

# **ARCHAEOLOGY, MAGNETIC METHODS**

Encyclopedia of Geomagnetism and Paleomagnetism

David Gubbins and Emilio Herrero-Bervera (eds)

Springer, New York

Schmidt, A. 2007. Archaeology, magnetic methods. In D. Gubbins and E. Herrero-Bervera (eds) *Encyclopedia of Geomagnetism and Paleomagnetism*: 23-31. Encyclopedia of Earth Sciences Series Heidelberg, New York: Springer.

Dr Armin Schmidt  
Senior Lecturer in Archaeological Geophysics  
Department of Archaeological Sciences  
University of Bradford  
Bradford BD7 1DP, U.K.

A.Schmidt@Bradford.ac.uk  
Tel: 01274 – 23 3542  
Fax: 01274 – 23 5190

# ARCHAEOLOGY, MAGNETIC METHODS

Armin Schmidt

## Magnetism and Archaeology

### *Introduction*

Magnetic methods have become important tools for the scientific investigation of archaeological sites, with magnetic prospection surveys and archaeomagnetic dating being the most prominent ones. The principles behind these techniques were initially applied to larger and older features, for example prospecting for ore deposits (see *Magnetic anomalies for geology and resources*) or paleomagnetic dating (see *Paleomagnetism*). When these techniques were adapted for archaeological targets it was soon established that very different methodologies were required. Archaeological features are relatively small and buried at shallow depth, and the required dating accuracy is in the order of tens of years. More importantly, the relationship between archaeological features and magnetism is often difficult to predict and the planning of investigations can hence be complicated. Related is the problem of interpretation. Geophysical results on their own are only of limited use to resolve an archaeological problem. It is the archaeological interpretation of the results, using all possible background information (site conditions, archaeological background knowledge, results from other investigations etc.), which provides useful new insights. If the relationship between magnetic properties and their archaeological formation is unknown, such interpretation may become speculative.

All magnetic investigations depend on the contrast in a magnetic property between the feature of interest and its surrounding environment, for example the enclosing soil matrix. The most important magnetic properties for archaeological studies are magnetisation and magnetic susceptibility.

### *Remanent magnetism*

Thermoremanent magnetisation is probably the best understood magnetic effect caused by past human habitation. If materials that are rich in iron-oxides are heated above their Curie temperature and then allowed to cool in the ambient earth's magnetic field they have the potential to acquire a considerable thermoremanence (see *Thermoremanence*) that is fixed in the material until further heating. Typical archaeological examples are kilns and furnaces, often built of clay, which during their heating cycles often exceed the Curie temperatures of magnetite ( $\text{Fe}_3\text{O}_4$ ) and maghaemite ( $\gamma\text{-Fe}_2\text{O}_3$ ) (578 °C and 578-675 °C, respectively). Such iron-oxides are commonly found in the clay deposits that were used for the construction of these features. Even if the clays only contained weakly magnetic haematite or goethite, the heating and cooling cycles may have converted these into ferri-magnetic iron-oxides (see *Changes in magnetic mineralogy due to heating and methodological implications*). Similarly, fired bricks and pottery can exhibit thermoremanence but when the finished bricks are used as building material their individual vectors of magnetisation will point into many different directions producing an overall weakened magnetic signature (Bevan, 1994). The same applies to heaps of pottery shards. The strong magnetic remanence of kilns led to their discovery with magnetometers in 1958 (Clark, 1990), which triggered the widespread use of archaeological magnetometer surveys today. Kilns also helped to establish the archaeomagnetic dating technique as a new tool for chronological studies in archaeology (Clark *et al.*, 1988).

Detrital remanence is caused when the earth's magnetic field aligns magnetised particles that are suspended in solution and gradually settle (see *Detrital remanent magnetism*). An example is stagnant water loaded with 'magnetic sediments'. The resulting deposits can exhibit a weak but noticeable remanence, which could be used for dating and prospection. It is suspected that similar effects have produced a small remanence and hence a noticeable positive signal in Egyptian mud-bricks, which were made from wet clay pushed into moulds and dried in the sun (Herbich, 2003).

However, other magnetometer surveys over mud-brick structures (Becker and Fassbinder, 1999) have shown a negative magnetic contrast of these features against the surrounding soil. Although it is possible to consider burning events that could lead to such results during the buildings' demolition, it is more likely that these bricks were made from clay that has lower magnetic susceptibility than the soil on the building site.

### ***Induced magnetism***

Any material with a magnetic susceptibility will acquire an induced magnetisation in the earth's magnetic field (see *Magnetic susceptibility*). Hence, if past human habitation has led to enhanced levels of magnetic susceptibility in the soils, magnetic measurements can be used for their detection. The relationship between human activities and the enhancement of magnetic susceptibility was investigated by Le Borgne (1955, 1960), distinguishing thermal and bacterial enhancement. When soil is heated in the presence of organic material (for example during bush- or camp-fires) oxygen is excluded and the resulting reducing conditions lead to a conversion of the soil's haematite ( $\alpha\text{-Fe}_2\text{O}_3$ , anti-ferromagnetic) to magnetite ( $\text{Fe}_3\text{O}_4$ , ferri-magnetic) with a strong increase of magnetic susceptibility. On cooling in air some of the magnetite may be re-oxidised to maghaemite ( $\gamma\text{-Fe}_2\text{O}_3$ , ferri-magnetic), thereby preserving the elevated magnetic susceptibility. In contrast, the 'fermentation effect' refers to the reduction of haematite to magnetite in the presence of anaerobic bacteria that grew in decomposing organic material left by human habitation, either in the form of rubbish pits ('middens') or wooden building material. This latter effect requires further research but it is reported that changes in pH/Eh conditions as well as the bacteria's use of iron as electron source are responsible for the increase of magnetic susceptibility (Linford, 2004). The level of magnetic susceptibility that can be reached through anthropogenic enhancement also depends on the amount of iron-oxides initially available in the soil for conversion. The level of enhancement can hence be quantified by relating a soil's current magnetic susceptibility to the maximum achievable value. This ratio is referred to as 'fractional conversion' and is determined by heating a sample to about 700°C to enhance its magnetic susceptibility as far as possible (Crowther and Barker 1995, Graham and Scollar, 1976). Whether the initial magnetic susceptibility was enhanced by pedogenic or anthropogenic effects can however not be distinguished with this method. It is also worth remembering that magnetite and maghaemite have the highest magnetic susceptibility of the iron-oxides commonly found in soils and in the absence of elemental iron a sample's magnetic susceptibility is hence a measure for the concentration of these two minerals.

