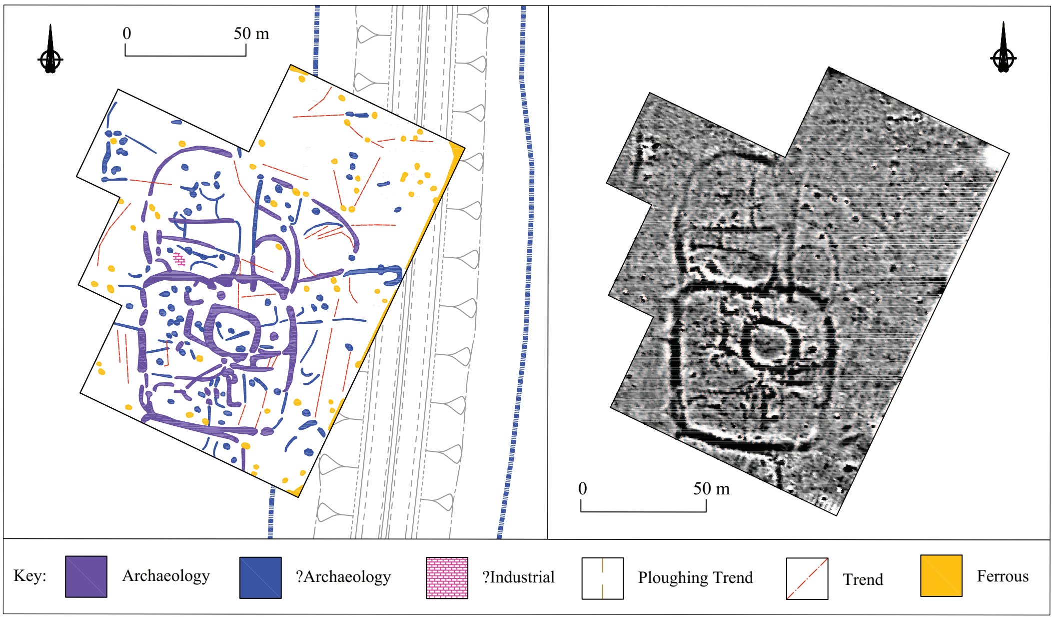
1. Back and forth: paving the way forward by assessing 10 years of geophysical surveys on Irish road schemes

James Bonsall, Chris Gaffney & Ian Armit

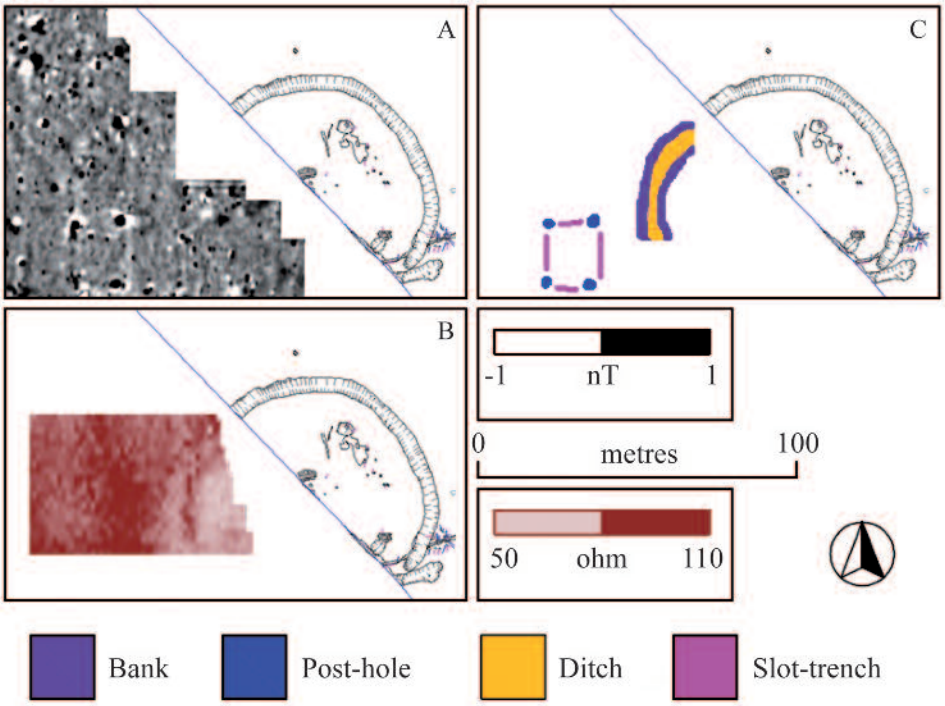


Illus. 1—Magnetometer surveys are capable of identifying a wide range of features. A magnetometer survey at Garretstown, Co. Meath, on the M3 motorway identified a series of interlinking enclosure ditches, pits and hearths, much of which lay beyond the road corridor (after GSB Prospection 2002).

