallet et al. (2006) and Gallet and Genevey (2007) noted that some of the climatic variations (i.e. toward drier conditions) that may have caused social disruptions in the Middle East and in Mesoamerica (e.g. deMenocal, 2001; Weiss et al., 2001; Hodell et al., 1995) were synchronous with archeomagnetic jerks detected in Western Eurasia. If significant, that connection may indicate that the secular variation of the Earth's magnetic field has had an indirect impact, through its influence on regional or global climate, on the history of human civilization. While archeological baked materials such as pottery strongly reflect past human activity, their archeomagnetic study could in return provide information on the climate and environmental conditions which to some extent have shaped the history of humanity.

6c. Other techniques and applications of Archeomagnetism

Although efficient, the main application of archeomagnetism, however, cannot only be reduced to the dating of baked archeological materials. For instance, attempts have been made to recover a geomagnetic signal from pre-Columbian lime-plaster samples collected from the archeological site of Teotihuacan (Mesoamerica; Soler-Arechalde et al., 2006) or from sun-dried adobe bricks sampled in Peru and Egypt (Games, 1977; 1980). For the latter objects, laboratory experiments showed that a consistent but rather weak magnetic remanence was acquired in the ambient field, while the clay mixed with water was thrown and shaped in a wooden mold (inducing a "shear remanent magnetization"; Games, 1977), rather than during the drying itself (see also Genevey, 2002). In order to obtain intensity values, Games (1977; 1980) proposed to use a non-thermal method, involving the replacement of the ancient NRM measured on a brick sample by a new magnetization acquired after re-fabrication of the sample in known field conditions. The first results obtained by this author from Egyptian ancient adobe bricks were relatively promising, although scattered, but the effort was not pursued. One of the main reasons for this probably arose from the difficulty in routinely reproducing in the laboratory the original manufacturing process (with a significant change in scale between a whole brick and a small sample). Moreover, the physical process leading to the acquisition of the stable magnetization in adobe bricks remains poorly controlled, and much less understood than in the case of baked materials. Other attempts were also made to derive ancient geomagnetic field directions from mural paintings (Chiari and Lanza, 1997; 1999; Zanella et al., 2000; Goguitchaichvili et al., 2004). According to Chiari and Lanza (1997; 1999) and Zanella et al. (2000), the physical process of the magnetization acquisition in red colored painting is related to grains of hematite free to orient along the direction of the Earth's magnetic field when the paint applied to a wall is liquid; the magnetization becomes locked when the paint dries, thus forming a consistent "pictorial" remanent magnetization. Tests carried out in Italy, in particular in Pompei where the red color was often used for the backgrounds of wall paintings (Zanella et al., 2000), and in Mesoamerica have shown that it was possible to recover a rather consistent geomagnetic field direction from mural paintings. The precision of these determinations (α_{95} comprised between ~5° and ~10°) is not sufficient to derive strong dating constraints for the studied paintings or to integrate the data into a reference archeomagnetic directional database. But further investigation, for instance on the influence of roughness and porosity of the painted surfaces on the magnetic record, should strengthen this particularly interesting and promising approach dealing with sometimes very well dated materials.

Finally, although not directly relevant to the purpose of this paper, we briefly mention the important and fruitful application of soil magnetism to archeological prospection survey (e.g. see in Evans and Heller, 2003). Moreover, magnetic parameters, such as susceptibility, hysteresis and isothermal remanence, are increasingly used to characterize the nature and origin of non-heated archeological materials. This again concerns the properties of ancient iron-bearing paints found not only on walls but also on pottery (e.g., Stewart et al., 2002). Similar analyses were also performed to trace the provenance of archeological ochres from Australia (Mooney et al., 2003). In these examples, relatively simple magnetic measurements were indeed effective in discriminating between different materials and clearly appeared as a useful complement to more sophisticated geochemical analyses.

7. Conclusion

This paper aims at illustrating recent developments in archeomagnetism. Significant progress has been made on the regional and global description of the Earth's magnetic field for the past few millennia. For instance, archeomagnetic investigations in Western Europe and in the Middle East have led to the detection of a new type of geomagnetic events, the so-called archeomagnetic jerks, that may correspond to century-scale (global) episodes of maximum geomagnetic field hemispheric asymmetry. These events appear coincident with climatic cooling events, at least in Western Europe, which might reflect an influence of the Earth's magnetic field on cosmic ray flux ionizing the atmosphere. This connection is currently hotly debated, and calls for further investigation and thorough collaboration between researchers involved in Earth sciences and archeology. On the other hand, our increasing knowledge of geomagnetic field time variations, in particular in Western Eurasia, makes archeomagnetism a powerful dating tool for archeological purposes. Until recently, only directional geomagnetic variations have been used to constrain the age of burnt structures. Methodological progress in the determination of ancient geomagnetic field intensities and subsequent acquisition of new archeointensity data now make it possible to use geomagnetic field intensity fluctuations in order to obtain chronological markers. This development should allow one to use the archeomagnetic dating technique on potentially all in-situ and displaced baked materials. A few archeomagnetic studies have also shown that non-baked archeological objects, such as sun-dried bricks or paintings, may possess a stable, albeit weak remanent magnetization providing useful information on the ancient geomagnetic field. These many new results should foster renewed mutual interest between archeo-geomagnetism and archeology.

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Figure captions

Figure 1. Polar Maps up to the equator (hemispheres North and South) of the radial component of the Earth's magnetic field at 1600 AD derived from direct geomagnetic field measurements (Jackson et al., 2000). The color magnitude scale is in nT.

Figure 1. Cartes polaires jusqu'à l'équateur (hémisphères Nord et Sud) de la composante radiale du champ géomagnétique calculées pour 1600 ap. J.-C. à partir des mesures magnétiques directes (Jackson et al., 2000). Le code de couleur pour les intensités est en nT.

