

The use of Geophysical Techniques in Archaeological Evaluations

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Chris Gaffney, John Gater and Susan Ovenden

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Edited by Alison Taylor

The authors

John Gater – Partner

BTech Archaeological Sciences (Bradford University 1979) MIFA (1983)
John has been involved in archaeological geophysics for over twenty one years. While five of those were with British Gas, he also worked for the Ancient Monuments Laboratory (English Heritage) and Bradford University Research Limited. In 1986 he set up *Geophysical Surveys of Bradford*, an independent consultancy in geophysics for archaeology. He is a Member of the External Advisory Board to the Department of Archaeological Sciences, Bradford University, and visiting Lecturer. He is also Associate Editor of *The Journal of Archaeological Prospection* and geophysics presenter on Channel 4's *Time Team*.

Chris Gaffney – Partner

BTech Archaeological Sciences (Bradford University 1984)
PhD Archaeological Geophysics (Bradford University 1990)
Chris has worked in geophysics for over seventeen years. Included in this period was his doctoral research into Earth Resistance in Archaeological Geophysics. His

work has led to extensive site based experience in the UK, Greece and the former Yugoslavia. He formed a partnership with John in 1989. He is a visiting Lecturer in the Department of Archaeological Sciences, Bradford University and Associate Editor of *The Journal of Archaeological Prospection*. During 1994 & 1995 Chris was part of the CBA Advisory Committee on Archaeological Science and he is currently a member of the NERC Geophysical Equipment Pool Steering Committee.

Susan Ovenden – Senior Geophysicist

BSc Exploration Geophysics (University of London 1987)
PhD in Archaeological Geophysics (Bradford University 1990)
Susan's background is in geological geophysics, while her second degree was on Induced Polarisation as a Prospecting Tool in Archaeology. Her knowledge of geological prospecting has led Susan to specialise in non-archaeological aspects of shallow prospecting and more recently on the use of GPR in archaeological investigations. Susan has worked for GSB Prospection since her Doctorate graduation and is the company's Senior Geophysicist.

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*GSB Prospection, Cowburn Farm, Market Street,
Thornton, Bradford, BD13 3HW, UK.

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THE USE OF GEOPHYSICAL TECHNIQUES IN ARCHAEOLOGICAL EVALUATIONS

1. Introduction

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It is more than a decade since the appearance of *Technical Paper No. 9* (Gaffney *et al* 1991). The use of geophysical techniques in archaeological evaluation has increased tremendously during this time and this revision will update the professional archaeologist in light of recent work. The paper is still aimed at people writing briefs or commissioning a geophysical survey as part of an archaeological evaluation. At the outset, therefore, geophysical strategies will be discussed with particular respect to the location and delimitation of sites. Emphasis will now be on the main geophysical techniques used in site investigation, indicating the limitations of the methods. The type of archaeological features that are likely to be detected will be discussed and the conditions which make a site suitable for survey will also be considered. Limiting factors such as geology, pedology, ground conditions and modern disturbances are also referred to.

It is not our intention to instruct people in how to carry out geophysical surveys or how to use the variety of instruments available. Field procedures will only be discussed insofar as they are relevant to the design of an archaeological project. Similarly, interpretation of results will not be described in detail, as these aspects are covered in instruction manuals and, to some extent in Clark's (1996) book on archaeological geophysics. The advanced reader should consult the work by Scollar *et al* (1990) which discusses more theoretical details. The most important advance in publication since the 1991 version of this technical paper is the foundation of a dedicated journal to the use of non-destructive techniques in archaeology: *Archaeological Prospection*, published by John Wiley & Sons Ltd (members of IFA enjoy a considerable reduction in the price of this journal).

It should be stressed that techniques described here have been adapted and borrowed from geological geophysics, and therefore the basic theory may be found in the many 'standard' text books (eg Keller and Frischnecht 1966, and Telford *et al* 1976). Theoretical aspects are the same in archaeological prospecting but it is methodologies that are unusual. More recent geophysical textbooks have sections on archaeological geophysics (eg Musset and Khan 2000).

This paper is written primarily with assessment work in mind and we are not concerned here with research projects, where time is less pressing. When carrying out assessments, it is often only possible to investigate a site with one geophysical method. In research, experiments can be instigated, tests can be repeated and mistakes can be made without disastrous consequences. Such luxuries are not available to the contract fieldworker. Instead, considered decisions have to be made, invariably at short notice and often only after a preliminary analysis of results. The time scale of most projects poses severe constraints on field geophysicists because, for most professional archaeologists, the dates of planning meetings are immovable. This requires that the geophysical fieldwork, interpretation and report be promptly completed so that follow-up investigators have enough time to produce their own report. This compressed time scale makes it essential for both the commissioning archaeologist and the geophysicist to be aware of the potential limitations and pitfalls of archaeological geophysics. In view of this, we are of the opinion that geophysical work in archaeological assessments should only be carried out by specialist operators, with recognised geophysical experience and qualifications. The IFA Directory of Members includes members advertising their fields of consultancy. In 1991 there were neither separate sections specifically for geophysicists, nor standards for those advertising. As this is still the case we strongly advise those commissioning investigations to take independent advice.

2. Strategies in Field Geophysics

Geophysical techniques were first used to identify promising areas for excavation and to place excavations in a wider context. Today, areas requiring evaluation are often immense and the time scale short. Although the speed of survey has increased dramatically, it is still often necessary to adopt a sampling strategy. Fortunately these have been long practiced in archaeology and archaeologists are aware of their uses and limitations. Large scale geophysical evaluation strategies have evolved considerably during the last decade.

Strategies adopted for a small area of cropmark evidence for settlement will be different from those for a large development with the same evidence tucked into the corner of only one of many fields. It is likely that the former will go directly to total survey of the area, while the latter will see selection of areas for detailed survey. At what size area does one abandon a total survey and opt for a sampling strategy? As a general rule, it is often inappropriate to sample a threatened area of under 2 hectares, and considerable disadvantages for 1 hectare or less. Such sites should be surveyed in their entirety.

If the development is larger than 2 hectare and not unusually archaeologically sensitive, then some form of sampling is normally undertaken. This is usually a systematic, random or some form of modified sampling strategy (which is most frequently used in Britain). Modification may result from aerial photographic evidence or rapid assessment using geophysical techniques (eg scanning or susceptibility sampling).

Rapid assessments are normally undertaken by 'scanning' with a fluxgate gradiometer or a magnetic susceptibility field coil. Both techniques have advantages and limitations. Scanning with a fluxgate gradiometer involves an experienced operator assessing the background level of magnetic response as he or she walks along each traverse, usually spaced 10–15m apart. If any anomalies are noted, then markers are placed at each point and/or marked on a map. Detailed survey using the fluxgate gradiometer can then be undertaken in sample blocks over the targets. In some cases,

perhaps if few targets are found, apparently 'blank' areas also will be sampled using the same instrument. This will assess the potential for archaeological features that produce anomalies below the scanning threshold (normally 2nT). It should be stressed that 'scanning out' anomalies can be very difficult and, on certain sites/geologies, even experienced personnel may have limited success in detecting *areas* of interest, let alone individual anomalies. Problems occur where, for example, there are beds of magnetic gravels, or the magnetic contrast between fills and subsoil is too weak, as in deep undifferentiated sands. Apart from search-line transects, it is not possible to scan with resistivity.

In magnetic susceptibility sampling, measurements are recorded systematically across an area; data are usually collected on a 5–20m sample grid and a map of topsoil susceptibility is produced. The 'hotspots' (and 'blank' control areas) within the data set can then be assessed with the fluxgate gradiometer using sample blocks. The main advantage is that data can be analysed later as opposed to the scanning approach that only notes potential targets. However, disadvantages are that the history of landuse and modern use will produce spurious variations, along with many natural/pedological factors. This form of assessment takes longer than scanning with a gradiometer.

