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AN INTRODUCTION TO ARCHAEOMAGNETIC DATING

GREGG McINTOSH and GIANLUCA CATANZARITI
Fisica de la Tierra, Astronomia y Astrofisica I, Facultad de Ciencias Fisicas
Universidad Complutense de Madrid, Avda Complutense s/n
28040 Madrid, España
(emails: gregc@fis.ucm.es, gcatanza@fis.ucm.es)

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Abstract: An introduction to the archaeomagnetic dating technique is given. The technique exploits the secular variation of the geomagnetic field and the ferromagnetic remanence properties of natural material to permit the relative dating of archaeological features. The main features of the method are described, including the acquisition of remanent magnetisation, the determination of archaeodirections and intensities and the construction and application of reference secular variation curves. Data are presented from an archaeological site in Cordoba, Spain. A kiln from an area of ceramic production has been dated using the archaeomagnetic method, giving an age of 1161-1342 AD, consistent with the early medieval activity inferred from archaeological considerations.

1. INTRODUCTION

Archaeomagnetic dating is a relative dating technique that relies on 2 physical phenomena: the secular variation of the geomagnetic field and the ability of certain archaeological features to acquire a stable remanent (permanent) magnetisation in the geomagnetic field. The intensity (F) and direction (inclination, I, declination, D) of the geomagnetic field vary in both space and time, and for any particular region secular variation (SV) curves can be constructed. If these curves are sufficiently well-defined they can be used as relative dating tools for archaeological features from the same region. By comparing the remanent magnetisation of an archaeological feature with a reference SV curve, the age of the magnetisation can be determined. If the magnetisation can be related to a known archaeological event, then this gives the age of the event. This condition can be met in heated material (e.g. ceramics, bricks, tiles, combustion structures, burnt horizons), painted surfaces and cements, volcanic rocks and sediments.

Archaeomagnetic dating can be carried on short (thousands of years) and long (millions of years) time scales. The latter is an application of the geomagnetic polarity timescale, and has been used to date archaeological events older than 0.78 million years (the time of the last geomagnetic polarity reversal) - usually applied to hominid sites (e.g. Partridge *et al*., 1999). This aspect of the dating technique is not addressed in this paper which concentrates on the application over the recent archaeological past (the last few thousand years). Section 2 describes the remanence acquisition processes in archaeological material. In section 3, the main features of the archaeological method are set out, including sampling and analytical techniques, and the construction and application of reference SV curves. Finally, in section 4 the method is illustrated by dating a medieval kiln from Cordoba, Spain. The subject is described in more detail by Aitken (1990) and Eighmy and Sternberg (1990), both of which provide accessible and comprehensive reviews.

2. REMANENT MAGNETISATION IN ARCHAEOLOGICAL MATERIAL

The rocks and sediments from which archaeological features are made contain trace amounts of iron oxides, which may be associated with the original rock-forming processes, or with secondary processes such as heating and weathering. The main minerals are magnetite (Fe_3O_4), haematite (αFe_2O_3) and maghaemite (γFe_2O_3), where some of the Fe may be substituted by other cations (e.g. Ti, Al). Due to their ferromagnetic properties, they are capable of acquiring a remanent magnetisation in the presence of the geomagnetic field that is stable over archaeological (and geological) timescales. The remanence associated with the archaeological event under investigation is known as the characteristic remanent magnetisation (ChRM). The natural remanent magnetisation (NRM) of the material consists of the ChRM plus any other remanence components that may be present.

Acquisition of ChRM in heated material

Heated material is by far the most common material used for archaeomagnetic dating. It includes baked clays and adobes, ceramics, tiles, bricks, combustion structures - kilns, furnaces, domestic ovens and hearths, and burnt horizons - floors, soils and walls. Such material carries a *thermoremanent magnetisation (TRM)*. After heating, the material cools and a remanent magnetisation is preserved that is parallel with and proportional to the ambient field in which it cooled. If the heating temperature exceeds a critical temperature, known as the Curie or Néel temperature, a *total TRM* is acquired in which all of the material carries the same magnetisation. Each time the material is heated (and cooled) it may acquire a new TRM, so that the event being recorded is the last heating/cooling. Fired material (ceramics, bricks and tiles) that has not been reheated preserves a TRM associated with its production, whilst burnt horizons carry a TRM associated with the fire. Combustion structures (kilns, furnaces, ovens) preserve a TRM acquired when last used, which is usually associated with their abandonment.