Figure 2. Directional evolution of the Earth's magnetic field in France during the past three millennia. The curve reported with a double line is deduced from French archeomagnetic data averaged over 80 year-long sliding windows shifted every 25 years between 0 AD and 1600 AD (Bucur, 1994) and over 160 year-long sliding windows shifted every 50 years between 1000 BC and 0 AD (Gallet et al., 2002). The mean directions are computed with their 95% confidence ovals using the bivariate Fisher statistics (Le Goff, 1990). The thick black line indicates the directional geomagnetic variations during the past centuries derived from direct field measurements (after Thellier, 1981).

Figure 2. Evolution directionnelle du champ géomagnétique en France durant les trois derniers millénaires. La courbe représentée par un trait double a été obtenue à partir des données archéomagnétiques françaises moyennées suivant des fenêtres glissantes de 80 ans déplacées tous les 25 ans entre 0 AD et 1600 AD (Bucur, 1994) et suivant des fenêtres glissantes de 160 ans déplacées tous les 50 ans entre 1000 BC et 0 AD (Gallet et al., 2002). Les directions moyennes sont calculées avec leur ovale de confiance à 95% à partir de l'extension bivariate de la statistique de Fisher (Le Goff, 1990). Le trait noir épais indique les variations géomagnétiques directionnelles durant les 4 derniers siècles obtenues à partir des mesures directes (d'après Thellier, 1981).

Figure 3. Archeomagnetic dating of the La Fanfarline lime kiln (Orgon, southeastern France; Brochier and Livache, 2004). (a) Picture of the kiln during the archeomagnetic sampling. (b) Comparison between the archeomagnetic direction obtained from the kiln (grey oval) and the reference French directional variation curve over the past two millennia built using sliding time windows of varying duration (Le Goff et al., 2002).

(c) Angular distance (γ-γ_c; grey curve) and associated “p” parameter (black curve) computed between the direction obtained from the Fanfarline kiln and each dated mean direction defining the reference French directional variation curve between 0 and 1625 AD (see text for further explanation). The archeomagnetic dating interval at 95% is indicated by the grey band.

Figure 3. Datation archéomagnétique du four à chaux de La Fanfaline (Orgon, sud-est de la France; Brochier et Livache, 2004). (a) Photo du four durant l’échantillonnage archéomagnétique. (b) Comparaison entre la direction archéomagnétique obtenue sur le four (ovale grisé) et la courbe française de référence des variations directionnelles du champ géomagnétique durant les deux derniers millénaires construite à l’aide de fenêtres glissantes de durée variable (Le Goff et al., 2002). (c) γ-γ_c (courbe grise) et paramètre “p” associé (courbe noire) calculés entre la direction obtenue sur le four de Fanfarline et chacune des directions moyennes datées définissant la courbe Française des variations directionnelles entre 0 et 1625 après J.-C. (voir le texte pour plus d’explications). L’intervalle de datation archéomagnétique à 95% est indiqué par une bande grisée.

Figure 4. Picture of the Triaxe magnetometer (Le Goff and Gallet, 2004).

Figure 4. Photo du magnétomètre Triaxe (Le Goff and Gallet, 2004).

Figure 5. Magnetic property measurements carried out on pottery fragments collected from La Castellina (Italy; code IT11) and Vanves (France; code VAN01/02) which yielded suitable archeointensity determinations. (a) Normalized IRM acquisition curves obtained for all fragments up to 0.8 T. (b)-(d) Examples of hysteresis loops obtained from two samples from Vanves and one sample from La Castellina. (e)-(h) Examples of normalized bulk susceptibility versus temperature curves.

Figure 5. Mesures des propriétés magnétiques des fragments de poteries échantillonnés à La Castellina (Italie; code IT11) et à Vanves (France; code VAN01/02) ayant donnée des résultats d’archéointensité exploitables. (a) Courbes normalisées d’acquisition d’aimantation rémanente isotherme jusqu’à 0.8 T obtenues pour tous les fragments. (b)-(d) Exemples de cycles d’hystérésis obtenus pour deux échantillons de Vanves et un échantillon de La Castellina. (e)-(h) Exemples de courbes de variations de la susceptibilité magnétique en fonction de la température.

Figure 6. Archeointensity results from La Castellina (a) and Vanves (b) obtained using the Triaxe magnetometer. Each curve represents the intensity data obtained from one sample over a large temperature interval (see text for further explanation).

Figure 6. Résultats d'archéointensité obtenus à La Castellina (a) and Vanves (b) en utilisant le magnétomètre Triaxe. Chaque courbe représente les données d'intensité obtenues pour un échantillon sur une large gamme de température (voir le texte pour plus d'explications).

Figure 7. Geomagnetic field intensity variations in Western Europe for the past three millennia as deduced from a compilation of archeointensity results which satisfy a set of reasonable selection criteria. Symbols, color codes and associated references are indicated to the right of the diagram. The data quoted with a * were corrected from a 5% cooling rate effect. Several data obtained from the Middle East are also reported (open and filed purple squares). All data were transferred to the latitude of Paris.

Figure 7. Variations de l'intensité du champ géomagnétique en Europe de l'Ouest au travers des trois derniers millénaires déduites d'une compilation de données d'archéointensité satisfaisant un ensemble raisonnable de critères de sélection. Les symboles, les codes de couleur et les références associées sont indiqués sur la droite du diagramme. Les données marquées par un * ont été corrigées d'un effet de vitesse de refroidissement de 5%. Quelques résultats obtenus au Moyen-Orient sont également reportés (carrés pleins et vides de couleur violet). Toutes les données ont été transférées à la latitude de Paris.

Figure 8. Geomagnetic field intensity variations obtained from Western Europe (same data and symbols as in Figure 7 for the past two millennia) and the Middle East (for the last 4 millennia BC) against climatic fluctuations in the eastern North Atlantic-Western European region (modified from Gallet and Genevey, 2007). The data from the Middle East are from Genevey et al. (2003; open squares), Gallet et al. (2006; filed squares) and Gallet et al (2008; filed triangles). An overall good coincidence is observed between periods of field intensity increase (horizontal bands) and cooling events (vertical bands) marked by glacier advances on land (Holzhauser, 1997; Holzhauser et al., 2005) and increases in ice-rafted debris in deep-sea sediments (after Bond et al., 2001). See in Gallet et al. (2006), Bard and Delaygue (2008) and Courtillot et al. (20080 for discussion.