More recent investigations have indicated additional avenues for the enhancement of magnetic susceptibility. One of the most interesting is a magnetotactic bacterium that thrives in organic material and grows magnetite crystals within its bodies (Fassbinder *et al.*, 1990) (see also *Biomagnetism*). Their accumulation in the decayed remains of wooden postholes led to measurable magnetic anomalies and is probably responsible for the detection of palisade walls in magnetometer surveys (Fassbinder and Irlinger, 1994). Other causes include the low-temperature thermal dehydration of lepidocrocite to maghaemite (e.g. Özdemir and Banerjee, 1984) and the physical alteration of the constituent magnetic minerals, especially their grain size (Linford and Canti, 2001; Weston, 2004). Magnetic susceptibility can also be enhanced by the creation of iron-sulphides in perimarine environments with stagnant waters (Kattenberg and Aalbersberg, 2004). These may fill geomorphological features, like creeks, that were used for settlements and can therefore be indirect evidence for potential human activity.

## **Archaeological Propection**

Archaeological propection refers to the non-invasive investigation of archaeological sites and landscapes for the discovery of buried archaeological features. To understand past societies it is of great importance to analyse the way people lived and interacted and the layout of archaeological sites gives vital clues; for example the structure of a Roman villa's foundations or the location of an

Iron-aged ditched enclosure within the wider landscape. Such information can often be revealed without excavation by magnetic surveys. These techniques have therefore become a vital part of site investigation strategies. Buried archaeological features with magnetic contrast will produce small anomalies in measurements on the surface and detailed interpretation of recorded data can often lead to meaningful archaeological interpretations. The techniques are not normally used to ‘treasure-hunt’ for individual ferrous objects but rather for features like foundations, ditches, pits or kilns (Sutherland and Schmidt, 2003).

### ***Magnetic Susceptibility Surveys***

Since human habitation can lead to increased magnetic susceptibility (see above), measurements of this soil property are used for the identification of areas of activity. Such surveys can either be carried out *in situ* (i.e. with non-intrusive field measurements) or by collecting soil samples for measurements in a laboratory. These two methods are often distinguished as being volume- and mass specific, respectively, although such labelling only vaguely reflects the measured properties.

Most instruments available for the measurement of low field magnetic susceptibility internally measure the ‘total magnetic susceptibility’ ( $k_t$  with units of  $\text{m}^3$ ), which is proportional to the amount of magnetic material within the sensitive volume of the detector: the more material there is, the higher will be the reading. For field measurements, the amount of investigated material is usually estimated by identifying a ‘volume of sensitivity’ ( $V$ ) for the employed sensor (e.g. a hemisphere with the sensor’s diameter for the Bartington MS2D field coil). The ‘volume specific magnetic susceptibility’ is then defined as  $\kappa = k_t / V$  (dimensionless). In contrast, laboratory measurements normally relate instrument readings to the weight of a sample ( $m$ ), which can be determined more accurately. The ‘mass specific magnetic susceptibility’ is then  $\chi = k_t / m$  (with units of  $\text{m}^3 \text{kg}^{-1}$ ). Accordingly, it is possible to calculate one of these quantities from the other using the material’s bulk density ( $\rho$ ):  $\chi = \kappa / \rho$ .

The main difference between field and laboratory measurements, however, is the treatment of samples. It is common practice (Linford, 1994) to dry and sieve soil samples prior to measuring their magnetic susceptibility in the laboratory. Drying eliminates the dependency of mass specific magnetic susceptibility on moisture content, which affects the bulk density. Sieving removes coarse inclusions (e.g. pebbles) that are magnetically insignificant. In this way, laboratory measurements represent the magnetic susceptibility of a sample’s soil component and can therefore be compared to standard tables. For field measurements, however, results can be influenced by non-soil inclusions and the conversion of volume specific measurements to mass specific values is affected by changes in environmental factors (e.g. soil moisture content).

The measured magnetic susceptibility depends on the amount of iron oxides available prior to its alteration by humans (mostly related to a soil’s parent geology), and also on the extent of conversion due to the anthropogenic influences. As a consequence, the absolute value of magnetic susceptibility can vary widely between different sites and ‘enhancement’ can only be identified as a contrast between areas of higher susceptibility compared to background measurements. There is no predetermined threshold for this contrast and it is therefore justifiable to use the more qualitative measurements of field based magnetic volume susceptibility (see above) for archaeological prospection.

The instrument most commonly used for field measurements of volume specific magnetic susceptibility is the Bartington MS2D field coil consisting of a 0.2m diameter ‘loop’, which derives 95% of its signal from the top 0.1 m of soil (Schmidt *et al.*, 2005). Since most archaeological features are buried deeper than this sensitivity range, the method relies on the mixing of soil throughout the profile, mostly by ploughing.

Magnetic susceptibility surveys, either performed as *in situ* field measurements or as laboratory measurements of soil samples, can be used in three different ways: (i) as primary prospection method to obtain information about individual buried features, (ii) to complement magnetometer

surveys and help with their interpretation by providing data on underlying magnetic susceptibility variations, or (iii) for a quick and coarse ‘reconnaissance’ survey using large sampling intervals to indicate areas of enhancement instead of outlining individual features. Figure 1a shows the magnetic susceptibility survey (MS2D) of a medieval charcoal burning area. Since a detailed study of this feature was required the data were recorded with a spatial resolution of 1m in both x- and y-direction. Corresponding magnetometer data (FM36) are displayed in Figure 1b. The magnetic susceptibility results outline the burnt area more clearly and are on this site well suited for the delineation of features. On former settlement sites where ploughing has brought magnetically enhanced material to the surface and spread it across the area, magnetic susceptibility measurements at coarse intervals of 5 m, 10 m or 20 m can be used to identify areas of enhancement, that can later be investigated with more detailed sampling, for example with a magnetometer (see below). Even where ploughing has mixed the soil, magnetic susceptibility measurements can vary considerably over short distances of about 2 m. It is hence not normally possible to interpolate coarsely sampled data and settlement sites can only be identified if several adjacent measurements have consistently high levels compared to the surrounding area. Figure 2 shows data from a survey at Kirkby Overblow, North Yorkshire, in search for a lost medieval village. The dots mark the individual measurements and their size represents the strength of the magnetic susceptibility, highlighting the singularity of each measurement. Nevertheless, areas of overall enhancement can be identified and these were later investigated with magnetometer surveys. The grey shading in this diagram visualises the data in a contiguous way, colouring the Voronoi cell around each individual measurement according to its magnetic susceptibility. The limitations of such diagrams for widely separated measurements should be considered carefully.

