2006

Archaeomagnetic Dating

Guidelines on producing and interpreting archaeomagnetic dates

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Contents

Introduction

Scientific dating methods are well established as important tools in archaeological chronology and their application as part of archaeological investigations is now routine. Quite a number of techniques are available and perhaps the best known and most heavily utilised are radiocarbon dating and dendrochronology. However, both require the preservation of sufficient quantities of organic materials and, when this is not available, different dating methods are required. One such is archaeomagnetic dating which has the attraction that it can directly date fired ceramic and stone materials which frequently occur in archaeological contexts. It is applicable to a more limited class of archaeological remains than radiocarbon dating although research is under way to redress this limitation (*see below* Future developments). Fortunately the periods where archaeomagnetic dating has the potential to be most precise coincide with those where radiocarbon dating is problematic, making it a valuable complement to the latter technique.

A long history of investigation underlies current archaeomagnetic practice and as a result of this research, the technique has developed to become a useful tool for archaeological chronology so that it is now possible to date archaeological structures in the United Kingdom from the last three millennia. However, the precision of the dates that can be obtained varies for different periods according to a number of factors (*see below* Dating precision and limitations).

As the result of a more stringent planning policy (Department of Environment 1990), greater emphasis has been placed on the protection and recording of the archaeological resource when new development is planned. This has led to an increase in the number of archaeological sites being investigated and thus to the discovery of many more features suitable for archaeomagnetic analysis. The purpose of these guidelines, therefore, is to provide information about the technique of archaeomagnetic dating and the types of archaeological feature for which it is suited.

Since it is not possible to exploit archaeomagnetic analysis to its full potential without an insight into the principles upon which it is based, Part 1 of this document provides an introduction to the theory behind it and how this has been translated into a practical dating method. This part is primarily aimed at those archaeological professionals who are unfamiliar with the technique.

Those wishing to use archaeomagnetic dating should find Part 2 most valuable, especially the sections dealing with planning and fieldwork. Archaeomagnetic practitioners, particularly newcomers to the field, should also find Part 2 useful in establishing a code of good practice when dealing with clients as this part discusses the practical issues of how archaeomagnetic dating may be used in an archaeological project. It includes advice on the processes involved, from planning to the dissemination of results. Part 2 also suggests guidelines for reporting archaeomagnetic results to ensure consistency and allow for their reuse in the future as the technique develops. Two case studies illustrate how the principles and techniques are applied in practice. Later sections provide a glossary of specialised meanings, useful contacts for information and advice, and brief notes on the history of archaeomagnetism.

Part I

An introduction to archaeomagnetism

Archaeomagnetism depends upon two important physical phenomena:

1 The Earth spontaneously generates a magnetic field which changes in both intensity (strength) and direction with time (secular variation).
2 Specific events can cause naturally occurring magnetic minerals to become permanently magnetised, recording the magnetic field pertaining at the time of the event.

The next two sections expand upon each of these phenomena in turn and describe how they are exploited to develop a useful dating technique.

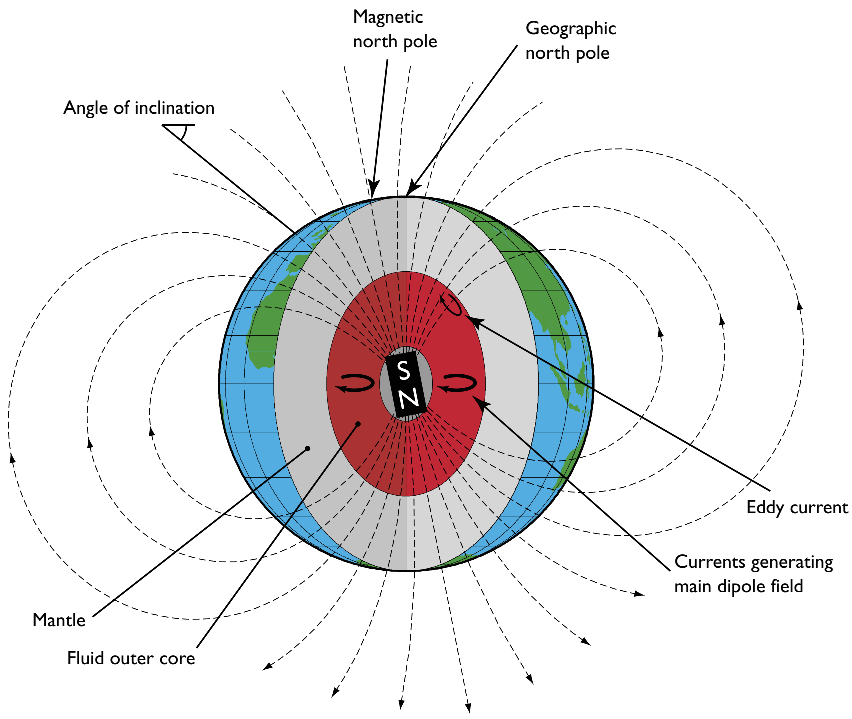


Fig 1 The Earth's main dipolar magnetic field is depicted with dashed lines. This is generated by electric current circulation in the outer core (shown in red) and is similar to the field that would be produced by a bar magnetic located at the Earth's centre tilted off-vertical by about 11.5°. Eddy currents near the core/mantle boundary perturb this main field. The angle of dip (or inclination) is the angle that the field lines make with the horizontal plane where they cut the Earth's surface.

The Earth's magnetic field

The details of the mechanism by which the Earth's magnetic field is generated are not completely understood. It appears to be associated with a region, 3000km beneath the planet's surface in the outer core, which is mostly composed of slowly churning molten iron. This layer is trapped between the solid inner core at the centre of the planet and the mantle, another solid layer extending from 3000km to about 40km beneath the surface. It is now generally accepted that free electron circulation within the convecting outer core creates the magnetic field, which behaves as a self-sustaining dynamo (*see*, for instance, Merrill *et al* 1996). The fluid motions that drive this dynamo derive from the Earth's rotation along with gravitational and thermodynamic effects in and around the core.

This results in an approximately dipolar magnetic field at the Earth's surface, as if a large bar magnet was situated at its centre with its long axis aligned almost parallel with the Earth's rotational axis (Fig 1). Near the equator, the field lines (which indicate the direction in which a freely rotating magnetised needle would point) are directed horizontally, parallel to the surface of the Earth; however, as either of the two magnetic poles is approached they rise out of, or dip into, the ground at an increasingly steep angle. This angle is known as the angle of dip or inclination. The positions of the Earth's magnetic poles do not exactly coincide with its geographic (rotational) poles and presently the axis of the dipolar field is inclined at 11.5° to the Earth's rotational axis. Because of this, the direction indicated by a compass needle at an arbitrary point on the Earth's surface will generally deviate from the direction of geographic, or true, north. The angle in the horizontal plane between magnetic north and true north is known as the magnetic declination.

Over geologic timescales the position of the magnetic poles appears to precess about the geographic poles and this is an effect of the same forces that generate the Earth's field. Superimposed upon this generally circulatory movement is an apparently random element, believed to be due to eddy currents in the Earth's fluid core and to the movement of charged particles in the upper atmosphere. It is not only the position of the magnetic poles that changes but also the strength or intensity of the magnetic field. The field intensity determines the strength of the attraction of a compass needle to the magnetic poles and the strength of magnetisation acquired by magnetic minerals. Over the last 150 years observations in London and Paris indicate that the Earth's field has changed in direction by about 0.25° and in intensity by about 0.05% each year (Tarling 1983, 146). These long-term changes in the terrestrial magnetic field, known as secular variations, form the basis for the archaeomagnetic dating technique. Provided that a data base of secular variation over archaeological timescales can be built up, objects recording the strength or direction of the Earth's field (*see below*) can be dated by comparison with it.

Unfortunately, some of the causes of change to the Earth's magnetic field are localised in their influence (the eddy currents and atmospheric movements). As a result, the magnetic intensity and pole positions calculated from measurements made at one point on the Earth's surface will not exactly match those calculated from measurements made at another position. For archaeomagnetic dating, this has the consequence of requiring the compilation of separate calibration data bases of the secular variation for different regions, each about 1000km in diameter.

One additional interesting aspect of the variation in the intensity of the Earth's field has been discovered through studies of the magnetisations recorded in igneous rocks. It appears that every few hundred thousand years the field intensity decreases almost to nothing then increases again with the polarity reversed, that is, the north and south poles change places (Hoffman 1988). Although of limited applicability for archaeological dating, early hominid remains have been dated by counting the number of magnetic reversals recorded in the sediments deposited above them (Partridge *et al* 1999).

Remanent magnetism

Some naturally occurring minerals are capable of retaining a permanent or remanent magnetisation. By far the most prevalent of these are the iron oxides – magnetite, maghaemite and haematite – which occur in most soils, clays and as trace components in many types of rock (Thompson and Oldfield 1986). In crystals of these minerals, quantum mechanical exchange interactions between neighbouring atoms force all the unpaired electron magnetic moments to align, resulting in a net spontaneous magnetisation (Néel 1955; Tauxe 2002). Such alignment will occur within a region of the crystal known as a magnetic domain and the shape and size of these domains will depend on the structure and size of the crystal as well as the impurities within it. Each may correspond to one physical grain of the mineral crystal (single domain), or a single grain may be divided into several magnetic domains to lower the overall energy of the system (multidomain). Each magnetic domain will have one or more preferred directions of magnetisation, or easy axes, determined by its shape and underlying crystal structure. Magneto-crystalline energy is minimised when the magnetisation within the domain lies in one of the two directions parallel to an easy axis, so the domain will tend always to magnetise in one of these favourable directions.

As each domain will typically be magnetised in a different, randomly orientated, direction, a macroscopic sample of the mineral containing a large number of domains will usually exhibit a negligible net magnetisation. However, if the mineral is heated, thermal agitation of the crystal structure leads to a diminution of the spontaneous magnetisation in each domain until, at a certain critical temperature, known as the blocking temperature, it disappears entirely (Fig 2). On cooling, each domain will remagnetise in the direction of the easy axis most closely parallel to any ambient magnetic field direction. Although most individual domains' magnetisations will not be exactly aligned with the ambient field direction, they will tend to favour it on average. Thus, after heating, the mineral will exhibit a net thermoremanent magnetisation (TRM) in the direction of the prevailing magnetic field at the time it cooled.

The blocking temperatures of different magnetic domains vary. The maximum blocking temperature is limited by the Curie temperature of the particular mineral involved (585°C for magnetite and 675°C for haematite) but considerations of grain size, crystal structure and purity can reduce it below this limit. Indeed even without heating, and in the absence of an external magnetic field, some domains will spontaneously lose their directions over time. Generally, the probability that such a change will occur during a set time span depends on the domain's blocking temperature (the lower it is the more likely it is that a change will take place). Naturally occurring samples of rocks and clays will usually contain a heterogeneous mineral and domain-size composition and thus exhibit a spectrum of blocking temperatures. To be capable of retaining a stable TRM, they must contain a high proportion of magnetic domains with blocking temperatures about 200°C. Domains with blocking temperatures below 200°C are likely to realign over archaeological timescales even without heating and their directions will track changes in the Earth's magnetic field. This phenomenon, called viscous remanent magnetisation (VRM), can lead to a partial overprinting of the TRM acquired when the sample was originally heated. When measuring archaeomagnetic samples, care must be taken to identify and remove the effects of such viscous remanences.

As well as TRM, a second mechanism, called depositional remanent magnetisation (DRM), also occurs in archaeological contexts. This involves water-borne sediment particles that possess a weak overall magnetisation, often because they are composed of thermoremanently magnetised minerals (although chemical effects during crystal growth can also result in remanent magnetisation). If suspended in relatively still water, they will attempt to rotate so that their directions of magnetisation align with the prevailing magnetic field (Fig 3). Gravitational forces will tend to pull the particles to the bed of the body of water where they will settle to form a layer magnetised in the direction of this ambient field. As more sediment accumulates above this layer, frictional forces caused by its weight eventually lock the magnetised particles in place so that they are no longer free to rotate and realign themselves. Further sediment accumulation results in a stratigraphic sequence of magnetic layers, thus recording changes in the Earth's magnetic field over the duration of their deposition. In certain instances the sediment particles may not become locked into position until some time after they are deposited and it is also possible that chemical or other effects can modify the initial depositional magnetisation. In these cases the resulting magnetisation is referred to as a post-depositional remanent magnetisation (pDRM). Such magnetised sediments can occur on lake beds and have also been found in palaeochannels and

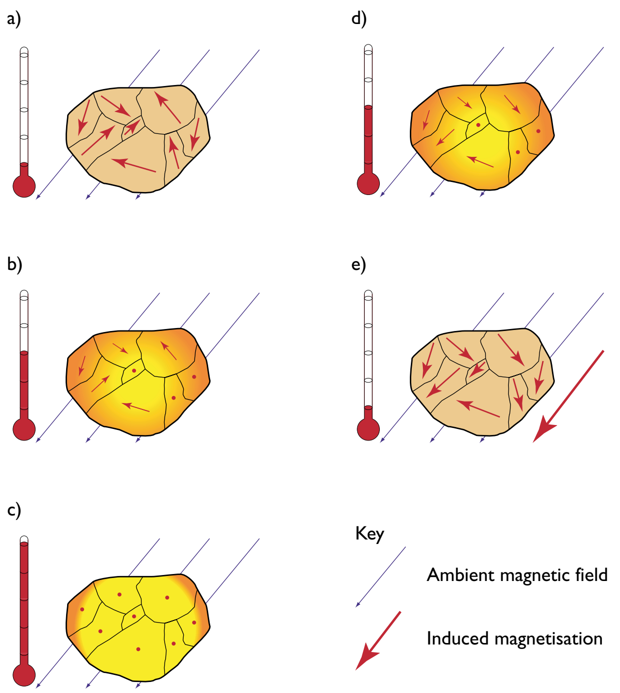


Fig 2 Thermoremanent magnetisation. Initially magnetic domains within a sample are magnetised in random directions that cancel out (a). As the sample is heated the domains demagnetise as the temperature exceeds their blocking temperatures (b and c). On cooling, the domains remagnetise in a direction close to the prevailing ambient magnetic field, resulting in a net magnetisation within the sample (d and e).

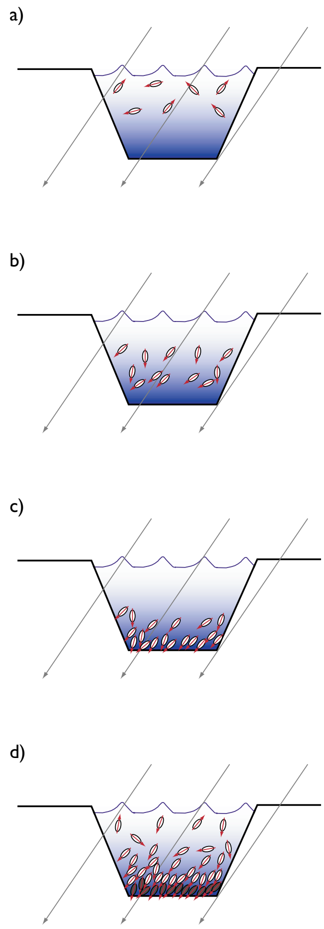


Fig 3 Depositional remanent magnetisation. Sediment particles, each with a weak magnetisation, settle out of still water. As they fall through the water column they rotate to align their internal magnetisation directions with the Earth's magnetic field (a, b, and c). Once settled on the bed of the body of water, the weight of sediment accumulating on top of the particles locks them in place, leaving a layer magnetised in the direction of the Earth's field (d).

archaeological ditch sections where the rate of water flow was relatively low.

Archaeomagnetic dating techniques

If the history of the changes in the Earth's magnetic field is known, then there are two principal ways to date an archaeological artefact, structure or deposit that has acquired a remanent magnetisation at some time in the past.