Figure 8. Comparaison entre les variations de l'intensité du champ géomagnétique obtenues en Europe de l'Ouest (mêmes données et symboles que ceux de la Figure 7 pour les deux derniers millénaires) ainsi qu'au Moyen-Orient (pour les 4 derniers millénaires av. J.-C.) et les fluctuations climatiques dans la zone Est de l'Atlantique Nord et en Europe de l'Ouest (figure modifiée d'après Gallet et Genevey, 2007). Les données du Moyen-Orient sont celles de Genevey et al. (2003; carrés ouverts), Gallet et al. (2006; carrés pleins) et Gallet et al. (2008; triangles pleins). Une bonne coïncidence est observée entre les périodes d'augmentation forte de l'intensité du champ géomagnétique (bandes horizontales) et des épisodes de refroidissement (bandes verticales) marqués à terre par des avancées de glaciers (Holzhauser, 1997; Holzhauser et al., 2005) et des augmentations de la proportion de débris glaciaires dans les sédiments océaniques (d'après Bond et al., 2001). Pour une discussion, voir Gallet et al. (2006), Bard et Delaygue (2008) et Courtillot et al. (2008).

Table caption

Table 1. New archeointensity results obtained from La Castellina (IT11) and Vanves (VAN01/02) using the Triaxe method. Tmin-Tmax, temperature interval (in °C) for intensity determination; Hlab, laboratory field used for TRM acquisition; NRM T1(%), fraction of NRM involved from T1 in intensity determination; Slope R' (%), slope of the R'(Ti) data (see text for further explanation); F Triaxe, Intensity value in µT derived from each fragment; F mean, mean intensity value in µT obtained at the site and its standard deviation; F mean in Paris, mean intensity value in µT obtained at the site transferred to the latitude of Paris.

Tableau 1. Nouvelles données d'archéointensité obtenues à La Castellina (IT11) et à Vanves (VAN01/02) en utilisant la méthode du Triaxe. Tmin-Tmax, intervalle de température (en °C) considéré pour les déterminations d'intensité; Hlab, champ de laboratoire utilisé pour acquérir des aimantations thermorémanentes; NRM T1(%), fraction d'aimantation comptée à partir de T1 considérée pour déterminer une valeur d'intensité; Slope R' (%), pente définie par les données de R'(Ti) (voir le texte pour plus d'explications); F Triaxe, valeur d'intensité obtenue pour chacun des fragments; F mean, valeur moyenne d'intensité (en µT) obtenue au site et sa déviation standard; F mean in Paris, valeur moyenne d'intensité (en µT) transférée à la latitude de Paris.

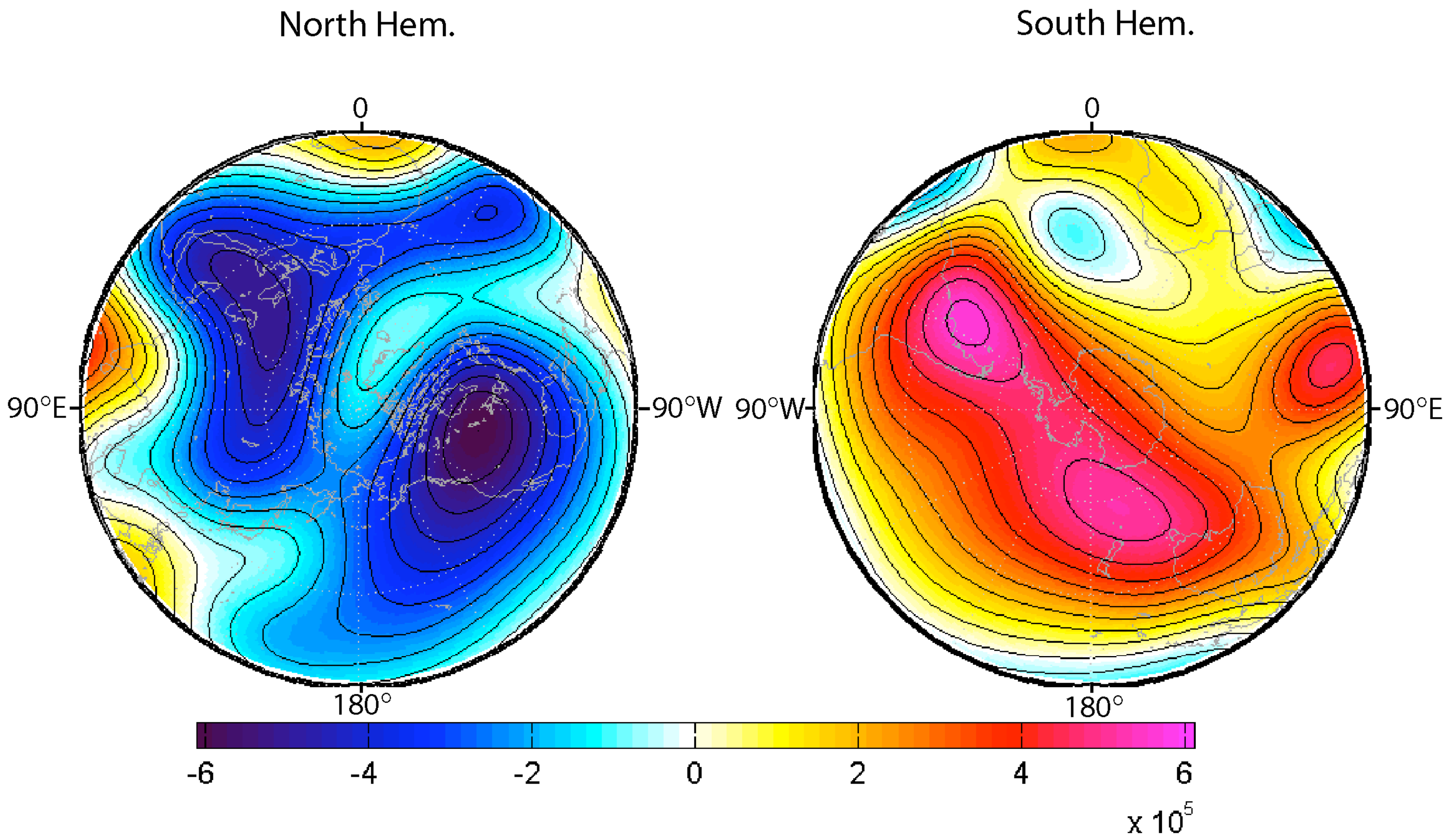


Figure 1.

