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Electrical and Magnetic Methods in Archaeological Prospection

by Armin Schmidt

Introduction

Geophysical methods are an essential tool for archaeological prospection on all scales of investigation: whether for detailed analysis of a single archaeological feature, to provide an overview of all features on an archaeological site, or for the assessment of a whole landscape. The relationship between geophysical measurements at the surface and buried archaeological features is complex and the interpretation of resulting data requires geophysical and archaeological insight. This chapter is a brief introduction to the two main geophysical techniques used in landscape archaeology, namely earth resistance and magnetic surveying. More detailed discussions have been published elsewhere (Clark 1990; Gaffney & Gater 2003; Schmidt 2007; Scollar *et al.* 1990) and current research is mainly made available through the journal *Archaeological Prospection*.

Earth Resistance Surveying

Archaeology and Earth Resistance

The general idea underpinning earth resistance surveying is fairly simple: an electrical current that is injected into a homogeneous ground spreads evenly (Fig. 1); but where it encounters obstacles in the form of archaeological features it has to change its course leading to measurable electrical effects at the surface. A map of the lateral surface variations will hence be a representation of buried archaeological remains.

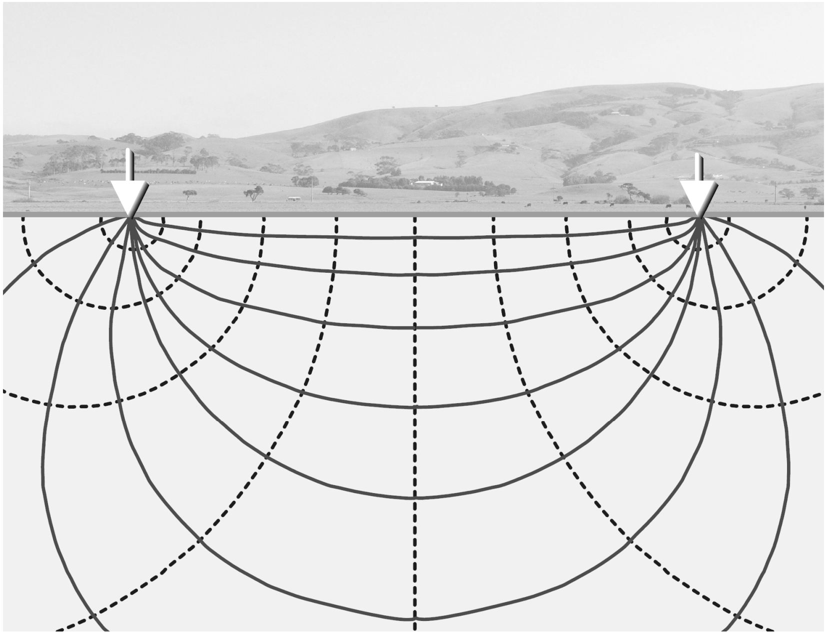

Figure 1: The spread of electrical current through homogeneous ground. Solid lines show the current flow, broken lines the resulting equipotential lines.

Electrical currents are carried by moving charged particles. In a metallic wire the current consists of electrons that freely move through the cable, its connectors and a battery or power supply. Such closed circuit will never show depletion or accumulation of electrons, since they can continue to flow around this loop. In contrast, a current through soil or sediments is entirely carried by ions, which are large charged particles. They are created when salt crystals in the ground (e.g. NaCl) dissociate in the presence of soil water (e.g. to form Na^+ and Cl^- ions). Since ions cannot leave the soil, their movement, and hence any current, would stop once they had all arrived at the surface. To avoid this, the polarity of a current used for earth resistance measurements has to be reversed continuously, forcing ions to alternatively move forward and backward.

There may be various obstacles to the movement of these ions in the ground and the associated weakening of any current is described by a soil's 'electrical resistivity'. Firstly, this is influenced by the initial abundance of salts. While there are some salts in all soils their concentration varies considerably between different soil types. Secondly, and more importantly, electrical resistivity depends on the availability of water. Water is needed to dissolve the salts into their constituent ions and also to facilitate their transport. Soil resistivity is hence mainly governed by the moisture content of the ground. The major factors influencing soil moisture are the sizes of individual soil particles (grains), the space between them (pores) and the availability of water. In addition, resistivity also depends on the mobility of ions in the water, which decreases with temperature and ceases when the water is frozen to ice (Scollar *et al.* 1990).

A typical example of a buried feature left by past human occupation is a ditch (Fig. 2). After the abandonment of a settlement it may have gradually filled with sediments and is possibly no longer visible from the ground. However, it will still affect the flow of current, as its fill is normally loosely packed, allowing the pores to retain water and the ditch will hence have a lower resistivity than the surrounding soil.

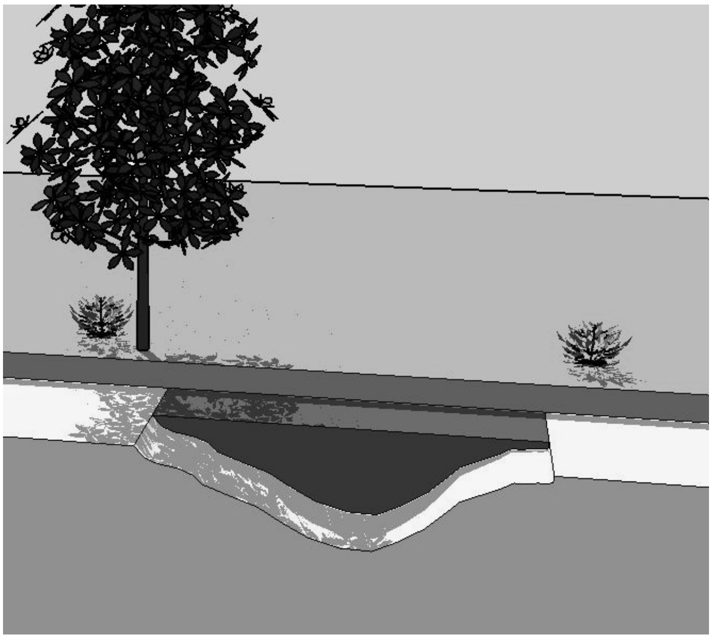

Figure 2: A buried ditch shows contrast to the surrounding material in several physical parameters.