The first method is to exploit the fact that the direction of the Earth's magnetic field has changed over time. When the Earth's field is recorded by a magnetic material as described above it is generally easier to deduce the field direction from measurements made on the material than it is to infer the field intensity. Hence, archaeomagnetic research in the UK especially has concentrated on developing the archaeodirectional technique which involves only the direction of the Earth's magnetic field. The technique involves establishing the apparent magnetic north pole position indicated by the declination and inclination of the field within the sample and determining when in the past local magnetic north was in that position. Clearly, the artefact must have remained in exactly the same position as it was when it acquired its remanence, limiting the types of object that can be dated to non-portable structures. To this end, analysis of lake sediment data (depositional remanence), a large number of well-dated archaeological structures (thermoremanence), as well as direct compass measurements from the last 400 years, has led to the construction of the United Kingdom archaeomagnetic calibration curve (Clark *et al* 1988).

Based upon these data, Fig 4 shows the variation in the apparent position of the magnetic north pole as viewed from the UK over the past 3000 years. In principle, the date at which an unmoved archaeological object acquired its remanence can be inferred by measuring the declination and inclination of its magnetisation, determining the corresponding magnetic pole position and comparing this to the dated timeline.

The main problem with the archaeodirectional technique is that if a magnetised object is moved, the direction of magnetisation within it is no longer meaningful. Hence a second archaeomagnetic dating method has also been developed that infers the intensity of the Earth's field at the time that an aretefact acquired its remanence from the strength of the magnetisation in the artefact. As the direction of the field is not involved, this has the attraction that it allows portable archaeological objects such as potsherds to be dated. The strength of magnetisation acquired by a fired sample depends on the strength of the Earth's magnetic field at the time it was fired but it can be influenced by many other factors such as mineralogical composition and firing temperature. A technique to correct for these other factors and to estimate the ambient field strength at the time of firing was developed by E Thellier (1938) and has subsequently undergone a number of refinements. It involves repeatedly heating the sample in a controlled (or zero) magnetic field to a number of increasing temperature stages and measuring the intensity of the magnetisation remaining after each stage. Once all the magnetisation is removed, the process is repeated but with the sample exposed to a known reference magnetic field during each heating. From a comparison of the results it is possible to infer the strength of the Earth's field at the time the sample was originally heated in antiquity. However, many measurements are required for this technique, as compared with directional dating, and more sources of error are involved. These can arise from sample inhomogeneity, sample anisotropy, differences between the original and laboratory firing atmosphere and differences between the original and laboratory heating and cooling rates (Tarling 1983, 149).

Whilst archaeointensity studies have met with success in a number of European countries (*see*, for instance, Lanos *et al* 1999; Kovacheva *et al* 2000), little work has been undertaken in the UK owing to the problems involved. Knowledge of the Earth's past magnetic field intensity in the vicinity of the British Isles is based upon only six studies, none of which was made with modern equipment or methodologies. However, as outlined below in Future

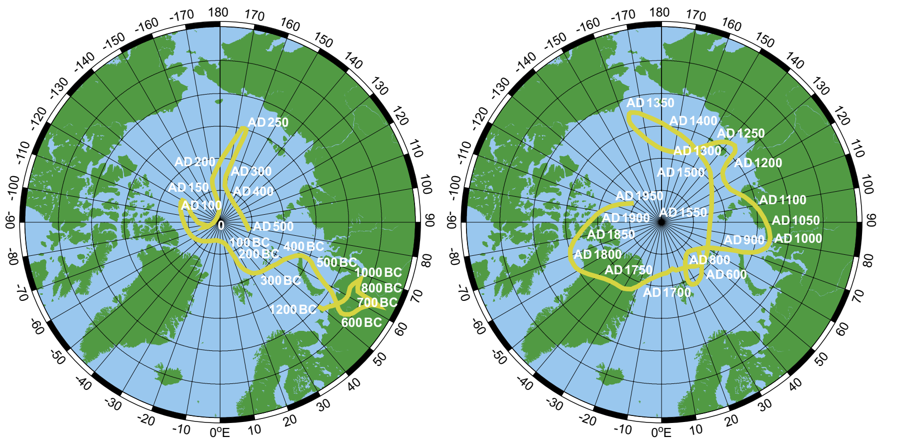


Fig 4 Movement of the apparent position of the Earth's magnetic north pole with time, based upon archaeomagnetic measurements made in the UK. The left-hand diagram shows movement from the Bronze Age until AD 500, the right-hand diagram shows movement from then until the present.

developments, a new demagnetisation technique shows great promise and is likely to stimulate renewed interest in UK archaeointensity studies over the next few years.

What can be dated?

Given the paucity of archaeointensity calibration data for the UK, the archaeointensity technique is at present unlikely to be encountered except in a research context for English archaeological features. Hence, the following sections concentrate on the archaeodirectional technique which is sufficiently well developed in the UK for a dating service to be available.

Directional archaeomagnetic dating imposes three constraints on the types of archaeological features that can be dated. They must:

1. contain magnetic minerals capable of carrying a stable remanent magnetisation;
2. have experienced a remanence-inducing event at some time in their history, for example, heating above a blocking temperature or non-turbulent sediment deposition;
3. have remained undisturbed since acquiring the remanence so that the magnetisation directions they record are still meaningful.

Fig 5 (top) Base of a Roman pottery kiln (~1.5m in diameter), constructed of fired clay, discovered at Heybridge, Essex and dated to the 2nd century AD.

Fig 6 (bottom, left) Medieval hearth constructed of vertically stacked tiles at Burton Dassett, Warwickshire. Archaeomagnetism demonstrated that it was last used at the time of the documented abandonment of the settlement in the late 15th century.

Fig 7 (bottom, right) Fired clay soil originally beneath a Tudor glassmaking furnace at Bagot's Park, Staffordshire. Archaeomagnetic dates on soils beneath 15 such furnaces have contributed to the knowledge of the economics of glassmaking in 16th-century England.

Hence, it is mostly fired structural features that are suitable for analysis. Remains of furnaces and kilns are best suited. These are typically composed of clay, tile, brick or stone, all of which usually contain suitable magnetic minerals. Furthermore, during their operation, these features reach temperatures in excess of 700°C above the Curie temperatures of all the remanence carrying minerals. For example, Fig 5 shows the base of a Roman kiln constructed of fired clay discovered at Heybridge, Essex (Noël 1996). However, it is not always necessary for such high temperatures to be reached and the remains of domestic hearths and ovens can often be dated, even though they tend to possess weaker magnetisations. The example shown in Fig 6 is a medieval hearth composed of ironstone from Burton Dassett, Warwickshire (Linford 1990). Similarly, burnt or heated natural soil that has lain beneath a fire or fired structure can also be suitable in some instances. Dates have been obtained from the fired clay soil beneath medieval and Tudor glass-making furnaces at Bagot's Park, Staffordshire (Fig 7). At this site, the remains of the furnaces were removed in the 1960s to allow the area to be ploughed (Linford and Welch 2004). Although these examples are predominantly fired horizontal surfaces, burnt walls (eg kiln walls) can also be dated when they survive and have not collapsed or moved since the firing event. Furthermore, whilst the majority of features that are dated archaeomagnetically are composed of clay or ceramic materials, it should be emphasised that burnt stone structures are also often suitable. Even stone types not usually associated with iron minerals, such as limestone, can often contain trace quantities of magnetic minerals capable of retaining a magnetic remanence.

With all thermoremanent features it is important to bear in mind that each time they are fired their magnetisation will be reset. Hence, the event dated by archaeomagnetic analysis will be the final firing of the feature. However, a caveat to this restriction can occur in the case where the final heating of a feature was to a lower temperature than reached in a previous firing. In such instances, it may be possible to date both firings.

Features possessing depositional remanence are less commonly encountered. However, where a waterlogged ditch has filled due to slow accumulation of sediment, such as the example shown in Fig 8 from Yarnton, Oxfordshire, it is sometimes possible to

Fig 8 (above) Ditch section at Yarnton, Oxfordshire. Archaeomagnetic analysis showed that the sediment filling the ditch accumulated between 200 and 100 BC, indicating that it had fallen out of use by this time.

Fig 9 (right, top) Marine sediment sequence laid down during the Middle Pleistocene period at Boxgrove, West Sussex. Sampling from different heights within the sequence has revealed a history of magnetic field changes over thousands of years.

date the time at which sedimentation occurred. In this case, it was established that a prehistoric drainage ditch fell out of use and silted up during the Iron Age (Linford *et al* 2005). Pictured in Fig 9 is a Middle Pleistocene sequence of marine sands from Boxgrove, West Sussex (David and Linford 1999). Here a stratigraphically related sequence of archaeomagnetic directions was obtained showing the changes in direction of the Earth's field during the time over which the sediment layers accumulated (~500,000–200,000 BP). This sequence is too old to date by comparison with present UK calibration data but it confirms that the site is less than 780,000 years old (when the last magnetic polarity reversal occurred). Using the same technique, analysis of a similar sediment sequence from Gran Dolina, Spain has demonstrated that hominid remains are much earlier than first supposed, dating to before the last geomagnetic reversal (Gutin 1995).

For depositional remanences to occur, the body of water from which sedimentation is taking place needs to have a slow rate of flow. Hence, lake and pond sediments are often well suited as are palaeochannels that become cut off and then silt up. Low-energy flood deposits have also been dated. Subsequent bioturbation (eg by tree roots) can disturb the sediment and render the remanence undatable but small particles of organic matter deposited at the same time as the sediment do not necessarily affect the locking-in process. It should be noted that with all DRMs the event being dated is the time when the sediment particles became locked into position within the sediment column. A sufficient accumulation of sediment is required above the layer in question to cause adequate compaction. Whilst sediments composed of fine-grained clays may be locked in almost simultaneously during ongoing sedimentation, coarser grained silts such as loess sediments may not be locked in until several metres of sediment have accumulated above them (Evans and Heller 2003, 86). Clearly, the time required for a sufficient weight of sediment build-up will also depend on the rate of sedimentation. This uncertain time-lag between sediment deposition and lock-in means that it is often difficult to associate depositional remanences with an archaeological event and Batt (1999) cautions that this presently poses a significant obstacle to dating sediments using archaeomagnetism. For this reason, depositional archaeomagnetism is typically useful for dating older, prehistoric sediments where such time-lags may be less significant.

Sampling procedure

Since the direction of magnetisation within an archaeological feature must be measured relative to true north and the horizontal plane, it is necessary to orient each sample before it is extracted or moved. For well consolidated features this is usually done by creating a flat surface on the material to be sampled upon which a direction arrow can be marked. To date, the most common method for achieving this employed by UK practitioners has been to attach, with epoxy resin, a horizontally levelled plastic marker disc at the sampling position (Fig 10). This is levelled using a bull's eye spirit level while the resin sets to ensure

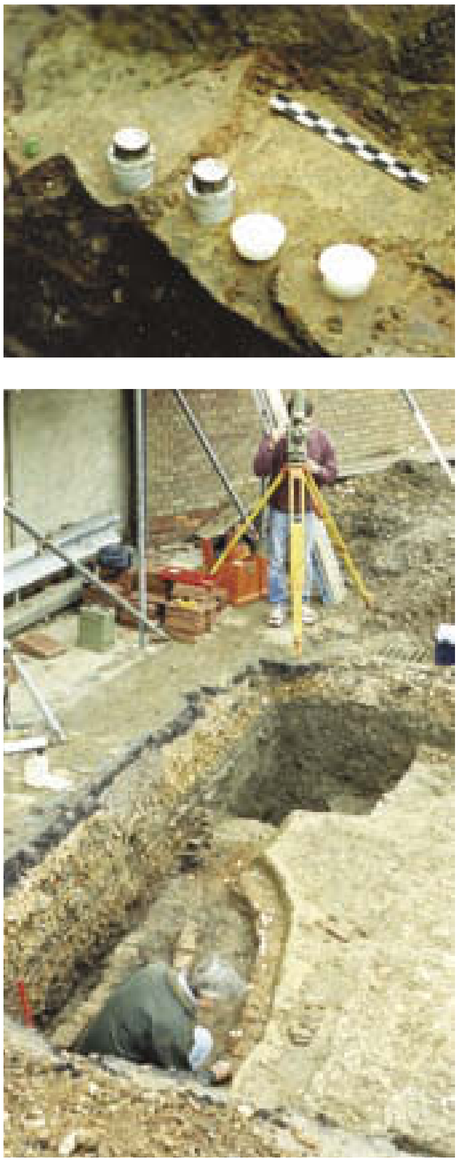


Fig 10 Sampling consolidated features. Horizontally levelled markers are attached to the materials to be extracted in the middle picture. In the bottom picture, the true north direction is being transcribed onto each marker with the aid of a gyro-theodolite.

its top surface is horizontal. However, an appropriate surface may also be prepared either by simply skimming the surface of the material to be sampled itself or by attaching plaster to it then flattening the plaster's top surface as it dries. In these cases, the flat surface created is not always horizontal. Instead, an inclinometer is used to determine the degree and direction of the surface's slope.

Whichever method is used to create a flat sampling surface, an arrow must be marked onto it denoting an accurately established reference direction, typically true north. Usually, a sun compass or gyro-theodolite is used to establish the reference direction. However, a magnetic compass bearing can be employed in situations where there is little localised disturbance to the magnetic field (which can be caused by nearby ferrous structures or by the feature to be dated being strongly magnetised). Once these procedures have been completed the sample can be removed. Less well consolidated sediments are often sampled by enclosing a short pillar of sediment within a specially manufactured plastic cylinder (Fig 11), which can be oriented as above, then removed and sealed. Regardless of the method of sampling 10 to 20 samples must be extracted from different parts of each feature to be dated to average out random perturbations in the recorded magnetisation direction caused by material inhomogeneity and other factors.

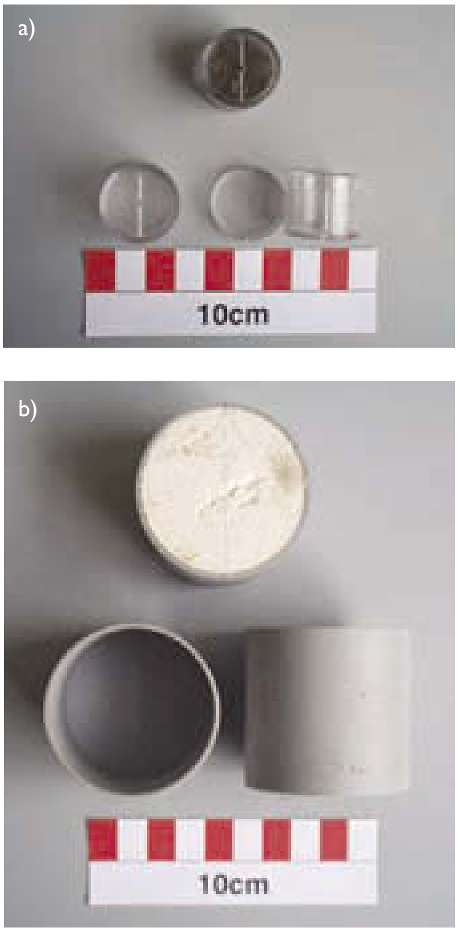


Fig 11 Sampling unconsolidated features. (a) 10cc perspex cylinders that can be pushed, open end first, into sediments. They have an arrow marked on the base, so the cylinder can be rotated to align with the fiducial direction. A close-fitting lid closes the open end of the cylinder after it is excavated. (b) Larger cylinders, with both ends open, that can be fitted over excavated monoliths of sediment. The sediment is then sealed in with plaster of Paris.

Laboratory measurement

Before measurement, friable samples are often treated with a consolidant such as PVA (polyvinyl acetate) in acetone or sodium silicate to ensure they do not fragment during measurement. Subsequently, where large samples have been collected from a feature, or where each sample is an entire brick or tile, they are often sub-sampled in the laboratory to produce a set of specimens. The magnetisation of each specimen is measured individually then the measurements of all specimens taken from a particular sample can be averaged to produce a mean magnetisation for the sample. The advantage of this approach is that poor samples, where the magnetic material does not record a consistent magnetisation direction, can be readily detected and rejected from further analysis. The disadvantage is that much larger quantities of material usually have to be removed from the archaeological feature to be dated. Where smaller samples have been extracted (as is typical with the disc method), a single measurement is often made on each entire sample instead of averaging measurements on a number of specimens taken from it.