Geophysical surveys have played an important role in the discovery of archaeological sites on Irish national road schemes. The NRA has recently funded a Research Fellowship for the critical review of all of the archaeological geophysical surveys conducted on such schemes between 2001 and 2010. The review, which is being carried out by the University of Bradford and its industrial partner Earthsound Archaeological Geophysics, has reappraised the success or otherwise of these geophysical assessments and has suggested ways to enhance the effectiveness of future surveys on NRA-funded roads.

What is archaeological geophysics?

Archaeological geophysics has been defined simply as the 'examination of the Earth's physical properties using non-invasive ground survey techniques to reveal buried archaeological features, sites and landscapes' (Gaffney & Gater 2003). A number of techniques can be used to assess archaeological features without disturbing or digging the ground. The best-known techniques are magnetometer (Illus. 1) and earth resistance surveys. Other techniques include ground-penetrating radar, electromagnetics, magnetic susceptibility and metal-detecting.



Illus. 2—Two different geophysical investigation techniques are often preferable to one. At Magheraboy, Co. Sligo, magnetometer (A) and earth resistance (B) surveys were used to determine the extent of an early medieval ringfort beyond an excavated road corridor. The interpretation (C) summarises the findings. Magnetometry (A) did not identify the ringfort ditch but did identify a previously unrecorded structure, interpreted as Neolithic in date owing to its proximity to contemporary structures and location within a Neolithic causewayed enclosure (Danaher 2007, 91–107). The earth resistance survey did not identify the structure but clearly identified the ringfort ditch and potential banks on either side of it (after Danaher 2007).

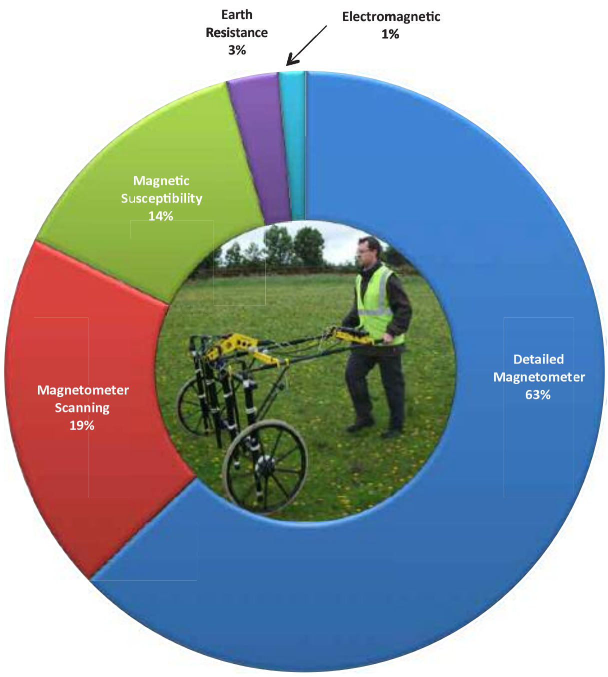
Soils that have been altered by human action contrast strongly with the natural or background soils (Clark 1996). Each geophysical technique is capable of mapping a different contrast in the properties of a soil; these contrasts can be magnetic, electrical or electromagnetic. Some archaeological features may create significant magnetic contrasts but little or no electrical contrast and vice versa; thus two or more techniques are often required to identify an archaeological site. For example, adjacent to a multiperiod site excavated at Magheraboy, Co. Sligo[1] (Danaher 2007), a previously unknown structure (probably Neolithic in date) could be clearly interpreted from a recent magnetometer survey carried out by the Research Fellowship (Illus. 2). An early medieval ringfort just a few metres from the probable Neolithic structure could not, however, be determined by the magnetometer survey owing to poor magnetic contrasts between the ringfort ditch fills and the limestone geology, although it could be seen in an earth resistance survey.

[1] NGR 168690, 335180; height 50 m OD; Excavation Reg. No. 03E0538; Excavation Director Ed Danaher; RMP No. SL014-282.