The contrast of archaeological features

It is clear from this example that it is not the absolute value of low electrical resistivity that allows to reveal the presence of such ditches, but the fact that this soil property is different from the surrounding material. It is this ‘contrast’, which makes them detectable. In this respect the geophysical measurement is no different from an archaeological excavation, where features can only be identified through their contrast to the surrounding soil or sediment matrix, either in their colour or texture. For example, mud-brick walls were not identified in Mesopotamian archaeology until archaeologists realised in the late 19th century the subtle contrast that this building material exhibits (Matthews 2003: 12). Geophysical prospection extends this concept and allows to look for archaeological features that may exhibit a contrast to their surrounding matrix in one or more physical properties that are not normally detectable by an excavator, for example electrical resistivity, magnetic susceptibility, remanent magnetisation etc. The geophysical technique to use for the detection of the buried features hence depends on the properties in which a contrast exists. Unfortunately it is often difficult to predict which property shows a pronounced contrast and in many case a number of trial surveys have to be undertaken with different methods to identify those that most suitable for the particular archaeological features, site and environmental conditions.

Influence of climate on results from earth resistance surveys

For a ditch that retains more moisture than the surrounding soil matrix the resistivity contrast is often referred to as being ‘negative’, since the resistivity of the feature is lower than that of the matrix in which it is embedded. However, there are situations in which this may change.

The moisture content of soil varies with external environmental factors (such as temperature, rain, wind and sunshine), which therefore also affect the electrical resistivity contrast. This can again be illustrated with the example of a buried ditch.

- In a warm and dry British summer, the soil matrix may have dried out considerably and only the ditch retains some moisture. This will lead to a pronounced negative contrast.
- If the dry weather continues, the ditch will also loose its moisture and the contrast will gradually disappear.

- Then it starts to rain heavily and the large pores of the ditch soak up the water very quickly, probably even quicker than the surrounding soil with its smaller pore size. This leads again to a significant negative contrast.
- Heavy rain continues and after several days all ground is thoroughly wet. By then the contrast will have been almost entirely lost.
- Next, sun and strong winds appear and the large pores of the ditch give off their moisture more easily than the surrounding soil, which therefore can lead to a *positive* resistivity contrast.

These exaggerated and idealised weather conditions help to understand the possible variations of soil moisture and resistivity contrast. An additionally complicating factor is the subsoil geology. Depending on the underlying drainage (e.g. good for chalk, poor for clay) further avenues for water loss or retention are available.

For a stone foundation, the resistivity cannot normally become lower than the surrounding soil and the contrast will hence always be positive (wet surrounding soil) or nearly zero (very dry surrounding soil).

Measurement of Earth Resistance

To measure electrical resistance of the ground, an electrical current is injected through two steel electrodes. As the current flows through soils and sediments an electrical potential ('voltage') develops. It can be visualised through equipotential lines that connect points with the same value of electrical potential (Fig. 1), similar to contour lines in a topographical survey. These hypothetical lines are distorted by any buried feature with a resistivity contrast. For example, current will tend to flow preferably through wet soil (e.g. within a ditch), but will be diverted around dry features, like walls and stones. However, these often pronounced changes in the ground only have a small effect at the surface, where the altered equipotential lines can be measured with two 'potential electrodes' in an earth resistance survey, providing indirect evidence for the presence of features in the ground.

Consequently, four electrodes are needed for an earth resistance survey (two for current injection and two for potential measurement) and there are many ways in which they can be arranged. Some of the possible 'four-electrode arrays' are more common than others. In archaeological prospection the most commonly used arrangement is the 'twin-probe array' (Fig. 3) in which one current and one potential electrode are mounted on a frame together with an earth resistance meter and this unit is moved across the survey area. The other two electrodes are located at a distance and are connected with the measuring device through a long cable. The small spacing of the mobile electrodes on the frame leads to good spatial resolution and the arrangement is compact enough to make detailed mapping possible, for example in a raster with 1 m × 1 m resolution. Data collected systematically can subsequently be plotted so that the resulting map of earth resistance measurements provides clues about the resistivity contrast, and hence the archaeological features, in the ground.