Laboratory measurement of magnetisation is usually carried out using a spinner magnetometer in which specimens are spun within a pickup coil or ring fluxgate (Fig 12). In such magnetometers the specimen is placed in a magnetically shielded measurement chamber to exclude the influence of external magnetic fields. The specimen sits on a platform atop a shaft, which is then turned at a fixed speed to rotate it about its vertical axis. The rotating magnetic field caused by the specimen's magnetisation generates an electrical current in collecting coils wound around the measurement chamber, using the same principle as a dynamo. The magnitude of the current generated is proportional to the strength of the specimen's magnetisation in the horizontal plane. By re-measuring the specimen in three orientations at right angles to each other, it is possible to determine the total direction and strength of its magnetisation.

For rapid measurement of very weakly magnetised specimens, cryogenic SQUID magnetometers can be used. Introduction of a magnetised specimen into a superconducting ring causes a persistent current to flow that is proportional to the magnetisation parallel to the axis of the ring. Again, three different measurement orientations are usually needed to completely determine the magnetisation direction. Typical archaeomagnetic specimens tend to be relatively strongly magnetised and the spinner magnetometer is usually the most appropriate measurement instrument. However, SQUID magnetometers are employed in research studies, particularly when measuring weakly magnetised sediments or where only very small samples could be collected (eg from fired clay artefacts). More information about the various types of magnetometer can be found in Collinson (1983).

The accumulation of VRM in a magnetic material left undisturbed in a magnetic field for a long period of time has been referred to above in the section on Remanent magnetism. The new viscous remanence partially overprints the original magnetisation, altering the measurements of magnetisation direction and intensity made on untreated specimens in the laboratory. Thus, it is desirable to remove the viscous remanence whilst causing as little change as possible to the primary magnetisation. This is done by partially demagnetising the specimen, exploiting the fact that the viscous magnetisation will be carried by the magnetic domains of lower stability. One of two methods is typically employed: either heating the specimen (thermal demagnetisation) or exposing it to an alternating magnetic field (AF demagnetisation).

Thermal demagnetisation involves heating the specimen in a zero field environment to a temperature above the blocking temperature of the viscous domains but below that of the stable domains carrying the remanence of interest. On cooling, the magnetisation directions of all domains with blocking temperatures below the threshold temperature will have been randomised. By successively reheating the specimen to higher temperatures and measuring the change in the direction of the sample's

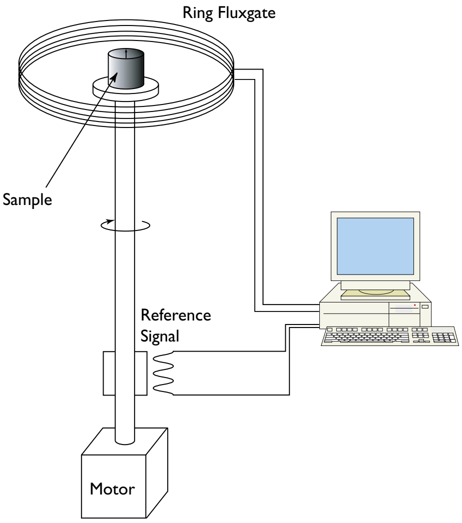


Fig 12 Spinner magnetometer used to measure the magnetisation within a sample by placing it on a rotating platform inside a measuring coil or ring fluxgate. The current generated by the rotating magnetic dipole within the sample will be proportional to the strength of its magnetisation.

magnetisation at each step, the temperature necessary to completely remove the VRM component can be established.

AF demagnetisation uses a weak alternating magnetic field instead of heating the specimen. Generally, magnetic domains with low blocking temperatures will also have low coercivities, so their magnetisation directions will move to track the alternations of the applied field. The stable domains carrying the thermoremanence of interest will have high coercivities and the forces induced by the applied alternating field will be too weak to alter their magnetisation directions. The peak strength of the alternating field is then slowly reduced to zero, leaving the magnetisation directions of the domains with low coercivities randomised. As with thermal demagnetisation a succession of increasing peak alternating field strengths can be used to determine the optimum value for removal of the viscous component.

Thermal demagnetisation has the advantage that it is similar to the process that caused the initial TRM to be acquired (heating) but repeated heating and cooling of the specimen can cause chemical changes to the magnetic minerals being measured. AF demagnetisation does not cause chemical changes but there is some evidence to suggest that magnetic domains do not react to AF demagnetisation in exactly the same way as they do to the thermal changes which magnetised them in the first place. More information about techniques of demagnetisation can be found in Collinson (1983).

Typically, a specimen's magnetisation will be re-measured after partial demagnetisation at a sequence of increasing temperatures or peak field strengths. The succession of changes in direction and strength of magnetisation are then statistically analysed using principal components analysis (Kirshvinck 1980) to determine the optimal direction of magnetisation for the specimen. If the changes at each stage are too great, the magnetisation in the specimen may be ruled unstable, in which case the specimen would be excluded from the next stage of analysis, the calculation of the mean remanence direction for the feature.

The mean remanent direction

If several specimens from the same feature are measured, it will be found that their remanent magnetisations differ slightly in both direction and intensity. In part this will be due to random errors introduced by the sampling and measurement process. Tarling (1983) estimates that when sampling and using a sun compass, errors of orientation should be within 2°. Empirical evidence suggesting that this estimate is likely to be correct has been obtained by Hathaway and Krause (1990) who compared azimuthal directions marked on samples from a number of experimental hearths orientated using both magnetic and sun compasses. The standard deviations for differences between the two measurements averaged over all samples from a particular hearth was typically of the order of 1° (thus within 2° for 95% of the samples). Provided the intensity of remanence of specimens exceeds the noise level and sensitivity of the instrument, all types of magnetometer should be capable of measuring magnetisations with a repeatability of some 0.5–1.0° for direction and 1–2% for intensity. Taking account of the need to make several measurements after different partial demagnetisation on each specimen (and, if appropriate, to calculate a sample average from several specimen magnetisation determinations), it should still be possible to determine the directions of magnetisation of individual samples to within about 2–3° and certainly no more than 5°. Intensities of magnetisation should be measurable to within about 5%.

However, the variation in remanence observed in a typical set of samples is often greater than this (Tarling *et al* 1986) and the following other factors have been suggested as additional causes of variation in the magnetisation within a feature:

1. The feature has been slightly disturbed since it acquired its remanence causing different parts of the feature to shift slightly in different directions (this affects the magnetisation directions only).
2. Varying material composition within the feature. In the case of thermoremanence, different magnetic minerals have different blocking temperatures and it is possible that parts of the feature containing large quantities of minerals with high blocking temperatures were not heated sufficiently to fully realign the magnetisation directions (variable heating across the feature causes similar effects).
3. Due to their composition, some magnetic materials exhibit anisotropy which means that they are easier to magnetise in some directions than in others. The magnetisation direction recorded in such materials will tend to be distorted from its true value towards one of these more favourable directions. This distortion can also affect the apparent intensity of the field recorded.
4. The feature was in close proximity to an object with its own strong magnetic field when it acquired its remanence. This can occur in iron furnaces which have cooled with slag inside them.
5. Related to the above, and specific to TRMs, a feature composed of strongly magnetised material can exhibit distortions to the magnetic field recorded within it due to its own shape. For instance, it has been noted that

the inclinations of samples taken from the walls of well-magnetised kilns are several degrees steeper than for samples taken from the floors of the same kilns. It has been proposed that this is due to the phenomenon of magnetic refraction (Aitken and Hawley 1971; Schurr *et al* 1984) or that it is due to the magnetisation of those parts of the feature that cool first, distorting the magnetic field through the feature (Tarling *et al* 1986), but the phenomenon is not well understood.

For the above reasons it is necessary to take a number of samples from all around the feature to be dated and calculate a mean remanent magnetisation direction from the magnetisations of the individual samples. As has been described, the samples originally extracted from the feature may have been subdivided into several specimens for analysis, in which case all the specimens from a particular sample will first be averaged to calculate a mean magnetisation direction for each sample. Samples may be rejected from the calculation of the feature's mean remanence direction at this stage if their individual specimen directions differ widely or if the changes in magnetisation during partial demagnetisation indicate that the remanence recorded is not stable.

Calculation of the mean direction of remanence is performed by vector addition of the individual sample magnetisation directions as shown in Fig 13. In this calculation the strength of the magnetisation of each sample is ignored as there is no reason to suppose that samples exhibiting high remanence intensity are more reliable than those with weaker intensities. Hence, each sample's magnetisation is represented by a vector of unit length. As the mean remanence direction is calculated from a distribution of sample magnetisations with different directions, there is a degree of uncertainty attached to the calculation. A statistical method specific to the problem of analysing distributions of unit vectors in three dimensions was developed by R A Fisher (1953) in which the uncertainty is represented by the α_{95} (alpha-95) parameter. This is the semi-angle of a cone of confidence centred on the mean vector direction within which there is a 95% chance that the true mean vector of the distribution lies (*see* Fig 13c). It can be thought of as analogous to the standard error in more familiar Gaussian statistics. The smaller α_{95} is, the more precisely the mean direction is known and, in general, the more precisely the feature can be dated. Once the mean vector and α_{95} statistic have been established, they can be compared to the UK archaeomagnetic calibration curve to establish the date (or dates) when the Earth's field had this direction. As the Earth's field direction also varies with location, the comparison is usually done by establishing the north pole position indicated by the mean remanent magnetisation direction, taking into account the position of the site on the Earth's surface. Such a pole position is called a virtual geomagnetic pole (VGP). The magnetic field declination and inclination that such a pole position would cause at Meriden (a central reference location for the UK) is then calculated (Tarling 1983, 116; Shuey *et al* 1970; Noël and Batt 1990). The corrected direction can then be compared with the UK archaeomagnetic calibration curve which has been calculated at Meriden (Clark *et al* 1988; Tarling and Dobson 1995; Batt 1997); a typical calibration comparison is depicted in Fig 13d.

It has been noted that the remains of a magnetised archaeological feature might be disturbed after the remanence has been acquired and it is of interest to determine the degree of displacement that can be sustained before it becomes undatable. The value of the α_{95} statistic varies approximately inversely with the square root of the number of samples used to calculate the mean magnetisation direction, N (Tarling 1983, 121). Typically, N will be between about 10 and 18 and, as a rule of thumb, an α_{95} value of 2.5° or less is necessary for an adequate archaeomagnetic date for most periods using the available UK calibration data. This suggests that the total directional error for an individual sample should not exceed about 10°. Hence, allowing for sampling and measurement errors of the order of 2–3°, deflections due to post-remanence acquisition disturbance must not exceed 7–8°. This assumes that the feature breaks up and different parts move randomly in different directions. It might be thought that taking an increased number of samples (ie increasing N) would allow greater degrees of disturbance to be compensated for. However, a law of diminishing returns is rapidly encountered, as the analysis above assumes that each sample position has moved randomly, and completely independently, of all other sample locations, and this condition rarely holds in practice. Nevertheless, where the entire feature has moved as a whole, it

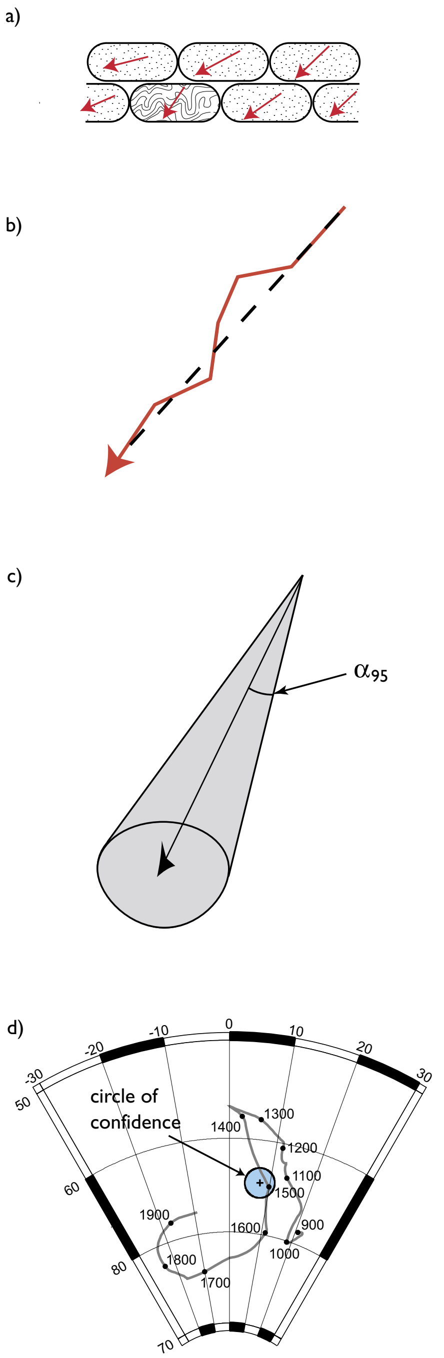


Fig 13 The mean direction of remanent magnetisation. (a) The magnetisation directions of each sample will be slightly different. (b) A mean direction is calculated by vector addition of the individual sample directions (attaching each sample direction vector to the end of the last). (c) The calculated mean direction is only an estimate of the true mean direction. The alpha-95 statistic, α_{95}, describes the semi-angle of a cone around the calculated mean direction within which there is a 95% probability that the true mean direction lies. (d) Comparing the circle of confidence of a mean direction with an archaeomagnetic calibration curve (that of Batt 1997) using an equal angle stereogram plot.

may be possible to estimate and correct for greater degrees of slumping if it can be assumed that the feature was level when fired (Clark *et al* 1988).

Dating precision and limitations

The precision with which a feature can be dated using directional archaeomagnetic analysis clearly depends inversely on the magnitude of the α_{95} confidence statistic calculated for the mean remanence direction of the feature. Generally, the smaller this angle, the more precisely the field direction can be established and thus the shorter the segment of the calibration curve intersected.

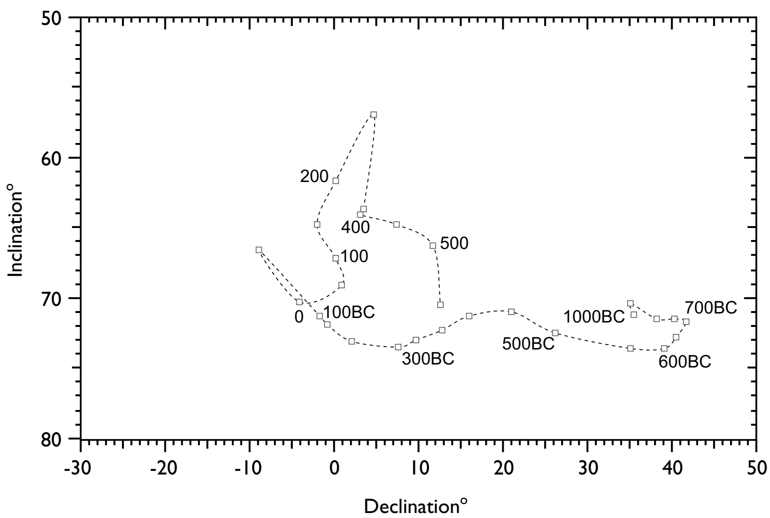
The accuracy of the calibration data for the period in question is equally important. The calibration curve has largely been constructed from archaeomagnetic analysis of features of known age and, in each case, the archaeomagnetic remanence direction has been determined to a certain precision governed by its own α_{95} statistic. Furthermore, there is also likely to be a degree of uncertainty in the independent dating evidence for the feature, resulting in the date the remanence was acquired being known only within certain limits. Hence, the quantity and quality of the available archaeomagnetic calibration data will impose a limit to the precision to which a feature can be dated. With the present calibration data for the UK, the practical limit on the maximum resolution of dates is around 50 years at the 95% confidence level.

However, a third factor, the rate at which the VGP position changes, also governs the precision of archaeomagnetic dates. The rate of change of the magnetic field direction has varied considerably over the last 3000 years. In periods where movement was rapid, features can be dated to within a smaller time window than in periods where movement was slow. This places a fundamental limit on the relative precision with which the dates of features from different periods can be determined, regardless of the quality of the calibration evidence or precision to which the mean remanence direction is known.

