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How to cite

HEDLEY, Ian George. New directions in archaeomagnetism. In: Journal of radioanalytical and nuclear chemistry, 2001, vol. 247, n° 3, p. 663–672. doi: 10.1023/A:1010627821170

This publication URL: https://archive-ouverte.unige.ch/unige:164453
Publication DOI: 10.1023/A:1010627821170

Journal of Radioanalytical and Nuclear Chemistry, Vol. 247, No. 3 (2001) 663–672

New directions in archaeomagnetism

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(Received August 25, 2000)

Since the first magnetic analyses of archaeological materials were carried out over a century ago, archaeomagnetic reference curves are now available covering the last few millennia. It would seem to be an appropriate time to examine the archaeomagnetic record to see how it can be improved. For directional studies the disturbing factors include magnetic refraction, mechanical deformation, local magnetic field anomalies, and magnetic anisotropy. In the complex field of archaeointensity determination there is a real need for faster and more reliable methods. The use of sediments on Palaeolithic sites will be increasingly important for the dating of early hominids.

Introduction

Direct measurements of the geomagnetic field, which began in Europe during the 16th century, have shown that the field varies slowly over a time scale of many centuries, and this is known as secular variation. For earlier times one must use the magnetic record carried by archaeological baked clays.

The magnetic study of archaeological artefacts began over a century ago with the investigation by an Italian scientist, Guiseppe FOLGHERAITER[1] of some ancient Italian and Greek vases. This pioneering work gave the surprising result that the geomagnetic field in Italy had a negative inclination in the 7th century BC, which could be interpreted as a reversal of the geomagnetic field. However, this was most probably due to the uncertainty in the vases' orientation in the potter's oven and more recent studies have shown that the field was definitely not reversed at this time.

It is only during the last 50 years that intensive studies of ovens and hearths have enabled standard curves of the variation of the earth's magnetic field to be established in the United States, Europe and Asia. These regional reference curves are valid over an area some 600 to 1000 km in radius and cover a time period reaching back two to six millennia depending on the geographical location.

Basic principles

Archaeomagnetism is based on two phenomena, one geophysical: the slow temporal variation of the earth's magnetic field, and the other physical: the recording of this field by the iron oxides present in baked clay during the last cooling-down of a burnt structure. This record is in the form of a thermoremanent magnetization (TRM) which is not only strong but also has a considerable stability. Under the hypothesis that the TRM is parallel and proportional to the ambient magnetic field, laboratory magnetic analysis of the baked clay enables the ancient magnetic field to be determined. Baked clay is a common feature of archaeological sites in the form of hearths, ovens and potsherds, so there is a potentially abundant source of material for archaeomagnetic analyses. The validity of the basic premise of archaeomagnetism: that the remanent magnetization is an accurate record of the ancient geomagnetic field, is examined below.

Directional studies

Experimental techniques used in laboratory analysis, which are basically the same as those used in palaeomagnetic studies on rocks, are now well established. They are considered to accurately measure the magnetization of archaeomagnetic samples.[2] Although field orientation procedures vary according to the laboratory, even with small one-inch samples, the precision of the azimuth of an individual specimen is within 2°. Values given in the literature vary from 1°[3] to 0.25°.[4] As a dozen specimens are normally taken from each structure, the effect of a random orientation error on the mean direction probably does not exceed 1°.

However, examination of direction-time plots of the raw archaeomagnetic data,[5,6] shows a surprisingly large scatter. In the case of the British archaeomagnetic data set this situation has previously been commented on.[7] Although some part of the scatter could be due to dating errors, there must be a considerable contribution from the magnetic data itself, despite careful controls to eliminate poor quality results.

The different factors which could falsify the recording process will be discussed in detail.

Local field distortion

It is normally assumed that the local magnetic field around an archaeological burnt structure is homogeneous and the geomagnetic elements (declination, inclination, and total intensity) correspond to those of the regional

Akadémiai Kiadó, Budapest
Kluwer Academic Publishers, Dordrecht

magnetic map. Distortion of the local magnetic field in archaeomagnetism is generally thought to be unimportant.[7] The presence of a significant local magnetic anomaly (in declination) can be checked by using a sun compass, and HATHAWAY and KRAUSE[8] even report finding a 1.6° error in the published regional magnetic map. Even if it is not possible to use a sun compass (e.g., cloudy conditions or inside a building), the presence of a significant magnetic anomaly can be simply detected on-site using a digital magnetic compass as a dip meter.