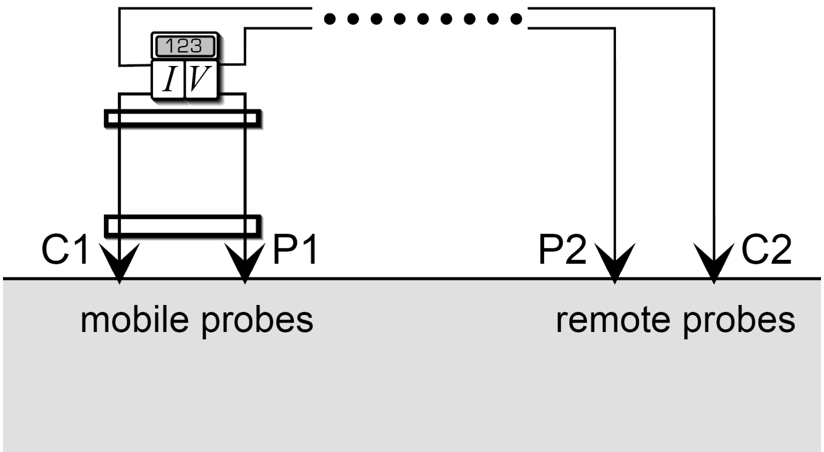

Figure 3: *Twin probe electrode array.*

Resistivity of Soil Features

The electrical resistance (R) is calculated and displayed by the earth resistance meter as the ratio of the electrical potential measured at the surface to the current injected into the ground ($R = V / I$) and is expressed in Ohms (symbol Ω). This earth resistance depends on two parameters: the resistivity of the ground and the arrangement of the electrodes. The latter dependency becomes clearer if one considers that the location of potential electrodes determines which voltage is sampled, even if the current electrodes are left in the same position.

The electrical resistivity of the buried feature (ρ) is measured in Ohm-metres (Ωm). As the current travels through the ground it will encounter areas of different resistivities, and the single value of earth resistance measured at the surface will be a complicated average of all these resistivites in the ground (Fig. 4). To describe this behaviour, the concept of 'apparent resistivity' has been introduced. Given an earth resistance measurement R (in Ω) made with a certain electrode array, it is possible to calculate an associated value for the apparent resistivity ρ_A (in Ωm), which accounts for the spatial arrangement of the electrodes and represents the measured value of earth resistance in terms of the material property (i.e. electrical resistivity). To be useful, this conversion has to be such that in the simple case of a homogeneous ground the apparent resistivity is identical to the true resistivity of this ground, ρ. In the heterogeneous case the apparent resistivity becomes 'some sort of average' of all the resistivities in the ground. For its calculation, the exact electrode positions are taken into account and for the most common electrode arrays simple mathematical expressions exist. It follows from this brief discussion that earth resistance measurements do not allow an exact determination of the ground's resistivity at a single point since some averaging along the current path is unavoidable.

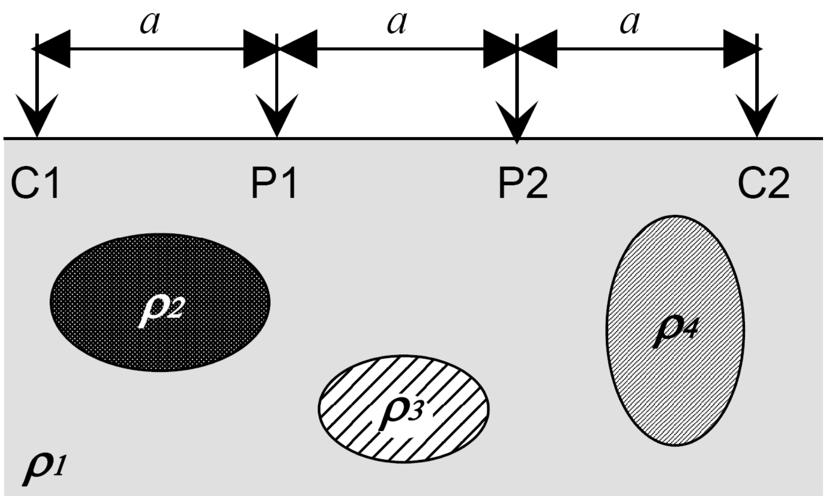

Figure 4: A single earth resistance measurement will be influenced by all resistive bodies in the ground.

Depth of Investigation

By increasing the separation between the two current electrodes electrical current is able to penetrate deeper into the ground (Fig. 5) and the measured earth resistance is affected by features at greater depth. This relationship between electrode separation and depth of investigation can be used to probe the ground's resistivity at different depths. For example in a 'pseudosection' the electrode separation of a chosen array configuration is systematically increased and the array then gradually moved forward along a defined line. The measured earth resistance is converted to apparent resistivity to make measurements with different electrode separations comparable and the apparent resistivity of each measurement is then plotted at a depth calculated from the electrode spacing (e.g. half the spacing between current and potential electrodes (Griffiths & Barker 1994)). As discussed above, earth resistance measurements are influenced by the average of the ground's resistivites and assigning one value of apparent resistivity to a particular depth is hence wrong. Nevertheless such pseudosections provide useful first insights into the vertical distribution of resistivities in the ground. Figure 6 shows a pseudosection recorded over two model ditches created in a water tank, illustrating clearly the potential of this technique.

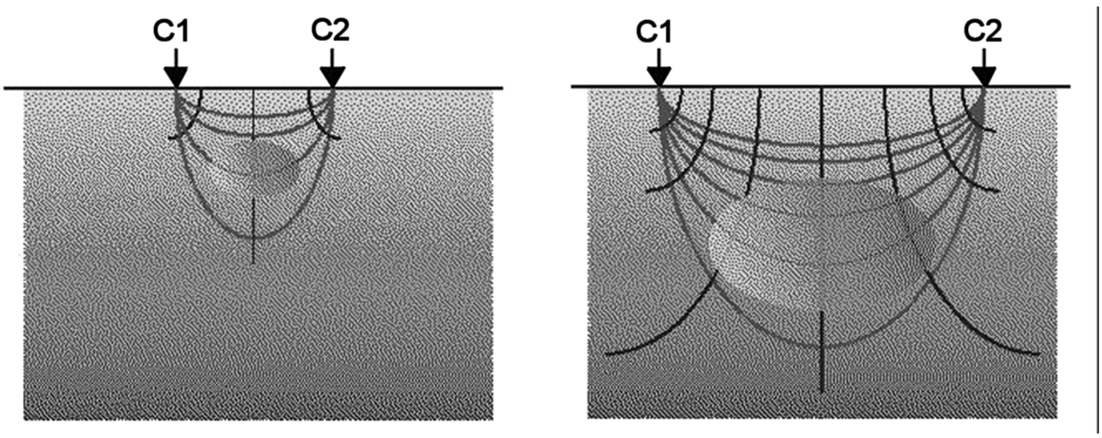

Figure 5: A wider spacing of current electrodes forces the current to flow to greater depth and the measured earth resistance is hence influenced by deeper features.