In addition to changes in the rate of movement, it also appears that the VGP has reoccupied the same positions at several different times over the period covered by the UK calibration data. Hence, the calibration curve crosses itself leading to uncertainty as to which of two dates is correct for a particular remanence direction. Furthermore, given the limits on precision of archaeomagnetic measurements, a similar situation occurs when two segments of the calibration curve lie close to each other, even if they do not cross.

Since the late 1980s three archaeodirectional calibration curves have been published for the UK and these are summarised in Table 1.1. It will be clear from the foregoing that calibration curve construction is not straightforward since it requires methods to take account of uncertainties in multivariate calibration data points distributed unevenly over time (with a distinct paucity for some periods). As statistical and computational methods capable of tackling the complexities of this process have been developed, there has been an evolution from subjective evaluation of the available calibration data to a more objective assessment of the uncertainties involved and this is reflected in the curves cited in the table. It may be noted that the oldest feature that may presently be dated with reference to any of these curves would be around 1000 BC. However, less precise estimates can be obtained for earlier features by direct comparison with lake sediment data which covers approximately the last 10,000 years (Thompson and Turner 1979; Turner and Thompson 1981). As noted in the next section, Future developments, recent advances are likely to result in a much improved UK calibration curve within the next few years.

The UK calibration curve of Clark, Tarling and Noël (1988), is depicted in Fig 4 as a pair of VGP plots, one for the period up to about AD 500, and the other for the period from then until the present day. The resultant variation in inclination and declination of the Earth's field that would have been observed in the centre of the UK is depicted in Fig 14. As a broad guide, the movement of the VGP as inferred from present calibration information and the consequences for archaeomagnetic dating have been generalised in Table 1.2.



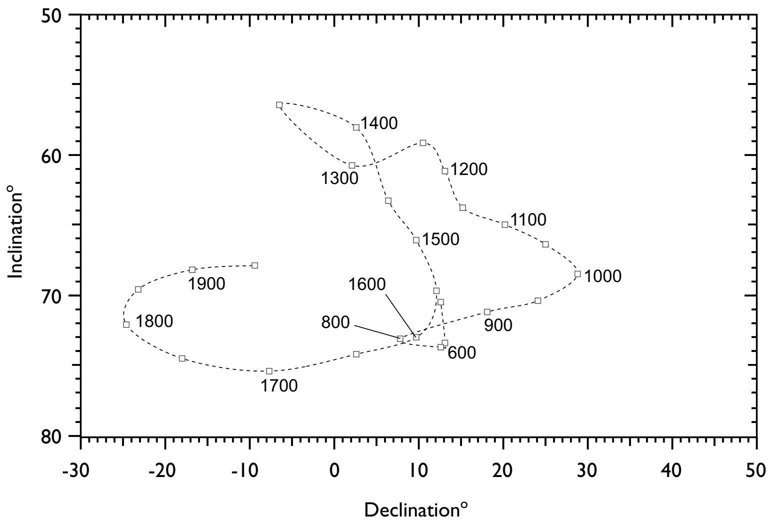


Fig 14 The directions of magnetic declination and inclination that would have been observed at Meriden in the centre of the UK over the past three millennia, based upon the data of Clark, Tarling and Noël (1988). Upper figure: 1000 BC to AD 550, lower figure: AD 550 to AD 1950. On both figures, dates with no suffix are AD, negative declinations are west of true north.

Table 1.1 Archaeodirectional calibration curves for the UK published since the late 1980s

calibration curve	*date range covered*	*description*
Clark, Tarling and Noël (1988)	1000 BC to present	Based upon ~92 calibration points from independently dated archaeological features as well as historical observations and lake sediment data. No assessment of the uncertainty inherent in the calibration curve was possible.
Tarling and Dobson (1995)	100 BC to present	Based upon ~172 calibration points but did not use lake sediment data for prehistoric period. No objective assessment of uncertainty but stated to be no more that 5° for all periods.
Batt (1997)	1000 BC to present	Used a similar database of calibration data to the above but lake sediment data were not included. Applied an objective moving window averaging method that provides an assessment of the uncertainty in the calibration curve at each point in time.

Table 1.2 Assessment of the potential of archaeomagnetic dating for the various broad periods of UK archaeology

period	*VGP movement*	*potential for archaeomagnetic dating*
Post medieval AD 1485–present	Rapid movement. First a rapid steepening of inclination with constant declination between AD1450 and 1600. Then a rapid westerly change in declination from AD 1600 to 1800. Finally an easterly change in declination to present. Inclination shallows between AD 1700 and present.	Precision ~50 years at 95% confidence or better, possibly ~20 years for dates after AD 1700. Good potential owing to rapid VGP movement. Excellent calibration data from AD 1570 when direct observations began. Possible confusion with Iron Age or early medieval dates around 17th century.
Medieval AD 1066–1485	Rapid movement throughout period. Large westerly swing in declination and drop in inclination. Apparent 'loop' between about AD 1280 and 1425.	Precision ~50 years at 95% confidence. Good potential owing to rapid VGP movement Ambiguity with dates near AD 1280 and 1425 owing to a tight loop or possible crossover, also possibility of confusion with Roman dates during early 14th century.
Early medieval AD 410–1066	Slow movement from AD 400 to 850. Then more rapid increase in declination.	Precision ~100–200 years at 95% confidence, better towards end of period. Poor potential due to very slow VGP movement and present paucity of good calibration evidence. Possible confusion with Iron Age and 17th century AD for dates between AD 600 and 800.
Roman AD 43–410	Relatively rapid drop in inclination between AD 100 and 250. Inclination then increases again. Declination fairly constant throughout.	Precision ~50 years at 95% confidence. Potentially good precision between AD 100 and 300, but ~75–100 before and after this period. Double-back at AD 250 means independent evidence is often needed to determine if date is early or late Roman. Possible confusion with 14th century near AD 250.
Iron Age 700 BC–AD 43	Rapid, linear, westerly change in declination with inclination relatively constant for most of the period. Reversal of direction of change in declination around 50 BC causes 'hairpin' in 1st century BC.	Precision ~70–100 years at 95% confidence. Potentially good but at present a paucity of calibration evidence limits precision. Hairpin in 1st century BC can complicate dating at this period.
Bronze Age 2500 BC–700 BC	Very slow, almost stationary at a position with very easterly declination, and steep inclination.	Precision ~200 years at 95% confidence. Poor due to slow movement and paucity of calibration information. Extreme position of VGP far from true north does allow features dating from this period to be easily distinguished.

Future developments

Research is continuing to improve the quality of the calibration data base for those periods where the UK directional archaeomagnetic dating curve is presently not well defined. It is evident from Tarling and Dobson (1995) that there is a lack of good quality calibration information for the period before 100 BC as well as for the period between AD 400 and 800. This results in less precise and less reliable archaeomagnetic dates during these time periods. Whilst some headway might be made by investigating ways of incorporating existing European data into the UK Database, more examples of independently dated features from these periods are needed to fully resolve this problem.

In tandem with gathering more calibration data, statistical research is being conducted to investigate better ways of compiling calibration curves from the Database of known-age archaeomagnetic determinations and then comparing magnetisation vectors from features of unknown age with such curves. To date, UK calibration curves have been constructed by visual inspection (Clark *et al* 1988), which is prone to subjectivity, or by moving window averaging methods (Batt 1997) that tend to dampen or flatten out real trends within the data (Lengyel and Eighmy 2002). New adaptations of Bayesian statistics to spherical distributions promise to improve the reliability and precision with which archaeomagnetic features can be dated (Lanos 2004). Furthermore, new techniques for modelling changes in the geomagnetic field over large regions promise to overcome the need to correct all measurements to a central reference location and allow the integration of reference data over much larger regions (Korte and Holme 2003).

However, perhaps the greatest weakness of archaeomagnetic dating in the UK is the lack of calibration information for variation in the intensity of the Earth's magnetic field over past millennia. Dating using the intensity as well as the direction of the Earth's field could resolve many of the ambiguities caused by crossovers in the calibration curve discussed in the previous section. One of the problems that has hampered the development of a UK archaeointensity calibration curve has been the necessity for the use of thermal demagnetisation to determine the strength of magnetisation within each sample. This process can lead to chemical alteration of the magnetic minerals carrying the remanence, thus changing the results obtained. However, a microwave demagnetisation technique has been developed that results in very little bulk heating of the samples being measured (Shaw *et al* 1996; Shaw *et al* 1999). Initial tests on archaeological material from the UK show promise (Casas *et al* 2005) and it is hoped that over the next few years research can be directed towards constructing a UK archaeointensity calibration database using the new microwave technique.

To coordinate archaeomagnetic research across Europe and to address the present shortage of trained archaeomagnetic practitioners, a European research training network, Archaeomagnetic Applications for the Rescue of Cultural Heritage (AARCH), has been established. The network is being coordinated by Dr Cathy Batt at the University of Bradford. Information about the network and its participants is available at the AARCH website: www.brad.ac.uk/acad/archsci/aarch/ or by contacting aarch@bradford.ac.uk

As part of this initiative, researchers in the network would be extremely interested to be able to sample archaeomagnetic features for which independent dating evidence is also available. In the event of a suitable feature being discovered, contact Dr Cathy Batt or Paul Linford at English Heritage (*see* Appendix 1 for contact details).

Other applications of archaeomagnetism

Although this document focuses on the use of archaeomagnetic analysis as a dating technique, it can also provide other types of information to the archaeologist. Directional archaeomagnetic measurement can determine which way up an object was when fired, test whether fired material is in situ or if it has collapsed or been redeposited and may even be able to help determine if sherds of a tile (or other fired ceramic object) were once fitted together. Remanence and other magnetic properties have been used to estimate the firing temperatures of pottery (Coey *et al* 1979) and burnt sediments (Linford and Platzman 2004) as well as the duration of firing experienced by hearths (Meng and Noël 1989). The use of portable magnetometers as a prospecting tool is now well established in British archaeology (Clark 1990; English Heritage 1995; Gaffney and Gater 2003) and magnetic analysis of sediments is increasingly being applied to study environmental changes in antiquity (Thompson and Oldfield 1986; Evans and Heller 2003). Magnetic properties have also been used to determine the provenance of obsidian (McDougall and Tarling 1983), limestone (Williams-Thorpe and Thorpe 1993) and ceramics (Rasmussen 2001). This is far from an exhaustive list of the possibilities that have already been investigated and new applications of archaeomagnetism will doubtless emerge in the future.

Part 2

Practicalities: interactions between user and practitioner

Archaeomagnetic analysis should be part of an integrated project framework. The procedures and principles of such project management should follow those set out in *Management of Archaeological Projects* (MAP2) (English Heritage 1991 and familiarity with *Management of Research Projects in the Historic Environment* (MoRPHE) (English Heritage forthcoming) is also advisable. The model for project management described in MAP2 is composed of six stages. These are relevant to any archaeological project, whether or not such a project is stimulated by a development proposal. The role of archaeomagnetic analysis at each stage is set out below.

Planning

The integration of archaeomagnetic dating into an archaeological project must generally be undertaken in a more reactive way than is the case for most other specialist services. This is because it is often not clear that suitable features will be uncovered on a site until excavation is at a relatively advanced stage. Even when the presence of a substantial thermoremanent feature is anticipated prior to excavation, the likelihood of disturbance since its remanence was acquired cannot be assessed until it is exposed for inspection.

However, the requirement for archaeomagnetic analysis should be considered at the planning stage of an archaeological project. Background information concerning the site may suggest whether suitable features are likely to occur – for instance, is industrial activity involving kilns or furnaces expected to be present? The potential precision of archaeomagnetic dating for the likely age of the site, as compared with other possible dating techniques, should also be considered. However, where a suitable feature can already be well dated by other means, the European archaeomagnetic community would still be interested in sampling it as noted above in Future developments. The sections in Part 1, What can be dated? and Dating precision and limitations, provide guidance when assessing the suitability of archaeomagnetic dating for a particular project. Further information about how archaeomagnetism is complemented by other scientific dating techniques can be found in Clark (1987) and Aitken (1990; 1999) and advice on the application of the various physical dating techniques is available from the English Heritage Scientific Dating Team (*see* Appendix 1).

As the orientation of archaeomagnetic samples must be precise and the areas to be sampled carefully chosen, a specialist will normally be required to visit the site during excavation to undertake the sampling. It is important to bear in mind that, at the time of writing, there are few archaeomagnetic practitioners who are able to provide a regular dating service in the UK. Since none of these specialists is dedicated exclusively to providing archaeomagnetic dates, their availability to work on a particular project may be limited. Therefore, such specialists should be contacted as soon as possible, preferably prior to the onset of excavation, for projects where archaeomagnetic analysis is likely to be required and they will need to discuss the:

- potential scale of the work;
- types of features that are likely to need sampling;
- timescale for the excavation phase of the project;
- dates by when results will be required.

Such early discussion allows for scheduled site visits, thus avoiding unnecessary interruptions and delays to tight excavation deadlines, especially if it is envisaged that a large number of features will need sampling.

Fieldwork

The above notwithstanding, it is often only during the fieldwork phase of a project that the requirement for archaeomagnetic analysis is identified. If an initial survey component is involved in the fieldwork, then information about the possible presence of suitable features can be gained before excavation. Collection of surface finds can suggest that industrial processes that are likely to have involved kiln or furnace structures took place at the site (English Heritage 2001) and geophysical survey can detect the presence of the remains of such structures (English Heritage 1995). Magnetic prospecting techniques are particularly useful as they can often discriminate anomalies possessing TRM.

Suitability

When excavation commences, potential features can be inspected to confirm their suitability for archaeomagnetic dating. The section, What can be dated?, describes the considerations involved and a brief checklist is presented in Table 2.1.

With regard to thermoremanent magnetisation of clays and clay soils, these often exhibit visible reddening when compared to unfired samples of the same material. Unfortunately this visual test is not always diagnostic as the precise colour change will vary depending on mineral composition of the clay. Furthermore, Canti and Linford (2000) caution that soils in temperate northern hemisphere climates may not exhibit significant reddening even when subjected to high temperatures. In such cases, magnetic susceptibility measurements can be used as an additional tool to identify areas that might have been exposed to suitable temperatures in antiquity (Linford and Platzman 2004; Linford and Welch 2004). Further advice on the application of archaeomagnetic analysis to specific archaeological features can be sought (*see* Appendix 1) and the provision of photographs or plans of the feature(s) under consideration can assist this process if a site visit is not immediately possible.

Once the suitability of a feature for analysis has been established, arrangements can be made for an archaeomagnetic dating specialist to visit and collect samples. Prior to the visit, features to be sampled should ideally be kept covered to avoid either excessive waterlogging, or drying and shrinkage of surfaces in intense sunlight. If weather conditions permit, the cover can be removed on the day of the visit to allow any condensation to dry from the surfaces to be sampled.

Safe working practice

As with all work on archaeological sites, archaeomagnetic dating specialists should carry out their work under a defined health and safety policy and observe safe working practices at all times. Risk assessments should be carried out and documented where necessary. On building sites and archaeological excavations specialists must also comply with the health and safety policies of the contractor. For further information *see* SCAUM (Standing Conference of Archaeological Unit Managers 1991).

Table 2.1 Checklist of factors influencing the suitability of a feature for archaeomagnetic analysis

All features	Is the feature still in the same position as it was when it acquired its remanence? This is a fundamental requirement of the archaeodirectional method. The feature should be inspected for cracking that might indicate that it has moved or been disturbed since firing/deposition.
	In the absence of cracking, has the feature slumped or lost its structural integrity?
	If there is evidence for slumping (see Part 1, The mean remanent direction) can the feature be assumed to have been level originally? Is it possible to estimate the direction and degree of movement (strike and dip)?
	Is the feature free of bioturbation, eg tree roots, mole activity?
	At a smaller scale, is the material comprising the feature still well consolidated? For instance, loose sand or soil may become friable and individual particles may have moved realigning their stored magnetic field directions.
	Is the feature likely to have been in close proximity to ferrous material when it acquired its remanence, eg an iron-smelting furnace that cooled with slag left inside it? This can distort the magnetic remanence recorded in the feature.
Thermoremanent features	Has a suitably intense firing event taken place? (Usually determined by changes in the coloration of the fabric or magnetic susceptibility measurements.) If the feature is composed of clay, has it been baked hard?
Depositional remanent features	Is it likely that the sediment has settled out of solution in low-energy conditions so that a DRM can form?