A recent study of a medieval hearth in the old town of Winterthur revealed a surprising magnetic anomaly. The flat hearth gave a remarkably good archaeomagnetic result (alpha 95% = 0.7°, $k = 3390$) but the mean direction of remanence indicated an age in the 14th century based on the French archaeomagnetic reference curve[9] (Fig. 1). This is much younger than the 9–10th century date given by the archaeological context and available radiocarbon dates.

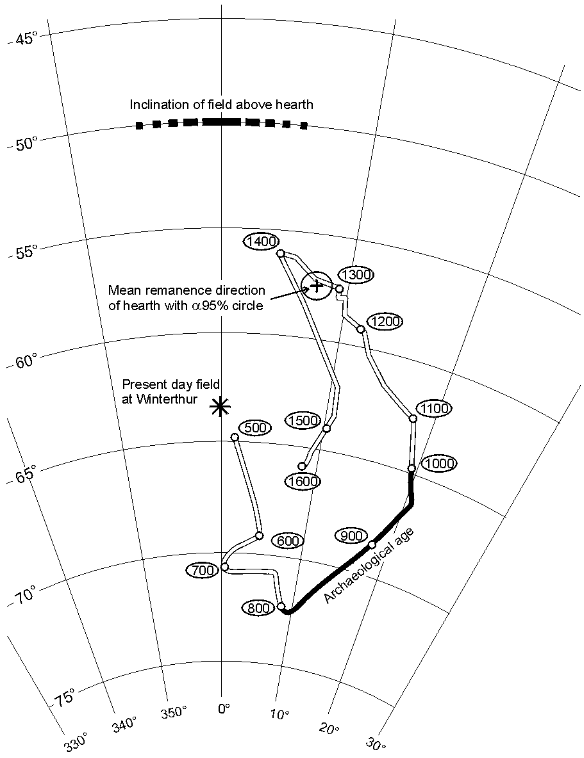

Fig. 1. Archaeomagnetic result from hearth 319 in the basement of Obergasse 30, Winterthur, Switzerland. The stereographic projection shows part of the archaeomagnetic reference curve for Paris from 500 to 1600 AD adapted from BUCUR[9]

It was not possible to use a sun compass to check any discrepancy in declination, as the hearth was well inside the house, but a detailed magnetic survey was made above the remains of the hearth using a triaxial fluxgate magnetometer (Applied Physics Systems 520). This revealed that the inclination (Fig. 2) was 11° to 14° lower than the expected value[10] of 63.4°. The hearth was in the basement of a house built of wood and stone, with the only iron nearby being the remains of a modern reinforced concrete floor about 1 m 50 cm away. The observed shallowing of the present geomagnetic field inclination is enough to explain the difference between the archaeomagnetic age and the archaeological age. However, the field anomaly would have had to been present in the Middle Ages when the hearth was used, long before the use of iron as a structural element in buildings. The basement of the house underneath the hearth was recently completely excavated, but no scrap iron or possibly magnetic erratic blocks were discovered and the cause of the magnetic field anomaly remains unexplained. This unexpected result shows that the local magnetic field should always be routinely checked as part of the archaeomagnetic sampling procedure, especially on urban sites.

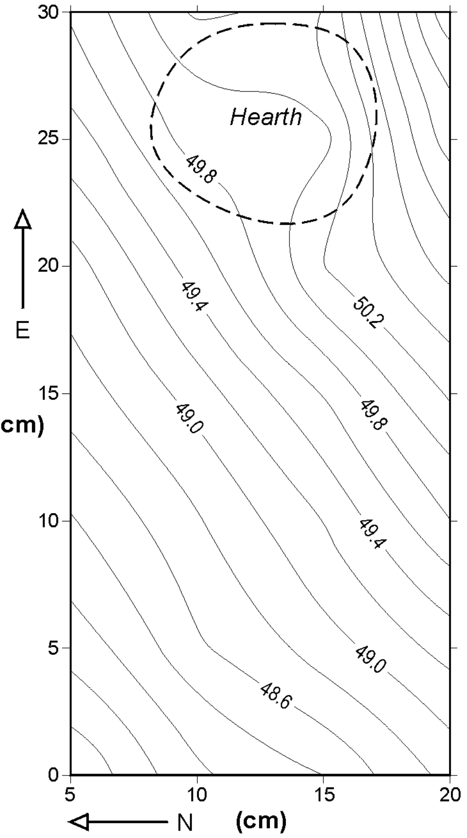

Fig. 2. Magnetic inclination in the basement of Obergasse 30, Winterthur, ZU, Switzerland, at a height of 10 cm above the remains of the hearth. Regional inclination is 63.4°[10]

Magnetic refraction

Of all the possible sources of error in archaeomagnetic studies, that produced by magnetic refraction has probably received the most attention in the literature. This effect is thought to occur when a burnt structure, which is sufficiently magnetic, cools down in its own field. Depending also on the shape of the structure, the direction of the final TRM is no longer parallel to the ambient magnetic field.