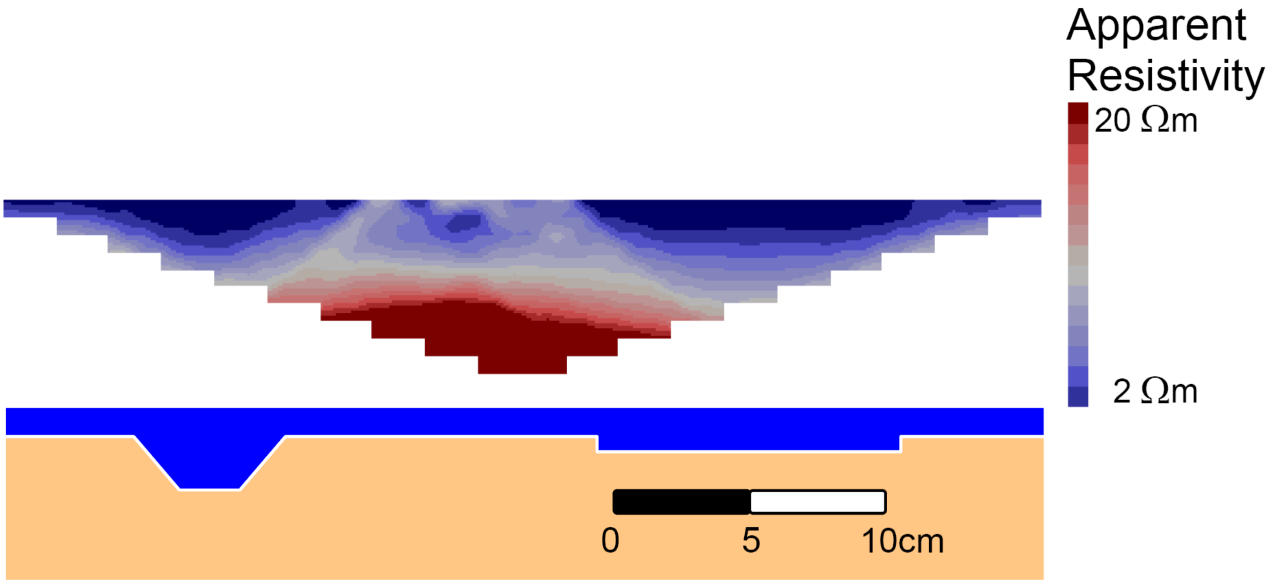

Figure 6: *Wenner pseudosection of two ditches in a water tank.*

Mathematical methods are available to further process the collected data and to calculate resistivity distributions that would result in exactly the measured earth resistance values. This process is referred to as 'inversion' (Loke & Barker 1996), but unfortunately it has no unique solution since several different resistivity distributions can be calculated that would all lead to the same measured earth resistance values. Some of these solutions produce overly smooth shapes for the buried features and are hence not always appropriate in an archaeological context. Results should therefore "be considered low-resolution (i.e., blurry and blunted) versions of reality" (Day-Lewis *et al.* 2006).

Earth Resistance Anomalies

When measuring earth resistance, either in a grid or along a profile, it would be best if recorded data reflected the shape of the buried features. For example, it would be convenient if a profile measured over a buried ditch would show a single dip over the centre of the ditch. However, due to the complicated paths that the electrical current will take around buried features, the resulting distribution of voltages on the surface can be very complex and plotting the apparent resistivity values along a profile may hence exhibit unexpected results. Figure 7 shows calculated traces over a localised archaeological feature (approximated as a sphere) with the same size as the twin-probe array that is used to measure it (e.g. a 0.5 m wide grave cut) for various depths of the feature. It is important to realise that the sequence of 'low-high-low' data in this profile is caused by one single feature and not by three separate entities. Data in Figure 8 show results from an earth resistance survey over suspected Mediaeval graves and the theoretically predicted effect can clearly be observed in the outlined area which is hence interpreted as one single grave cut. It is important to realise that such diagrams are not images of the subsurface features but are representations of the collected data, with all the inherent complications of geophysical signatures. It is therefore useful to clearly distinguish between the geophysical *anomalies* as manifest in the data and the causative archaeological *features* buried in the ground. Knowledge of geophysical signatures has to be combined with the relevant historical context for a successful interpretation of results. In the above example it was known that narrow graves were suspected in the investigated area and measured anomalies could hence be interpreted with greater confidence.