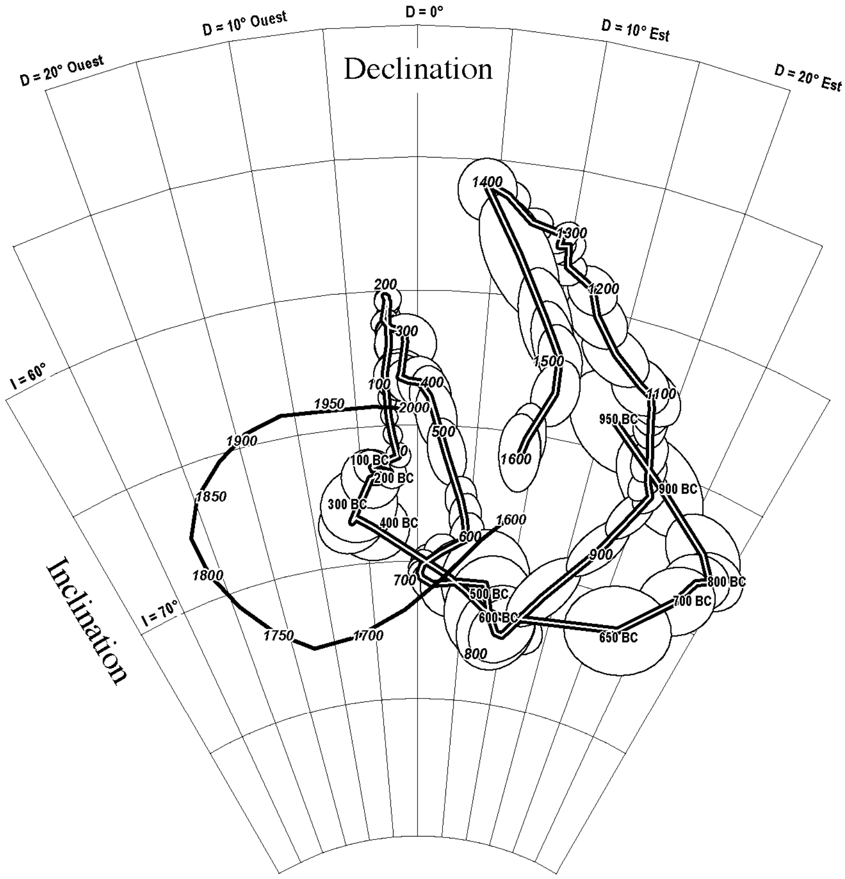

D = 20° Ouest
D = 10° Ouest
D = 0°
D = 10° Est
D = 20° Est
Declination
Inclination
I = 60°
I = 70°
1400
1300
1200
1100
1500
1600
950 BC
900 BC
900
800 BC
700 BC
650 BC
600 BC
500 BC
800
700
600
1600
200
300
400
100
2000
500
100 BC
200 BC
300 BC
400 BC
1950
1900
1850
1800
1750
1700

Figure 2.