The solution of this problem is theoretically difficult but a simplification by COE[11] enables the effect to be estimated. EVANS and HOYE[12] have applied the COE's approach to archaeological structures in the form of a flat sheet and conclude that for a remanence value of 3.7 A/m (median value of specimens from 30 Mediterranean kilns) the maximum possible median value of the deflection of the remanence is 1.2°. Only in the case of very strong specimens does the theoretical deflection exceed 4°.

Experimental studies

Because of the theoretical intractability this effect has been more thoroughly investigated experimentally. An early study of six Roman and Saxo-Norman kilns[13] revealed an average shallowing of the inclination in the floors compared to the walls of 2.4°.

The variation in direction in samples taken from the walls of experimental kilns shows an effect different from that expected from a simple magnetic refraction for instead of $\sin 2\theta$ dependence of declination a $\sin\theta$ one is observed.[14] This was called "kiln wall fall-out" as it corresponds to an outward movement of the kiln walls of a few degrees. However, subsequent study of two circular replica kilns[15,16] failed to reveal such mechanical tilting apart from irregular movements less than 1.5°. Clearly, some form of magnetic refraction was present.

Recent detailed experiments on hemispherical experimental kilns[17] also show a strong refraction effect with a deflection of up to 40° in declination and 15° inclination but for a high mean magnetization of 20 A/m. If enough samples are taken the effects of refraction in the latter study are drastically reduced which supports the recommendation given some 20 years previously[18] that all parts of a structure should be sampled in order to minimize the effect of magnetic distortion and so obtain a more reliable result. However, the ambient magnetic field direction still lies outside the alpha 95% confidence circle around the mean direction of the kiln.

A recent study of two experimental bronze casting furnaces (both Iron and Bronze Age types) sampled at the Reinach Folk Museum in Switzerland is shown in Fig. 3a. The local field direction lies inside the largest alpha 95% circle (8.2±0.3 A/m) but is well outside the smallest (3.1±2.1 A/m). Another experimental oven, a rectangular Iron Age bronze casting furnace (mean remanence 5.9±2.1 A/m) at Schloss Wildegg, (Canton of Aargau), shows the same disagreement between the local geomagnetic field and the mean remanence direction (Fig. 3b).

This infidelity of the recording of the direction of the geomagnetic field is also seen in a whole series of experimental hearths in Colorado.[2] In half of these the ambient field direction is outside the alpha 95% cone of confidence centred around the mean direction of magnetization and in a few cases it lies at an angle greater than twice alpha 95%.

The source of these differences is not certain but magnetic refraction is the most likely cause with each specimen in a particular structure being affected differently according to its orientation and magnetic properties. An appreciation of these discrepancies is important for the interpretation of the archaeomagnetic record and its application to dating.

Magnetic anisotropy

Alignment of the plate-like clay particles during working of the unfired clay leads to anisotropic magnetic properties, which are further enhanced by firing.[19] Archaeological ceramics such as tiles and pottery are made by compression or by turning, which produces a considerable magnetic anisotropy.[20] A consequence of this anisotropy is that the induced magnetization is no longer parallel to the external magnetic field.

In the case of a substantial anisotropy it is necessary to apply a correction to determine the direction and intensity of the ancient geomagnetic field.[21] However, in the case of hearths and ovens made from massive clay the anisotropy is less marked and usually no correction is made in archaeomagnetic directional studies.

However, a directional study of a lime-kiln in the Roman fort of Vindonissa (Windisch, AG) was the subject of an anisotropy correction, because of the unusual construction of the circular inner wall (Fig. 4a) using tiles.[22] This was determined by giving the tiles successive laboratory TRM's in three perpendicular directions.[21] The magnetic properties of the tiles were very variable probably due to the reducing atmosphere produced by the carbon dioxide released by the decomposing limestone. Very strong (J>8 A/m) and weak (J<0.5 A/m) specimens were rejected.