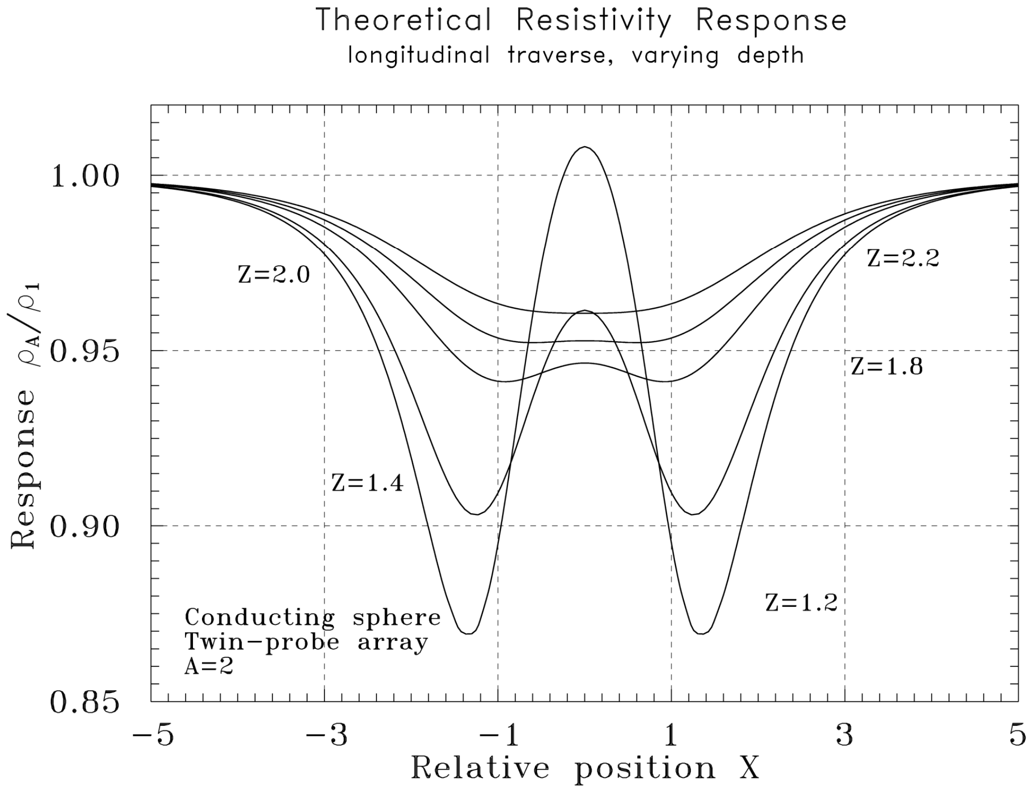

Figure 7: Earth resistance anomaly for a buried spherical conductor (radius r), measured with a twin-probe array. All length measurements are relative to the radius of the sphere: the electrode separation is $a = A{\cdot}r = 2r$, the depth to the centre is $z = Z{\cdot}r$, the lateral distance from the centre is $x = X{\cdot}r$. The resistivity of the matrix in which the feature is embedded is ρ_1.

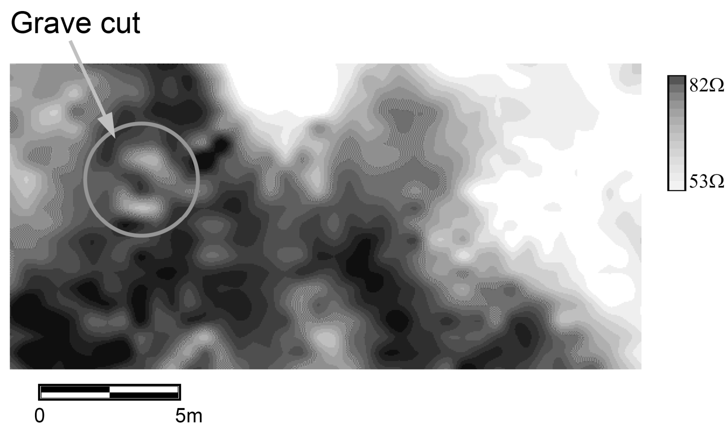

Figure 8: Earth resistance data over a Medieval graveyard, measured with a 0.5 m twin-probe array. The anomaly produced by a shallow and narrow grave cut is comparable to the theoretical results from Figure 7.

Magnetic Methods of Survey

Magnetic Field of the Earth

Magnetic methods of archaeological prospection have proven to be immensely successful because many archaeological features show a contrast in magnetic properties compared to the surrounding material. Underpinning the detection of such a contrast is the earth's magnetic field. Research on the causes of this field are still ongoing but it is most likely created by the movement of ions and electrons at the interface between the liquid core and the solid mantle deep inside the earth. In a first approximation, the resulting field can be portrayed as if it were produced by a large magnet situated at the earth's centre, its magnetic south pole pointing towards the northern hemisphere and hence attracting the northern tip of compass needles.

Magnetism and Archaeology

Magnetism is usually described by 'magnetic fields', which at each point indicate how strongly a compass needle would be pulled and in which direction. All magnetism is caused by the movement of electrical charges. On the macroscopic scale this can be in the form of electric currents flowing through a coil while on a microscopic scale it is due to spinning and orbiting electrons and protons. Every atom therefore has a 'magnetic moment' that can be visualised as a small compass needle, its strength depending on the particular material.

Induced magnetism

By applying an external magnetic field (e.g. the earth's field), the elementary magnets of a feature become partly aligned with the external field and will therefore enhance it. The ease of alignment determines the strength of this enhancement and is described by the 'magnetic susceptibility' of a material. The higher the magnetic susceptibility, the bigger will be the magnetisation that is created by the overall alignment of the magnetic moments in a feature. A larger feature will create a bigger overall magnetic moment and to account for this, magnetic susceptibility is usually quoted with regards to the amount of the magnetic material measured, either its mass or its volume. In the SI system of units, mass specific susceptibility (χ) is quoted in m^3 / kg . Volume specific susceptibility (κ) has no units in this system but to remind readers of this fact the expression '(SI)' is sometimes appended to a measurement (e.g. "$\kappa = 2 \times 10^{-5}$ (SI)").

Human habitation can lead to an increase of magnetic susceptibility, forming a contrast with the surrounding soil matrix, which is the reason why many archaeological features can be detected with magnetic methods. There are five main pathways through which soil magnetic susceptibility can be enhanced.