If the last heating reaches temperatures less than the Curie/Néel temperature (585, ca 625 and 675°C for magnetite, maghaemite and haematite, respectively) or less than previous heatings, a *partial TRM (pTRM)* is acquired. The material may then carry 2 distinct magnetisations of different ages. This is more important for domestic ovens, hearths and burnt horizons which generally reach relatively low temperatures. Reheated fired material will preserve a part of the TRM related to its original firing. Burnt soils and native rock used as construction material may preserve a part of the remanent magnetisation associated with their original formation.

Acquisition of ChRM in non-heated material

Non-heated material may also acquire an archaeologically relevant magnetisation. In some parts of the world, bricks were (and still are) made by throwing wet clay into moulds, then dried by baking in the sun. They have been shown to acquire a remanence at the time of moulding, called *shear* or *shock remanent magnetisation (SRM)* (Games, 1977), which is proportional to the ambient field. The event being recorded is the production of the bricks and not their use (i.e. construction date), although the two may be closely related. Murals and cements may also acquire a stable magnetisation, if they have a ferromagnetic content. Whilst in the wet substrate, the magnetic particles can align themselves with the ambient magnetic field, and they become fixed in this position when the paint or cement dries. Known as *pictorial remanent magnetisation (PiRM)* in paints (Chiari and Lanza, 1997), this is essentially the same mechanism that occurs in sediments, known as a *post-depositional remanent magnetisation (pDRM)*. The event being recorded is the application of the paint or cement.

Acquisition of secondary remanence in archaeological material

Not all remanent magnetisations are stable over time. Part of the magnetisation may change over relatively short periods and acquire a new magnetisation in the presence of a new magnetic field. This is known as a *viscous remanent magnetisation (VRM)*. Most archaeological material can suffer VRM "overprinting", especially if it suffered post-burial alterations. Stepwise demagnetisation experiments or viscous cleaning can be used to separate VRM from the ChRM. The new VRM may be acquired during laboratory storage or during burial. The latter, acquired over longer time periods when the material remained buried in the same position, is generally magnetically "harder" (i.e. it is harder to demagnetise). As such VRM hardness may be used as a rough dating method (viscosity dating, e.g. Heller and Markert, 1973).

The strong magnetic field associated with lightning can remagnetise material in close proximity to the strike. The magnetisation is termed an *isothermal remanent magnetisation (IRM)* and it leads to spurious magnetisations. It can be distinguished from VRM and ChRM by its very strong intensity and by stepwise demagnetisation experiments. Similarly, exposure (of archaeomagnetic samples) to strong electrical currents or magnetic fields can lead to IRM "contamination".

Acquisition of ChRM in geological material

Geological material may also be useful in an archaeological context. Lava flows, lake and cave sediments and ditch infills may all acquire a remanence in the recent past. Volcanic eruptions may produce lava (and pyroclastic) flows which acquire a TRM on cooling in much the same way as heated archaeological material, and dated sequences of flows may be used to construct SV curves. Deposited materials, such as lake and cave sediments, ditch infills, etc., may acquire a pDRM at some time after their deposition, producing continuous records of directional (and occasionally relative intensity) SV. The main drawbacks with sediments are that there is a delay in the acquisition of pDRM (related to the depth at which the pDRM is locked in and to the sedimentation rate), the amplitudes of SV may be smoothed and the values of I shallower than the actual field values. This can make comparison with archaeomagnetic data problematical.

3. THE ARCHAEOMAGNETIC METHOD

The details of the method are set out below. Field sampling, laboratory analysis (of NRM and its stability, determination of archaeomagnetic directions and intensity) and the construction and application of reference SV curves are all described.

Sample preparation

Field sampling is governed by the kind of information being sought (F only or D, I and F) and by the amount of material available. Unoriented samples may be used to determine F, as is commonly the case for ceramic fragments. In order to extract directional information, oriented samples must be taken from archaeological features that have remained in situ since acquiring their magnetisation (e.g. combustion structures, burnt horizons). Disturbed material may yield F, and directional information if its position during remanence acquisition is known. This is sometimes the case for fired material that was stacked in a regular way during production (e.g. tiles, amphorae, bricks), from which it is possible to determine I (but not D).