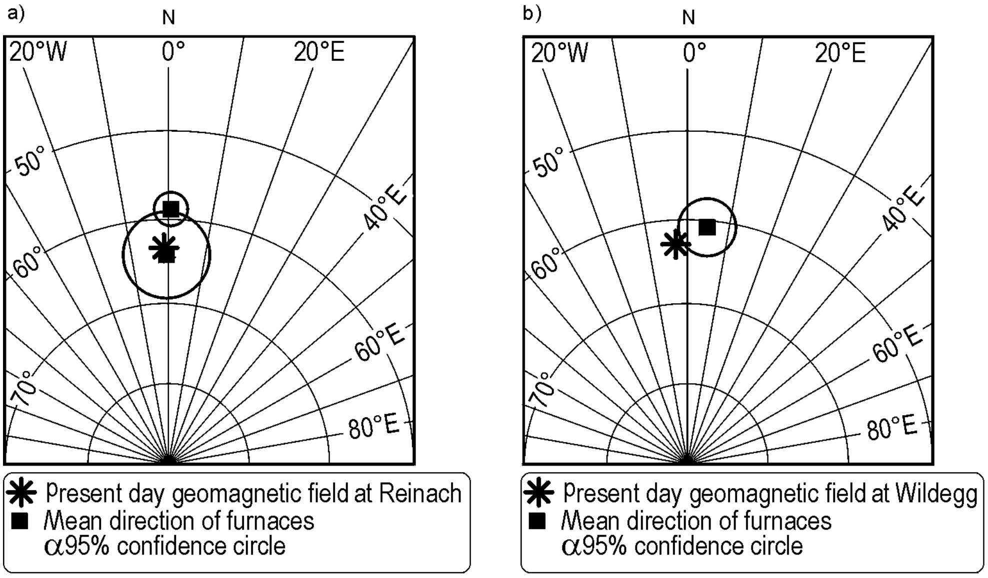

Fig. 3. Archaeomagnetic results from experimental bronze casting furnaces at: (a) Reinach Folk Museum, BL, and (b) at Schloss Wildegg, AG. Switzerland

Because of the highly dispersed orientation of the tiles with respect to the direction of the geomagnetic field the mean direction calculated from 13 tiles does not change significantly with the correction; from 358.2°, 61.1° to 357.6°, 61.8°. However, the dispersion of individual directions is slightly reduced (Figs 4b and c) with the alpha 95% dropping from 2.19° to 2.04°, and the precision parameter rising from 360 to 414. The anisotropy of the thermoremanence of the tiles was very variable (2–20%) with the direction of remanence being deflected up to 5°. If an overall anisotropy correction is applied to all the tiles a minimum dispersion of the remanence directions was obtained with an anisotropy of 15%.

Although the end effect on the mean direction is not important in this lime-kiln, the considerable magnetic anisotropy of Roman tiles means that a hearth made up of flat tiles could have its remanence shallowed by several degrees.[23] Archaeomagnetic studies on potentially anisotropic material should include a check of the magnetic anisotropy.

Mechanical deformation

As well as the condition that the baked clay should have been heated to beyond its Curie point (570–670 °C) a second essential condition for an archaeomagnetic study is that the burnt structure should have remained undisturbed since its abandon. The sources of site disturbance are very varied, ranging from burrowing animals to earthquakes.[24] Considering the heavy overburden and the plastic nature of soil strata, deformation could be potentially important, particularly on ancient sites.

STERNBERG[25] has shown how aberrant archaeomagnetic results obtained on ovens from Tel Ashkelon, Israel can be interpreted in terms of mechanical shifting and suggests that seismic activity and the steep topography could be major factors on this site.

A recent study of Late Bronze Age flat hearths in the south of France[26] has shown that it is possible to correct for post abandon deformation and also use it as a magnetic stability test. One of the hearths was markedly dome shaped and a simple tilt correction on the specimens to make them horizontal not only dramatically reduced the dispersion of individual directions but also brought the mean direction into coincidence with those of two other hearths on the same site, and which had no marked deformation (Fig. 5). After the correction the alpha 95% dropped from 3.36° to 1.44° and the precision parameter k increased from 90.5 to 490 ($n=21$). This observation has since been confirmed on deformed hearths from two other Protohistoric sites.