1. **Heating**. Soils often contain weakly magnetic iron oxides (e.g. haematite) that can be converted to more magnetic forms (e.g. magnetite or maghaemite) through heating in reducing conditions, in the presence of organic matter. The temperature at which this process starts is not well defined and values between 150°C and 570°C have been reported, with lower temperatures requiring longer exposure (Linford & Canti 2001; Maki *et al.* 2006). This pathway was first discussed by Le Borgne (Le Borgne 1955) and is often attributed to him.
2. **Microbially mediated**. Microbes thriving in rich organic deposits can change soil conditions sufficiently to trigger the conversion of weakly magnetic iron oxides to more magnetic forms (Linford 2004). Historically, this is referred to as 'fermentation' although strictly speaking methanogenesis is not required for this biogenic pathway (Weston 2002).
3. **Magnetotactic bacteria**. Some bacteria actively create intra-cellular crystalline magnetite to navigate in the earth's magnetic field (Fassbinder *et al.* 1990). These magnetic crystals remain in the soil even when the magnetotactic bacteria die and lead to an enhanced magnetic susceptibility.
4. **Incorporated magnetic material**. Magnetic enhancement of topsoil is also caused by the addition of magnetic material, for example broken pottery or brick fragments (Weston 2002). Such material is often found as discard or rubbish in archaeological middens and has been spread on arable fields with other manure, mainly in Medieval times.
5. **Pedogenesis**. Enhancement of soil magnetic susceptibility also occurs during soil formation processes, even without human influence. Maher and Taylor (1988) reported the formation of ultra-fine grained magnetite in soil despite the absence of any microorganisms.

The first three pathways rely on the availability of organic matter, which is usually more abundant in the upper soil horizon than in the subsoil, hence creating a magnetic differentiation of topsoil and subsoil. In addition, anthropogenic input further enhances these conditions (either through fire or deposition of organic material, like middens), sometimes allowing the identification of settlement areas through magnetic susceptibility mapping, or the differentiation of buried land surfaces (e.g. covered by non-magnetic windblown or alluvia deposits) from the magnetic stratigraphy. Archaeological environments with rich organic deposits include, for example, middens and decayed wooden posts. Fassbinder demonstrated that magnetic anomalies of post holes that were apparent in high-sensitivity magnetometer surveys are attributable to magnetotactic bacteria (Fassbinder & Irlinger 1994; Fassbinder & Stanjek 1993). Metalworking remains, for example hammerscale and slag, also become incorporated into soil layers and can greatly increase the magnetisation. Unfortunately, iron and steel fragments broken or fallen from modern farming machinery can also create undesirable magnetic anomalies in survey data. Whenever a cut archaeological feature (e.g. a ditch or a pit) is filled with magnetically enhanced soil the magnetic susceptibility contrast of the feature with the surrounding soil or sediment matrix makes it magnetically detectable.

Remanent magnetism

Induced magnetisation would disappear if the earth's magnetic field ceased, and it will follow any slow changes in the direction of the earth's field. In contrast, remanent magnetisation is created once and stays fixed in a material afterwards. For example, thermoremanent magnetisation is caused by heating a sample to about 650° C so that all elementary magnets become very mobile and align easily with the ambient earth's magnetic field. On subsequent cooling, this state of alignment is 'frozen' and a strong magnet is created. Remanent magnetisation will not change even if the earth's magnetic field alters its direction, as it has done in the past. By comparing the 'frozen' remanent magnetisation with calibration curves for ancient directions of the earth's field, the date for the last heating event can be established. This forms the basis for 'archaeomagnetic dating'.

Most soil features that were exposed to high temperatures during heating (e.g. hearths, kilns, kiln-fired bricks) or burning (e.g. burnt walls or houses) have acquired remanent magnetisation and exhibit a magnetic contrast.

Magnetic Susceptibility Surveys

Since human habitation can enhance magnetic susceptibility, mapping this material property can provide useful archaeological information (Linford 1994). Collecting soil samples and measuring their magnetic susceptibility in a laboratory provides accurate data but is time consuming. More convenient are measurements directly from the surface, using appropriate field instruments. The most commonly used instrument, the "MS2 Field Coil", has a penetration depth of only about 0.1 m (Lecoanet *et al.* 1999) but allows the rapid assessment of topsoil magnetic susceptibility. Areas of interest can either be mapped in detail (e.g. with sampling intervals of 1 m) to reveal individual archaeological features (e.g. charcoal burning areas (Schmidt 2007)), or with sparser sampling (e.g. 5-20 m) to obtain an overview of the magnetic susceptibility variation over a larger area and to identify 'hotspots' that can later be investigated with higher spatial resolution. Since the magnetic susceptibility of soil can vary considerably even over a short distance, it is advisable not to estimate (i.e. interpolate) values for areas between actual measurements. A display of the data as 'symbol plots' is often the most appropriate representation (Fig. 9).