Geophysical data archive

Geophysical surveys have previously been used on commercial archaeological projects to investigate the potential for subsurface archaeology. In the past, these assessments relied on magnetometer surveys to map rapidly a variety of archaeological deposits on favourable soils. The review of archaeological geophysical surveys on national roads comprised the appraisal of 174 geophysical reports, representing a body of 'legacy data' from 2001–10. The details of each report were entered into a database, documenting how, when, what and where the geophysical data were collected, processed, interpreted and presented. The database also recorded why a geophysical survey was commissioned in the first place (Illus. 3), along with important local information such as geology, land use and the weather at the time of the assessment. Each geophysical report forms part of the on-line National Roads Authority Archaeological Geophysical Survey Database, which was launched in April 2013 (see http://field2archive.org/nra).

Geophysical surveys were conducted on 73 road schemes across the country, covering a total area of just over 1,750 hectares (4,330 acres). Of these, 733 surveys were undertaken at individual locations, including Recorded Monuments or Areas of Archaeological Potential (areas highlighted by desk-based research or field inspection that might contain significant archaeological features). Geophysical surveys for prospecting purposes also took place along the entire length of 26 road schemes, over areas of unknown archaeological potential (Illus. 4).



Illus. 3—Geophysical techniques used on NRA road schemes. An isolated ground-penetrating radar survey also accounts for <1% of the techniques used. Magnetometer scanning is a method of preliminary assessment that does not collect any data and relies on the operator's ability to interpret data in the field; under favourable conditions, scanning identified approximately 32% of subsequently excavated archaeological sites. Detailed magnetometer surveys collect large quantities of data for a detailed interpretation of the soil, allowing for a more comprehensive site analysis (University of Bradford).

The success of a geophysical survey can only be determined by verifying the results on the ground. This process involves comparing the geophysical data with the results of full excavation. Of the geophysical surveys carried out on road schemes in 2001–10, 67% were followed by subsequent ground observation in the form of excavation reports.

Geophysical data and interpretation plots are produced digitally, and many of the archaeological excavation plans were also available in a digital format. Where these two sets

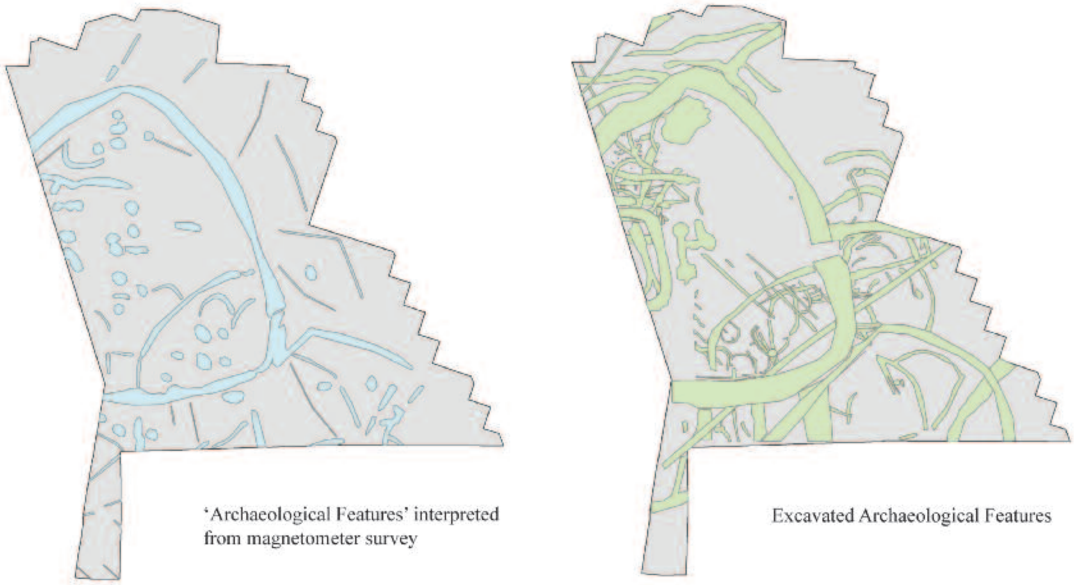
Illus. 4—Distribution of geophysical surveys carried out on the national road network. Blue dots represent isolated surveys along road schemes and red lines represent roads that have been surveyed from end to end (University of Bradford).

of data coincided for a specific archaeological site or a road scheme, the geophysical survey and archaeological excavations could be directly compared (Illus. 5) and interrogated using a Geographical Information System (GIS). The GIS was used to assess the results of geophysical surveys and to determine which factors were most important to the success or otherwise of the surveys.