Samples are oriented with respect to the local horizontal plane and geographic north. Orientation with respect to geographic north can be achieved by using a gyro-theodolite, a theodolite or a solar compass. A magnetic compass may also be used, as long as there are no local field anomalies. Many burnt archaeological features can be strongly magnetic and may cause local field deviations, so that magnetic orientation is usually complemented by non-magnetic techniques.

The sample size is governed by the availability of material and whether the archaeological feature is to be preserved. When there are no constraints, large block samples (10's of cm across) or cored samples are taken. If material is limited, or conservation is important, then less intrusive methods are employed. Small samples can be prepared by attaching a plastic or wooden disc to the surface of the material, which is then oriented and removed, along with a small amount of sample material. At least three, and preferably more than ten independently oriented samples are needed, distributed across the whole of the archaeological feature under investigation. This is in order to take into account inhomogeneity (of magnetic concentration, acquisition of remanence), sampling errors, post-magnetisation movements and other factors such as magnetic anisotropy and magnetic refraction.

Remanent magnetisations are measured using spinner magnetometers, cryogenic magnetometers or inductometers. Most require regular shaped specimens (cylinders or cubes), the size of which depends on the magnetometer in question. Specimens are either cut or drilled from the samples, transferring the orientation mark to the specimen. Large sample spinner magnetometers or inductometers may sometimes be available, so that sub-sampling is not required.

Analysis of the NRM

Magnetic stability tests are carried out in order to isolate the NRM components and determine their direction, intensity and stability. Magnetic viscosity, alternating field and thermal demagnetisation are the most commonly used methods.

Magnetic viscosity tests can be used to determine the VRM acquired in a known field during a fixed time period. *Viscous cleaning* is a closely associated technique where the specimens are stored in zero field for a fixed time. The unstable VRM decays, allowing the stable ChRM to be isolated. It is only effective for materials carrying a single, stable component and is restricted to materials carrying a total TRM (i.e. well-heated material such as kilns and furnaces).

Modern practice tends towards the use of stepwise demagnetisation of NRM. In *alternating field (AF) demagnetisation,* the specimen is exposed to a peak AF which is slowly reduced to zero, in a zero constant field. The magnetisation of grains with *coercivities* less than the peak field becomes randomised. For *thermal (TH) demagnetisation*, the specimen is heated to, and cooled from, a peak temperature whilst in zero field. Grains with *unblocking temperatures* less than or equal to the peak temperature are demagnetised. Stepwise demagnetisation is achieved by applying incrementally larger peak fields or temperatures, measuring the NRM after each step. From this the stability of NRM can be determined and the ChRM isolated. *Soft* magnetisations can be demagnetised in relatively low fields or temperatures and they are usually associated with VRM or IRM components. Stepwise demagnetisation must be carried out on material carrying a pTRM and where more than one NRM component is expected (i.e. partially heated features). *AF* or *TH cleaning* refers to the application of a single demagnetisation step (usually 5-20 mT or ≤ 300°C) to remove VRM (or IRM) components. It should be complemented with stepwise demagnetisation of pilot specimens to confirm the efficiency of the cleaning step.

Determining the archaeomagnetic direction

The archaeomagnetic direction is determined by taking the mean of the ChRM directions of the samples taken from the archaeological feature under investigation. If viscous, AF or TH cleaning has been used, the ChRM direction is the NRM direction after application of the cleaning step. If stepwise demagnetisation has been used, the ChRM direction can be determined from orthogonal vector plots of the demagnetisation curve (**Fig. 1b**). Principal component analysis is used to fit a least-squares line to a linear segment of the curve (Kirschvink, 1980) corresponding to the ChRM. The best-fit direction and its scatter (maximum angular deviation, MAD) is then calculated for this component. For the example shown in **Fig. 1b**, AF demagnetisation defines a linear segment from 10 to 100 mT, trending towards the origin. The NRM of this specimen consists of an unstable (probably VRM) component between 0-10 mT and a ChRM which is successfully isolated between 10-100 mT.