Both techniques produce good responses over large Iron Age/Romano-British settlements. The results are more variable when assessing small or short-lived sites, especially when settlement or industrial activity is absent. However samples for detailed gradiometer survey are chosen it is always preferable to investigate large continuous areas. This allows better understanding of background variations that may be the result of geological and topographical factors. As a broad guideline, 60m by 60m is preferable and certainly areas less than 40m x 40m are often uninformative. Transects (ie sample strips) should be a minimum of 20m wide.

Detailed survey usually covers 10–50% of the total development. Most briefs/specifications allow for contingency should extensive archaeological anomalies be found. A rapid scan or magnetic susceptibility field coil survey without detailed survey to test the results is of little value.

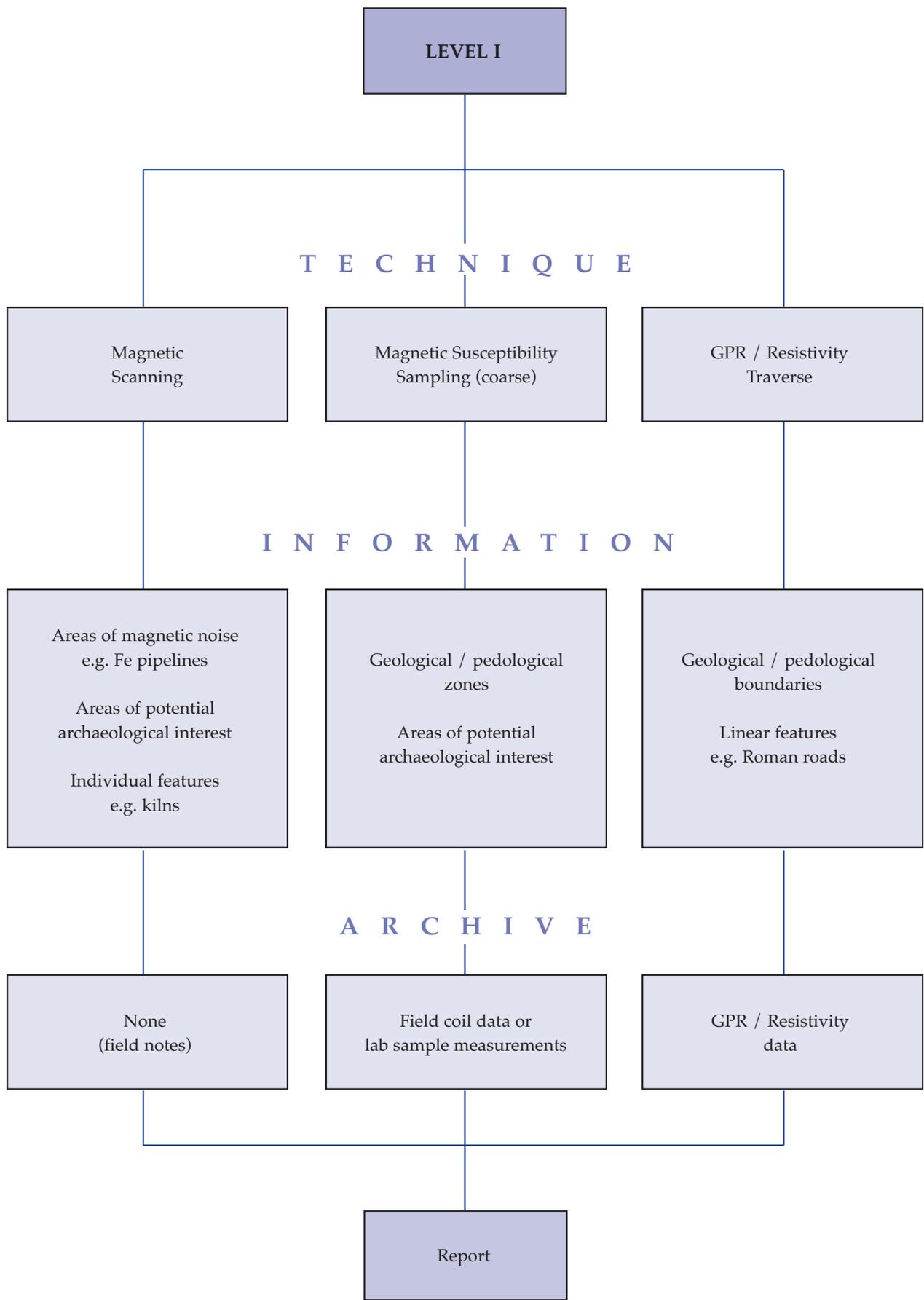


Table 1

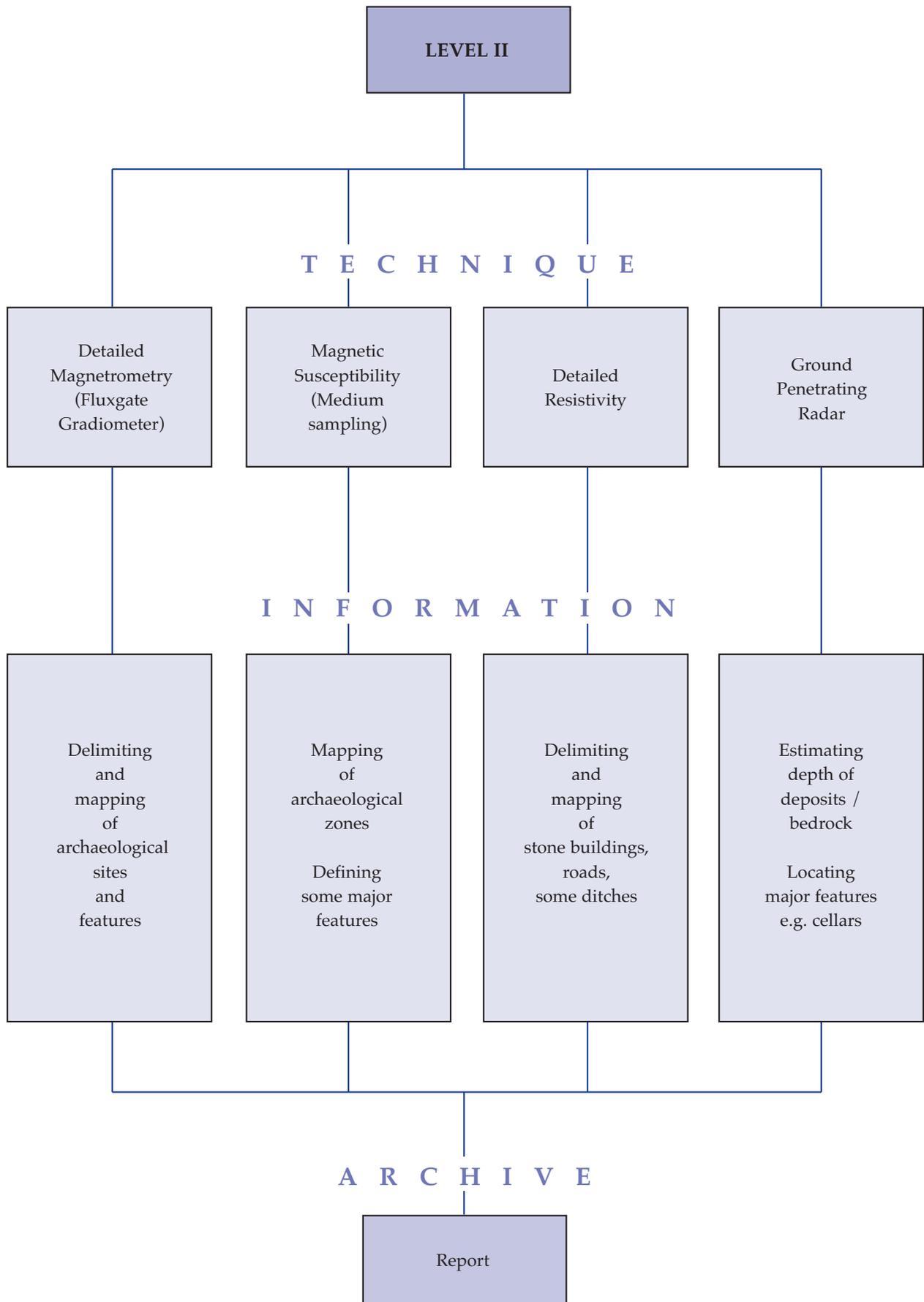


Table 2

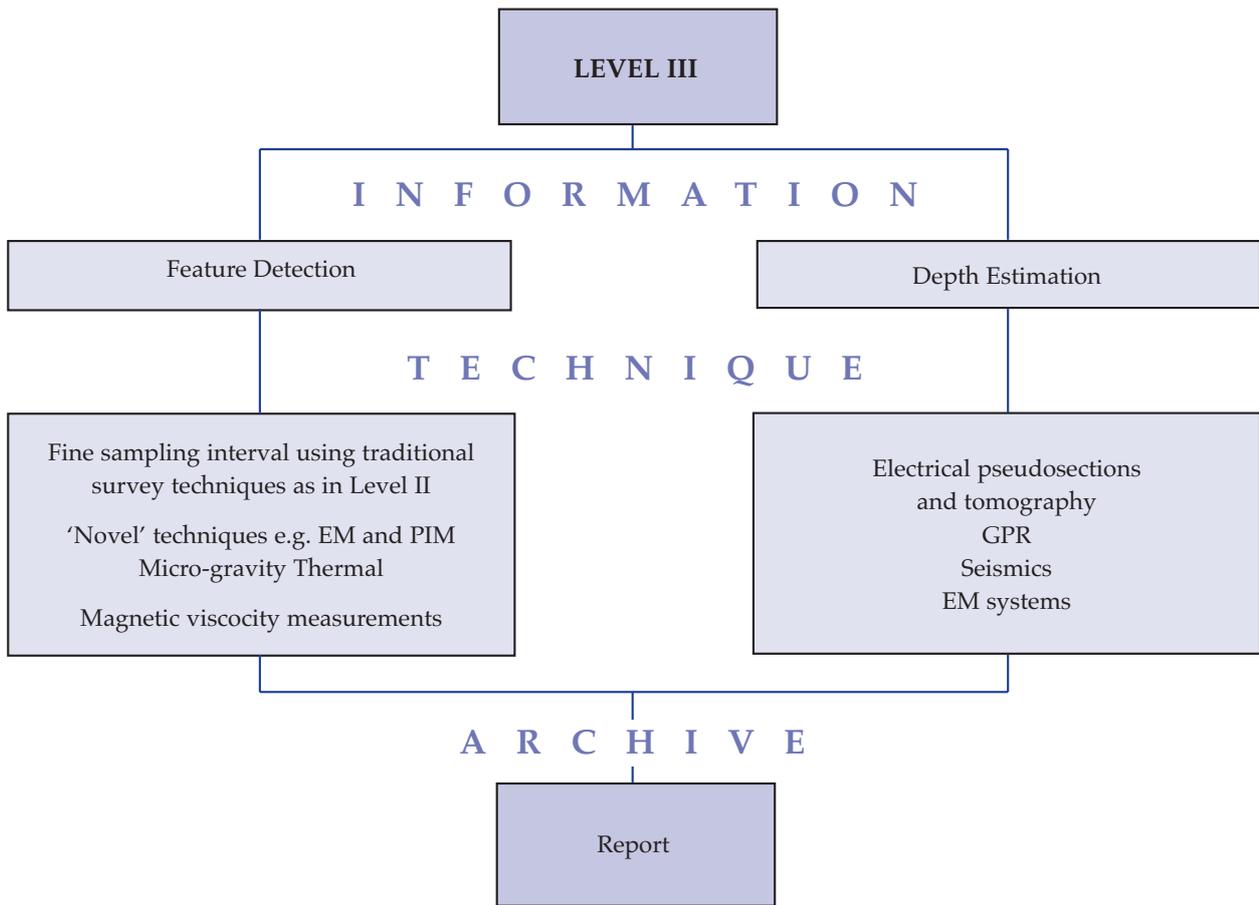


Table 3

Tables 1–3 (after Gaffney and Gater 1993) provide a simplified summary of geophysical strategies. Most evaluations involve one or two ‘levels’ of survey. Level I involves prospecting, that is locating sites or areas of interest, while Level II assesses known or suspected remains. Level III is less common in evaluation work, but indicates the strategies available for detailed investigation of specific factors.

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3. The Basis of Geophysical Methods

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Although an unusually large number of detection devices have been used for archaeological prospecting (see Wynn 1986 for a history), only a few have become

standard in evaluation projects. Whilst research avenues appear to be ever widening, a perusal of the excellent but rarely seen 1960s journal *Prospezione Archeologica* indicates the variety of techniques that have been experimented with, and illustrates the problems of each. Some were simply due to instrument stability, whilst others were inherent in the techniques. For the most up-to-date information world wide, see *Archaeological Prospection*.

The following section will describe geophysical techniques most frequently used in archaeology. The basis for each and their potential for evaluation are discussed.

3.1 Electrical

Electrical methods use the fact that although most rock-forming minerals are insulators, electrical current can be