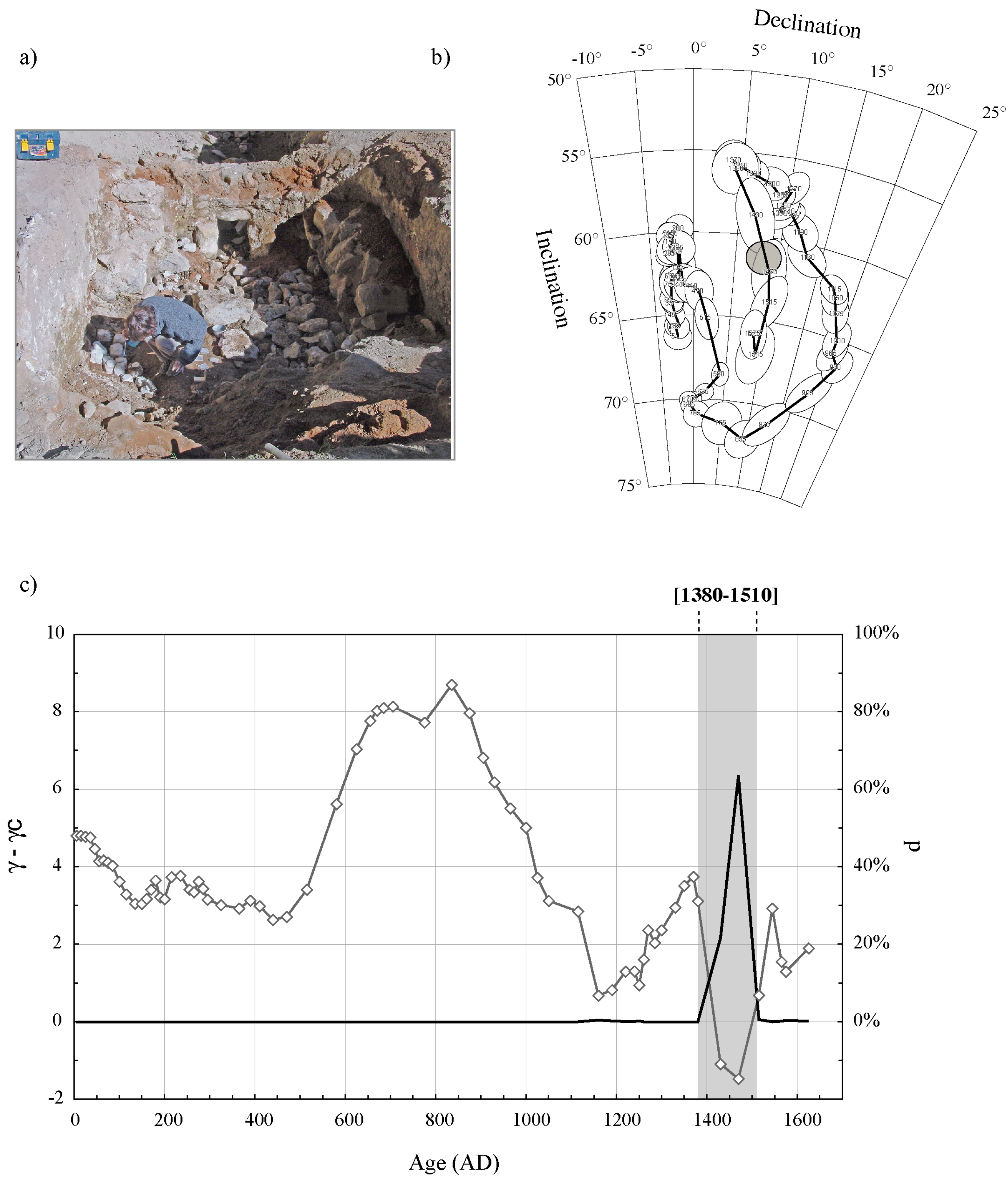

a)
b)
Declination
-10°
-5°
0°
5°
10°
15°
20°
25°
50°
55°
60°
65°
70°
75°
Inclination
c)
[1380-1510]
10
8
6
4
2
0
-2
100%
80%
60%
40%
20%
0%
γ - γc
p
0
200
400
600
800
1000
1200
1400
1600
Age (AD)

Figure 3.

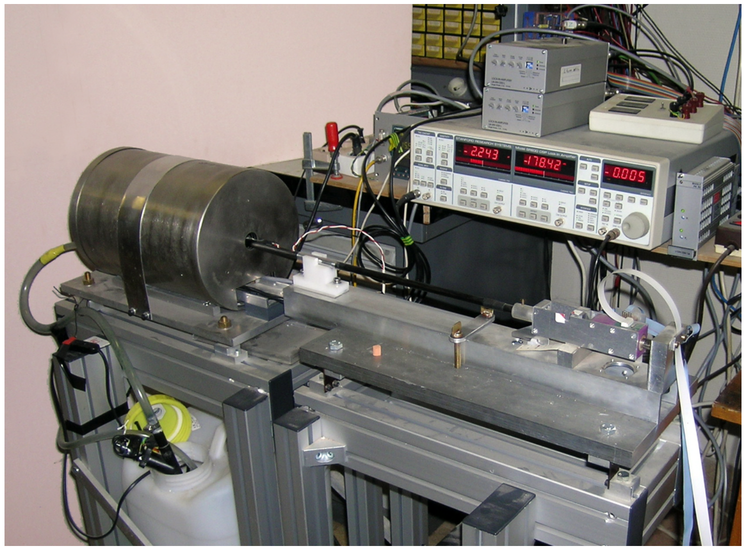


Figure 4.