The situation is more complicated for specimens with more than 1 stable NRM component. Partially heated material may carry a ChRM associated with the last heating, plus a further stable component associated with earlier heating or with its original formation. Provided that the 2 components demagnetise in discrete AF or temperature ranges, two linear segments of the demagnetisation curve can be identified and their directions and intensities determined. Thermal demagnetisation is usually better than AF demagnetisation in isolating complex remanences. Furthermore, it allows the ChRM to be assigned with more confidence, since the component demagnetised at lower temperatures is associated with the last heating (i.e. the ChRM). In some cases, the two components have overlapping demagnetisation spectra, and the demagnetisation curves are not linear. The ChRM can be extracted from these data if one of the two components is randomly oriented. This is the case in construction features (walls, kilns, etc.) when the position of the bricks or blocks has not been controlled (i.e. up versus down, front versus back), so that the NRM component associated with original formation/firing is randomly oriented. The common direction (which will be the ChRM direction) can be calculated using the remagnetisation circle method proposed by McFadden and McElhinny (1988).

Once the ChRM directions have been defined for all of the specimens, the mean ChRM direction can be calculated by vector addition of the individual directions, giving each direction unit weight. A hierarchical structure is generally followed, calculating the mean of specimens from the same, independently oriented sample, followed by the mean of the samples. If the individual directions are normally distributed, then the statistics developed by Fisher (1953) to describe unit vectors in three dimensions are used to estimate the precision and reliability of the data (given by *alpha-95,* α_{95} and *concentration or shape parameter, k*). The higher the k and smaller the α_{95}, the more reliable the mean. These estimates are less reliable for a low number of samples, and there is an increasing uncertainty of k for less than 7 samples and of α_{95} when $k < 10$ (Tarling, 1971).

Determining the archaeointensity

The intensity, F, of the geomagnetic field as determined by archaeomagnetism is termed *archaeointensity*. It can be established for material whose ChRM is a TRM, i.e. for heated material, since the TRM intensity is proportional to the intensity of the magnetic field in which it was acquired. By comparing the ChRM intensity with the intensity of a TRM acquired in a known laboratory field, the only unknown, F, can be determined

$$F = \frac{ChRM \cdot F_{laboratory}}{TRM_{laboratory}} \tag{3.1}$$

The method was first set out by Thellier and Thellier (1959) and this still forms the basis of most archaeointensity methods and their variants. Experimentally, it is much more complicated to determine than either D or I. Multiple demagnetisation (zero field, TH demagnetisation of NRM) and remagnetisation (in-field, pTRM acquisiton) steps are carried out at successively higher temperatures up to the specimen Curie/Néel temperature. A plot of NRM lost versus pTRM gained should give a straight line whose gradient is used to calculate F. The error in the determination can be determined from the goodness of fit of the slope (regression). Deviations from linearity can be caused by multi-component NRMs and by thermally induced alteration. The linear part of the NRM-pTRM plot corresponding to the stable ChRM needs to be isolated from such deviations in order to calculate F.

Specimens must meet stringent internal tests in order to yield reliable archaeointensity estimates, related to thermal and magnetic stability, magnetic mineralogy and TRM properties (e.g. anisotropy, cooling rate dependence). As with directional experiments, results may vary due to experimental errors, heterogeneous magnetic properties, anomalous remanence acquisition, etc., so that multiple specimens should be studied for a given archaeological feature (e.g. dated ceramic collection, kiln). The mean and variance are usually described using the normal distribution.

One of the main difficulties is that physical or chemical changes may be induced by the heating involved in the experiment, which alters the proportionality between the ancient and laboratory magnetisations. A relatively modern development is the use of microwaves in intensity experiments. Microwaves act to demagnetise the specimen in much the same way as thermal demagnetisation (see Walton *et al.*, 1993) without the need for direct heating, thus reducing the problem of physicochemical alteration. In addition, the experimental procedure is much quicker than conventional intensity experiments, taking hours rather than days.