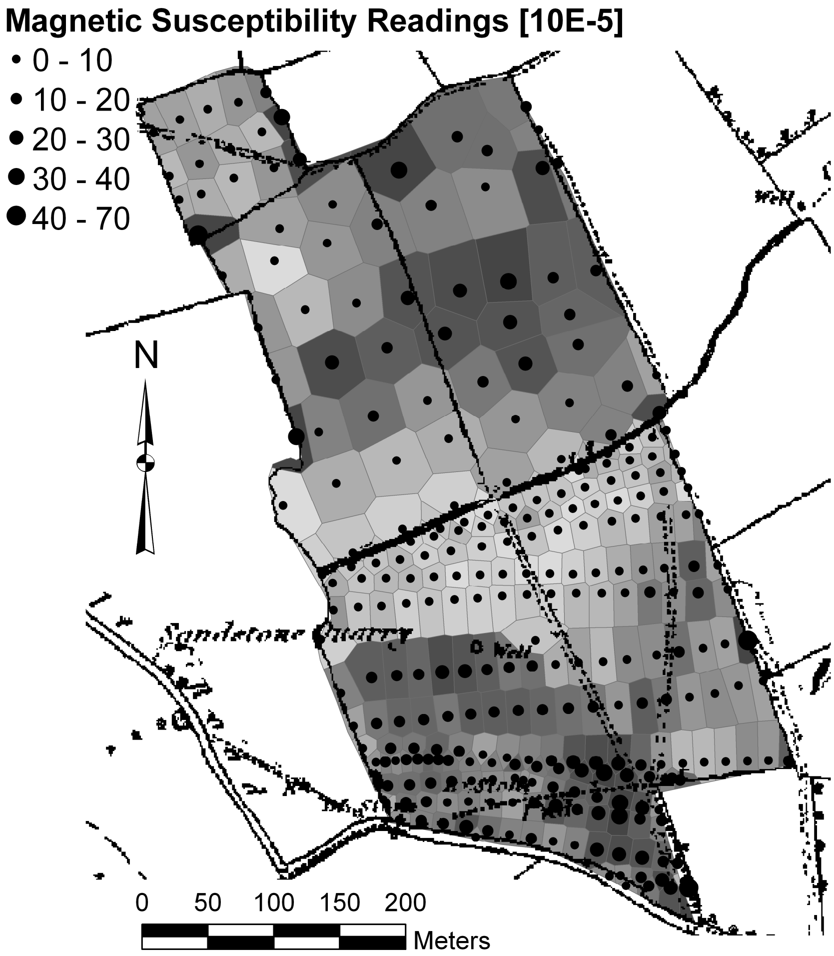

Figure 9: Sparsely sampled magnetic susceptibility survey. Each individual measurement is represented by a symbol of varying size ('symbol plot'), which is superimposed on the representation of the same data as Voronoi cells.

Magnetic Anomalies

Buried archaeological features with a contrast in either induced or remanent magnetisation will act like bar magnets and create a magnetic field around them, the so-called 'anomaly field'. This anomaly combines with the earth's magnetic field to form the 'total field' that can be measured at the surface with a magnetometer and is usually expressed in 'Tesla', or more conveniently in 'nano Tesla' (1 nT = 10^{-9} T). The strength of the earth's magnetic field is about 30,000-50,000 nT. Mapping the magnetic field and its anomalies hence produces data plots that can be used to identify buried archaeological features. As with earth resistance surveys, the data plots show particular characteristics and are not a direct image of the buried remains. A localised archaeological feature can often be represented by a 'magnetic dipole' (i.e. a very short bar magnet) for which the magnetic field can easily be calculated. Figure 10 shows the magnetic anomaly that would be measured with a fluxgate gradiometer at 70° latitude, carried from south to north over the centre of a localised feature (the signal recorded by a caesium gradiometer at this latitude would look similar). This anomaly has two important characteristics:

1. The positive peak is slightly shifted to the south of the buried feature.
2. To the north of the feature is a pronounced negative trough in the data.

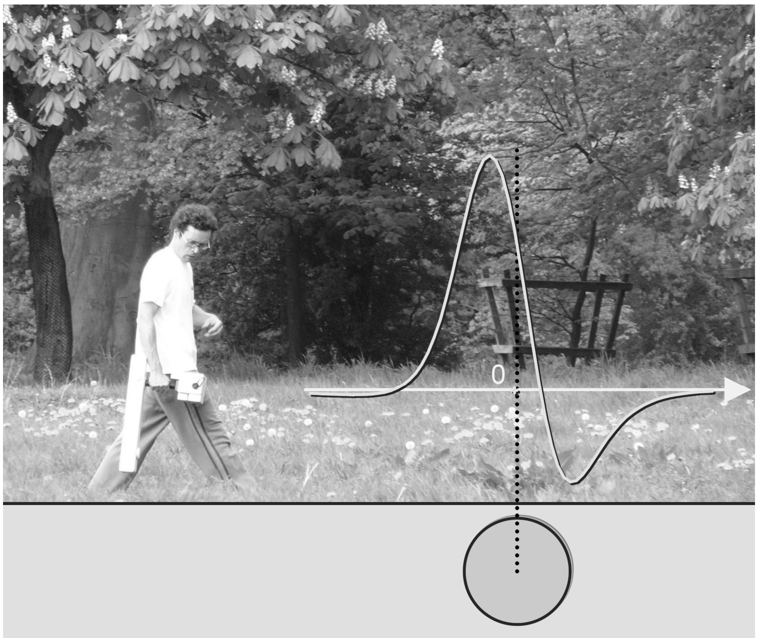

Figure 10: Magnetic anomaly over a localised archaeological feature.

The additional negative data are very characteristic of magnetic anomalies. Figure 11 shows the survey of an Iron Age enclosure where the positive signal of the ditch is accompanied by a fringe of negative data. To interpret these data correctly (i.e. as a single feature), it is important to take the signature of magnetic anomalies into account. The large circular pit in the SW of the enclosure also shows the effect of a halo of negative data, mainly to its north.