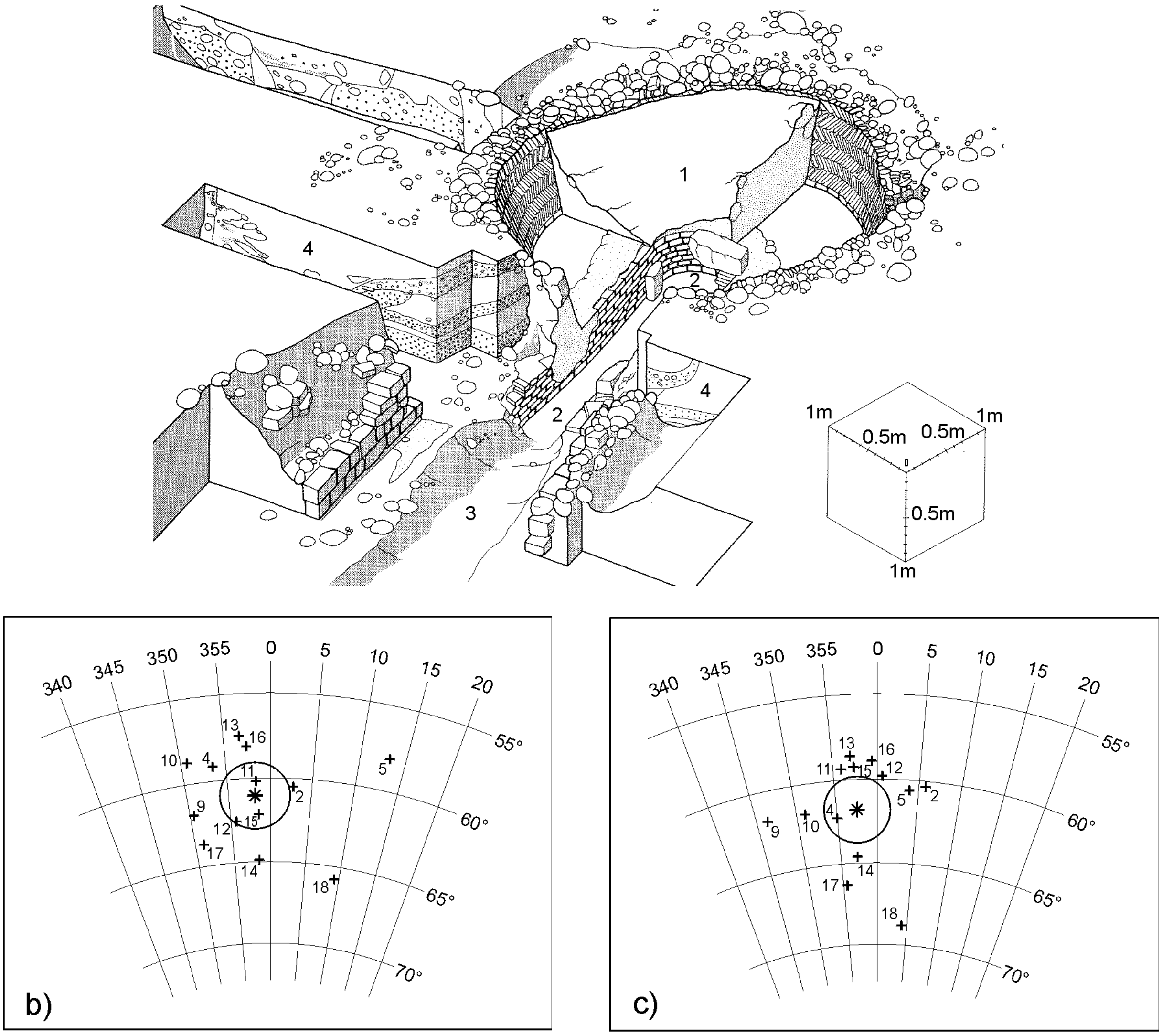

Fig. 4. 3D view of the Vindonissa lime-kiln (a); specimen directions before anisotropy correction with mean direction and confidence circle (b); specimen directions after anisotropy correction (c)

Although it is not always possible to assess the presence of a post-abandon deformation of an oven or hearth, an attempt should always be made during sampling by measuring the inclination of any quasi–horizontal or -vertical surfaces.

Internal consistency

Multiple contemporary hearths from the same archaeological site are a valuable control on the fidelity of the archaeomagnetic recording process. The variability observed in three series of experimental hearths in Colorado[2] has already been mentioned.

In this context the study of some late Hallstatt flat hearths from the south of France, which gave high quality archaeomagnetic results and which cover a time span of no more than 40 years, is relevant. Only 3 of the 7 hearths have mean directions, which overlap within their alpha 95% cones (Fig. 6). The mean directions of the other hearths are more dispersed and even a rapid change in geomagnetic field during this short period would not explain the dispersion of directions observed. It is difficult to see how a magnetic refraction could be responsible as the strongest hearth also has the largest inclination, whereas a refraction effect would be expected to produce a shallowing. Instability of the ground could be the cause, with a tilting of the entire hearth as a single rigid block.