carried through the earth by interstitial water held in the soil/rock structure. Resistivity, Self Potential and Induced Polarization can all be used, although only resistivity has become a standard technique.

3.1.1 Resistivity

This has the longest association with archaeological investigation (Aitken 1974) and is the most widely used electrical method. Its elegant theory has been well documented within the geological and geophysical literature, from which it has been adopted. Its simple practicalities have also been borrowed from this source.

Resistivity relies on the relative inability of materials to conduct an electrical current. As resistivity is linked to moisture content, and therefore porosity, features such as wall foundations will give a relatively high resistivity response, while ditches and pits, which retain moisture, give a lower one.

The method involves injection of a small electrical current through the earth and measurement of subtle sub-surface variation in resistance over a given area. The resistance (measured in ohms) is a 'bulk' measurement of the restriction of the current within a particular piece of ground, while the resistivity (measured in ohm-metres) is the term for the electrical restriction within a standard volume of earth. Whilst the latter is the critical measurement when comparing measurements made by different arrangements of probes (see below), the former is usually adequate when discussing results collected using the same arrangement. The majority of detailed surveys for archaeological purposes simply measure resistance and should be reported as such.

Resistivity surveys can be carried out in one of two ways. Firstly, a constant spacing traverse, i.e. electrical profiling, measures lateral variations in resistivity and is most widely used for planning features. Vertical electrical soundings, i.e. electrical drilling, study horizontal or near horizontal interfaces (archaeological layers). Comparisons with theoretical curves enable the depth of such interfaces to be calculated. More recent surveys have highlighted this vertical component, using pseudo-sections or tomography. These surveys rely on

the theory that as one expands the probes, data are recorded at a greater depth. Complex switching systems control long lines of electrodes and the resulting data provides a vertical section through the ground. These lines can generate a 3D image of the subsurface.