Constructing and using reference SV curves

To carry out an archaeomagnetic dating, there must be a reference SV curve available with which to compare the archaeomagnetic data. Reference curves for the last 2000-3000 years or so are available for the UK (Clark *et al.*, 1988), the USA (Sternberg, 1989; Labelle and Eighmy, 1997), Belgium (Hus and Geeraerts, 1998), France (Chauvin *et al.*, 2000; Genevey and Gallet, 2002; Gallet *et al.*, 2002), Hungary (Marton, 2003) and Germany (Schnepp and Lanos, 2005). For Bulgaria, the record extends back some 8000 years (Kovacheva, 1997; Kovacheva *et al.*, 1998), although with some gaps. Recently, Korte *et al.* (2005) published a compilation of archaeomagnetic and palaeomagnetic data covering the last 7 millennia. Since geomagnetic SV varies spatially as well as temporally, the reference curves are regional in nature. The area over which they are applied is of the order of 200,000 km^2, within which the SV properties can be considered to be similar. Data are compiled for a given region, then corrected to some arbitrary, reference location, usually via the virtual geomagnetic pole (VGP) (Shuey *et al.*, 1970). The D and I values at a given site are used to calculate the position of the VGP, which is then used to calculate the D and I values expected at the reference location. This approach is valid on the regional scales commonly applied in archaeomagnetism (e.g. Nöel and Batt, 1997).

Observatory, historical, archaeomagnetic and palaeomagnetic data can be used to construct reference curves. Archaeomagnetic data must be dated by independent means, either through absolute or relative techniques (e.g. ^{14}C, thermoluminescence, dendrochronology) or by archaeological considerations (e.g. documents, typology, context, coins). Palaeomagnetic data is usually dated through documentary or radiometric techniques. Great care should be taken when incorporating palaeomagnetic data, due to their different remanence acquisition processes.

Reference curves can be fitted to a regional data set in a number of different ways, the main problems being an uneven time distribution of the data and potentially large dating errors. Sliding time windows may be moved through the data, calculating the mean and variance for each window using the Fisher (1953) distribution for directions and the normal distribution for intensity. Data may be weighted according to dating and archaeomagnetic uncertainties and window widths may be fixed (e.g. Sternberg and McGuire, 1990) or varied (e.g. Le Goff *et al.*, 2002). The stratigraphic and hierarchical approaches common in archaeology (and archaeomagnetism) facilitate the use of Bayesian statistical approaches (e.g. Buck *et al.*, 1991, Lanos, 2004). This allows for the use of variable window widths, the movement of data within their dating range and the application of a priori knowledge (for example stratigraphic constraints).

To date an archaeological feature, its ChRM must be compared with an appropriate reference curve. Statistical analyses in the univariate case (for D, I and/or F) allow probability density functions of possible dates to be calculated (e.g. Lanos, 2001), which may then be combined to determine the most probable date and associated uncertainties. A bivariate approach using Fisher (1953) statistics may be adopted in the case of directions, using the statistical test of McFadden and McElhinny (1990), as suggested by Sternberg and McGuire (1990), or a modification of the test described by Le Goff *et al.* (2002).

The precision and accuracy of archaeomagnetic dating is limited by the quality and number of data used to construct the reference curves. Most of the data are provided by independently dated archaeomagnetic studies, each having associated archaeomagnetic and dating uncertainties. As more data become available, the better the dating potential. The rate of change of the SV is also important. Periods of rapid change can be dated with more precision than periods of slow change. Finally, the quality of the archaeomagnetic data of the feature being dated imposes its own limit - the smaller the uncertainties (as expressed by α_{95} and k), the more precise the dating. Together, this means that the precision varies from one archaeological period to another. Typical values are of the order of ±25 to ±200 years. Non-uniqueness can be a problem when similar directions are observed for different time periods. This can be reduced by considering the full field vector, although in practice very few regions have well-developed intensity SV curves. In this case, archaeological data (stratigraphy, context, typology) are required in order to distinguish between alternative ages.

Problems

As mentioned above, non-uniqueness in the SV properties of a particular region may lead to dating problems. Directional data requires the use of in situ material, and in the field it can be difficult to assess the extent of any small (a few degrees) post-magnetisation movement. Other problems are associated with the acquisition of remanence in the sample materials and the ambient field in which they were magnetised. *Magnetic anisotropy* may occur due to mineral alignments within the sample material and to the shape of the sample itself. This is commonly found in bricks, tiles and some ceramics. It can affect the direction and intensity of the sample remanence, causing deviations from the ambient magnetic field. Archaeointensity studies usually incorporate tests for TRM anisotropy. *Magnetic refraction* can also occur in strongly magnetic features (e.g. large kilns and furnaces), giving rise to steeper values of I from the walls than from the floor of the structure. This may be due to magnetic interactions or to differential cooling and magnetisation (e.g. Tarling *et al.*, 1986), although it is poorly understood. The influence of all of these effects can be tested for by sampling all parts of the structure, in order to identify systematic differences, principally in the recorded directions. Whilst archaeomagnetic directions can be calculated to within 2° of precision (α_{95}), the above-mentioned factors can give rise to values of 5° or more.