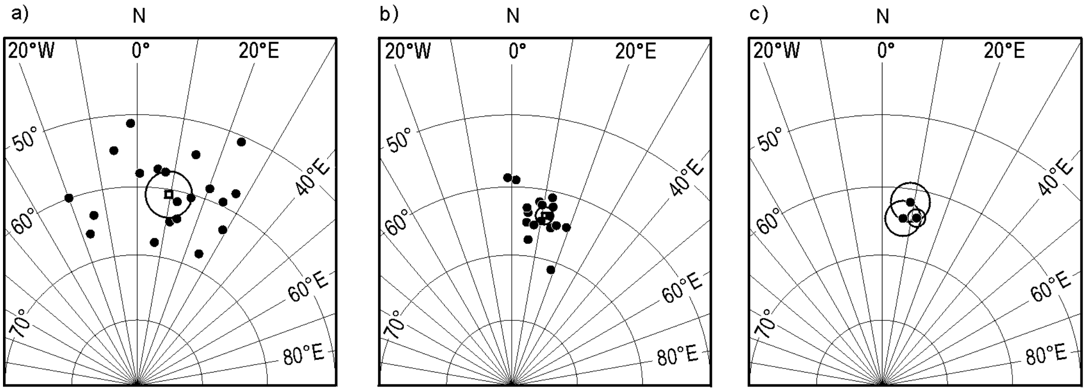

Fig. 5. Archaeomagnetic result from a deformed Bronze age flat hearth (No. 2014) in the Rhone valley, France; (a) in situ, (b) all specimens of 2014 placed horizontal, (c) comparison of mean direction of 2014 (tilt corrected) with hearths 1012 and 1019

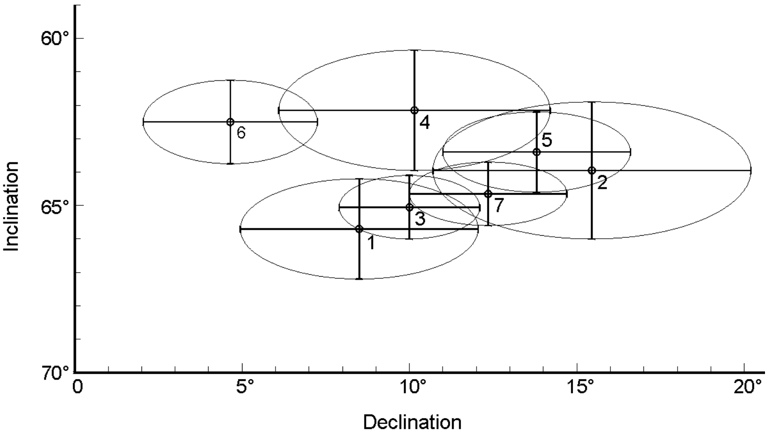

Fig. 6. Archaeomagnetic mean directions and confidence circles of contemporaneous Late Hallstatt flat hearths

Archaeomagnetic sampling inevitably involves at least partial destruction of the feature studied. Sample size varies between 10 and 2.3 cm, depending on the analytical laboratory.

When confronted with exceptional burnt structures, which as part of the national heritage must be preserved, it would be an advantage to take much smaller samples, say only a few millimetres in size. As burnt clay samples are usually strongly magnetized this should not be a problem at the instrumentation level. The difficulty lies in maintaining the precision in specimen orientation.

Palaeointensity

Unlike directional studies, which require carefully oriented in-situ material, estimation of the palaeointensity can be carried out using unoriented baked clay such as potsherds. The abundance of ceramics on archaeological sites and the fact that they can often be well dated from their typology is a great advantage compared to the less frequent occurrence of ovens and hearths. Unfortunately not all ceramics are magnetically suited for the time consuming analyses and the success rate is low.

Samples containing single domain magnetic grains or the slightly larger pseudo-single domain grains are thought to give the best results. Baked clays containing mainly multi-domain grains have a non-ideal behavior and should be avoided.[27]

Because of the geophysical importance of palaeointensity studies a great deal of work has been done on trying to improve the analysis techniques not only for archaeological baked clays but also for Plio-Pleistocene lavas. Nevertheless, palaeointensity techniques are probably the most complex of those used to unravel the history of the geomagnetic field.

The most commonly used method is derived from that of THELLIER-THELLIER[28] and is known as the zero field or COE modification.[29] This consists of stepwise thermal demagnetization and partial remagnetization at increasing temperatures up to the Curie point.

The other frequently used method is based on the similarity between anhysteretic remanent magnetization (ARM) and TRM.[30] It involves only one heating step compared to at least twenty used in the previous method and so the extent of any mineralogical changes due to heating is reduced, but without completely avoiding any alteration.

Sample selection

To increase the success rate of palaeointensity analyses various selection procedures have been used based on rock magnetic tests. These include low temperature variation of magnetic susceptibility[31] based on a study of Tertiary basalts by SENANAYAKE et al.[32] as well as the frequency variation of magnetic susceptibility,[33] which is null for multi-domain grains. Other selection tests include coercivity spectrum analysis using alternating field demagnetization and the reversibility of high field thermomagnetic curves.