### ***Magnetometer Surveys***

In contrast to surveys that measure magnetic susceptibility directly, magnetometer surveys record the magnetic fields produced by a contrast in magnetisation, whether it is induced as a result of a magnetic susceptibility contrast, or remanent, for example from thermoremanent magnetisation. If the shape and magnetic properties of a buried archaeological feature were known, the resulting magnetic anomaly could be calculated (Schmidt, 2001) (see also *Modelling magnetic anomalies*). The inverse process, however, of reconstructing the archaeological feature from its measured anomaly, is usually not possible due to the non-uniqueness of the magnetic problem and the complex shape and heterogeneous composition of such features. Some successful inversions were achieved when archaeologically informed assumptions were made about the expected feature shapes (e.g. the steepness of ditches) and magnetic soil properties (for example from similar sites) (Neubauer and Eder-Hinterleitner, 1997; Herwanger *et al.*, 2000). If surveys are conducted with sufficiently high spatial resolution, the mapped data often already provide very clear outlines of the buried features (Figure 3), allowing their archaeological interpretation even without data inversion. However, when interpreting measured data directly, the typical characteristics of magnetic anomalies have to be taken into consideration. For example, in the northern hemisphere anomalies created by soil features with induced magnetisation have a negative trough to the north of the archaeological structure and a slight shift of the positive magnetic peak to the south of its centre (Figure 4).

To estimate the strength of a typical archaeological response it is possible to approximate the anomaly with a simplified dipole field:  $B = \mu_0 m/r^3 = \Delta\kappa V B_{\text{earth}}/r^3$ , where  $\mu_0$  is the magnetic permeability of free space ( $4\pi \times 10^{-7} \text{ Tm A}^{-1}$ ),  $m$  is the total magnetic moment of the feature,  $r$  the distance between measurement position and sample,  $\Delta\kappa$  its volume specific magnetic susceptibility contrast,  $V$  its volume and  $B_{\text{earth}}$  the earth’s magnetic flux density. For a buried pit, the following values can be used:  $\Delta\kappa = 10 \times 10^{-5}$ ,  $V = 1 \text{ m}^3$ ,  $B_{\text{earth}} = 48,000 \text{ nT}$  and  $r = 1 \text{ m}$ . This yields an anomaly strength of only 4.8 nT, which is typical for archaeological soil features (e.g. pits or ditches). Anomalies created by the magnetic enrichment of soils through magnetotactic bacteria, for example in palisade ditches, can be as low as 0.3 nT (Fassbinder and Irlinger, 1994) and are

therefore only detectable with very sensitive instruments and on sites where the signals caused by small variations in the undisturbed soil's magnetic properties are very low (low 'soil noise'). Peak values higher than approximately 50 nT are normally only measured over ferrous features with very high magnetic susceptibility, or over features with thermoremanent magnetisation, like furnaces or kilns. As shown by the numerical approximation above, the anomaly strength depends both on the magnetisation and the depth of a buried feature, and can therefore not be used for the unambiguous characterisation of that feature. More indicative is the spatial variation of an anomaly (see Figure 4), since deeper features tend to create broader anomalies.

Surveys are normally undertaken with magnetometers on a regular grid. The required spatial resolution obviously depends on the size of the investigated features, but since these are often unknown at the outset, a high resolution is advisable. Recommendations by English Heritage have suggested a minimum resolution of 0.25 m along lines with a traverse spacing of 1 m or less (0.25 m × 1 m) (David, 1995). However, to improve the definition of small magnetic anomalies even denser sampling is required. Such high-definition data can even show peaks and troughs of bipolar anomalies from small, shallowly buried iron debris (e.g. farm implements) and therefore help to distinguish these from archaeological features with wider anomaly footprints. More recently, it has become possible to collect randomly sampled data with high accuracy (Schmidt, 2003) that can either be gridded to a predefined resolution or visualised directly with Delaunay triangulation (Sauerländer *et al.*, 1999).

Due to the often small anomaly strength caused by archaeological features, very sensitive magnetometers are required for the surveys. The first investigations (Aitken *et al.*, 1958) were made with proton-free precession magnetometers (see also *Observatory Instrumentation*) but due to the slow speed of operation and their relative insensitivity, these are rarely used for modern surveys. In Britain, the most commonly used magnetometers use fluxgate sensors (see also *Observatory Instrumentation*), which can achieve noise levels as low as 0.3 nT if sensors and electronics are carefully adjusted. In Austria and Germany some groups use Caesium vapour sensors that are built to the highest possible specifications and have reported sensitivities of 0.001 nT (Becker, 1995). On loess soils, which produce very low magnetic background variations, the weak anomalies caused by magnetotactic bacteria in wood (see above) were detected with Caesium magnetometers, revealing palisade trenches of Neolithic enclosures (Neubauer and Eder-Hinterleitner, 1997).