In recent years we have seen a number of advances in resistance survey for archaeology. The main UK manufacturer (Geoscan Research) has introduced a multiplex system that allows many Twin Probe measurements to be taken at one point (Walker 2000). This allows resistance maps to be produced for different depths. A reasonably practical towed system has also been formulated in France and tested at Wroxeter (Hesse *et al* 2000). The towed system produced good results but requires relatively flat ground and is likely to be unsuitable for ploughed fields or earthworks.



Resistance Survey with multi-probe array

3.2 Magnetic

The basis for magnetic prospecting is weakly magnetised iron oxides in the soil. Depending on the state of iron oxides, the material will exhibit either a



Fluxgate Gradiometer

weak or a strong magnetisation. Two phenomena relevant to magnetic anomalies are thermoremnance and magnetic susceptibility.

Thermoremnance describes weakly magnetic materials that have been heated and thus acquired a permanent magnetisation associated with the direction of the magnetic field within which they were allowed to cool. For this to be possible the body in question must be heated above a specific value, known as the Curie Point (CP). This wipes the inherent magnetic orientation of the body clean, so on cooling the material acquires a new magnetic property specific to its relative position in the Earth's magnetic field. Archaeological features that have been through this mechanism include baked clay hearths, and kilns used for ceramic manufacture. Importantly, whilst this creates a readily identifiable, even characteristic, signal, the same property makes

magnetic results on some igneous geologies very difficult to interpret.

Magnetic Susceptibility is the key to coherent results from magnetic surveys. Moreover, not only can the difference in magnetic susceptibility between topsoil and subsoils be used in a predictive manner, but also the spatial variation of susceptibility enhancement throughout the topsoil itself indicates 'activity' in the archaeological context.

The theories of Le Borgne (1955; 1960) are the most frequently cited in the discussion of magnetic susceptibility. He suggested a simplified transition of iron oxides as follows:

haematite > magnetite > maghaemite

This is achieved by conditions of reduction followed by oxidation. He proposed two mechanisms which produce these conversions: fermentation and burning. The burning mechanism is fairly well understood and hinges upon the thermal alteration of weakly magnetic/antiferromagnetic iron oxides to more magnetic oxide forms. The fermentation pathway is both a subject of debate and an unhelpful misnomer. This pathway explains the general tendency for topsoils to have a higher magnetic susceptibility than subsoils, assuming a non-igneous parent. The mechanism is a product of biological-pedological systems and probably involves the interaction of microbia, soil organic matter and soil iron (Fassbinder *et al* 1990: Fassbinder and Stanjek 1993).

Anthropogenic activity generally increases susceptibility and produces detectable anomalies (Tite and Mullins 1971). Even in the absence of the heating mechanism of enhancement, detectable features can be produced, for example by the infilling of a ditch with relatively enhanced topsoil materials.

3.2.1 Magnetometry

Although the changes in the magnetic field associated with archaeological features are usually weak, changes as small as 0.2 nanoTesla (nT) in an overall field strength of 48 000 nT, can be accurately detected using a

dedicated instrument. Mapping the anomaly in a systematic manner will allow an estimate of the type of material beneath the ground. Anomalies that are of interest are the product of relative contrasts between the subsoil and magnetically enhanced topsoil.

In terms of archaeological features, one can imagine a ditch cut into subsoil. Silting or deliberate infilling of the ditch with magnetically enhanced topsoil or other materials will create a magnetic contrast which would produce a characteristic anomaly. The anomaly changes in shape depending on the interaction of the localised field with the earth's magnetic field. In Britain, a pit or ditch containing enhanced deposits will produce an anomaly with a positive peak to the south and a corresponding negative to the north. The displacement will be no more than 0.25m, better than the precision on the sampling interval.

The earliest magnetometers used in archaeological geophysics were proton magnetometers, which proved successful in the 1950s and 1960s (Aitken 1974). The principles of their measurement are based around the magnetic properties of protons in water molecules. These instruments measure absolute values of the magnetic field, but data capture time is slow. It is more usual to use a fluxgate magnetometer (also referred to as gradiometers), at least in Britain, where the instrument has been developed for rapid archaeological survey (eg Philpot 1973). These instruments use two fluxgate sensors placed vertically above one another, at a set distance apart (normally 0.5m). The key is the alignment of the two sensors. An instrument that has been poorly set up will produce results due to misalignment of the sensors, rather than buried features. A third type of instrument used widely outside Britain is an alkali vapour magnetometer (alternative names are caesium, rubidium, optically pumped or optical absorption magnetometers). These are very high sensitivity magnetometers, though their claimed resolution of 0.01nT is of little value in Britain because background topsoil noise is generally much greater than this. The costs are prohibitively high for most independent operators, and the commercially available instruments are hand-held rather than wheeled devices used on the continent.

Given these factors, it is unlikely that the instruments will find a substantial role in evaluations in Britain. However, there will always remain a niche for specialist requirements, such as detecting features buried under alluvium.

3.2.2 Magnetic Susceptibility

Measurement of magnetic susceptibility can be carried out by two methods. Firstly, there is the field coil, which allows rapid measurement of large areas. One disadvantage is poor penetration (c 10cm) of the signal, although this in part can be circumvented by judicious use of field sensors or use of a field probe inserted into augered holes. Another is that it gives a bulk measurement of soil, stones, air and water. The second technique is the laboratory determination of susceptibility for a standard volume or mass. This gives a truer measurement as the samples are dried and the coarse fraction (all materials, such as stones and foreign bodies, over 2mm in diameter) is excluded by sieving. The downside is the time it takes to prepare samples. However, if soil physical and chemical property analyses (such as trace element analysis, total P, particle size analysis or loss-on-ignition) are to be undertaken, laboratory analysis becomes feasible.

3.3 Ground Penetrating Radar (GPR)

The primary advantage of GPR is its ability, when more than one section is investigated, to provide a three dimensional view of a buried site. A short pulse of energy is emitted and echoes return from interfaces with differing dielectric constants. These reflections may respond to the changes at the interface between strata or materials. The travel times are recorded and converted into depth measurements, giving a geo-electric depth section.

The technique is being used more frequently and several systems are available. To date, it has been argued that it is best used in small scale evaluations over deeply stratified areas where traditional prospecting techniques do not perform well, eg urban sites (Stove and Addyman 1989). More interaction is



Ground Penetrating Radar

needed between the radar specialist and the archaeologist, especially at the level of data interpretation (Milligan and Aitken 1993). While GPR clearly has its place in urban archaeology where other techniques are problematic, it has limitations, for these sites have complicated stratigraphy that would be difficult to understand even by trenching.

In Britain, GPR is rarely used on green-field sites, for other techniques such as gradiometry and resistance survey are suitable and are quicker and cheaper. Secondly, the clayey nature of many British soils limits the effectiveness of GPR, with a rapid attenuation of the signal and a consequential inability to record data to an adequate depth. However, in many ways 'quieter' green-field sites produce clearer GPR results, especially over buildings. GPR surveys at Wroxeter (Nishimura and Goodman 2000), for example, have produced excellent results. Speed and cost prevent its use as a general prospection tool, but it can be very useful as a follow-up, targeted investigation or where no other technique is viable.

Whilst initially the main advantage of GPR was viewing a vertical section through the ground, experience has shown that it is far easier to view data as a map. By collecting many parallel lines and

merging them into a block it is possible to produce a series of time-slice, or amplitude, maps. These sum the data between a selected time or depth range for every traverse and save the data as an XYZ file which can then be displayed as a plan of anomalies at that particular depth range.