High temperature alteration

It is widely recognized that the major problem in archaeointensity studies is the alteration of the samples on heating. This is despite tests such as PTRM during the experiment, as was first proposed by THELLIER[34] to monitor such high temperature mineralogical changes.

The controversy over the Greek archaeointensity curve[35,36] showed that, even with the stringent controls used, the experimental results could be widely different between laboratories. This called into question the reliability of the published results and showed that high temperature alteration was not easily detected.

A new demagnetization technique, using microwave energy instead of heating, produces only a moderate increase in sample temperature.[37] Exposure time to microwaves replaces the heating temperature of the conventional method. A repeat study of a collection of Peruvian ceramics,[38] that had been previously analyzed using conventional methods, shows a much-reduced scatter in the palaeointensity–age plot. However, it has not been demonstrated that microwave demagnetization and remagnetization are exactly analogous to the thermally activated processes, and control experiments are needed on synthetic samples. Although requiring specialised equipment and possibly a correction for the very fast treatment (2–12 s), this method shows promise, particularly for those samples which are greatly affected by heating.

Another approach that has been adopted is to try and recover a paleointensity result even when high temperature alteration has taken place. In the case of the THELLIER-THELLIER method the characteristics of the new magnetization are different from a true thermoremanent magnetization and so can be distinguished.[39]

In the case of the ARM method a correction can be applied if the alteration is not too important. On theoretical grounds TANAKA[40] suggests that this is possible if the ARM capacity changes by less than 15–20%, but recommends further experiments with test samples.

Future developments in palaeointensity studies clearly require faster and more reliable experimental techniques.

Magnetic viscosity

Despite the remarkable magnetic stability of baked clays, they all have, to a greater or smaller extent, part of their remanent magnetization slowly changed due to the influence of the ambient geomagnetic field. The logarithmic increase of viscous magnetization (VRM) with the time of exposure to the field opens up the possibility of using viscosity as a magnetic clock.

HELLER and MARKERT[41] have carried out a pioneering study using dolerite blocks from Hadrian's Wall in Northern England to calculate its age of construction. However, the complexity of the magnetic relaxation phenomena, which makes the evaluation of the law linking VRM with time very problematic, has prevented this attractive idea from been further exploited.

A special application of magnetic viscosity dating to monuments made from limestone blocks has been developed recently by BORRADAILE.[42] If exactly the same limestone has been used in the construction of buildings of known historic age then a calibration curve can be established which could then be used to date the incorporation of this limestone in other buildings. Known as remagnetization dating, it enables ages to be assigned to the different phases in the construction of a building. Effective saturation of the viscous magnetization in the limestone limits its use to a couple of thousand years.

Archaeomagnetic dating

An archaeomagnetic date is obtained by reference to a regional secular variation curve and this has been dealt with in detail by STERNBERG and MCGUIRE.[43] The latter authors have proposed a statistical matching procedure, which takes into account both the error in the reference curve and in the direction to be dated. This approach is more satisfactory than a graphical method and deserves to be more widely used. An archaeomagnetic date is not an absolute date and has been referred to as a regional pattern matching method.[44]

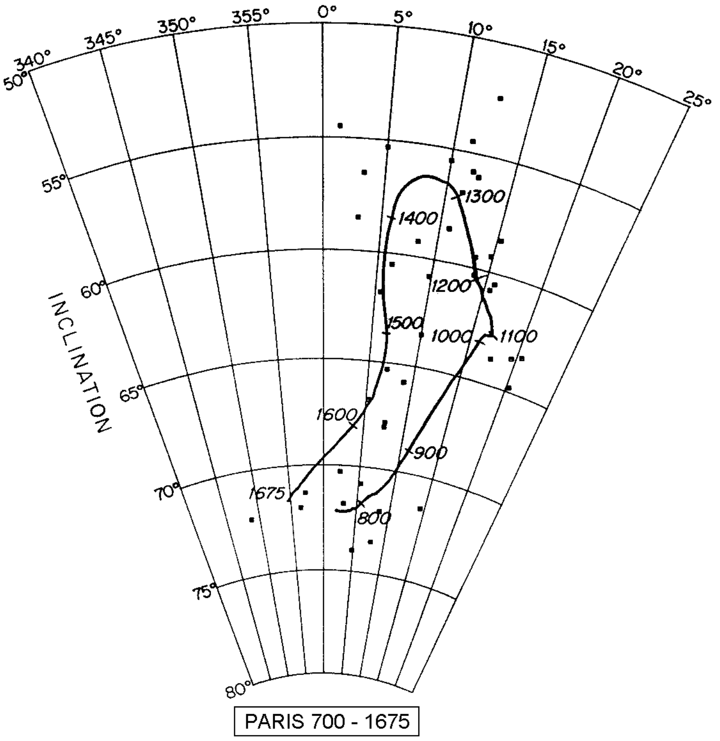

Fig. 7. Cubic spline fit for the archaeomagnetic data (700-1675 AD) of THELLIER[5] for Paris