Magnetometer sensors measure the combination of the archaeological anomaly and the earth's magnetic field. Hence, to reveal the archaeological anomalies, readings have to be corrected carefully for changes in the ambient field, caused by diurnal variations (see *Geomagnetic Secular Variation*) or magnetic storms (see *Storms and substorms*). Proton free-precession instruments are often used in a differential arrangement ('variometer') by placing a reference sensor in a fixed location to monitor the earth's magnetic field. The survey is then carried out with an additional sensor, which is affected by the same ambient field. Subtracting the data from both sensors cancels out the earth's field. The same can be achieved with a gradiometer arrangement where the second sensor is usually rigidly mounted 0.5m to 1m above the first so that both are carried together. Their measurements can be subtracted instantly to form the gradiometer reading. Despite the heavier weight of such an arrangement it allows for improved instrument design. Especially for fluxgate sensors a signal feedback system, linked to the upper sensor, can be used to enhance the sensitivity of the instrument. Archaeological features that can be detected with magnetometers are often buried at shallow depth and a gradiometer's sensor separation is then similar to the distance between the feature and the instrument. Therefore, the gradiometer reading is not an approximation for the field gradient and is better recorded as the difference in magnetic flux density (nT) between the sensors, and not as a gradient (nT m<sup>-1</sup>). The magnetic field created by the feature of interest and the ambient magnetic field combine at the sensor and the recorded signal depends on the vector component measured with the particular instrument. For example, fluxgate sensors measure a single component of the magnetic field (usually the vertical component) and a gradiometer therefore records exactly this component of the archaeological anomaly. In contrast, gradiometers built from field intensity

sensors, like proton free-precession and caesium vapour sensors, measure the component of the anomaly in the direction of the ambient earth's magnetic field, since this is much larger than the anomaly. Its direction governs the vector addition of the two contributions and the gradiometer reading can be approximated as  $|\mathbf{B}_{earth} + \mathbf{B}_{anomaly}| - |\mathbf{B}_{earth}| \approx \mathbf{B}_{anomaly} \cdot \mathbf{e}_{earth}$  where  $\mathbf{e}_{earth}$  is the unit-vector in the direction of the earth's magnetic field (Blakely, 1996). As a consequence, vertical fluxgate sensors record weaker signals in areas of low magnetic latitude (i.e. near the equator) and data from the two sensor types cannot be compared directly.

The 'detection range' of archaeological geophysical surveys depends on the magnetisation and depth of the features (see above) as well as the sensitivity of the used magnetometers and can therefore not easily be specified. Based on practical experience with common instruments, it is estimated that typical soil features, like pits or ditches, can be detected at depths of up to 1-2 m, while ferrous and thermoremanent features can be identified even deeper. Weak responses were recorded from paleochannels that are buried by more than 3 m of alluvium (Kattenberg, and Aalbersberg, 2004).

Prior to their final interpretation, magnetometer data often have to be treated with computer software for the improvement of survey deficiencies and the processing of resulting data maps (Schmidt, 2002). Data improvement can reduce some of the errors introduced during the course of a survey, such as stripes and shearing between adjacent survey lines. To reduce the time of an investigation, adjacent lines of a magnetometer survey are often recorded walking up and down a field ('zig-zag' recording). However, since most magnetometers have at least a small heading error, a change in sensor alignment resulting from this data acquisition method can lead to slightly different offsets for adjacent lines, which are then visible as stripes in the resulting data (Figure 5a, middle). A common remedy for this effect is the subtraction of the individual mean or median value from each survey line. This helps to balance the overall appearance but also removes anomalies running parallel to the survey lines. If the sensor positions for the forward and backward survey direction are systematically offset from the desired recording position (e.g. always 0.1 m 'ahead') anomalies will be sheared and data will appear 'staggered' (Figure 5a, left). If this defect is sufficiently consistent, it can be removed (Figure 5b) by fixed or adaptive shifting of every other data line (Ciminale and Loddo, 2001). Another common problem found with some instruments is the 'drift' of their offset value, mostly due to temperature effects. If regular measurements are made over dedicated reference points the effects of drift can be reduced numerically. All these methods of data improvement require detailed survey information, for example about the length of each survey line, the direction of the lines, the size of data blocks between reference measurements *etc.* It is hence essential that metadata are comprehensively recorded (see below). Once all data have been corrected for common problems and all survey blocks balanced against each other, they can be assembled into a larger unit (often referred to as 'composite') and processed further. Typical processing steps may include low- and high-pass filtering and reduction-to-the-pole. However, most processing can introduce new artefacts into the data (Schmidt, 2003) and should therefore only be used if the results help with the archaeological interpretation.

Many archaeological magnetometer surveys are commissioned to resolve a clearly defined question, for example to find archaeological remains in a field prior to its development for housing. However, most data are also of potential benefit beyond their initial intended use and should therefore be archived. For example, the removal of all archaeological remains during the development of a building site may mean that the collected geophysical data are the most important record of an ancient settlement. It is therefore essential that data archiving is undertaken according to recognised standards. In particular detailed information describing data collection procedures and the layout of site and survey is important. Such information is usually referred to as 'metadata' (Schmidt, 2002) and complements the numerical instrument readings as well as processed results. Related to the archiving of data from geophysical surveys is the recommendation that at least a brief report should be provided and archived, whenever possible.

## Archaeomagnetic Dating

As with paleomagnetic dating (see *Paleomagnetism*), the magnetic remanence preserved in archaeological structures can be used for their dating. Although some research has been undertaken on depositional ('detrital') remanence in sediments (Batt and Noel, 1991), archaeomagnetic dating is mainly applied to thermoremanent magnetisation. By firing archaeological structures that are rich in iron-oxides above their Curie temperature (ca 650-700°C) they become easily magnetised in the direction of the ambient field, which is usually the earth's magnetic field. On subsequent cooling below the blocking temperature this acquired magnetisation will form a magnetic remanence. When archaeological features that were exposed to such heating and cooling are excavated, oriented samples can be recovered and their thermoremanent magnetisation measured. By comparing these data with an archaeomagnetic calibration curve that charts the variation of magnetic parameters with time, a date can be determined for the last firing of the archaeological feature.

Most archaeomagnetic dating methods use two or three components of the remanent magnetisation vector (inclination, declination and sometimes intensity). It is therefore a pre-requisite that samples are collected from structures that have not changed their orientation since the last firing. Typical features include kilns, hearths, baked floors and furnaces. Unfortunately, it is not always possible to assess whether an archaeological feature is found undisturbed and *in situ*. For example, due to instabilities following the abandonment of a kiln, the walls may have moved slightly or the area around a fire place may have been disturbed by modern agricultural activities. Only the final statistical analysis (see below) can ascertain the validity of results. In recent years advances in archaeointensity dating have been made, using only the magnitude of the magnetisation for age determinations (see *Microwave and Shaw techniques*). It is therefore possible to magnetically date materials that are no longer in their original position, like fired bricks that were used in buildings or even non-oriented pottery fragments (Shaw *et al.*, 1999, Sternberg, 2001).