3.4 Other Detection Techniques

These techniques are of secondary interest in evaluation work.

3.4.1 Electromagnetic

Electromagnetic methods make use of the response of the ground to the propagation of electromagnetic (EM) waves. The most important aspect of the modern EM systems, such as the Geonics EM38, is the ability to provide a measure of both the magnetic susceptibility and the electrical component of the soil. The latest version allows both values to be measured simultaneously. Some instruments take measurements at different frequencies, but their potential in archaeological evaluation is still to be proved. EM instruments are frequently used for archaeological work on the continent (Tabbagh 1986a; 1986b) and while it is possible they may find a role in Britain, there has been little reported increase in use in the past decade. One of the reasons EM instruments are used in drier climates is that they do not require contact with the ground and that they perform better than electrical resistance techniques on sites with a dry surface. This means they can be used in summer or over tarmac surfaces. In other words, EM systems often work best in survey areas where resistivity techniques often fail. EM surveys can be used for mapping the remnants of mounds, tracing in-filled fortifications, locating buried stone structures or rubble, pits, and metallic artefacts.

3.4.2 Metal Detectors

Metal detectors are one of the most frequently used tools in searching for artefacts, rarely the main aim of an archaeological evaluation. However, when used within a structured design for an evaluation there are clear benefits.

3.4.3 Seismic

In seismic surveys, artificially generated seismic waves propagate through the subsurface. The travel times of the waves, which return to the surface by reflection and refraction at boundaries with differing reflection coefficients, are recorded. Travel times are converted into depth values giving a vertical section.

While seismic *reflection* has been used for the detection of tombs, it has several limitations. In most cases the soil layer is thin and may be beyond the resolution of the method. Interpretation can be extremely difficult when studying boundaries of complex geometry.

Seismic *refraction* surveys are better suited to archaeological prospecting as they can give detailed information about a small area, and the data collection and processing are relatively simple. For examples of such a survey, see Goulty and Hudson (1994) and Ovenden (1994). An important consideration is that this technique is best suited to conductive soils. As a result it may be considered as an alternative to GPR, which does not perform well in wet or saturated ground.

3.4.4 Gravity

A mass of material, or a cavity, will have a different density to that of the surrounding area, creating a density contrast which will locally distort the gravitational field, giving rise to a gravity anomaly. The survey method is time consuming and involves lengthy processing of data. Although not widely used in archaeology, some case studies have been reported (see Linford 1998).

3.4.5 Other Techniques

The Self Potential (SP) method, also known as Spontaneous Polarisation, is based on surface measurement of natural potential differences resulting from electrochemical reactions in the subsurface. The field procedure is relatively simple, involving two non-polarising electrodes connected via a high impedance millivolt meter. In theory, this method can detect corroding metallic artefacts, building foundations, pits

and underground chambers. However, it has not been used extensively and its best applications remain unclear.

The Induced Polarisation (IP) method is similar to resistivity and has comparable applications as it makes use of the passage of electrical current through the pore fluids by means of ionic conduction. Induced polarisation is measured by studying the variation of resistivity with the frequency of the transmitted current, with the earth acting as a capacitor. This has been tested on archaeological sites with some success, although research is required. It can detect metallic material (particularly disseminated material as the technique is dependent on surface area), in-filled ditches, and variations in the topsoil, particularly in the clay content.

Buried features can create temperature variations at the earth surface that may be measured either using airborne detectors or ground probes. This so-called thermal detection is a continuing area of research, although the data are, at present, slow to collect at ground level, and may be difficult to interpret (Bellerby *et al* 1992).

Dowsing has long been practiced in archaeology. Unfortunately the scientific principles are not understood (see van Leusen 1998). As such, the technique should not be used for evaluation purposes.

In summary, it is suggested that there are only four techniques of proven reliability required for evaluation work on shallow sites. That is resistivity, magnetometry, magnetic susceptibility and GPR. By highlighting these four techniques we do not dismiss the others. Their potential has been noted and further research may allow them to be used as evaluation tools. To our knowledge, SP, IP, Thermal Detection or Dowsing have not been used in archaeological evaluations.



4. Types of archaeological feature likely to be located using geophysical techniques

4.1 Fluxgate Gradiometer

These are the most widely used geophysical instruments in evaluations in Britain. Even under ideal survey conditions, however, it is unlikely that features of archaeological interest will be identified at a depth greater than one metre. Its speed means large areas are covered quickly, and anomalies are reasonably easy to interpret. Under *normal* survey conditions a gradiometer survey is likely to locate:

- ditches (>0.5m diameter)
- pits (>0.5m)
- pottery and tile kilns

- hearths and ovens
- ferrous debris, including some slags
- briquettage, pottery wasters, bricks and tile
- burnt material, fired stones (eg burnt mounds)
- palaeochannels and other fluvial/geomorphological features

Under *very favourable* conditions it is also possible that the following features may be located:

- larger postholes, slots and gulleys
- walls

Soils and materials traditionally used for building in many parts of Britain ensure that there is normally little magnetic contrast over buried walls and buildings, unless the materials have been burnt or deliberately fired. Occasionally walls are detected as negative anomalies, but this is usually because they are buried in highly enhanced magnetic soils (see Gaffney *et al* 2000).

Norse Road, Bedfordshire Fluxgate Gradiometer Data

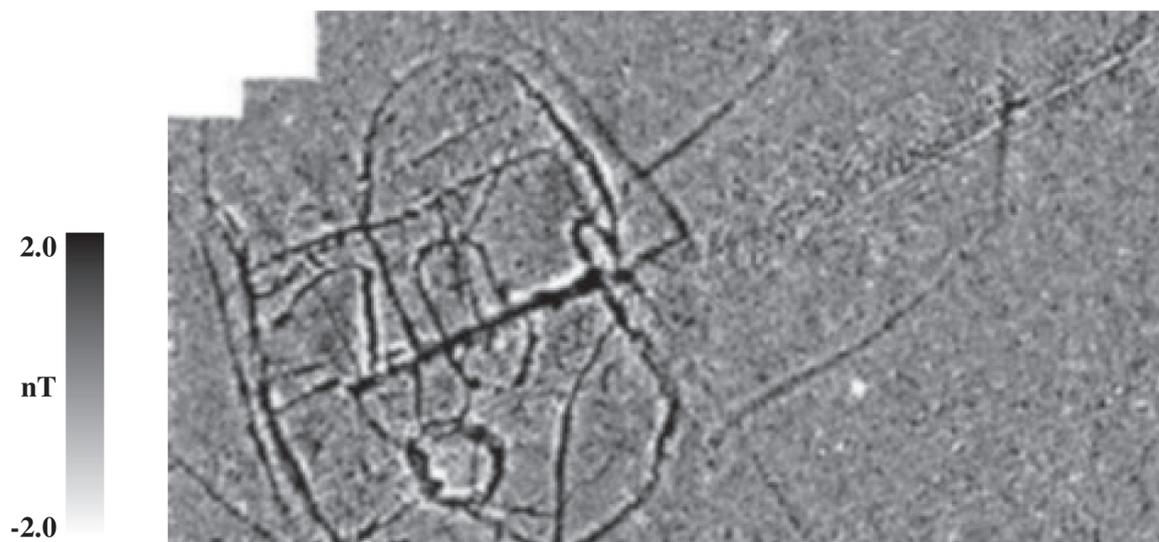
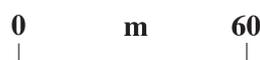


Figure 1. Fluxgate gradiometer survey of an Iron Age / Romano British settlement (see Dawson and Gaffney 1995)



Athelney Abbey, Somerset

Resistance Data



Figure 2. Resistance survey of monastic complex showing wall foundations of church and associated buildings

Occasionally, burials and ferrous grave goods may be detected, though these are generally difficult targets. While gradiometers can locate ferrous artefacts, non-ferrous metals such as gold, silver, copper alloys, tin, and lead will not be detected.