Influences on successful geophysical surveys

The role of geology

One of the strongest influences on the success or otherwise of a geophysical survey is that of the parent geology. This is particularly true in the case of magnetometer surveys, which map the magnetic contrasts of the underlying soil. If the underlying geology has a very low magnetic background, such as in areas with limestone-derived soils, it can be difficult to observe any human-induced contrast representing archaeological features. On the other hand, if the geology has a very high or variable magnetic background, such as areas with granite-derived soils, anomalies caused by archaeological features can be easily obscured. The reasons for this are elaborated below.



Illus. 5—Both the archaeological interpretation of the geophysical data and the plan of excavated features were imported into a GIS, in this case for the site of Roestown 2, Co. Meath, on the M3. The GIS allows us to calculate how successful a geophysical survey was at a particular location or for a particular road scheme (University of Bradford).

The solid geology of the Republic of Ireland comprises 49% limestone, which is found mostly across the centre of the country. When a soil is burnt, it attains a thermoremanent magnetisation which is much stronger than the surrounding soils. Limestones have a very low magnetic background, which means that areas of burning, such as mounds of burnt stone, hearths, kilns and furnaces, can be easily identified from magnetometer data as strongly contrasting magnetic anomalies against the background soils. Low-contrast archaeological features, however, such as infilled ditches and pits, create anomalies that can be stronger than, or similar to, the magnetism of the background soils; in some cases these features can be difficult to interpret from magnetometer data, depending on the geology. Buried stone structures, such as houses, souterrains and churches, built from local limestone have no magnetic contrast at all, as this limestone cannot be differentiated from the parent geology in magnetometer data.

The influence of limestone on magnetometer data has been particularly detrimental to the identification of ditched enclosures in the west of Ireland. Detailed magnetometer surveys were carried out on seven road schemes in this region to prospect for previously unknown archaeological features: N6 Galway–East Ballinasloe, N6 Loughrea Bypass, N17 Galway–Tuam, N18 Oranmore–Gort, N18 Gort–Crusheen, N6 Loughrea Bypass and the N18 Ennis Bypass. Of the subsequently excavated enclosures, 16% were clearly identified by magnetometer survey as circular ditches, a further 33% were partially identified as broken and discontinuous trends of weak magnetism, and 51% were not identified at all.

A typical example is that of the Late Bronze Age hillfort at Rahally, Co. Galway.[2]

[2] NGR 166007, 225872; height 104 m OD; Excavation Reg. No. E2006; Ministerial Direction Nos A024 & A041; Excavation Director Gerry Mullins; RMP No. GA086-212.

Rahally hillfort is a multivallate enclosure that dates from the 10th century BC; it is 455 m in diameter and encloses a total area of 14.4 hectares, of which 30% was subject to archaeological excavation (see Mullins & Bermingham 2009). It comprises four widely spaced concentric ditches (0.7–4.5 m wide; 0.5–1.5 m deep) and includes three early medieval ringfort enclosures across the hilltop (two of which were excavated). The existence of Rahally hillfort was unknown prior to an intrusive archaeological excavation (Illus. 6).

Before the excavations occurred, the area of the hillfort was identified as one of several Areas of Archaeological Potential along the N6 Galway–East Ballinasloe road scheme (subsequently upgraded to motorway status as the M6). A detailed magnetometer survey (Roseveare & Roseveare 2004) was conducted, using the most sensitive instruments available at the time (a caesium magnetometer) and at a higher rate of data collection than that specified owing to the geophysicists' choice of a particular instrument. The large ditches of the hillfort were not identified by this survey owing to a number of factors: (1) the ditches contrasted very poorly with the limestone background, (2) the entire survey area was overprinted by 19th-century cultivation furrows and field systems which contrasted very strongly with the limestone background, and (3) overlying peat across the site may have impeded the physical processes that create a contrasting magnetic anomaly. With the benefit of hindsight, and the ability to directly compare geophysical data and excavated site plans, it is possible to see one of the hillfort ditches (Ditch 5) in the magnetometer data as a very weak trend beneath the overprint of cultivation furrows.

Magnetometry is generally favoured for the assessment of buried archaeological sites, as it is a rapid technique that can identify a wide range of features. It is clear from the examples above that magnetometer surveys cannot be solely relied upon to identify even the largest of archaeological sites on magnetically 'quiet' soils such as limestone. In these cases another technique is required that examines a property other than soil magnetism.