A variety of different sampling methods exist, which all have their respective benefits. Some groups extract samples with corers, others encase the selected samples in Plaster of Paris before lifting them together with the plaster block, and in Britain plastic disks are commonly glued to the samples before extraction. As it is important to accurately record the orientation of the sample while still *in situ*, plaster and disks are usually levelled horizontally and the north direction is marked with a compass (either conventional, digital or sun-based). Determining the right sampling locations within a feature is important as the effect of magnetic refraction often causes magnetic field lines to follow the shape of heated features, similar to the demagnetisation effects observed in grains and elongated objects. Soffel (1991) reports an approximately sinusoidal dependence of both inclination and declination from the azimuthal angle in a hollow cylindrical feature while Abrahamsen *et al.* (2003) have found that sample declinations from a hemisphere of solid iron slag with 0.5 m diameter vary throughout 360°. It is therefore essential that several samples from different parts of a feature are compared to statistically assess whether a consistent magnetisation vector can be determined.

After the last firing of an archaeological structure, magnetically soft materials may have acquired a viscous remanent magnetisation that gradually followed the changing direction of the earth's magnetic field (see *Geomagnetic Secular Variation*). Its contribution to a sample's overall magnetisation can lead to wrong estimates for the age, and it therefore has to be assessed with a Thellier experiment (see *Paleomagnetic field: Intensity Thellier-Thellier method*) and then removed. This removal can either be accomplished through stepwise thermal demagnetisation (see *Demagnetization*) or with stepwise alternating field (AF) demagnetisation (Hus *et al.*, 2003). The subsequent measurement of a sample's magnetization vector, for example in a spinner magnetometer, is then a good approximation of its thermoremanence. Fisher statistics (see *Statistical methods for paleomagnetic data*) is used to assess the distribution of all the measured magnetisation vectors of an archaeological feature by calculating a mean value for the direction together with its angular spread  $\alpha_{95}$ . The latter describes the distribution of all measured directions

around the mean, and is half of the opening angle of a cone (hence appearing as a 'radius' on a stereographic plot) that contains the mean vector direction with a probability of 95%. The spread of the individual vector directions can be due to errors in sample marking, measurement errors and the distribution of different directions within a single feature (see above). It has therefore become common practice to expect  $\alpha_{95}$  to be less than  $5^\circ$  for a reliable investigation (Batt, 1998).

Once the magnetisation of an archaeological feature has been established it can be compared to a calibration curve to derive the archaeological age. The construction and use of such calibration data has been a matter of recent research. In Britain, a calibration curve was compiled by Clark *et al.* (1988) using 200 direct observations (since 1576 AD) and over 100 archaeomagnetic measurements from features that were dated by other means, as far back as 1000 BC. All data were corrected for regional variations of the earth's magnetic field and converted to apparent values for Meriden ( $52.43^\circ\text{N}$ ,  $1.62^\circ\text{W}$ ). After plotting results on a stereographic projection, the authors manually drew a connection line that was annotated with the respective dates. Measurements from any new feature could be drawn on the same diagram and the archaeological date was determined by visual comparison. This approach is compatible with the accuracy of the initial calibration curve but has clear limitations (Batt, 1997). Similar calibration curves exist for other countries and due to short-scale variations of the earth's magnetic field's non-dipole component (see *Non-dipole field*), they are all slightly different and have to be constructed from individually dated archaeological materials. The reference curve for Bulgaria, for example, now extends back to nearly 6000 BC (Kovacheva *et al.*, 2004). Although the calibration curve by Clark *et al.* (1988) has been a useful tool for archaeomagnetic dating, improvements are now being made. Batt (1997) used a running average to derive the calibration curve more consistently from the existing British data. Kovacheva *et al.* (2004) calculated confidence limits for archaeological dates using Bayesian statistics (Lanos, 2004) for the combination of inclination, declination and paleointensity of measured samples. To improve the accuracy and reliability of the archaeomagnetic method, more dated archaeological samples are required and comprehensive international databases are currently being compiled.

Some researchers have attempted to use magnetometer surveys over furnaces to derive archaeomagnetic dates for their last firing. For this, the magnetisation causing the recorded magnetic anomaly has to be estimated and can then be used with a calibration curve for the dating of the buried archaeological feature. To accommodate the complex shape and inhomogeneous fill of partly demolished iron furnaces in Wales, Crew (2002) had to build models with up to five dipole sources to approximate the measured magnetic anomaly maps. The dipole parameters were chosen to achieve the best possible fit between measured and modelled data and their relationship with the magnetisation of the furnaces' individual components is not entirely clear. In addition to the sought after thermoremanence, this magnetisation also has contributions from acquired viscous remanence and from the induced magnetisation in the current earth's magnetic field. Even after estimates for these two sources have been taken into consideration, the results were in poor agreement with the archaeomagnetic calibration curve. The magnetic anomalies from slag-pit furnaces in Denmark were approximated with individual single dipole sources by Abrahamsen *et al.* (2003). They found that the distribution of 32 adjacent furnaces produced an unacceptably high  $\alpha_{95}$  value of  $18^\circ$  and concluded that the method is therefore unsuitable for the dating of these features.

## Conclusion

There are many ways magnetic methods can be used in archaeological research and this application has made them popular with the public. Magnetometer surveys have become a tool for archaeologists, nearly as important as a trowel. In an excavation, many archaeological remains are only revealed by their contrast in colour or texture compared with the surrounding soil. Searching for a contrast in magnetic properties is therefore only an extension of a familiar archaeological concept. The science explaining the magnetic properties of buried features may be complex but the application of the techniques has become user-friendly. Similarly, archaeomagnetic dating is an

important part of an integrated archaeological dating strategy. For archaeological sites, dates are often derived with many different methods simultaneously, ranging from conventional archaeological typological determinations over radiocarbon dating to luminescence methods. Combining these different data, for example with Bayesian statistics, allows a significant reduction of each method's errors and leads to improved results. The wealth of information stored in the magnetic record has certainly made an important contribution to modern archaeology.