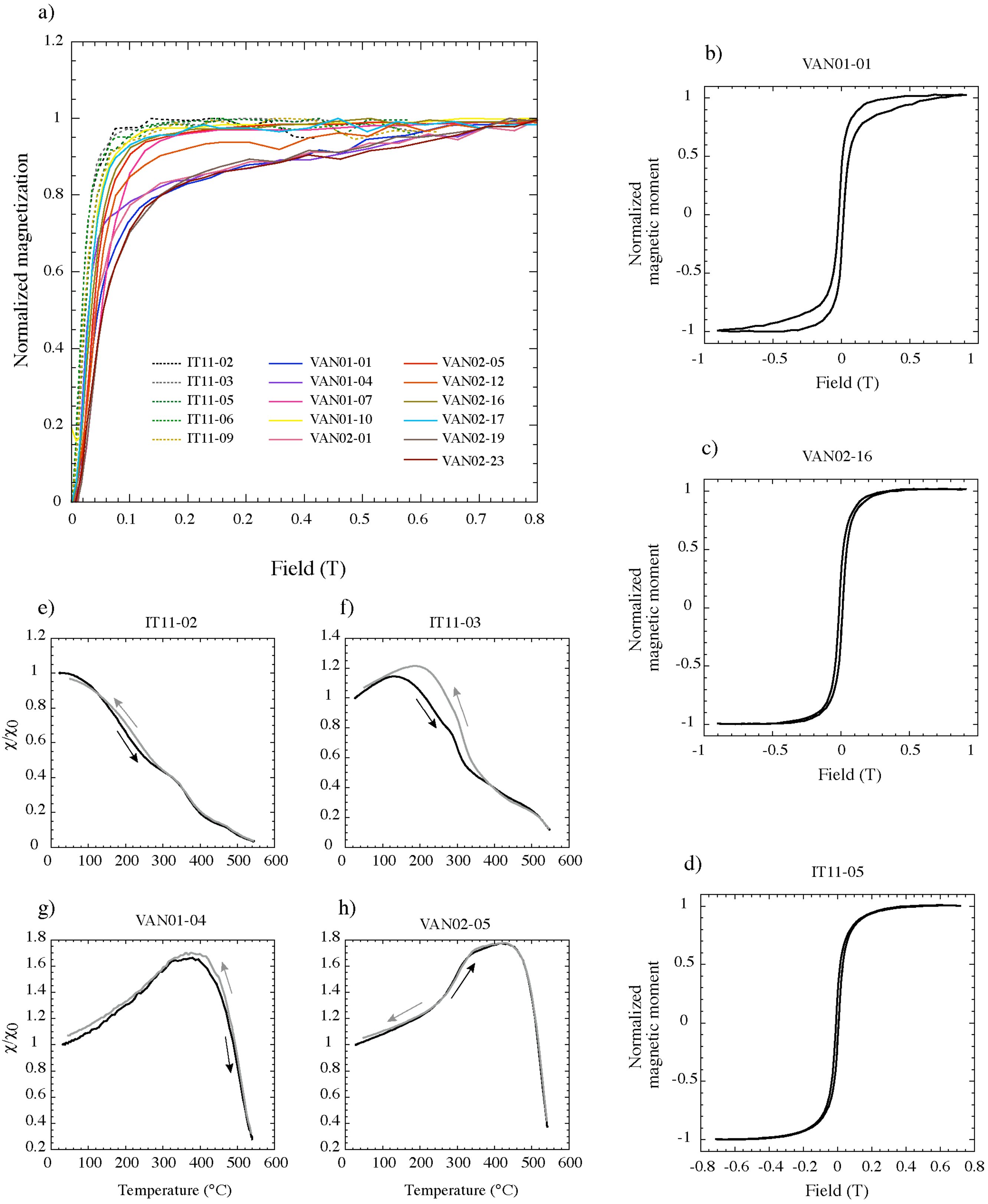
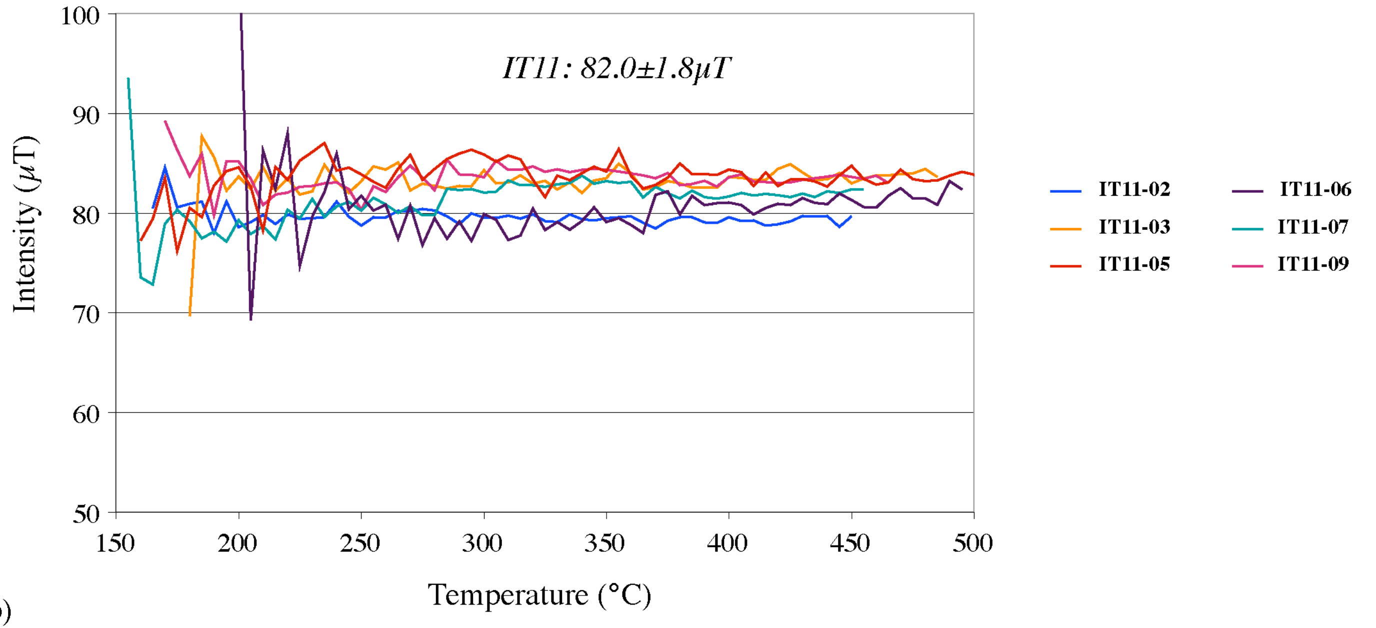

a)
Normalized magnetization
Field (T)
IT11-02
IT11-03
IT11-05
IT11-06
IT11-09
VAN01-01
VAN01-04
VAN01-07
VAN01-10
VAN02-01
VAN02-05
VAN02-12
VAN02-16
VAN02-17
VAN02-19
VAN02-23
b)
VAN01-01
Normalized magnetic moment
Field (T)
c)
VAN02-16
Normalized magnetic moment
Field (T)
d)
IT11-05
Normalized magnetic moment
Field (T)
e)
IT11-02
χ/χ_0
f)
IT11-03
g)
VAN01-04
χ/χ_0
Temperature (°C)
h)
VAN02-05
Temperature (°C)

Figure 5.

a)


IT11: 82.0±1.8μT
Intensity (μT)
Temperature (°C)
100
90
80
70
60
50
150
200
250
300
350
400
450
500
IT11-02
IT11-03
IT11-05
IT11-06
IT11-07
IT11-09

b)