Remanent magnetisations are acquired in the ambient magnetic field, which is considered to reflect the geomagnetic field. This is not the case if strong local magnetic anomalies are present. Metallic slag from iron furnaces may produce small local anomalies affecting the field in which the ChRM of the furnace was acquired. Similarly, volcanic records may be affected by the anomaly associated with the volcano itself. Deviations of a few degrees in direction observed in historical Italian lavas may be explained this way (e.g. Lanza *et al.*, 2005). The problems with sedimentary magnetisations relate to the smoothing of the SV features, the shallowing of I values and the delay in remanence acquisition. This last factor makes the association of the magnetisation with a particular archaeological event difficult.

4. AN EXAMPLE: PRELIMINARY DATING OF A POTTERY KILN FROM CORDOBA, SPAIN

A recovery archaeology investigation in Cordoba, Spain (**Fig. 1a**) revealed a complex of kilns associated with an important zone of pottery production. One of the kilns (structure COO94) was sampled for archaeomagnetic dating. Archaeological considerations (kiln construction, ceramic typology) place the period of use of the kiln in the early medieval period (Exposito, pers. comm.). Oriented block samples were taken from the interior kiln walls. These were sub-sampled in the laboratory, by drilling 2.2 cm diameter cylinders which were then cut into

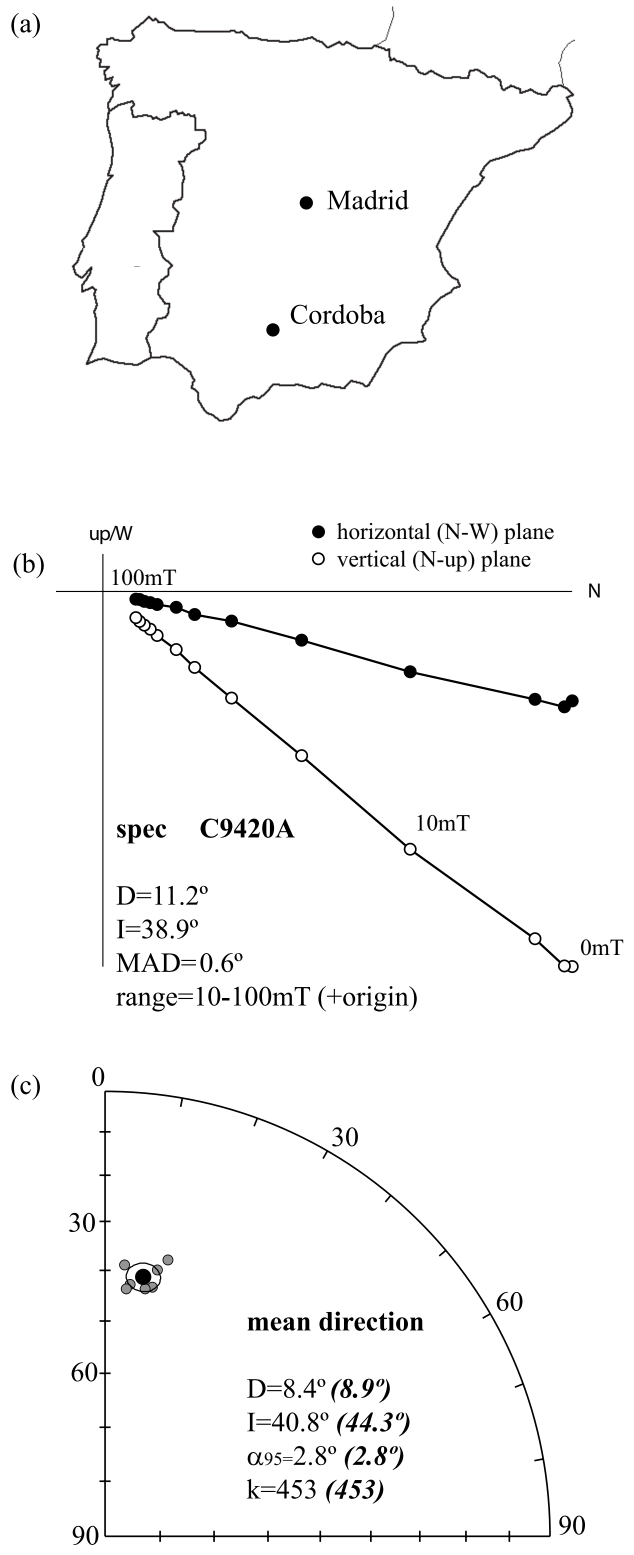

Fig. 1. *Archaeomagnetic data for site CO094. (a) Map of Spain showing Cordoba (site location) and Madrid (reference location). (b) Representative orthogonal vector plot of NRM demagnetisation. Solid (open) symbols indicate horizontal (vertical) plane. Best-fit values of declination (D), inclination (I), maximum angular deviation (MAD) are given in °. (c) Stereographic projection of best-fit ChRM directions for all specimens (in grey), along with site-mean direction and alpha 95 (α_{95}) cone of confidence (in black). Site-mean values are listed, along with equivalent values after relocation to Madrid (in parentheses). Definitions as in (b), with k = concentration parameter.*

2.5 cm length specimens. A total of seven specimens from the well-burnt, outer part of seven block samples were chosen for investigation. Stepwise AF demagnetisation of NRM was carried out using a Schönsted tumbling demagnetiser and NRM measurements were made using an AGICO JR5 spinner magnetometer.