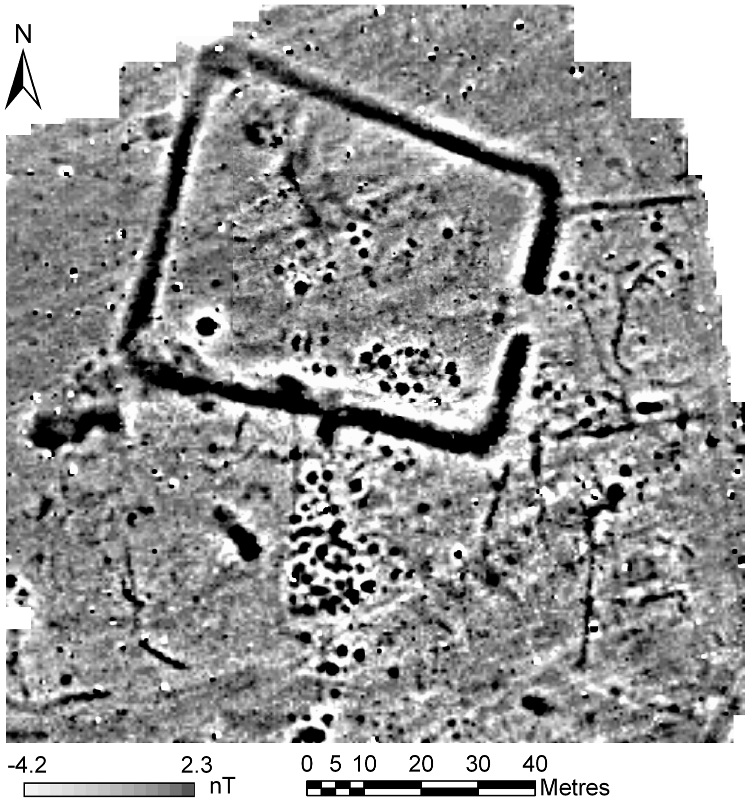

Figure 11: Magnetometer survey of an Iron-Age enclosure. The positive anomaly of the ditch is accompanied by a fringe of negative data. Similarly, the large pit in the SW corner of the enclosure has a negative halo, most prominently to the north. Survey data courtesy of Dr Alistair Marshall.

The intensity of the magnetic anomaly depends both on the strength of the magnetisation contrast and, very strongly, on the depth of the feature. It is hence impossible to use the signal amplitude for an estimation of a features' burial depths. However, the signal *width* is independent of the magnetisation contrast and can hence be used for its assessment (Schmidt & Marshall 1997): deep features (e.g. geological ore bodies) create broad anomalies, while shallow features (e.g. buried archaeological remains, modern ferrous parts fallen off a tractor) cause narrowly focussed anomalies.

Magnetometer Measurements

Sensor types

A magnetometer is a sensor that measures the 'total magnetic field', which is the field resulting from the combination of an anomaly with the ambient earth's field. The simplest sensor would be a compass needle suspended on a thread, but it is not sufficiently sensitive to measure typical archaeological anomalies, which are often in the order of a few nT. Instead, a variety of sophisticated sensors are available and are discussed elsewhere (e.g. (Gaffney & Gater 2003)). As mentioned before, the magnetic field is characterised by its direction and strength and magnetometers are usually classified according to whether they measure the former or the latter. Fluxgate sensors, for example normally only measure the vertical component of the total field, while Caesium sensors measure its strength. The former therefore are directionally sensitive and have to be carried very consistently, whereas the latter have a great tolerance to changes in survey direction.

Sensor arrangements

The total magnetic field measured by a sensor is composed of the archaeological anomalies, fields created by underlying geological bodies and the earth's magnetic field. In a single-sensor survey, it is hence impossible to distinguish which of these contributions has caused a change in the recorded data. This is particularly problematic as the earth's field varies slightly throughout the day ('diurnal variations') and may even show strong and rapid changes ('magnetic storms'). These variations are caused by charged particles emitted by the sun, the 'solar wind', which interfere with the earth's magnetic field. Diurnal variations are simply caused by the greater proximity to the sun during daytime.

To determine the cause for a change in recorded results it is hence necessary to monitor the earth's field with a second sensor. This is most commonly achieved with a 'vertical gradiometer' arrangement in which two sensors are mounted on top of each other and the difference between them is recorded in the data logger. This eliminates all effects of the earth's magnetic field as the two sensors measure identical signals from the earth's field and the gradiometer reading is hence zero in the absence of an anomaly. Even geological anomalies are suppressed if their sources are far enough away. Gradiometers are hence sometimes referred to as 'intrinsic highpass filters'.

Interpretation of Geophysical Surveys

It was shown for earth resistance and magnetometer measurements that recorded data are not simply an image of buried features but that resulting plots are strongly influenced by the geophysical signature of the measurement technique used. After data collection, interpretation of the results is necessary to relate geophysical measurements to possible archaeological features in the ground. This requires an understanding of the geophysical nature of the data as well as archaeological knowledge and an appreciation of the historical context. Combining different data sources (e.g. geophysical, remote sensing, aerial photography, old maps, historical texts) provides archaeological geophysicists with the plethora of data that is necessary to arrive at a meaningful archaeological interpretation of geophysical results. Similarly, geophysical prospection data alone cannot provide dating evidence for a feature. However, if geophysical data are combined with information on the morphology of detected archaeological structures (e.g. the typical trapezoidal shape of an Iron-Age enclosures, Fig. 11) or if a sequence of intersecting anomalies can be established (Schmidt & Fazeli 2007), broad dates may sometimes be estimated.

Useful resources

Archaeological Prospection Resources (www.bradford.ac.uk/archsci/subject/archpros.htm)

Journal *Archaeological Prospection* (www3.interscience.wiley.com/cgi-bin/jhome/15126)

International Society for Archaeological Prospection (www.archprospection.org)

MSc Archaeological Prospection (www.bradford.ac.uk/archsci/msc_ap.htm)

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