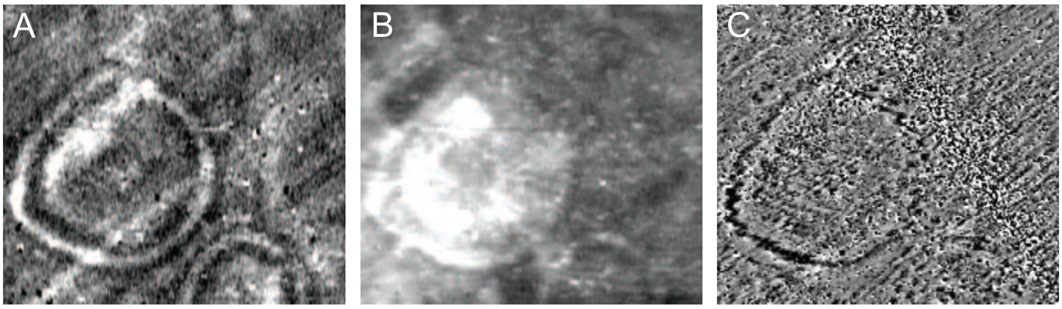
Historically, earth resistance surveys have been used for this purpose; they measure how easily an electrical charge can be passed through the ground. An electrical charge will pass more easily through moisture-retaining features, such as ditches and pits, creating an anomaly of low resistance compared to the background response. A charge will pass with greater difficulty (if at all) through stone features, such as walls and cobbling, creating anomalies of high resistance compared to the background. Earth resistance surveys cannot, however, identify areas of burning (hearths, kilns and furnaces), although a mound of burnt stone will create a high-resistance anomaly. In short, earth resistance surveys cannot identify as wide a range of features as magnetometer surveys and are comparatively much slower to carry out, as the geophysicist must place probes into the ground to obtain a measurement of resistance, whereas a magnetometer passively measures the magnetism of the earth.

Recent research (Bonsall et al., in press) has suggested that a new generation of electromagnetic instruments might be suitable for the assessment of limestone-derived soils. Electromagnetics measure two soil properties simultaneously, which can be calculated as the apparent magnetic susceptibility and apparent conductivity of the soil.

The magnetic susceptibility data demonstrate how easily a soil can become magnetised (which reflects, amongst other things, past human activity) rather than measuring the actual magnetism of a soil, as in magnetometry. Nevertheless, whilst the data are not directly comparable, they are reasonably similar. Conductivity is the numerical opposite of resistivity

Illus. 6—Top: caesium magnetometer data from Rahally hillfort, Co. Galway (black = 2 nT (nanotesla), white = -2 nT). Bottom: post-excavation aerial view of Rahally hillfort, with major enclosing features outlined. Faint traces of Ditch 5 can be seen in the magnetometer data as a low-contrast trend beneath the strongly contrasting overprint of 19th-century cultivation furrows (after Roseveare & Roseveare 2004; photo by Markus Casey).

data and indicates how easily an electrical charge can be passed through the soil. A low-resistance anomaly, such as a ditch, will appear as a high-conductance anomaly; a high-resistance anomaly, such as a buried wall, will appear as a low-conductance anomaly. By obtaining both apparent magnetic susceptibility and apparent conductivity simultaneously, two different properties are assessed over the same volume of earth. These enhance the archaeological interpretation and allow us to consider the material composition of a feature. For example, a limestone wall may have a low conductivity and a neutral magnetic susceptibility, whereas a wall comprised of fired (burnt) brick will have a low conductivity and a high magnetic susceptibility. A pit will have high readings for both conductivity and



Illus. 7—A number of surveys have been undertaken over two enclosure monuments at Kilcloghans, Co. Galway, with varying degrees of success. A: Electromagnetic apparent magnetic susceptibility survey, clearly indicating a large enclosure and half of a smaller enclosure. The remaining half was excavated as part of the N17 Tuam Bypass investigations. B: Electromagnetic apparent conductivity survey, indicating low-contrast anomalies for the enclosures. C: Magnetometer survey; the largest enclosure contrasts strongly with the background soils, but the remains of the smaller enclosure can barely be seen (University of Bradford).

magnetic susceptibility, whereas a hearth will have a low or neutral conductivity and a high magnetic susceptibility.