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### ***Crossreferences***

Biomagnetism  
 Changes in magnetic mineralogy due to heating and methodological implications  
 Detrital remanent magnetism  
 Geomagnetic Secular Variation  
 Magnetic anomalies for geology and resources  
 Magnetic susceptibility  
 Microwave and Shaw techniques  
 Modelling magnetic anomalies  
 Non-dipole field  
 Observatory Instrumentation  
 Paleomagnetic field: Intensity Thellier-Thellier method  
 Paleomagnetism  
 Statistical methods for paleomagnetic data  
 Storms and substorms  
 Thermoremanence

## Figures

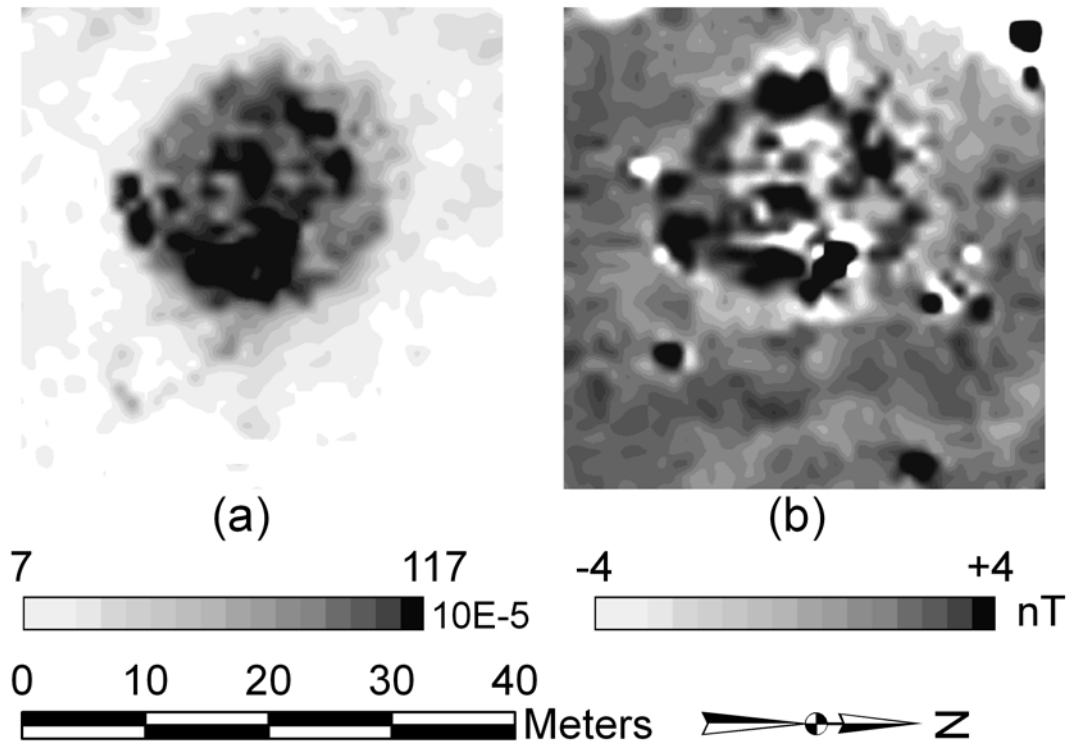


Figure 1: Medieval charcoal production site in Eskdale, Cumbria. (a) Magnetic susceptibility survey with Bartington MS2D field coil. (b) Fluxgate gradiometer survey with Geoscan FM36. Both surveys were conducted over an area of  $40\text{ m} \times 40\text{ m}$  with a spatial resolution of  $1\text{ m} \times 1\text{ m}$ .