Sampling

The sampling and orientation process is described in the Sampling procedure section above. It should be noted that whilst modern magnetometers allow very small samples to be taken, a degree of damage to the feature being sampled is still necessary. Depending upon the sampling technique employed and the type of material, it may be necessary to almost entirely remove a small feature. It is prudent, therefore, to ensure that any context to be sampled has been fully recorded prior to archaeomagnetic sampling. Copies of any available photographs and plans can also be useful to the archaeomagnetic dating specialist. The specialist should:

- make a sketch plan showing the positions of the samples within the feature;
- note relevant site context and sample numbers for future reference.

Care should be taken to avoid exposing samples to strong magnetic fields prior to measurement.

Assessment of potential for analysis

During an archaeological project, once fieldwork is completed, the material recovered will be catalogued and assessed to determine what potential, if any, it offers for post-excavation analysis. A report (in MAP2, the assessment report) will be produced detailing this information. Based upon this assessment, a decision will be taken as to whether post-excavation analysis of the material is warranted. If so, then the original project design will need to be updated to take account of the archaeological material actually recovered and its potential for further study. A revised project design document will then usually be produced (in MAP2, the updated project design) making proposals for the analyses deemed appropriate and the project steering group will need to agree the required costs and resources before post-excavation analysis proceeds.

As with the other archaeological material recovered during fieldwork, samples taken for archaeomagnetic analysis will need to be included in this process. Preliminary archaeomagnetic results can be produced within about four weeks, so dating work can, in some cases, proceed interactively with excavation. This is generally possible only when a small number of features are to be dated and the dating specialist does not have a queue of analyses to process. However, in such cases, final archaeomagnetic dates and a final archive report (*see below*) may already be available at the time when the potential of other archaeological material is being assessed. Final archaeomagnetic results can then be included in the assessment report.

On larger projects, when such rapid turnaround of final results is not possible, initial measurements of the samples can usually still be provided at the assessment stage. These measurements can indicate if a feature is likely to have been disturbed and is thus not archaeomagnetically datable. With these results, the project manager and dating specialist can agree priorities for analysis, to ensure that the most archaeologically important, and archaeomagnetically most promising, features are dated first. If analysis of the archaeomagnetic samples would also have the potential to address any other research issues, these should be identified, and the necessary work itemised, at this stage. This information can then be included in the assessment report and, if appropriate, a timetabled programme of archaeomagnetic analysis can be drawn up for the updated project design. The bulk of the archaeomagnetic analysis would then be completed in parallel with other post-excavation archaeological analyses.

Analysis and report preparation

Once the updated project design has been accepted, any additional archaeomagnetic analysis required to produce dates for the sampled features can proceed. This will include the measurement of the natural remanent magnetisation (NRM) of any samples not yet analysed and the production of demagnetisation curves for all, or a representative subset of, the specimens (Clark *et al* 1988). If detailed demagnetisation curves are not measured on all the specimens, then those remaining should be demagnetised using the set of optimal partial demagnetisation increments identified from the detailed curves. The direction of the primary magnetisation component recorded in each specimen can then be accurately determined using principal components analysis (Kirshvinck 1980). Statistical analysis of the final results for all the specimens can then be carried out to produce a mean direction of remanent magnetisation for the feature which can be compared with the relevant calibration curve. More information about these processes and references will be found in Part 1 under Laboratory measurement and Dating precision and limitations.

The archaeomagnetic dating report

Once the results of the archaeomagnetic analysis have been completed they should be presented as an archive report that is intelligible to the layperson as well as the specialist; this report may be edited for inclusion in the final project report and its suggested form and content are outlined below.

The primary function of the report is to record any dates deduced by the archaeomagnetic analysis but it is also essential to present the results in such a way that they could be replicated by another archaeomagnetic specialist. Regardless of how the archaeological investigation was instigated, an archaeomagnetic dating report is necessary to provide sufficient data to support conclusions drawn from the archaeomagnetic analysis.

The report should include pertinent information to allow for:

- assessment of the continuing validity of the archaeomagnetic date in the light of future advances;
- future recalibration of a date as the UK archaeomagnetic calibration curve is refined;
- an archaeomagnetic date that has supporting independent dating evidence to be incorporated into the UK Archaeomagnetic Database as part of the ongoing improvement of UK calibration data.

The minimum requirements necessary for a report to meet these criteria are:

1 The identification and description of the feature including cross references to any context or feature numbers assigned by the excavator.
2 The location of the feature should be stated in terms of its latitude and longitude to an accuracy of at least 0.1 degrees (the direction and magnitude of the Earth's magnetic field varies with position on the Earth's surface).
3 The number and composition of samples taken from the feature should be stated, as well as whether they were subsequently divided into specimens in the laboratory. If samples were subdivided, the number of specimens derived from each sample should be recorded.
4 The partial demagnetisation regime applied to the specimens to remove secondary magnetisation components should be described. Details of the principal components analysis for each specimen should be listed, eg the calculated MAD (maximum angular deviation) angles (*see* Kirshvinck 1980).
5 The number of samples, N, used to calculate the feature's mean remanent magnetisation should be stated. If samples were subdivided into specimens then the method used to determine the mean magnetisation vector for each sample should be described. It is also essential to outline the number of specimens and/or samples rejected from these calculations and the reasons for their exclusion.
6 The α_{95} circle of confidence angle for the calculation should be stated, in addition to the declination and inclination of the mean remanent direction. It is also desirable to state the associated estimate of the Fisher index (κ). A precision of one decimal place is usually sufficient for all these values, provided that angles are measured in degrees. *See* Tarling (1983, 117–22) for details of the calculation of precision parameters for Fisher distributions.
7 The mean magnetisation direction for each of the features analysed should be quoted before any corrections or adjustments are applied.
8 It should also be stated if a magnetic distortion correction was applied to the mean remanent direction before comparison with calibration data (Aitken and Hawley 1971; Shuey *et al* 1970).
9 The adjusted values of the declination and inclination should also be stated if the mean remanent direction was adjusted to a central reference location such as Meriden for comparison with calibration data. If calibration was via the calculation of a VGP then the inferred pole position and the polar error parameters (Tarling 1983, 127) should be provided instead.
10 It is desirable to discuss, alongside the archaeomagnetic date in the report, any other available chronological evidence that can bracket the date of the feature and which is independent of the archaeomagnetic analysis.

The exact layout of an archaeomagnetic dating report will necessarily vary depending on such factors as the specific methodologies employed and the number and type of features sampled. However, most reports can conform to an outline model, as suggested in Table 2.2 opposite, which allows all the specific pieces of information listed above to be included in the relevant places.

Dissemination

Archive reports for archaeomagnetic analyses funded by English Heritage are submitted for inclusion in the relevant English Heritage report series. These reports make available the results of specialist investigations in advance of full publication and are available on request from English Heritage (*see* Appendix 1).

The archaeomagnetic results should also be included in the report publication. By the time the analysis and report preparation stage of the project is complete (*see* the previous section) the project team will have decided which of the following options to pursue with regard to the presentation of the archaeomagnetic analysis:

- a summary of the archaeomagnetic results included in the main report text, while the archaeomagnetic report and related data is retained in archive;
- a summary of the results included in the main report text while the archaeomagnetic report is included as an appendix;
- the archaeomagnetic report is reproduced in the main report text (with only those modifications necessary for the sake of consistency).

Table 2.2 Outline model of an archaeomagnetic dating report

	function	*key features*
Summary	identifies the dating study, its objectives and results	
Introduction	outlines the background to the project, personnel involved, dates of sampling and the location of the site	• the sampling location(s) (especially latitude and longitude) and date(s) • identification of the sampled features (context, feature and/or sample numbers)
Methodology	describes the techniques and instrumentation used to sample and analyse the feature (text should be supported by annotated feature plans and/or photographs of the feature(s) sampled showing sample positions, *see* Figures below)	• a description of the sampling and orientation strategies employed • the number and composition of the samples recovered and any subsequent division into individual specimens • the techniques and equipment employed for laboratory measurement of the remanent magnetisation. (Where standardised procedures are used, this description is often placed in an appendix and only departures from the standard methodology are noted here.)
Results	discusses the results of the above measurements (text should be supported by tables listing the results of all measurements and interpretive graphical illustrations, *see* Tables below)	• the partial demagnetisation applied to each sample and discussion of the reasons why any samples were rejected • the calculated mean remanent direction for each feature analysed in terms of declination and inclination (and intensity if determined) along with the number of samples used and the associated precision parameters • any corrections made to the mean remanence direction to compensate for magnetic distortion (unless already noted under Methodology) • any adjustment to a standard reference location required to allow the calculated mean to be compared with calibration data (the mean parameters both before and after adjustment should be stated) • a comparison of the mean remanent direction with calibration data and, if it is possible to date the feature, the derived date range
Conclusion	summarises the main findings of the archaeomagnetic analysis	• if an archaeomagnetic date could not be obtained for a feature possible reasons should be discussed • if a date was obtained, the date range can be compared with any other independent dating evidence. Such discussion is particularly important where crossovers or contiguities in the archaeomagnetic calibration curve result in two or more alternative possible date ranges.
Acknowledgements		
Date summary	summarises the minimal information requirements outlined above for each date	• reiterates information that should have already been noted in the text. However, it can be useful to summarise key points for ease of reference, for example: laboratory feature code: 1DF archaeological feature identification: brick kiln, context 1034 location: longitude 0.9°W, latitude 51.3°N number of samples/specimens: 16/16 number of samples used in mean: 16 AF demagnetisation applied: 10–100mT mean MAD angle of samples used in mean: 0.5° distortion correction applied: none declination (at Meriden): -7.4° (-7.4°) inclination (at Meriden): 74.4° (75.1°) α_{95}: 0.9° k: 1762.3 date range (63% confidence): AD 1700 to 1720 date range (95% confidence): AD 1690 to 1725 archaeological date range: AD 1698 to 1721 (documentary)
Tables (often placed at the end of the report to aid readability)	should include	• NRM measurements of magnetisation declination, inclination and intensity for all specimens/samples and the same measurements after optimal partial demagnetisation • measurements of declination, inclination and intensity at each partial demagnetisation stage for all samples for which full demagnetisation curves were measured
Figures (often placed at the end of the report to aid readability)	should include	• annotated feature plans and/or photographs of the feature(s) sampled showing sample positions • appropriate plots of the distribution of sample magnetisation directions both for their NRM directions and after optimal partial demagnetisation • plots of the demagnetisation curve(s) for a representative subset of those samples for which full demagnetisation curves were measured • graphs comparing the mean remanent direction of each feature dated with the relevant calibration information

It should be noted that under the Copyright, Designs and Patents Act 1988 the organisation or person undertaking field and reporting work retains the copyright to the material, unless this has been varied in the contract for the work. This position should be made clear to all relevant parties at the outset of work (Institute of Field Archaeologists 1999, appendix 6).

As for all project work, close liaison between the archaeomagnetic dating specialist and the project team is essential – no less so at this stage where it will be important to ensure that the archaeomagnetic analysis is presented in appropriate proportion to its contribution to the stated objectives of the project.

Summarising archaeomagnetic dates in publications

Where the results of archaeomagnetic analysis are to be summarised in a project publication, a certain minimum amount of information should be included for each feature dated to allow it to be evaluated and compared with other archaeomagnetic results. Where possible the archaeomagnetic summary section should include all of the minimally required information listed in the section on the archaeomagnetic dating report. However, when considerations of space mean that this is not possible, the following parameters must be quoted along with the date range for each archaeomagnetic date:

- the declination and inclination of the mean remanent direction at the site specified in degrees to one decimal place;
- the number of samples used to calculate the mean direction, N;
- the α_{95} precision parameter in degrees to one decimal place. Preferably also the estimate of the Fisher index (κ) quoted to unit value.

It is presumed that the location of the site, and the features dated, can be determined from information elsewhere in the report. If this is not the case then the longitude and latitude of the features dated should also be stated in degrees to at least one decimal place.

A draft of any written work that includes archaeomagnetic results should always be sent back to the archaeomagnetic specialist for checking. This will avoid any misrepresentation of the results.

Citing archaeomagnetic dates

Archaeomagnetic dates should be cited using the formula: <*oldest date*> to <*youngest date*> at <*confidence level*>% confidence. For example, AD 1465 to 1510 at 95% confidence or 100 BC to AD 30 at 95% confidence. Recent archaeomagnetic analyses will provide a date range at the 95% confidence level and, where available, it is this that should be quoted. However, a date range at a different confidence level may be all that is available with dates produced in the past. In all cases the discussion should provide an indication of where the more detailed information outlined above may be found.

Data archiving

It is essential that a report on any archaeological intervention, even if it goes no further than an evaluation, should be lodged as promptly as possible with the Historic Environment Record (HER), a mainly local authority-based service. This is necessary to inform future interventions and guide the local planning authority on future decisions. The archaeomagnetic analysis should form part of this overall project report. However, if no other archaeological investigation takes place as part of the project, a copy of the archaeomagnetic dating report should instead be sent to the HER.

The National Geophysical Data Center in Boulder, Colorado, USA houses the International Archaeomagnetic Database from which the UK calibration data are mainly derived (Tarling and Dobson 1995). This database contains archaeomagnetic analyses of features from many parts of the world together with information about any independent evidence that can establish the date of the feature. A sizeable subset of the data is from the UK and has been used to compile the UK archaeomagnetic dating calibration curve. The database is available at http://www.ngdc.noaa.gov/seg/geomag/paleo.shtml

Archaeomagnetic dating reference curves have largely been built up from an accumulation of analyses of features that can also be dated using other independent evidence. Hence, any successful archaeomagnetic analysis where some complementary dating evidence is also available should be considered for inclusion in the International Archaeomagnetic Database by the specialist concerned.

Case studies

The following case studies describe two situations where archaeomagnetic dating has proved an effective aid to dating archaeological features. They are intended to illustrate how the principles and techniques described in this document are applied in practice and, where relevant, cross-references are made to the appropriate sections in Part 1.

Dogmersfield House brick kiln (thermoremanent magnetisation)

In 2003, during a watching brief in advance of construction work at Dogmersfield House near Fleet, Hampshire, archaeologists from Wessex Archaeology discovered the remains of an updraught brick kiln (context 1034 in Wessex Archaeology 2003). The St John family inherited Dogmersfield House in 1712 and the present house was built on the site in 1728, possibly incorporating an earlier Elizabethan house. Further substantial extension works were made in 1744 and it was thought that the kiln related to one of these two construction phases. It was brick-built and aligned north-east to south-west, consisting of two flues with a large stokepit at the south-western end (Fig 15). Subsequent excavation showed that it had been built on top of the remains of a smaller updraught kiln on a different alignment and it appears that the later kiln was constructed as soon as the earlier one was abandoned, possibly because the latter could not manufacture bricks in sufficient quantities. The survival of the remains of two updraught kilns is relatively rare in the Hampshire region where most of the remains so far studied have dated from the 19th century and been of the more substantial downdraught design (Moore 1988). Given the importance of the discovery and its potential to relate to historical evidence as well as the likelihood that fired bricks from the kiln would contain a TRM, the English Heritage Geophysics Team was asked to sample it for archaeomagnetic analysis.

Seven bricks were removed from the kiln but, before disturbing them, orientation discs were attached using the disc method (*see above* Sampling procedure) and oriented relative to true north using a gyro-theodolite. In the laboratory, 16 specimens were obtained by cutting away approximately 8cc of the brick material immediately beneath selected discs (some discs were left attached to the remaining material for future analysis). The specimens were then partially demagnetised (*see above* Laboratory measurement) using a series of alternating field strengths ranging between 1mT and 100mT. Their directions of magnetisation were re-measured after each demagnetisation increment and principal components analysis was then used to examine the linearity of the demagnetisation curves produced for each specimen. Inspection of the MAD angles indicated that all were acceptably linear between the 10mT and 100mT demagnetisation steps, some viscous overprinting being evident in the directions measured before the 10mT demagnetisation increment. As a rule of thumb, MAD angles less than ~2° indicate acceptable linearity and an acceptably linear demagnetisation curve suggests that the magnetisation is likely to be stable. The optimal direction of magnetisation recorded by each specimen was calculated using the measurements in this range and these are listed in Table 2.3.