Reference curves

Although early reference curves were drawn by hand, this is a very difficult task considering the uneven nature of the raw data. Some form of quantitative construction is now the preferred method.[45] Various techniques have been proposed such as a weighted moving window,[46] cubic splines[47] and an extension of Fisher statistics, called bivariate statistics.[48] The advantage of these statistical approaches is that an uncertainty can be assigned to each part of the reference curve. This is illustrated in Fig. 7 showing the reference curve for Paris using a cubic spline fit to the French data of THELLIER.[5] Using such a curve the error in the reference curve can be incorporated in the error estimation of an archaeomagnetic date and this is to be recommended in future dating procedures.

Rock magnetic studies

Since the early studies by the French school several decades ago, little systematic study has been carried out to understand the origin of the highly stable magnetic memory of baked clays and recent efforts in this direction by EVANS and JIANG[49] and JORDANOVA et al.[50] are to be commended. The recognition and detailed study of the carriers of the archaeomagnetic record will clearly lead to an improvement in the quality of the data.

Archaeological sediments

Although archaeomagnetism is classically concerned with the TRM of baked clays another promising material is the sediment encompassing the archaeological layers. A fraction of the magnetic oxides in a sediment are aligned with the local magnetic field on or shortly after deposition to produce a detrital remanent magnetization (DRM). Clayey sediments deposited under calm conditions are need to give a reliable DRM The advantage of using sediments is that they offer a quasi-continuous record of the secular variation although their magnetic stability is inferior that of baked clays. Studies of flood deposits[51] and irrigation canals[52] show that even on sites without fired structures it is still possible to refer to archaeomagnetic reference curves and obtain a date by a curve matching procedure.

Reversal dating

Archaeomagnetic reference curves using baked clays only extend back to the Neolithic[6] possibly because earlier hearths were often made of stones and were also not well enough baked to survive intact. The rarity of baked clays means that in the case of much older sites one is obliged to use the reversals of the geomagnetic field as recorded in the DRM of sediments. As the last definite reversal occurred 780 ka ago this allows the use of reversals as stratigraphic markers on Palaeolithic sites. If possible, a long stratigraphic sequence should be accessible to avoid ambiguity in the recognition of the reversal(s). Unlike secular variation, which is a regional phenomenon, reversals occurred on a global scale, which greatly extends their utility.

A recent important study at Atapuerca in northern Spain puts the Brunhes-Matuyama boundary just above the hominid finds making them slightly more than 780 ka old[53] and so pushes back the chronology by almost 300 ka. Magnetostratigraphic studies on Palaeolithic sites in the Italian peninsular and southern France[54] are also in agreement with an early presence of hominids in Europe. Clearly the use of the magnetostratigraphic time scale in combination with other methods of dating will play an important role in the dating of early sites in Europe.

Conclusions

Compared to other dating methods archaeomagnetism has always been a poor sister and archaeologists usually prefer "standard" methods such as radiocarbon or dendrochronology. This could be in part be due to the education or formation of archaeologists, who often have a classical background. As the setting up of the standard curve depends on the availability of suitable burnt structures and is consequently a slow process, it is even more important that all potential structures are sampled for an archaeomagnetic study. Here again, it is a question of informing archaeologists of the potentiality of the method and that there should also be a regional laboratory prepared to do the analyses and if necessary the sampling. This raises the question as to whether each country or region in Europe should have a specialized laboratory ready to intervene and save the archaeomagnetic information before it is lost forever by destruction at the end of the excavation.

The future of archaeomagnetism depends on its wider recognition as a dating method by the archaeological community and on a better understanding of those factors disturbing the magnetic recording process.

*

Archaeomagnetic research in Geneva has greatly benefited from the support of the Swiss National Science Foundation (2.756-0.87, 20-30288.90 and 20-36419.92). Thanks are also due to W. WILD, W. FASNACHT, Y. BILLAUD and C.-A. DE CHAZELLES for allowing access to the archaeological hearths that are discussed above. R. J. VEITCH carried out the anisotropy corrections on the Vindonissa tiles. E. BLEUER kindly gave permission for the reproduction of the Vindonnissa lime-kiln (Fig. 4a). J. METZGER drew the remaining figures.

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