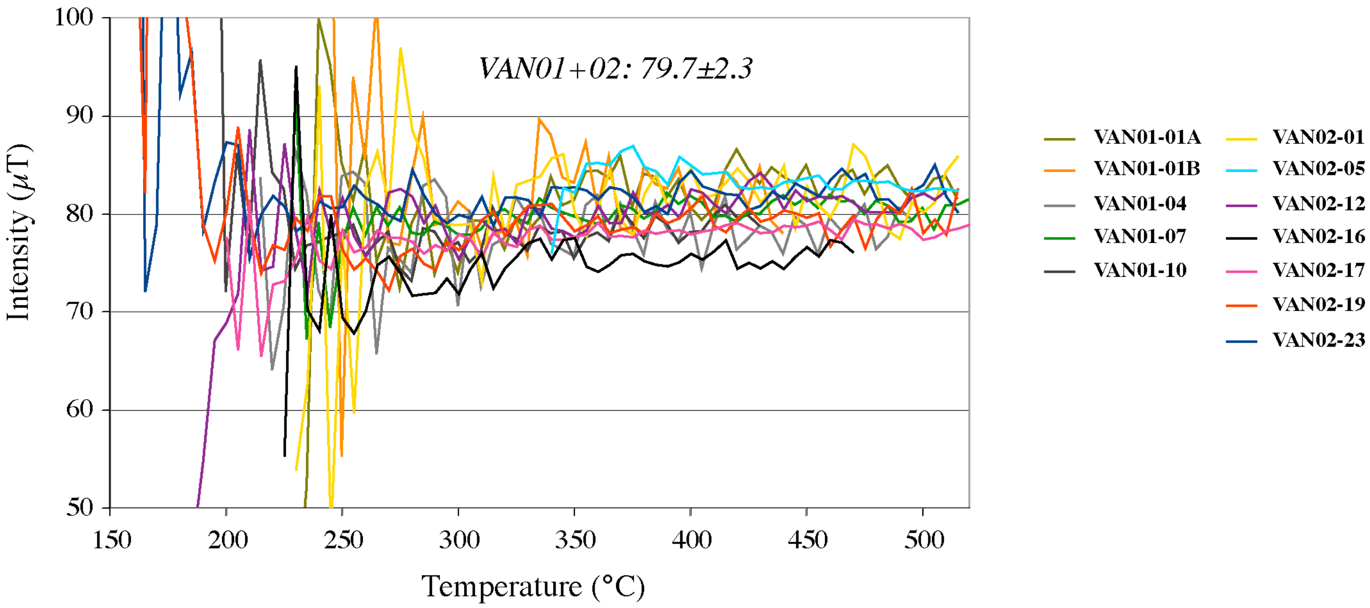

VAN01+02: 79.7±2.3
Intensity (μT)
Temperature (°C)
100
90
80
70
60
50
150
200
250
300
350
400
450
500
VAN01-01A
VAN01-01B
VAN01-04
VAN01-07
VAN01-10
VAN02-01
VAN02-05
VAN02-12
VAN02-16
VAN02-17
VAN02-19
VAN02-23

Figure 6.

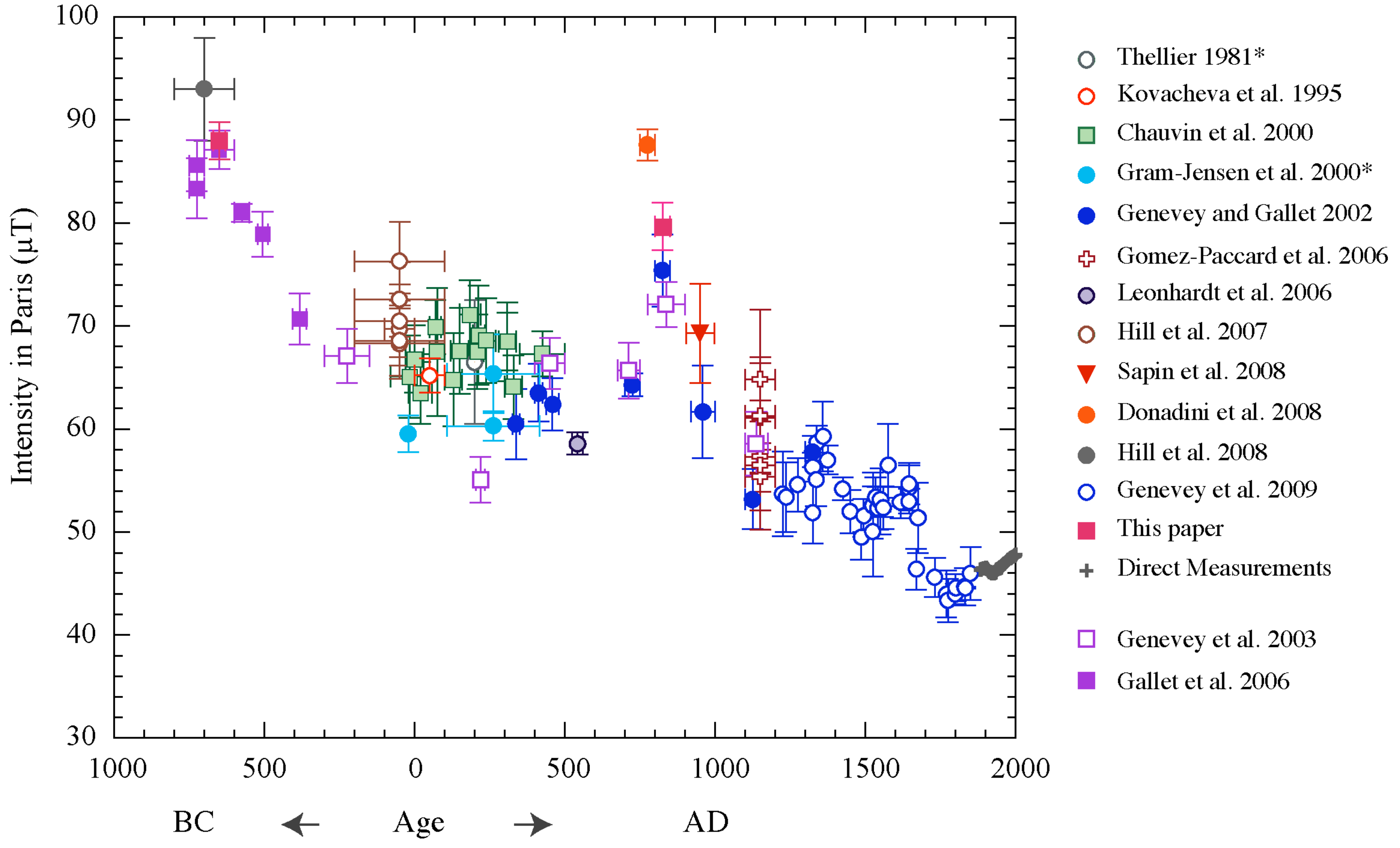
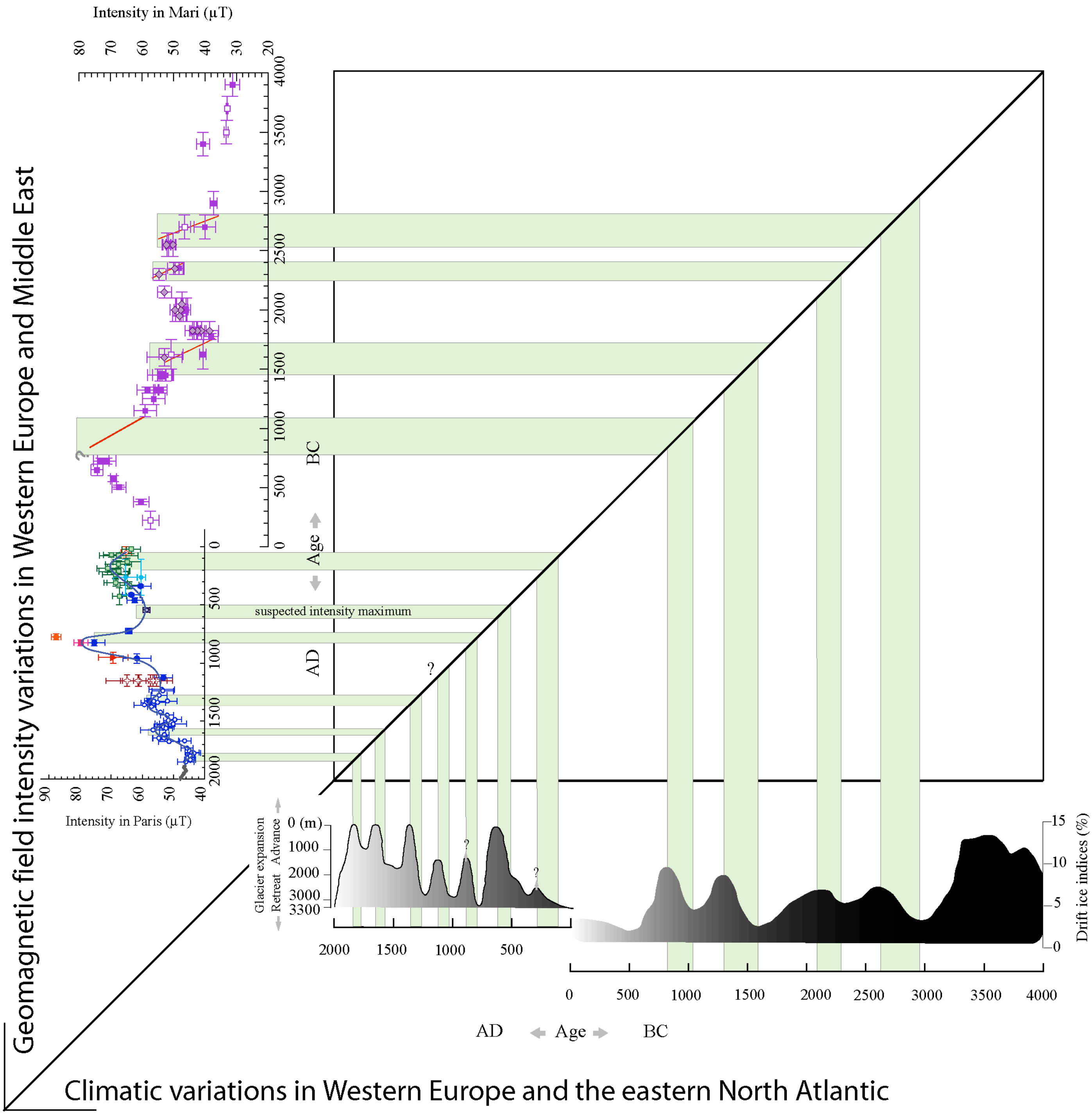