A mean TRM direction was calculated (*see above* The mean remanent direction) from the primary TRM directions determined for all 16 specimens using standard Fisher statistics. No correction for magnetic refraction was made as no systematic variation in the magnetisation directions of samples was observed in relation to their position within the kiln. The calculated mean TRM direction was:

at site
dec = -7.4°   inc = 74.4°
α_{95} = 0.88° κ = 1762.3

at Meriden
dec = -7.4°   inc = 75.1°

In the directions quoted above a negative sign for the magnetic declination indicates a direction to the west of true north. This archaeomagnetic direction was measured at Dogmersfield, Hampshire (longitude 0.9°W, latitude 51.3°N), so it was converted to the equivalent direction that would have pertained at Meriden (longitude 1.6°W, latitude 52.4°N) to allow for comparison with UK calibration data. The converted direction was compared with a modified version of the calibration curve of Batt (1997) (*see above* Dating precision and limitations) which incorporated additional calibration data from the UK and northern France and which has been assembled since Batt's curve was produced.

Fig 15 The Dogmersfield House brick kiln during sampling, looking south.

Table 2.3 NRM measurements of specimens and principal components of measurements after partial AF demagnetisation for the Dogmersfield brick kiln

	NRM measurements			after partial demagnetisation			
sample	*dec°*	*inc°*	*J*(mAm^{-1})	*dec°*	*inc°*	*MAD angle°*	*R*
1DF01	-14.6	77.2	1698.6	-8.1	75.9	0.5	
1DF02	-20.0	74.7	27999.4	-20.3	74.5	0.4	
1DF05	-8.6	77.6	6453.4	-5.2	74.3	0.7	
1DF06	-17.8	75.1	7848.2	-15.0	73.7	0.6	
1DF07	-13.0	70.2	5059.6	-7.9	72.2	0.4	
1DF08	-6.3	76.4	1980.4	-6.6	76.5	0.3	
1DF10	4.8	77.5	21366.0	-7.0	74.5	0.4	
1DF11	5.7	74.3	24532.8	-4.7	73.1	0.5	
1DF12	23.0	76.4	6180.3	5.7	74.3	0.7	
1DF13	-11.3	75.1	989.6	-10.3	75.4	0.3	
1DF14	-13.9	73.8	1873.9	-8.9	73.9	0.4	
1DF16	0.3	74.0	5924.0	1.1	74.5	0.5	
1DF17	-4.9	74.3	12101.2	-8.4	74.5	0.5	
1DF18	-12.8	73.1	3526.8	-9.5	73.9	0.6	
1DF20	-2.0	74.3	11518.2	-2.9	75.3	0.6	
1DF21	-15.0	72.2	8454.6	-9.8	73.0	0.6	

Notes
J = magnitude of magnetisation vector
MAD = maximum angular deviation (see text and Kirshvinck 1980)
R = sample rejected from mean calculation

Fig 16 depicts the resulting calibration curve graphically with the mean TRM direction from the Dogmersfield kiln superposed upon it along with the latter's 95% confidence limits. The date range deduced for the last firing of the kiln is AD 1690 to 1725 at the 95% confidence level. This is earlier than either of the two documented construction events but accords remarkably well with information discovered subsequently which indicates that the Dogmersfield estate leased a house to John Reading, a bricklayer, between 1698 and 1719. Hence it is likely that the kiln was in operation earlier than first thought and probably supplied bricks for alterations or repairs to the house and garden walls immediately after the St John family inherited the estate.

Yarnton ditch sediment (post-depositional remanent magnetisation)

Archaeological excavations in the 1990s by Oxford Archaeology in advance of gravel extraction at the village of Yarnton, near Oxford revealed a wealth of settlement activity on the floodplain of the north bank of the Thames. The underlying archaeological landscape consisted of a concentration of prehistoric funerary activity, focused around a Neolithic enclosure as well as evidence for domestic settlement. A ditch (feature 12036, pictured in Fig 8) located ~600m to the west of the Neolithic enclosure appeared to mark a boundary between the ritual element of the site and the occupation activity found elsewhere on the floodplain. Excavation of the ditch in 1997 suggested that the sediment comprising its fill was likely to have been deposited from a body of water and tests by the English Heritage Geophysics Team indicated that it possessed significantly enhanced magnetic properties compared to the surrounding substrate. An organic-rich layer was identified at the base of the ditch and the most strongly magnetised sediment was associated with it. Subsequently sufficient material for radiocarbon dating was also extracted from this layer. Given the importance of this boundary for the interpretation of the site and the likelihood that a depositional or post-depositional remanence was recorded by the sediment, it was sampled for archaeomagnetic dating whilst the ditch section was exposed.

Sampling was carried out by pushing cylindrical 10cc plastic pots into the face of the ditch section and marking arrows

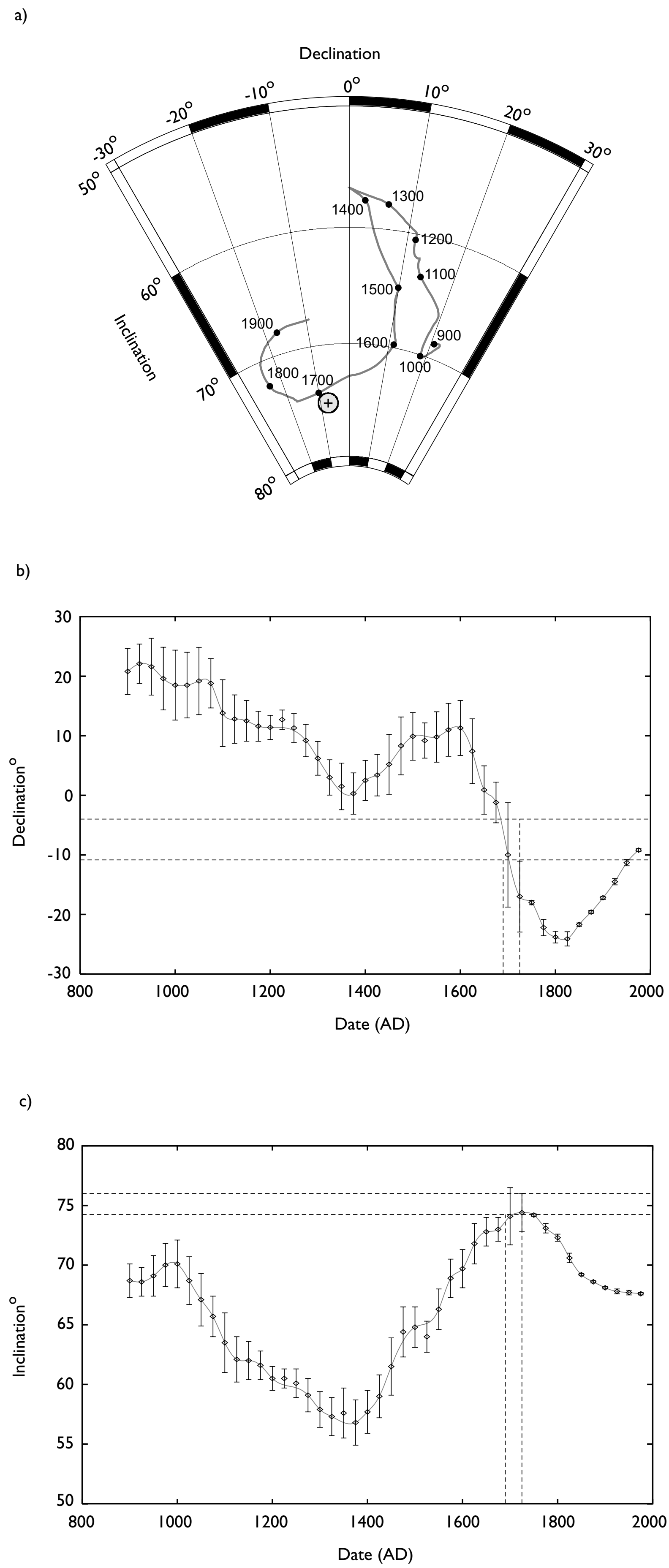


Fig 16 Comparison of the mean remanent direction recorded by the Dogmersfield brick kiln with the archaeomagnetic dating calibration curve of Batt (1997). (a) Equal angle stereogram showing the variation of declination and inclination with time (dates are all AD, negative declinations are west of true north). (b) Variation of declination with time showing error bars determined for control points. (c) Variation of inclination with time, showing error bars. The mean thermoremanent direction calculated for the kiln with its 95% confidence limits has been superimposed on all three diagrams.

on the base of each indicating the direction of vertical (*see above* Sampling procedure). A gyro-theodolite was used to establish the vertical orientation as well as the angle of the face of the ditch section relative to true north. Thirty-one sediment samples were recovered from the section (sample 26 failed during extraction) by excavating a small area around each pot to extract it then sealing the open ends with airtight lids. No subdivision of the samples was carried out in the laboratory so in this case each sample taken from the site equated to an archaeomagnetic specimen. The NRM of each specimen was measured before any partial demagnetisation (*see above* Laboratory measurement) was carried out and this revealed that those taken from the top of the ditch section (specimens 01 to 11) contained very little magnetic material. The remaining specimens derived from parts of the section either in or near the organic-rich layer and these were partially demagnetised using a series of alternating field strengths ranging between 1mT and 199mT. Their directions of magnetisation were re-measured after each demagnetisation increment and principal components analysis was then used to examine the linearity of the demagnetisation curves produced for each specimen. All the measured magnetisation directions are listed in Table 2.4.

As greater measurement error is often encountered when analysing weakly magnetised sediments, a MAD angle of less than, or equal to, 3° was considered to indicate acceptable linearity when examining the specimens' demagnetisation curves. Using this criterion it was found that specimens 15 and 22 did not retain stable magnetisation directions and these samples were excluded from the calculation of the mean remanence direction. Specimen 21 was also excluded as its remanence direction was anomalously far from the cluster of directions formed by the other specimens. A check on the site notes revealed that this specimen, along with specimen 22, had been located next to a stone inclusion within the sediment and this may well have distorted the recorded magnetisation direction. The optimal directions of magnetisation determined for the remaining 17 specimens were averaged using standard Fisher statistics (*see above* The mean remanent direction). No correction for magnetic refraction was made as no systematic variation in the magnetisation directions of samples was observed in relation to

Table 2.4 NRM measurements of specimens and primary magnetisation components after partial AF demagnetisation for ditch 12036 at Yarnton, Oxfordshire

	NRM measurements			*after partial demagnetisation*			
sample	*dec°*	*inc°*	*J(mAm^{-1})*	*dec°*	*inc°*	*MAD angle°*	*R*
01	0.9	75.4	0.6335	-	-	-	R
02	3.4	75.7	0.6346	-	-	-	R
03	79.3	63.9	0.4900	-	-	-	R
04	-0.4	46.5	0.6228	-	-	-	R
05	-88.8	-19.3	6.5037	-	-	-	R
06	7.9	54.6	0.3636	-	-	-	R
07	4.5	68.5	0.7046	-	-	-	R
08	8.6	68.0	1.6987	-	-	-	R
09	0.3	64.1	9.5434	-	-	-	R
10	19	66.6	2.2329	-	-	-	R
11	32.4	81.0	0.5625	-	-	-	R
12	3.9	74.8	21.0829	4.5	75.1	1.7	
13	25.4	76.6	37.9892	18.2	78.1	2.7	
14	12.2	70.1	7.6265	14.5	69.7	2.0	
15	3.9	77.2	10.1836	4.9	77.7	4.4	R
16	14	68.8	36.5633	16.9	68.7	1.1	
17	30.2	61.3	8.3905	23.6	69.6	3.0	
18	20.3	73.4	46.8495	15.3	74.4	2.7	
19	16.1	68.2	58.1766	11.1	68.9	2.7	
20	-4.5	63.6	19.1388	-3.0	64.0	1.7	
21	-3.5	72.7	205.3024	32.4	65.0	1.7	R
22	16.9	69.6	68.0523	18.9	67.8	7.5	R
23	6.8	66.2	83.7510	8.4	66.1	2.6	
24	8.6	69.5	161.7178	-15.4	70.5	2.1	
25	10.7	66.8	59.3086	3.4	68.3	2.5	
27	-12	69.3	43.9266	-11.2	69.8	1.9	
28	13.9	74.8	37.7221	-8.9	76.2	2.4	
29	0.3	65.3	78.5048	3.8	64.4	2.5	
30	-5.2	70.7	96.0492	-2.8	67.6	3.0	
31	7.8	69.9	82.3529	0.9	70.8	2.1	
32	-15.6	69.6	33.1742	-1.6	64.6	1.0	

Notes
J = magnitude of magnetisation vector
MAD = maximum angular deviation (see text and Kirshvinck 1980)
R = sample rejected from mean calculation

their position within the ditch section. The calculated mean remanence direction was:

at site
dec = -4.2°   inc = 70.1°
α_{95} = 2.4°   κ = 214.7

at Meriden
dec = -4.3°   inc = 70.5°

In the directions quoted above the positive sign for the magnetic declination indicates a direction to the east of true north. This archaeomagnetic direction was measured at Yarnton, Oxfordshire (longitude 1.3°W, latitude 51.8°N), so it was converted to the equivalent direction that would have pertained at Meriden (longitude 1.6°W, latitude 52.4°N) to allow for comparison with UK calibration data. The converted direction was compared with the calibration curve of Clark, Tarling and Noël (1988) as the prehistoric portion of this curve is based on the largest amount of calibration data (*see above* Dating precision and limitation). Fig 17 depicts the calibration curve graphically with the mean remanence direction from the Yarnton ditch sediment superposed upon it along with the latter's 95% confidence limits. The date range deduced for the locking-in of the sediment is 215 BC to 85 BC or 15 BC to AD 90 at the 95% confidence level. This date is in good agreement with radiocarbon determinations from two macro-fossil samples of aquatic plant material recovered from the organic layer which produced calibrated dates of 360 to 1 cal yr BC (OxA-10707) and 390 to 90 cal yr BC (OxA-10708) respectively. Furthermore, the radiocarbon dates suggest that the earlier of the two archaeomagnetic date ranges is to be preferred. Additional magnetic analysis suggested that the remanence carrier was likely to be almost pure magnetite (Linford *et al* 2005) and transmission electron micrographs of magnetic particles extracted from the sediment indicated morphologies characteristic of biogenic magnetite (magnetosomes) derived from magnetotactic bacteria (Fig 18). These bacteria indicate that a micro-aerobic environment existed in the ditch in the late Iron Age and their numbers would have rapidly increased whilst conditions within the sediment layer remained favourable. As each generation of bacteria died their magnetosomes would have become aligned with the ambient direction of the Earth's magnetic field, forming the post-depositional remanent magnetisation measured in the samples.

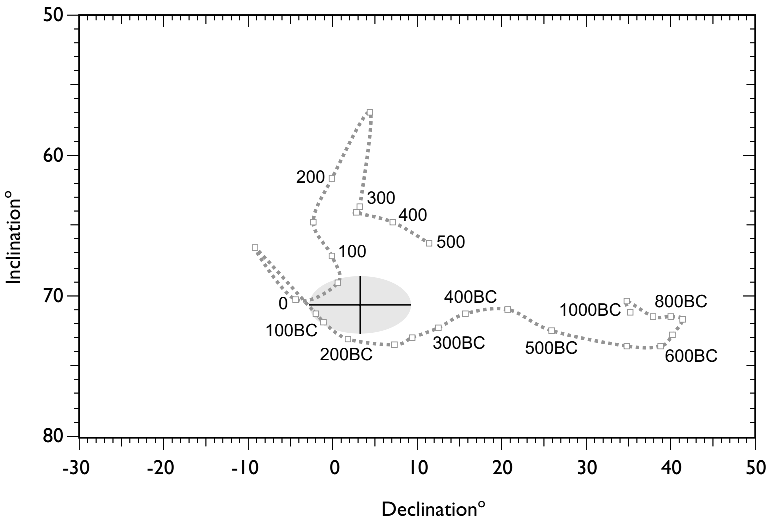


Fig 17 (above) Comparison of the mean remanent direction recorded by the Yarnton ditch sediment with the archaeomagnetic dating calibration curve of Clark, Tarling and Noël (1988) using a Bauer plot. The mean remanent direction together with its 95% confidence limits have been superimposed on the curve as a cross and shaded ellipse. Dates with no suffix are AD, negative declinations are west of true north.