4.2 Magnetic Susceptibility Sampling

Coarse sampling intervals, say every 5, 10 or 20m may detect:

- areas of archaeological activity
- occupation and 'industrial' working areas
- former fields in the form of areas of differing susceptibility which appear to respect former field boundaries.

Fine sampling intervals, say every 1 or 2m may allow:

- some feature identification

4.3 Resistance Survey

Unlike gradiometers, resistance instruments measure moisture content, a factor which is naturally severely affected by localised weather conditions and, to a lesser degree, pedological variation. The technique's depth limit is dependent upon the probe arrangement. In the case of the Twin-Probe, a 0.5m separation will rarely give information on features below 0.75m. Greater separation will increase the depth penetration, although at the expense of resolution. Features which are *normally* identified as *high* resistance anomalies include :

- walls and rubble spreads
- made surfaces such as yards
- metalled roads and trackways
- stone coffins or cists (these are difficult targets)

Features *normally* identified as *low* resistance anomalies include :-

- large pits and slots (>0.5m)
- ditches
- very occasionally graves
- drains and gulleys

Mine Howe, Orkney
GPR Data

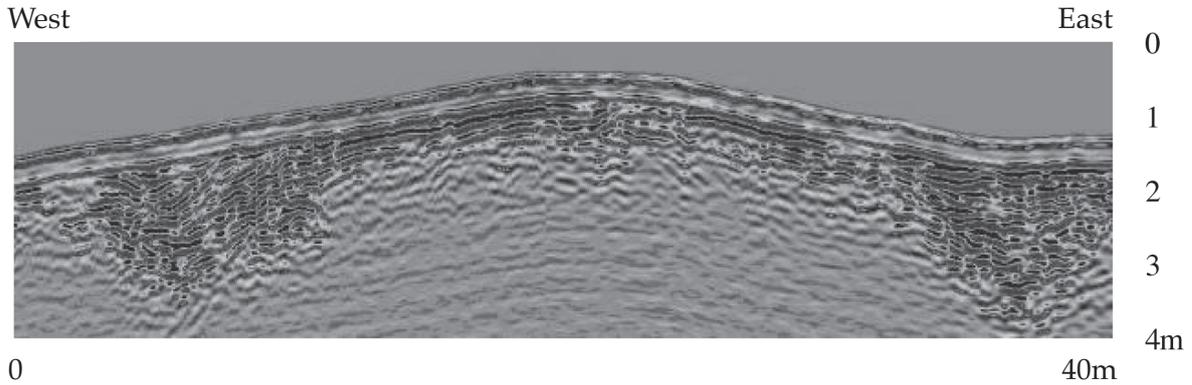


Figure 3. Topographically corrected radargram through the lower slopes of the mound at Mine Howe, Orkney where an Iron Age chamber survives surrounded by a large ring ditch that was identified by fluxgate gradiometer survey. The reflections indicate a ditch some 7–8m wide and up to 3m deep: this was confirmed by excavation

4.4 GPR Survey

GPR relies on dielectric contrast between differing materials. Under suitable conditions the following features may be identified (Conyers and Goodman 1997):-

- refilled pits and ditches
- voids eg chambers, tunnels
- buried paths and roadways
- walls, floors and rubble spreads
- stone coffins
- soil/bedrock interfaces

As stated earlier, success is dependent on the soils, in particular their moisture content, and subsequent activity on the site. These factors, together with the expected nature of the archaeology, have to be carefully considered when selecting the antenna frequency. On sites with a high moisture content or when investigating deeper features a lower frequency antenna is needed. This will reduce the near surface resolution, in itself advantageous as it may reduce the ‘clutter’ produced by modern near- surface debris.

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5. Complicating factors encountered in surveying
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5.1 Magnetic Survey

5.1.1 Field Factors

Wire Fencing

As a rule of thumb, data must be collected at least 1 metre away for each strand of wire in a fence

Overhead Power Cables

Contrary to popular belief, the majority of these do not affect results collected using a gradiometer though bands of noise may be visible in the data. Problems may

be encountered when setting up the instrument.

Underground Power Cables

These can produce massive magnetic anomalies that may restrict the usefulness of magnetic prospecting, sometimes up to several metres on either side.

Pylons

Pylons are problematic due to their large mass of ferrous material. In general 20 to 30 metres is the closest the operator can approach without spurious effects.

Radio / Cellnet / High Frequency Transmitters

The effects are difficult to predict, as the response is dependent on the frequencies at which they operate. Instrument manufacturers may have to be consulted. Alternatively, a rapid field assessment may be the only way of evaluating the effect. Experience has shown that, even when a transmission does interfere, there are some zones where gradiometers can be used.

Electrified Railways / Overhead Cables

The ferrous content is the overriding factor in determining whether the instruments will be affected. Passing trains will produce very large magnetic fields, which will cause temporary saturation of the gradiometer.

Vehicles

A stationary vehicle can be detected by the gradiometer 20 - 40 metres away. The amount of disturbance is dependent upon the ferrous material in the vehicle. Proximity to busy roads can present major problems, as passing lorries will produce very large, spurious anomalies.

Buildings

Modern buildings normally contain fired brick, magnetic stone, steel reinforced concrete and corrugated iron. All of these result in magnetic fields that are likely to swamp anomalies of archaeological interest. Mobile homes and caravans, including site offices, present similar problems.

Pipelines

Buried ferrous pipelines will have a marked effect upon the local magnetic field. Some of the utilities' larger pipelines will preclude effective use of a magnetometer up to 20 metres either side. Characteristic responses are recorded as a gradiometer passes over a buried pipe. When displayed as a dot density plot some pipelines can appear as a line of interrupted high readings/blobs – similar to a line of pits. An X-Y plot will indicate the true strength of the anomalies associated with the feature.

5.1.2 Ground conditions

Modern Dumping

Modern material, for example lumps of concrete and clinker in ploughsoil, along with the artificial build-up of ground surfaces (eg embankments, consolidation and landscaping), all pose interpretational problems.

Trees, Bushes and Shrubs

These are tolerable as long as the operator can walk in straight lines between them - dense vegetation will reduce survey work to a detail no greater than scanning.

Crops, Undergrowth and Flowerbeds

Apart from crop damage, a major consideration is whether the gradiometer can be kept in a vertical axis without brushing against vegetation. Excessive buffeting results in increased noise levels may preclude data collection. If in doubt, the project may have to be postponed until after harvest, or the vegetation be cleared. Pasture/crop height is probably the greatest cause of avoidable failed fieldwork.

Ploughed Fields

Wet, heavy soils will make work extremely difficult and can affect the quality of recorded data. Potato fields and deep ploughed areas should be avoided as they will often produce topographic effects, which can easily mask anomalies of archaeological interest. Similarly, tractor ruts can result in spurious anomalies.

Ridge and Furrow

If surviving as earthworks visible on the ground, it is

probable that the gradiometer will not record any major magnetic changes (unless preservation is so good that a topographic effect is produced). Earlier features should still be detectable. Where ridge and furrow has been ploughed out, a striped magnetic effect is likely to result because of the contrasts between infilled furrows and former ridges.

5.1.3 Geology

In general, the overriding factor is that there should be a measurable contrast in magnetic susceptibility between the topsoil and the subsoil/bedrock. Complications arise on some igneous geology and heavily metamorphosed rocks for reasons, outlined above, connected with thermoremanence.