All specimens exhibit a simple NRM structure, with the NRM vector decaying linearly towards the origin of the demagnetisation plot (**Fig. 1b**). The maximum available demagnetisation field (of 100 mT) was not high enough to fully demagnetise the specimens. Since the NRM vector trends towards the origin of the demagnetisation plot, the undemagnetised part of NRM carries the same direction as the demagnetised part, and the ChRM can be considered as being successfully isolated. ChRM directions were calculated between 10-100 mT, forcing the best-fit line through the origin. The directions are well-defined at both specimen and site level, with very low MAD values (< 1°) and very good grouping (**Fig. 1c**). Values of k = 453 and α_{95} = 2.8° indicate that the resulting mean is of a high quality.

This result can be dated using the reference SV curve for the Iberian Peninsula, recently proposed by Gomez-Paccard *et al.* (submitted). The first step is to relocate the site-mean direction from Cordoba to Madrid, the reference location for the Iberian curve. This is done via the VGP method, which leads to a slight increase in the I value (to be expected, as the reference location is further north and so closer to the magnetic pole). A hierarchical Bayesian approach was used in the calculation of the Iberian reference curve (Gomez-Paccard *et al.*, submitted) and has also been followed in dating the kiln. For this purpose, the software REN-DATE (Lanos, 2004) has been used, which calculates the probability densities of possible dates for both D and I, which are then combined to find the most probable solution. The I value is the most characteristic feature of the kiln, giving possible ages of 1150-1400 AD (**Fig. 2a**), which coincides with 1 of the 4 possible age ranges given by D (1150-1350 AD, **Fig. 2b**). Combining the probability densities (**Fig. 2c**) produces a well-defined density function, which at the 95 % probability range gives an age of 1161-1342 AD. Therefore the archaeomagnetic date of the last use of the kiln is between 1161-1342 AD, consistent with the early medieval activity phase inferred from archaeological evidence.

5. CONCLUSIONS

The main aspects of archaeomagnetic dating have been introduced and described, concentrating on the recent archaeological past (the last few millennia). The method has been illustrated using an example from a medieval kiln from Cordoba, Spain, yielding an archaeomagnetic date of 1161-1342 AD which is in good agreement with archaeological considerations.