100
90
80
70
60
50
40
30
Intensity in Paris (μT)
1000
500
0
500
1000
1500
2000
BC
Age
AD
Thellier 1981*
Kovacheva et al. 1995
Chauvin et al. 2000
Gram-Jensen et al. 2000*
Genevey and Gallet 2002
Gomez-Paccard et al. 2006
Leonhardt et al. 2006
Hill et al. 2007
Sapin et al. 2008
Donadini et al. 2008
Hill et al. 2008
Genevey et al. 2009
This paper
Direct Measurements
Genevey et al. 2003
Gallet et al. 2006

Figure 7.



Geomagnetic field intensity variations in Western Europe and Middle East
Intensity in Mari (µT)
Intensity in Paris (µT)
suspected intensity maximum
Age
AD
BC
Glacier expansion
Retreat Advance
0 (m)
1000
2000
3000
3300
Drift ice indices (%)
AD Age BC
Climatic variations in Western Europe and the eastern North Atlantic

Figure 8.

Fragment	Tmin-Tmax (°C)	H Lab (μT)	NRM T1 (%)	Slope R' (%)	F Triaxe (μT)	F mean ± SD (μT)	F mean in Paris (μT)
IT11, La Castellina (42.1°N, 11.2°E), [670-1630] BC							
IT11-02	155-450	80	76	-1	79,5	82.0±1.8	88,0
IT11-03	180-495	75	67	1	83,3		
IT11-05	155-505	80	78	1	83,7		
IT11-06	200-495	80	74	2	80,4		
IT11-07	155-455	80	78	5	81,3		
IT11-09	145-465	80	81	0	83,5		
VAN01/02, Vanves (48.8°N, 2.3°E), [800-850] AD							
VAN01-01A	225-515	75	89	5	81,9	79.7±2.3	79,8
VAN01-01B	245-445	80	56	-2	82,2		
VAN01-01					82.1±0.2		
VAN01-04	215-495	75	77	2	78,2		
VAN01-07	230-525	75	93	3	80,1		
VAN01-10	195-430	80	82	-1	78,4		
VAN02-01	230-515	70	89	2	81,8		
VAN02-05	370-515	75	94	-2	82,4		
VAN02-12	160-515	75	81	5	80		
VAN02-16	225-470	75	91	5	74,8		
VAN02-17	200-525	75	77	4	77,7		
VAN02-19	160-515	75	94	-2	79,3		
VAN02-23	160-515	75	92	-1	82		

Table 1