## Magnetic Susceptibility Readings [10E-5]

- 0 - 10
- 10 - 20
- 20 - 30
- 30 - 40
- 40 - 70

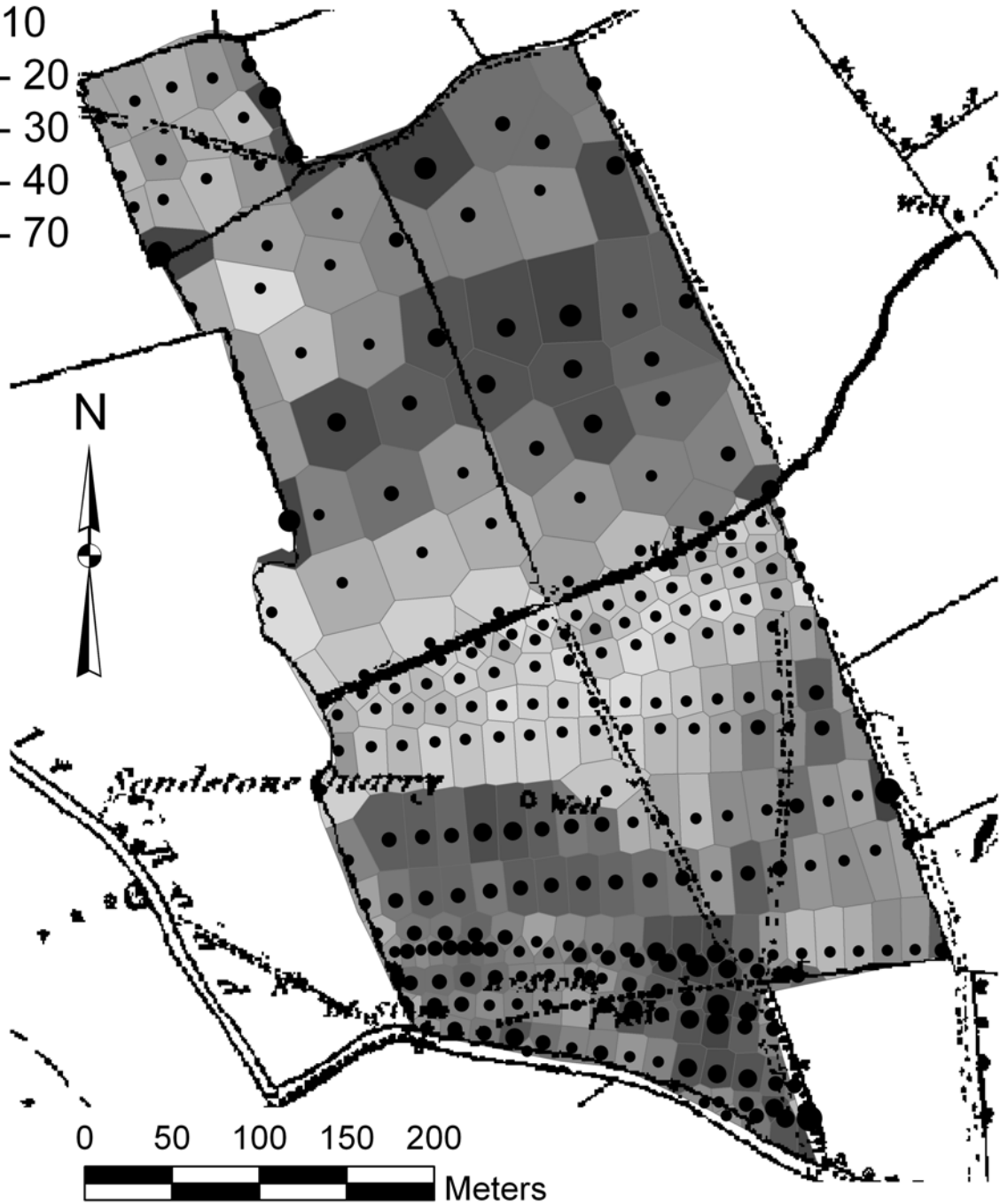


Figure 2: Kirkby Overblow, North Yorkshire. To search for a deserted medieval village, a magnetic susceptibility survey was undertaken with the Bartington MS2D field coil. The measurements are represented as scaled dots and as shaded Voronoi cells. Basemap from 1<sup>st</sup> edition Ordnance Survey data.

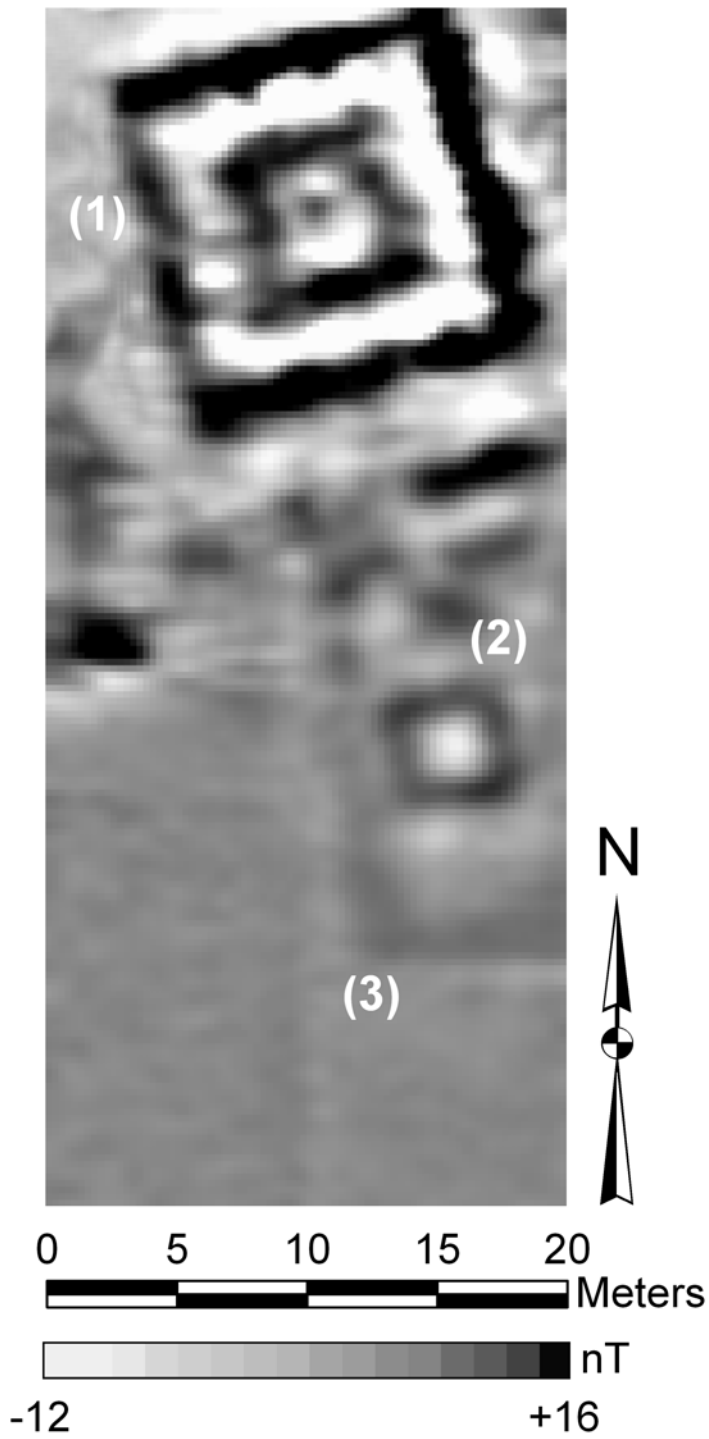


Figure 3: Fluxgate gradiometer data from Ramagrama, Nepal. The outlines of a small Buddhist temple complex are clearly visible, including the outer and inner walls of the courtyard building (1). In addition, the foundations of a small shrine (2) within an enclosure wall (3) can be discerned.