Archaeomagnetic dating is a relative dating technique that dates the remanent magnetisation associated with the archaeological event under investigation. It can be applied in regions having well-defined reference SV curves, which can be constructed from independently dated observatory and historical records, archaeomagnetic studies and palaeomagnetic data. Coverage is sporadic, with most of the reference curves currently available being from Europe, reflecting the volume of work carried out during the last decades. As more data become available, then regional coverage will improve. Accuracy and precision varies from archaeological period to period, depending on the quality of the reference data, particularly in terms of their age control, the rate of change of SV and the quality of the archaeomagnetic data used to date the archaeological event. Under ideal conditions (well-defined data, rapidly changing SV) a precision of ±25 years can be expected, which can fall to ±200 years when data are lacking and when SV rates are low.

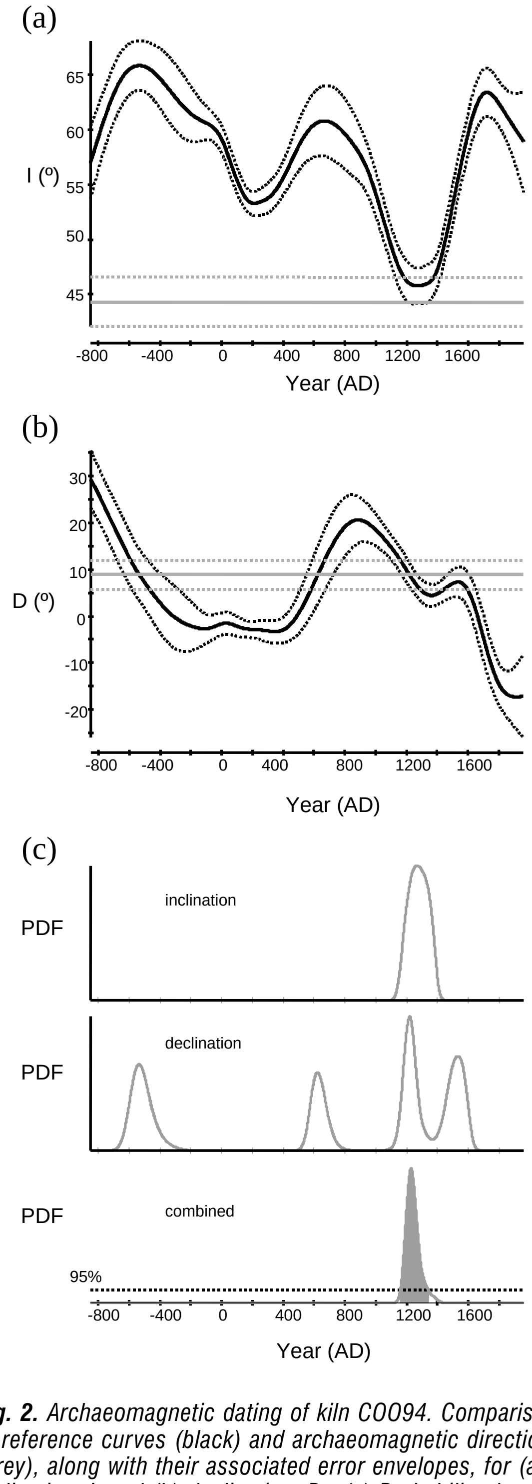

Fig. 2. *Archaeomagnetic dating of kiln COO94. Comparison of reference curves (black) and archaeomagnetic directions (grey), along with their associated error envelopes, for (a) inclination, I, and (b) declination, D. (c) Probability density functions (PDF) for I, D and I+D combined. Combined PDF is shaded at 95 % confidence limit.*

The technique can be applied to any archaeological feature that has acquired a stable remanence. This includes baked clays and adobes, ceramics, bricks, tiles, combustion structures (kilns, furnaces, ovens, hearths) and burnt horizons (soils, floors, walls), volcanic eruptions and sediments (lakes, caves, ditch infills). The key is in identifying the archaeological event associated with the remanence - such as the production of fired material or the last heating of combustion structures. In this respect, sediments are difficult to interpret as the age of magnetisation is normally older than the age of deposition and so it is hard to relate to an archaeological event.

As well as their dating use, archaeomagnetic data can be used in geomagnetic field modelling. Other archaeological applications include provenance and classification studies, reconstruction of firing conditions (firing position, temperatures), contemporaneity of use of combustion structures and restoration of broken ceramic. Although important and interesting, they fall beyond the scope of this paper and have not been described.

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