Fig 18 (right) Transmission electron micrograph of the magnetic particles extracted from the sediments extracted from the ditch at Yarnton. The distinctive size range, morphology and absence of metal impurities all suggest that these magnetite particles were created by magnetotactic bacteria.

Glossary

alpha-95 (α_{95}, circle of confidence) a measure of the uncertainty associated with a mean three-dimensional direction vector as calculated using **Fisherian statistics**. The mean direction is imagined to lie along the axis of rotational symmetry of a cone, directed away from the point towards the circular base. The α_{95} statistic is defined as the semi-angle of this cone such that there is a 95% probability that the true mean direction is fully contained within it (*see* Fig 13c and Aitken 1990, ch 9). The smaller the α_{95} angle, the smaller the circular base of the cone (hence the term circle of confidence) and thus the more precisely the mean direction has been determined. As a very approximate rule of thumb, for archaeomagnetic purposes, an α_{95} greater than 5° would generally be considered poor precision whilst a value less than 2.5° typically indicates good precision.

angle of dip *see* **inclination**

anisotropy (magnetic anisotropy, anisotropy of susceptibility) the ease with which a magnetic material becomes magnetised can depend on the direction of the magnetising field. This can lead to the direction of remanent magnetisation acquired by the material differing from that of the applied field (aligning more closely with an easy direction of magnetisation). Anisotropy is typically caused by either crystalline alignments in samples containing haematite or shape alignments in samples containing magnetite.

antiferromagnetic (antiferromagnetism) a form of **ferromagnetism** where the crystalline material contains two equally but oppositely magnetised sublattices. If the directions of magnetisation of the two lattices are exactly opposite, zero net magnetisation will result. However, if the sublattice magnetisation directions are not exactly opposed (canted antiferromagnetism) they will not entirely cancel each other and a weak net magnetisation can result at approximately 90° to the sublattice magnetisation directions. Haematite (α-Fe_2O_3) exhibits this form of permanent magnetisation.

archaeodirection the direction of the **geomagnetic field** in antiquity. This term is generally used to describe the archaeodirectional method of magnetic dating where the direction (rather than the intensity) of the geomagnetic field (and thus the apparent location of the magnetic poles) is determined for the time at which an object acquired its remanence.

archaeointensity the strength or intensity of the **geomagnetic field** in antiquity. This term is generally used to describe the method of magnetic dating where the strength (rather than the direction) of the geomagnetic field is determined for the time that an object acquired its remanence.

blocking temperature (unblocking temperature) associated with **thermoremanent magnetisation (TRM)**. On the cooling of a substance containing magnetic minerals, this is the temperature at which TRM becomes 'frozen in'. This temperature will depend on the precise mineralogical composition of the substance as well as its crystalline organisation (eg large or small **grains**). Materials with blocking temperatures below about 200–250°C often do not retain fully stable magnetisations at room temperature and may exhibit **viscous remanence**. When considering the heating of materials to remove their remanence, it may be referred to as unblocking temperature.

coercivity the strength of magnetic field that must be applied to an object possessing remanent magnetisation, in the opposite direction to its direction of magnetisation, to reduce its external magnetic field to zero whilst the coercive field remains switched on. Coercivity is often used in the analysis of the magnetic mineralogy of samples.

coercivity of remanence (B_{cr} or H_{cr}) the strength of magnetic field that must be applied to a material exhibiting remanent magnetisation, in the opposite direction to its direction of magnetisation, to result in the removal of that remanence (demagnetisation) after the coercive field is switched off. Alternating field demagnetisation is often used to study the coercivity of remanence of materials in archaeomagnetic studies.

Curie temperature (Curie point) on heating, the temperature above which a material loses its **ferrimagnetic** properties. The blocking temperature of a particular mineral is related to its Curie temperature but may be lower owing to such considerations as chemical impurities, crystal size and shape. Named after Pierre Curie (1859–1906).

declination the angle in the horizontal plane between magnetic and true north. Directions to the east of true north are considered positive, those to the west negative

depositional (detrital) remanent magnetisation (DRM) a **remanent magnetisation** acquired as a sediment is deposited. In archaeomagnetic terms, this is usually due to particles of sediment rotating to align their intrinsic magnetisations with the ambient field as they settle out of a relatively non-turbulent water solution. They then become locked into position by the weight of sediment settling above them.

easy axes one or more directions, relative to the crystal lattice, along which it is energetically favourable for a crystal to become magnetised. The crystal will always magnetise parallel to one of these directions which are referred to as its easy axes. The energy required to make the magnetisation direction flip to an alternate easy axis within the crystal will generally depend on the precise composition, shape and size of the particular **grain**.

ferrimagnetic (ferrimagnetism) a form of **ferromagnetism** where the crystalline material contains two oppositely but unequally magnetised sublattices resulting in a net overall magnetisation. For example magnetite (Fe_3O_4) where the iron atoms form a sublattice magnetised in one direction, opposed by the sublattice of oxygen atoms that are magnetised in the opposite direction.

ferromagnetic (ferromagnetism) permanent magnetisation resulting from strong exchange interactions between neighbouring atoms in a crystal lattice. This causes the magnetisations of all atoms in the lattice to spontaneously align in the same direction. Iron (Fe) is the most common ferromagnetic substance. In a looser sense ferromagnetism can be used as an umbrella term encompassing all related forms of permanent magnetisation such as **antiferromagnetism** and **ferrimagnetism.**

Fisher (Fisherian) statistics a system of statistics developed to characterise the distribution of unit vectors in three-dimensional space (Fisherian statistics describes the variation of directions whilst normal, Gaussian, statistics describes the variation of scalar quantities). Developed by Ronald Aylmer Fisher (1890–1962) (Fisher 1953).

fluxgate device designed to measure the strength of the ambient magnetic field along a single axis. It consists of two, oppositely wound solenoids with cores consisting of a soft magnetic material that reach their saturation magnetisation in a weak magnetic field. These solenoids are both magnetised using the same alternating electric current and in the absence of any external field, the magnetic fields they generate will cancel each other out. However, in the presence of a constant ambient field there will be a phase difference between the times at which the oppositely magnetised cores are saturated resulting in a measurable alternating magnetic field. The strength of the ambient magnetic field in the direction of the long axes of the solenoids can be inferred from the amplitude and frequency of this alternating field.

geomagnetic field the Earth's spontaneously generated magnetic field. Largely due to movements of electrically conductive material in the Earth's molten outer core but with a smaller magnitude contribution from ionic movements in the upper atmosphere.

geomagnetic reversal the phenomenon observed in the magnetisation of ancient rocks whereby the direction of the **geomagnetic field** appears to have periodically reversed (ie the magnetic north pole exchanges position with the magnetic south pole). The period of time between reversals is known as a chron and, in the recent geological past, these seem to have lasted just under one million years. We are presently in the Brunhes chron, named after Bernard Brunhes (1867–1910), and the last geomagnetic reversal (Brunhes-Matuyama) occurred about 780,000 years ago.

grain a macroscopic sample of a crystalline mineral will generally consist of multiple conjoined crystals of varying shapes and sizes. Each of these crystals, within which the atoms are usually arranged on a single regular lattice, is termed a **grain**.

gyro-theodolite a device capable of finding the direction of true north using the precession of a built-in gyroscope.

inclination (angle of dip) the angle between the local geomagnetic field direction and the horizontal plane. Conventionally downward directions are considered positive. In the present (Brunhes) chron, inclinations are typically positive in the northern hemisphere and negative in the southern hemisphere. The magnetic poles are defined as those places on the Earth's surface where the inclination angle is vertical (downwards at the north pole, upwards at the south).

magnetic domain a region within a crystal of a magnetic mineral within which the magnetisations of all atoms are parallel. For certain minerals and crystal sizes, this may result in each entire **grain** being magnetised in the same direction (single domain behaviour), whilst in other cases, a grain might be divided into several magnetic domains each magnetised in a different direction (multi-domain behaviour).

magnetic moment a measure of the strength of a magnetic dipole measured in Ampere metres squared (Am^2) in the SI system

magnetic refraction the phenomenon by which the direction of an ambient magnetic field changes as it crosses the interface between materials with different magnetic properties, analogous to the way that light rays refract when crossing the boundary between materials with different refractive indices. It has been postulated that this effect may be responsible for anomalous distortions to the directions of the magnetisation observed in different parts of kiln structures. However, the changes in magnetisation observed in practice do not always match those predicted by the theory, suggesting that other, less well understood, factors are also involved.

natural remanent magnetisation (NRM) the remanence of a natural sample as first measured in the laboratory (before any **partial demagnetisation**). The term implies nothing about the origin of the remanence which could be **thermoremanence, depositional remanence**, etc.

partial demagnetisation the process of removing the less stable components of a sample's magnetisation (resulting from **magnetic domains** with low **blocking temperatures**) to isolate the high coercivity or blocking temperature component. May be achieved via exposure to an alternating magnetic field (AF demagnetisation), heating in an oven to a specific temperature (thermal demagnetisation) or by irradiation with low-power microwave radiation (microwave demagnetisation).

post-depositional remanent magnetisation (pDRM) a **remanent magnetisation** acquired after a sediment is deposited. This can occur when a **depositional remanent magnetisation** does not become locked in until some time after the initial deposition of the sediment or when the initial depositional magnetisation is modified by chemical or other effects.

precision parameter (Fisher index) a dimensionless measure of the relative scatter of directions in a **Fisherian statistical** distribution. Its value can range from zero (directions drawn from the distribution are completely random and uncorrelated) to infinity (complete alignment on a single direction).

remanent magnetisation (magnetic remanence) permanent magnetisation of an object or material that persists even after the removal of any magnetising field.

secular variation gradual changes in the strength and direction of the geomagnetic field over time. Archaeomagnetic dating is only possible because of this temporal variation in the Earth's magnetic field.

specimen in archaeomagnetic studies a sample of magnetised material taken from a feature may be divided into a number of smaller specimens for measurement. Measurements from all specimens from the same sample are usually averaged to determine a sample mean, so reducing random measurement errors and differences caused by material inhomogeneity. Hence, 'specimen' defines the unit of magnetic material upon which measurements are conducted in the laboratory whilst 'sample' refers to the units of material originally extracted from the feature.

spinner magnetometer laboratory magnetometer capable of measuring weak magnetisations within samples. It exploits the fact that, when the sample is rotated relative to a fixed collecting coil (or ring **fluxgate**), the sample's rotating magnetic field will generate an electric current in proportion to its strength.

SQUID magnetometer SQUID = superconducting quantum interference device. A cryogenic laboratory magnetometer that exploits the phenomenon by which magnetic flux can only take fixed discrete values within superconducting materials. Particularly useful for measuring extremely weak magnetic fields and for large samples sets (as the instrumentation is amenable to semi-automation).

thermoremanent magnetisation (TRM) a remanent magnetisation acquired after a substance has been heated then cooled in an ambient magnetic field.

viscous remanent magnetisation (VRM) **magnetic domains** with **blocking temperatures** lower than about 200°C can realign their magnetisation directions even at room temperature if given enough time. Timescales for the process range from minutes to tens or even hundreds of years. Hence a magnetic material containing a reasonable proportion of such domains can exhibit a magnetisation that slowly changes over time, tracking changes in the geomagnetic field, albeit with some lag.

virtual geomagnetic pole (VGP) at any point on the Earth's surface the geomagnetic field has a direction which is conventionally expressed in terms of its **declination** and **inclination**. The VGP position is defined as that position on the Earth's surface where the north (or south) magnetic pole would have to be situated to cause the observed field direction, assuming that the Earth's magnetic field can be modelled as a geocentric dipole. Note that the true geomagnetic poles will generally not exactly coincide with such inferred VGPs owing to local perturbations in the Earth's magnetic field (ie the geocentric dipole model is only a first-order approximation to the true geomagnetic field).

Appendix 1

Contact addresses for UK archaeomagnetism

English Heritage

Within English Heritage the first point of contact for general archaeological science enquiries should be the regional English Heritage advisor for archaeological science who can provide independent non-commercial advice. Such advisors are based either in universities or in the English Heritage regional offices. Please contact regional advisors currently based in universities at their university address, using the regional office address as a further contact point when necessary.

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Specific advice on scientific dating and archaeomagnetism in particular can be sought from Alex Bayliss, the English Heritage Scientific Dating Coordinator, and Paul Linford of the English Heritage Geophysics Team respectively. Advice is available to all, free of charge. A limited archaeomagnetic assessment and analysis service is also available for features from English Heritage funded projects where prior arrangements have been made. Archaeomagnetic dating requests for excavations funded from other sources will also be considered, subject to the approval of the relevant English Heritage Inspector of Ancient Monuments, where features are of major archaeological significance or where good independent complementary dating evidence is available.

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Other sources of advice

Advice on aspects of archaeomagnetism may be sought from the contacts below, as noted.

Dr Cathy Batt
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Dr Batt is the coordinator of the Archaeomagnetic Applications for the Rescue of Cultural Heritage (AARCH) European research network (*see* Part 1, Future developments). She can provide advice on all aspects of archaeomagnetic dating. Research interests include calibration of UK archaeomagnetic dates, dating in the Northern and Western Isles of the UK and integration of archaeomagnetic dating with other methodologies. Limited contract dating services can be provided.

Dr Mark W Hounslow
Centre for Environmental Magnetism and Palaeomagnetism (CEMP)
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The CEMP performs contract archaeomagnetic dating services and can deal with all types of archaeomagnetic materials from clay linings, to more substantial heated wall rocks and bricks of any consistency and hardness, and strength of magnetisation. A wide variety of environmental magnetic measurements for 'ground-truthing' of magnetic survey data are also undertaken.

Prof Mark Noël
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GeoQuest Associates provide a commercial archaeomagnetic dating service for material sampled throughout the UK and Ireland. Advice is freely given by Prof Noël who has been researching in this area since 1973. Further interests include the archaeomagnetic properties of cave deposits and sediments, and various non-chronometric applications of the archaeomagnetic method.

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The Museum of London Archaeology Service Geomatics Team provide contract archaeomagnetic dating advice, assessment, and sampling service, with final sample analysis and report preparation carried out by the GeoQuest archaeomagnetic laboratory. The Museum of London Archaeology Service operates across the UK and abroad.

Appendix 2

Brief notes on the history of archaeomagnetism

Archaeomagnetism, the study of the magnetisation of archaeological materials, has a long history to which these brief notes cannot hope to do full justice. The earliest steps in the story involve the discovery of the principles upon which archaeomagnetism depends: the magnetic field of the Earth and remanent magnetisation. More detailed overviews of these aspects are provided by Tarling (1983, 1–8) and Good (1988 – *see* the entries on geomagnetism and palaeomagnetism) and Malin and Bullard (1981) provide a thorough catalogue of early observations of declination and inclination made in England including short biographies of many of the individuals concerned.

The phenomena of magnetic attraction and repulsion appear to have been known to the ancient Egyptians and Greeks. The ability of magnetised needles to point in specific directions is first recorded by the Chinese in the 1st century AD (although it had almost certainly been known for at least 300 years previously) and the Chinese were also aware of declination by AD 720, noting that the compass did not point due south (south being the Chinese prime meridian). However, this knowledge does not appear to have reached Europe until much later and the first European record of the magnetic compass is not until the 12th century AD. European observations of declination are not reported until the 16th century AD when the Flemish cartographer Gerhard Mercator and the Portuguese explorer João de Castro both reported differences between magnetic direction and true north. However, some 15th-century sundials and road maps are thought to have markings indicating compass settings that differ from true north. The angle of dip or inclination was also first recorded in the 16th century by Hartmann (1544) and independently by Norman in 1576 (Norman 1581). However, the crucial breakthrough in terms of archaeomagnetic dating was the discovery that declination and inclination changed over time (secular variation) and this was first realised by Henry Gellibrand in 1635 (Gellibrand 1635).