Sands and gravels can be particularly complex and their results can be highly variable, particularly where affected by a high water table. Some soils contain bands of magnetic sands and gravels that produce anomalies similar in character and strength to archaeological anomalies. In deep, undifferentiated coarse soils the change in magnetic susceptibility between the feature-fill and the surrounding soil is small, resulting in very weak anomalies. Reverse-anomaly effects are also sometimes encountered in coarse soils. Complicating factors such as these make rapid assessments particularly arbitrary. However, detailed sampling will often produce coherent results.

Perhaps of all the soils in Britain, chalk has long been recognised as a suitable geology for magnetic survey, due to the marked contrast between soil-filled features and the chalk itself. However, periglacial effects can produce polygonal patterning and striping. In general terms, the Coal Measures, slates, siltstones, limestones, Palaeozoic sandstones, *some* Mesozoic clays, and ironstones tend to produce good responses, although extraneous factors may intervene. In contrast, such geologies as Greensands, Gault clays, Wealden clays and recent alluvium tend to be problematic.

Features cut into alluvium and colluvium cause problems. Experience on such soils suggests that coherent anomalies, apparently indicating linear ditches, may prove difficult to confirm by excavation.

Features covered by alluvium are problematic as the depth reduces the magnetic signal (Weston, 2001). Alluvial environments often contain coarse soils in deep undifferentiated beds. A high water table may also obstruct thermally induced magnetic enhancement or the development of a significant, magnetically distinct topsoil. As a result, cut features may not possess or develop a detectable susceptibility contrast.

Heterogeneous geologies, such as drift or boulder clay, provide mixed results, as they can contain igneous erratics which can contribute to a higher magnetic noise level or resemble pit-type anomalies.

5.2 Resistance Survey

5.2.1 Field Factors

Moisture Content

This is complex, as there are optimum times of year for surveying dependent upon the type of feature and soil porosity. However, in a developer-funded situation a decision has to be made as to whether the technique is suitable. As a general rule, extremes of weather are not necessarily the best conditions for resistivity survey, eg a ditch may retain moisture during drought and thus be detectable, but a wall showing as a parchmark may not produce an identifiable anomaly compared with the dry soil surrounding it.

Buried Cables and Electric Currents

Modern instruments have sophisticated circuitry which can compensate for many of these effects, which tend to occur in urban or semi-urban contexts. Electrical noise is filtered out but this requires a slightly increased survey time.

5.2.2 Ground Conditions

Ploughed Fields / Parched Ground

Both scenarios not only change the moisture content at the surface but also produce probe contact problems. Modern instruments can circumvent these to some extent, however, under extreme conditions survey may not be possible.

Tree Roots and Bushes

Living plants can create their own anomalies by distorting the moisture content in their immediate environs. Bushes invariably reduce the area available to survey.

Differential Thawing of Ice and Snow

Work can be carried out in snow or ice but allowance must be made at times of thawing.

Areas of Waterlogging

Puddles do not usually present problems although waterlogged land should usually be avoided. Torrential rain may cause some instruments to behave erratically. Sharp downpours on long dry grass may increase noise levels.

5.2.3 Geology / Pedology

In general, problems only arise where the parent geology is close to the ground surface. Two significant factors are, firstly, conductive soils such as clays allow greater depth penetration of the electrical current giving a greater effective search depth. Secondly, in some environments, such as alluvial contexts or sandy soils, there is a marked spatial variation in soil texture. This causes a natural variation in moisture content which can give anomalies of an archaeological appearance.

5.3 Magnetic Susceptibility**5.3.1 Field Conditions**

Localised ferrous objects or magnetic debris will result in anomalous responses.

5.3.2 Ground Conditions

Magnetic susceptibility surveys are best carried out on areas stripped of topsoil, or with little or no vegetation. Ploughed fields, unless the ground has been harrowed, and vegetation covered ground, both present 'contact' problems for field coils.

5.4 Ground Penetrating Radar**5.4.1 Field Conditions**

Cellnet transmitters, electricity cables etc, can all introduce noise into the GPR data. In a few cases this may render the technique unsuitable, but for the majority of sites the data can be filtered to reduce these effects without degrading the data.

5.4.2 Ground Conditions*Vegetation and Surface Debris*

GPR requires a good contact between the ground surface and antenna. Tall/dense vegetation and surface debris will prevent this, introducing noise into the data.

Tarmac, Hardstanding and Concrete

GPR is one of the few techniques suitable for geophysical investigations on such sites and the level surface allows good contact between antenna and ground surface. However, areas of reinforced concrete are not suitable. Although the technique will accurately locate the steel reinforcements, very little information will be retrieved from any depth.

Mixed Ground Cover

Problems can be encountered where survey areas cover mixed ground, for example lawn and paths. The wide difference in surface response and signal attenuation results in marked variation from one to the other, which will limit the effectiveness of time-slicing the data.

5.4.3 Geology / Pedology

Careful consideration has to be given to the depth of the expected archaeological features and the nature of the soils. Clayey soils will dramatically attenuate the signal, thereby greatly reducing the effective depth of investigation. While lower frequency antennae can be used to enable greater penetration of the signal, this will be at the expense of near surface and lateral resolution.



6. Display and Interpretation of Data

There are a variety of display formats for presenting geophysical data, the most common being computer generated. While computers have become a necessity because of the large quantities of data, interpretation is not, as yet, an exact science.

At present, the display software commercially available attempts to enhance specific anomalies, *judged to be significant by the operator*, and is dependent upon the operator's knowledge and experience. It is essential, therefore, that when selective plots are produced in a report, adequate information is provided as to why particular plots have been chosen. At a minimum, information should be provided for plotting parameters and it should be stated whether the data has been filtered or smoothed. The provision of scales and a north sign is a basic requirement.

In order to get a fuller understanding of the significance of the results, it is often necessary to display the data in more than one format. For example, magnetic responses are unusual in that it is often possible to differentiate types of archaeological and non-archaeological information based on the form and shape of the anomalies. Greyscale or dot density plots are good at providing a plan of significant anomalies, whereas profiles or XY traces are better for analysing anomalies, for example, to identify iron spikes. These are some of the most common display formats:

6.1 Greyscales / half-tones

This format divides readings into a set number of classes, each with a predefined arrangement of pixels, the intensity increasing or decreasing with value. This gives an appearance of a toned or grey scale. A similar effect can be achieved by using a series of symbols to represent different levels. Plots can be produced in colour, either using a wide range of colours or by selecting two or three to represent larger bands of positive and negative values. The main advantage is that

they can be generated digitally and used as base maps in certain CAD packages.

6.2 XY traces or stacked profiles

This involves a line or graphical representation of the data. Each successive row of data is equally incremented in the Y-axis, to produce a stacked profile effect. This display may incorporate a hidden-line removal algorithm, which blocks out lines behind the major peaks and can aid interpretation. Advantages of XY traces are that they allow the full range of data to be viewed, showing the shape of individual anomalies, and it facilitates viewing profiles from differing angles.

6.3 Dot Density

While this is the classic display format, it has largely been superseded by greyscale images. In this display, minimum and maximum data cut-off levels are chosen. Any value that is below the specified minimum will appear 'white', while any value above the maximum will appear 'black'. Intermediate readings will be allocated a specified number of randomly plotted dots depending upon the relative position between the two cut-off levels. The advantage of this display is that data can be simplified. The main limitation is that multiple plots have to be produced to view the whole range of data. It is also difficult to gauge the true strength of any anomaly without looking at the raw data values. This display is much favoured for producing plans of anomalies, where the positioning of features is important.