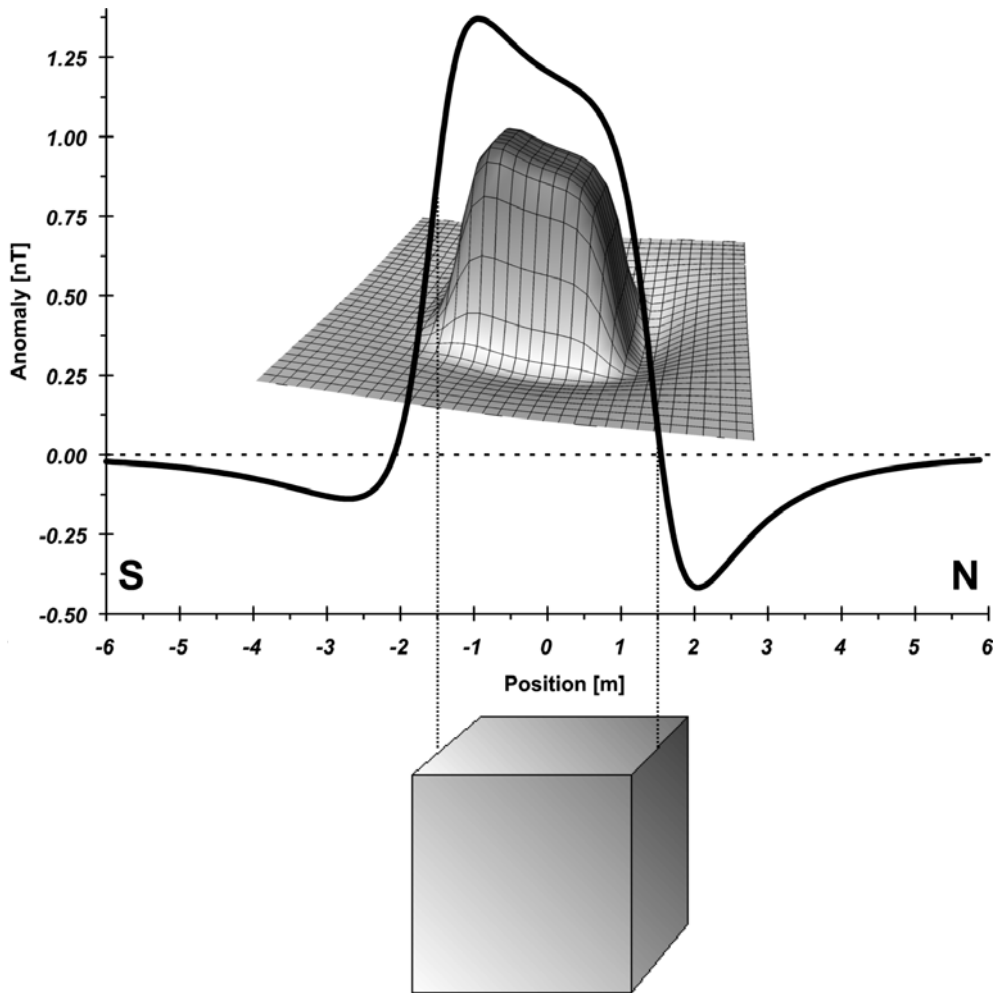


Figure 4: Calculated shape of the magnetic anomaly caused by the induced magnetisation of a buried cubic feature with 3m side length. The anomaly is measured with a vertical fluxgate gradiometer (0.5 m sensor separation), 0.5 m above the cube's top surface. The strength of the anomaly was calculated for an inclination of  $70^\circ$  and a magnetic susceptibility contrast of  $1 \times 10^{-8}$ .

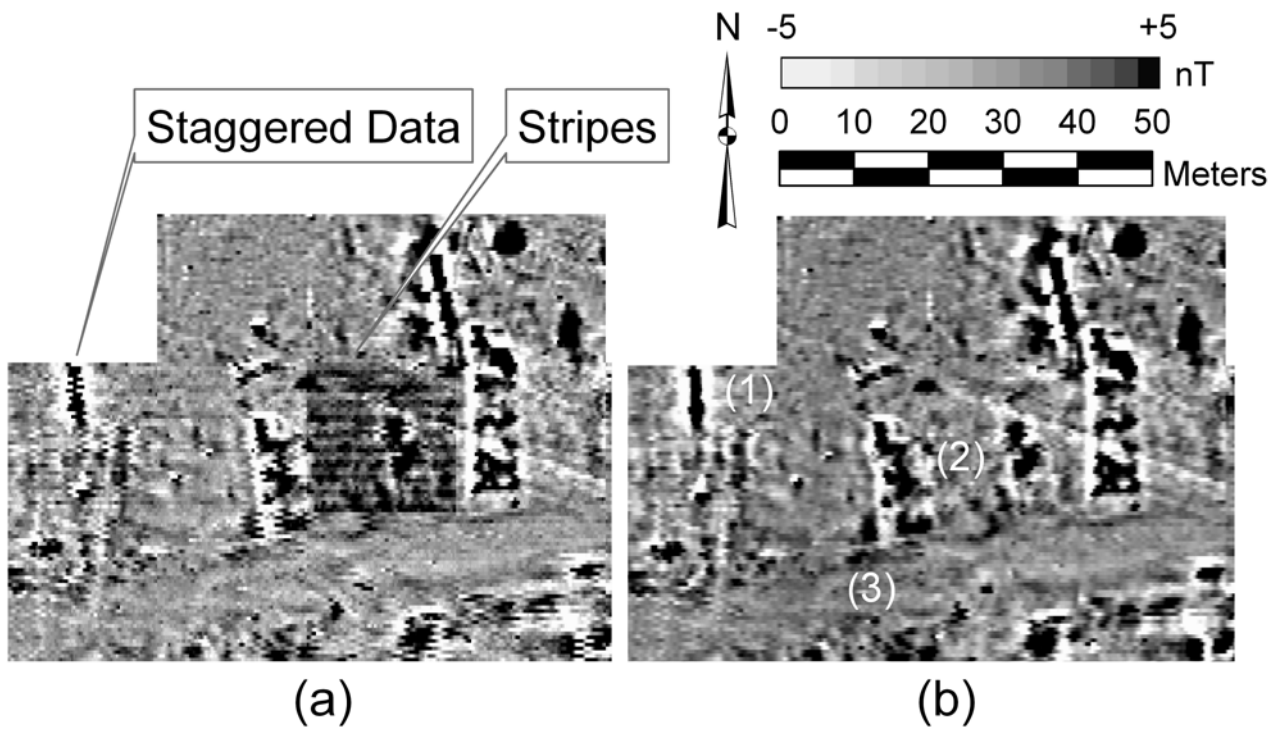


Figure 5: Fluxgate gradiometer data from Adel Roman Fort, West Yorkshire. (a) Field measurements with staggered data (left) and stripes (centre). (b) After their improvement the data clearly show a ditch (1) and the soldiers' barracks (2) to the north of the road through the Fort (3).