With respect to the acquisition of remanent magnetisation, Delesse (1849) and Melloni (1853) were the first to discover that volcanic rocks were magnetised and both concluded that the magnetisation was acquired on cooling. However, much earlier Boyle (1691) had observed that bricks became magnetised along their long axes on cooling in the Earth's magnetic field. Mercanton (1918) studied the magnetisation of ancient (2000-year-old) vase bases and showed that the individual magnetisation directions were randomised. This indicated that they retained their original magnetisation acquired during firing rather than a common magnetisation direction acquired in later fields after deposition in archaeological deposits.

The development of a scientific dating method based upon the above discoveries is a relatively recent innovation of the mid-20th century, mainly following from Thellier's ground-breaking work in France (Thellier 1938). In the UK the first archaeomagnetic studies were by Cook and Belshé (1958). Subsequent analysis of lake sediment data (Thompson and Turner 1979; Turner and Thompson 1981), well-dated archaeological structures (Aitken and Hawley 1966; Aitken 1970; Clark *et al* 1988; Tarling and Dobson 1995), as well as collation of direct laboratory measurements over the last 400 years (Malin and Bullard 1981), has led to the construction of the UK archaeomagnetic calibration curve (Clark *et al* 1988; Tarling and Dobson 1995; Batt 1997). In Europe, studies have also been made in Belgium (Hus and Geeraerts 1998), Bulgaria (Kovacheva 1997; Lanos *et al* 1999), Denmark (Abrahamsen 1973, France (Bucur 1994; Lanos *et al* 1999), Germany (Schnepp and Pucher 2000; Schnepp *et al* 2004), Greece (Kovacheva *et al* 2000) and Hungary (Márton 1996; 2003). Extensive investigation has also been carried out in the American Southwest (Sternberg 1989; Eighmy 1991; Lengyel and Eighmy 2002).

Bibliography

Abrahamsen, N 1973 'Archaeomagnetic tilt correction on bricks'. *Archaeometry*, **15**, 267–74

Aitken, M J 1970 'Dating by archaeomagnetic and thermoluminescent methods'. *Philosophical Transactions of the Royal Society of London A*, **269**, 77–88

Aitken, M J 1990 *Science-based Dating in Archaeology*. London: Longman

Aitken, M J 1999 'Archaeological dating using physical phenomena'. *Reports on Progress in Physics*, **62**, 1333–76

Aitken, M J and Hawley, H N 1966 'Magnetic dating – III: further archaeomagnetic measurements in Britain'. *Archaeometry*, **9**, 187–97

Aitken, M J and Hawley, H N 1971 'Archaeomagnetism: evidence for refraction in kiln structures'. *Archaeometry*, **13**, 83–5

Batt, C M 1997 'The British archaeomagnetic calibration curve: an objective treatment'. *Archaeometry*, **39**, 153–68

Batt, C M 1999 'Preliminary investigations into the acquisition of remanence in archaeological sediments' in Tarling, D H and Turner, P (eds), *Palaeomagnetism and Diagenesis in Sediments* (Geological Society Special Publication **151**). London: Geological Society, 9–19

Boyle, R 1691 *Experimenta et Observationes Physicae*. London

Bucur, I 1994 'The direction of the terrestrial magnetic field in France, during the last 21 centuries. Recent progress'. *Physics of the Earth and Planetary Interiors*, **87**, 95–109

Canti, M G and Linford, N T 2000 'The effects of fire on archaeological soils and sediments: temperature and colour relationships'. *Proceedings of the Prehistoric Society*, **66**, 385–95

Casas, L, Shaw, J, Gich, M and Share, J A 2005 'High-quality microwave archaeointensity determinations from an early 18th century AD English brick kiln.' *Geophysical Journal International*, **161**, 653–61.

Clark, A J 1987 *Scientific Dating Techniques*. (IFA Technical Paper **5**). Birmingham: Institute of Field Archaeologists

Clark, A J 1990 *Seeing Beneath the Soil: Prospecting Methods in Archaeology*. London: Batsford

Clark, A J, Tarling, D H and Noël, M 1988 'Developments in archaeomagnetic dating in Britain'. *Journal of Archaeological Science*, **15**, 645–67

Coey, J M D, Buochez, R and Dang, N V 1979 'Ancient techniques'. *Journal of Applied Physics*, **50** (B11), 7772–7

Collinson, D W 1983 *Methods in Rock Magnetism and Palaeomagnetism: Techniques and Instrumentation*. London: Chapman and Hall

Cook, R M and Belshé, J C 1958 'Archaeomagnetism: a preliminary report on Britain'. *Antiquity*, **32**, 167–78

David, A and Linford, P 1999 'Palaeomagnetic measurements' in Roberts, M B and Parfitt, S A (eds), *A Middle Pleistocene Hominid Site at Eartham Quarry, Boxgrove, West Sussex, UK* (Archaeological Report **17**). London: English Heritage, 297–9

Delesse, A 1849 'Sur le magnétisme polaire dans les mineraux et dans les roches'. *Annales de chimie et de physique*, **25**, 194–209

Department of Environment 1990 *Archaeology and Planning* (Planning Policy Guidance Note **16**). London, HMSO

Eighmy, J L 1991 'Archaeomagnetism: new data on the south-west U.S.A. master virtual geomagnetic-curve'. *Archaeometry*, **33**, 201–14

English Heritage 1991 (reprinted 1996) *Management of Archaeological Projects* (MAP 2). London: English Heritage

English Heritage 1995 *Geophysical Survey in Archaeological Field Evaluation*. (Research and Professional Services Guideline **1**). London: English Heritage

English Heritage 2001 *Archaeometallurgy*, (Centre for Archaeology Guidelines). Swindon: English Heritage

English Heritage (forthcoming) *Management of Research Projects in the Historic Environment* (MoRPHE)

Evans, M E and Heller, F 2003 *Environmental Magnetism: Principles and Applications of Enviromagnetics*. San Diego: Academic Press

Fisher, R A 1953 'Dispersion on a sphere'. *Proceedings of the Royal Society of London A*, **217**, 295–305

Gaffney, C and Gater, J 2003 *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus

Gellibrand, H 1635 *A Discourse Mathematical on the Variation of the Magnetic Needle*. London: William Jones

Good, G A (ed) 1998 *Sciences of the Earth: An Encyclopedia of Events, People, and Phenomena*. New York: Garland

Gutin, J C 1995 'Remains in Spain now reign as oldest Europeans'. *Science*, **26**, 754–5

Hartmann, G 1544 'Letter'. Published in *Sz. Ges. Endkunde*, **32**, 112–36

Hathaway, J H and Krause, G J 1990 'The sun compass versus the magnetic compass in archaeomagentic sample collection' in Eighmy, J L and Sternberg, R S (eds), *Archaeomagentic Dating*. Tucson: University of Arizona Press, 109–34

Hoffman, K A 1988 'Ancient magnetic reversals: Clues to the geodynamo'. *Scientific American*, **285**, 50–9

Hus, J and Geeraerts, R 1998 'The direction of the geomagnetic field in Belgium since Roman times and the reliability of archaeomagnetic dating'. *Physics and Chemistry of the Earth*, **9–10**, 997–1007

Institute of Field Archaeologists 1999 *Standard and Guidance for Archaeological Field Evaluations* (revised edn). Manchester: Institute of Field Archaeologists

Kirshvinck, J L 1980 'The least-squares line and plane and the analysis of paleomagnetic data'. *Geophysical Journal of the Royal Astronomical Society*, **62**, 699–718

Korte, M and Holme, R 2003 'Regularisation of spherical cap harmonics'. *Geophysical Journal International*, **153**, 253–62

Kovacheva, M 1997 'Archaeomagnetic database from Bulgaria'. *Physics of the Earth and Planetary Interiors*, **102**, 145–51

Kovacheva, M, Spartharas, V and Liritzis, I 2000 'New archaeointensity results from Greek materials'. *Archaeometry*, **42**, 415–29

Lanos, P 2004 'Bayesian inference of calibration curves: application to archaeomagnetism' in Buck, C E and Millard, A R (eds), *Tools for Constructing Chronologies: Crossing Disciplinary Boundaries* (Lecture Notes in Statistics **177**). Berlin: Springer, 43–82

Lanos, P, Kovacheva, M and Chauvin, A 1999 'Archaeomagnetism, methodology and applications: implementation and practice of the archaeomagnetic method in France and Bulgaria'. *European Archaeology*, **2**, 365–92

Lengyel, S N and Eighmy, J L 2002 'A Revision of the U.S. Southwest Archaeomagnetic Master Curve'. *Journal of Archaeological Science*, **29**, 1423–34

Linford, N, Linford, P and Platzman, E 2005 'Dating environmental change using magnetic bacteria in archaeological soils from the upper Thames Valley, UK' *Journal of Archaeological Science*, **32** (7), 1037–43

Linford, N T and Platzman, E 2004 'Estimating the approximate firing temperature of burnt archaeological sediments through an unmixing algorithm applied to hysteresis data'. *Physics of the Earth and Planetary Interiors*, **147** (2–3), 197–207

Linford, P 1990 'Archaeomagnetic dating: Burton Dassett, Warwickshire'. Ancient Monuments Laboratory Report. **8/90**

Linford, P and Welch, C M 2004 'Archaeomagnetic analysis of glassmaking sites at Bagot's Park in Staffordshire, England'. *Physics of the Earth and Planetary Interiors*, **147** (2–3), 209–21

Malin, S R C and Bullard, E C 1981 'The direction of the Earth's magnetic field at London, 1570–1975'. *Philosophical Transactions of the Royal Society of London A*, **299**, 357–423

Márton, P 1996 'Archaeomagnetic directions: the Hungarian calibration curve' in Morris, A and Tarling, D (eds), *Palaeomagnetism and Tectonics of the Mediterranean Region* (Geological Society Special Publication **105**). London: Geological Society, 385–99

Márton, P 2003 'Recent achievements in archaeomagnetism in Hungary'. *Geophysical Journal International*, **153** (3), 675–90

McDougall, I and Tarling, D H 1983 'The magnetic sourcing of obsidian samples from Mediterranean and Near Eastern sources'. *Journal of Archaeological Science*, **10**, 441–52

Melloni, M 1853 'Du magnétisme des roches'. *Comptes Rendus de l'Académie Scientifique de Paris*, **37**, 966–8

Meng, Z and Noël, M 1989 'Archaeomagnetic evidence for the age and duration of firing of mediaeval hearths from Coffee Yard, York'. *Geophysical Journal International*, **97**, 357–9

Mercanton, P L 1918 'Etat magnétique de quelques terres cuites pré-historiques'. *Comptes rendus des séances de l'Académie des Sciences de Paris*, **166**, 681, 949

Merril, R T, McElhinny, M and McFadden, P L 1996 *The Magnetic Field of the Earth: Paleomagnetism, the Core and the Deep Mantle*. San Diego: Academic Press.

Moore, P 1988 *The Industrial Heritage of Hampshire and the Isle of Wight*, Chichester: Phillimore

Néel, L 1955 'Some theoretical aspects of rock magnetism'. *Advances in Physics*, **4**, 191–243

Noël, M 1996 'Archaeomagnetic analysis of two kilns at Heybridge, Maldon, Essex'. GeoQuest Associates unpublished report

Noël, M and Batt, C M 1990 'A method for correcting geographically separated remanence directions for the purpose of archaeomagnetic dating'. *Geophysical Journal International*, **102**, 753–6

Norman, R 1581 *The New Attractive*, 1st edn. London: Jhon Kyngston for Richard Ballard

Partridge, T C, Shaw, J, Heslop, D and Clarke, R J 1999 'The new hominid skeleton from Sterkfontein, South Africa: age and preliminary assessment'. *Journal of Quaternary Science*, **14**, 293–8

Rasmussen, K L 2001 'FOCUS: Provenance of ceramics revealed by magnetic susceptibility and thermoluminescence'. *Journal of Archaeological Science*, **28**, 451–6

Schnepp, E and Pucher, R 2000 'The German archaeomagnetic secular variation curve'. *Geol. Carpathia*, **51**, 184

Schnepp, E, Pucher, R, Reinders, J, Hambach, U, Soffel, H and Hedley, I 2004 'A German catalogue of archaeomagnetic data'. *Geophysical Journal International*, **157** (1), 64–78

Schurr, K, Becker, H and Soffel, H C 1984 'Archaeomagnetic study of medieval fireplaces and ovens and the problem of magnetic refraction during the past 6000 years'. *Journal of Geophysics*, **56**, 1–8

Shaw, J, Walton, D, Yang, S, Rolph, T C and Share, J A 1996 'Microwave archaeointensities from Peruvian ceramics'. *Geophysical Journal International*, **124**, 241–4

Shaw, J, Yang, S, Rolph, T C and Sun, F Y 1999 'A comparison of archaeointensity results from Chinese ceramics using microwave and conventional Thellier's and Shaw's methods'. *Geophysical Journal International*, **136** (3), 714–8

Shuey, R T, Cole, E R and Mikulich, M J 1970 'Geographic correction of archaeomagnetic data'. *Journal of Geomagnetism and Geoelectricity*, **22**, 485–9.

Standing Conference of Archaeological Unit Managers (SCAUM) (1991). *Health and Safety in Field Archaeology*. [Lancaster]

Sternberg, R S 1989 'Secular variation of archaeomagnetic direction in the American southwest, A.D. 750–1425'. *Journal of Geophysical Research*, **94**, 527–46

Tarling, D H 1983 *Palaeomagnetism: Principles and Applications on Geology, Geophysics and Archaeology*, London: Chapman and Hall

Tarling, D H and Dobson, M J 1995 'Archaeomagnetism: an error assessment of fired material observations in the British directional database'. *Journal of Geomagnetism and Geoelectricity*, **47**, 5–18

Tarling, D H, Hammo, N B and Downey, W S 1986 'The scatter of magnetic directions in archaeomagnetic studies'. *Geophysics*, **51**, 634–9

Tauxe, L 2002 *Paleomagnetic principles and practice*. Dordrecht: Kluwer Academic.

Thellier, E 1938 'Sur l'aimantation des terres cuites et ses applications geophysiques'. *Annales de l'Institut de Physique du Globe*, **16**, 157–302

Thompson, R and Oldfield, F 1986 *Environmental Magnetism*. London: Allen and Unwin.

Thompson, R and Turner, G M 1979 'British geomagnetic master curve 10,000–0 yr BP for dating European sediments'. *Geophys. Res. Letters*, **6**, 249–52

Turner, G M and Thompson, R 1981 'Lake sediment record of the geomagnetic secular variation in Britain during Holocene times'. *Geophysical Journal of the Royal Astronomical Society*, **65**, 703–25

Wessex Archaeology 2003 'Dogmersfield Park, Hampshire: Archaeological Watching Brief (2001–2003)'. Wessex Archaeology unpublished report **44874.01**

Williams-Thorpe, O and Thorpe, R S 1993 'Magnetic susceptibility used in non-destructive provenancing of Roman granite columns'. *Archaeometry*, **35** (2), 185–95

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The overall text was compiled and written by Paul Linford. Every attempt has been made to present an evenly balanced, up-to-date and, above all, a useful document. Imperfections will certainly remain as well as areas where professional opinion is divided. Furthermore, simply for expediency, it has not been possible to incorporate every suggestion made by those who commented on drafts of the text. Revision is certain to be required in the light of ongoing research and thus any comments towards future editions would be welcome (*see* address in Appendix 1).

As part of the consultation process, a draft version of this document was made available to members of the AARCH network through the site www.meteo.be/CPG/aarch.net/linford.pdf

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These guidelines draw largely on the experience of the former English Heritage Centre for Archaeology and its predecessor for archaeological science, the Ancient Monuments Laboratory.

Cover figures: Research students from The University of Bradford collecting archaeomagnetic samples at Metchley, Birmingham

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