6.4 3D wire meshes

This display joins the data values in both the X and Y axis. The display may be changed by altering the horizontal viewing angle and the angle above the plane. Output can be colour or black and white. As with X-Y plots a hidden line option can be used. In some display packages a surface can be fitted to the mesh. This option is usually only used for simple data sets or those limited in size.

6.5 Contour

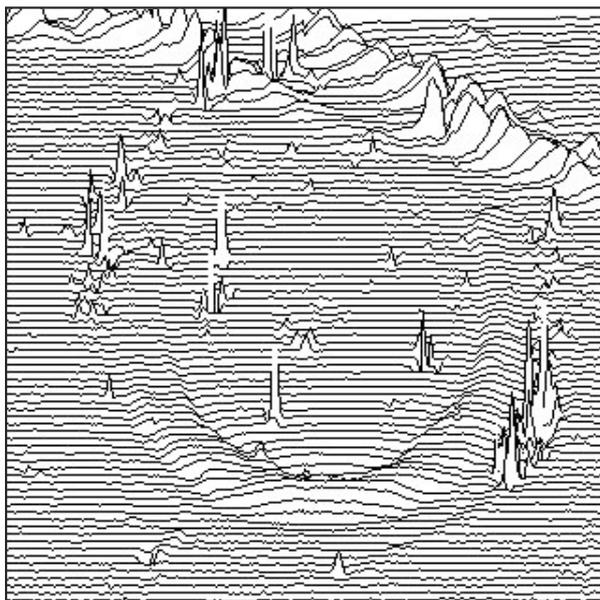
This joins data points of equal value by a contour line. Displays are generated on the computer screen or plotted directly on a flat bed plotter/inkjet printer. These can be generated in colour or black and white, depending on the output device used.

6.6 GPR Radargrams / Electrical Pseudosections

These represent vertical sections through the ground with the direction of the trace being recorded on each diagram. The vertical axis represents time and/or estimated depth, while the horizontal axis indicates distance.

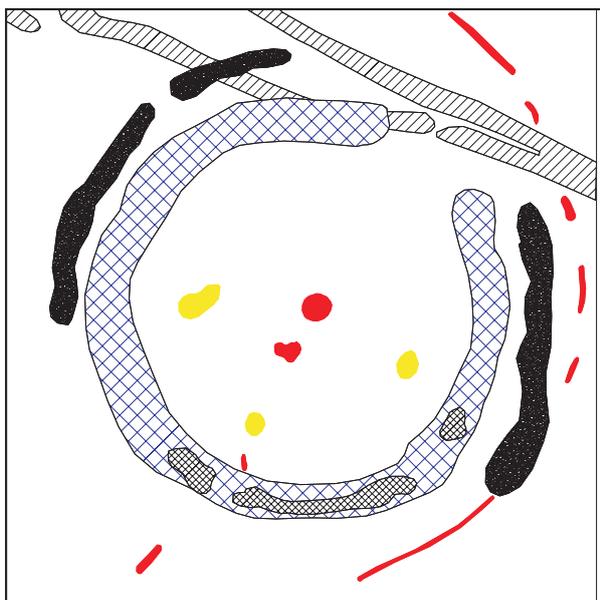
Stones of Stennes, Orkney Fluxgate Gradiometer Data

Figure 4. Gradiometer data showing henge ditch overlying igneous dyke



[25nT

Simplified Cad Interpretation

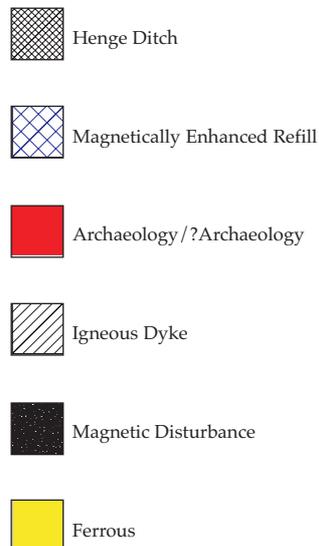


0

80m



-10 nT 25



6.7 GPR Time-slices / Pseudoslices

These combine the information from several parallel radargrams/pseudosections and provide plan views of the results at differing depths. By stacking the time slices/pseudoslices in a cube, a crude three-dimensional picture can be obtained.

6.8 Summary of Display Options

It is important to consider the reasons for data display; they are used:

- To help the geophysicist interrogate the often huge data sets that are collected
- To help the geophysicist display an interpretation of the data.

Often these two objectives are not possible within one display. It must be stressed that the display is only a means to an end. The end point is the correct interpretation of the buried archaeology, as well as the geological and pedological factors helping to produce or confuse the results. Aesthetic plots do not necessarily enhance one's ability to interpret the data. This is particularly true with colour, which can lead to non-geophysicists giving more emphasis than is warranted to the results.

Image enhancement, as opposed to display, is becoming increasingly important in archaeological geophysics, as in much archaeological analysis. This topic is beyond the scope of this paper, and the interested reader is advised to consult Scollar *et al* 1990. The use of algorithms to enhance data should be left to the specialist, but the report should detail any enhancements. However, excessive filtering often hides poor data or data collection, and raw data should always exist within a report.

The aim of any survey is to collect data that can be interpreted in an archaeologically meaningful way. The conclusion must be a report with an interpretation, both textual and graphical. It is no longer acceptable to draw interpretations onto area surveys. Indeed, it is expected

that interpretations should be created in digital format. Many groups produce these via a digitising tablet while other prefer on screen digitising. Both are acceptable as long as they are accurate and the output can be ported into the main CAD packages. Geophysical data should be available to export in a variety of formats to allow analysis in GIS platforms.

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7. Other Considerations

7.1 Scheduled Ancient Monuments

Prior to carrying out any geophysical survey on a scheduled monument, written permission has to be granted from the relevant authorities in England (English Heritage); Northern Ireland (DoE Northern Ireland); Scotland (Historic Scotland) and Wales (Cadw). This may take several weeks. Clients must be advised of this at an early stage.

7.2 Archiving Data

There is a great need to establish procedures to facilitate long term access to data sets. Companies or individuals should implement robust strategies to archive all data in a format that will allow access at a later date, including copies stored at different locations and media upgrading as technology advances. Data should be archived irrespective of how 'good' or 'bad' the results, as later analysis may prove beneficial.

While there is no requirement to centrally store geophysical data at the moment, the Archaeological Data Service has issued guidelines for good practice in the archiving of geophysical data (Schmidt 2001). This may lead to some form of data archive above the level already held by EH in their on-line database of surveys on scheduled and other selected sites (www.english.gov.uk/SDB).

8. Conclusion

Traditionally, throughout the 1970s and early 1980s, geophysical techniques were used to create a 'context' for the results of excavations. However, as the needs of archaeologists have changed, so has the role for geophysical techniques. Many surveys are now undertaken to identify the most promising area to concentrate scarce resources. Some planning authorities have taken this concept a stage further: increasingly the object of a geophysical survey is not to establish where the limits of the site are, or where best to excavate, but to answer the question 'is there any reason to excavate within this threatened area?'

Clearly there are problems with this approach on areas where there are limiting factors (see above). In these cases, the quality of any geophysical data may be open to question, and to dismiss an area because it is devoid of geophysical anomalies may well be erroneous. However, there can be no doubt about the overall contribution of geophysics to site evaluation.



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Institute of Field Archaeologists

University of Reading, 2 Earley Gate, PO Box 239,
Reading RG6 6AU, United Kingdom

TEL 0118 931 6446 • FAX 0118 931 6448

E-MAIL admin.ifa@virgin.net

WEBSITE www.archaeologists.net