The latest electromagnetic instruments are also capable of obtaining readings at multiple depths. This allows a judgement to be made regarding the depth of a feature in three dimensions rather than just the size and extent in two dimensions, which is a limitation of magnetometer data.

The Research Fellowship carried out a number of surveys as part of its review of geophysical assessments on national road schemes. These new surveys demonstrated that ditched enclosures on limestone soils can be clearly and coherently mapped by electromagnetic instruments. An electromagnetic survey is faster to conduct than earth resistance but slower than magnetometer surveys, which tend to use a bank of two or more instruments simultaneously to increase the speed of data collection.

The use of an electromagnetic instrument adjacent to the N17 Tuam Bypass at Kilcloghans, Co. Galway, demonstrated the benefits of the technique. Approximately half of an early medieval ringfort enclosure was excavated at Kilcloghans[3] within the land-take of the Tuam Bypass (McKinstry 2010). A magnetometer survey in 2007 subsequently mapped the undisturbed extent of the ringfort beyond the road scheme and identified a second previously unknown and much larger ringfort. Both enclosures appeared in the data as low-contrast anomalies compared to the background. A subsequent electromagnetic survey in 2011 clearly identified the pair of enclosures in both the apparent magnetic susceptibility and apparent conductivity data (Illus. 7). The apparent magnetic susceptibility data were particularly coherent. The electromagnetic data demonstrated that ditched enclosures contrast very strongly with the limestone background. The electromagnetic instrument simultaneously returned six datasets: magnetic susceptibility and conductivity data at three different depths. During the course of our research at various sites we have found that archaeological features are visible in at least one of the six datasets obtained, creating a very strong chance of identifying previously unknown archaeological features.

[3] NGR 142990, 253830; height 46 m OD; Excavation Licence. No. 06E1139; Excavation Director Liam McKinstry; RMP Nos GA029-212, GA029-211001 & -211002.

The role of weather

Earth resistance (as well as conductivity and ground-penetrating radar) is strongly influenced by the moisture content in the ground (Al Chalabi & Rees 1962; Hesse 1966; Clark 1980). In idealised circumstances, a moisture-retaining ditch creates a strong low-resistance contrast with the background soils and a stone wall will create a strong high-resistance contrast. Seasonal changes in rainfall and heat influence earth resistance surveys by altering the electrical resistivity of the soil. During very wet weather, excess water can saturate soils to the extent that a ditch cannot be distinguished from the background soils. Furthermore, water pooling upon a stone wall will allow an electrical charge to pass through easily, creating a low-resistance anomaly instead of a 'typical' high-resistance anomaly. Conversely, in particularly hot weather, evapotranspiration may cause vegetation to remove all of the moisture in an earth-cut ditch, which may then bake hard and create a high-resistance anomaly rather than a typical low-resistance anomaly. At the same time, a high-resistance stone wall may be difficult to distinguish from the surrounding soils that have baked dry. Thus it was an important aspect of the Research Fellowship to determine how the weather can affect an earth resistance survey on Irish soils.

Over an 18-month period, seasonality studies using earth resistance surveys were carried out every four weeks at the early medieval enclosure monuments at Kilcloghans, Co. Galway. The surveys occurred over a 40 m by 40 m area encompassing segments of both enclosure ditches. The surveys used three different probe arrays or 'geometries' inserted into the ground (Illus. 8). As an electrical charge is passed between the probes, the underlying earth resistance response can be altered by changing the 'probe geometry' (i.e. the location and separation distance of the probes with respect to one another). Changing the probe

Illus. 8—Three types of probe array were used to assess the seasonal effects upon earth resistance data at Kilcloghans, Co. Galway. Top left: Wenner array at Kilmurry standing stone complex, Co. Kilkenny. Bottom left: Twin-probe array at St Otteran's graveyard, Waterford. Bottom right: Square array at Kilcloghans. Top right: a selection of earth resistance data collected monthly during 2011 (University of Bradford).

geometry influences the depth of penetration and the resolution of the archaeological feature being examined; one probe array may be better suited to detecting deep archaeological features, whereas another may clearly identify shallow features. The probe geometry can also influence practical issues such as survey speed and set-out time.

The three probe geometries used at Kilcloghans were:

- the Twin-probe array (the most frequently used array in archaeological geophysics);
- the Wenner array (which can obtain very good depth penetration);
- the Square array (which returns two sets of data simultaneously and, when mounted on an articulated platform, is a fast method of earth resistance data collection).

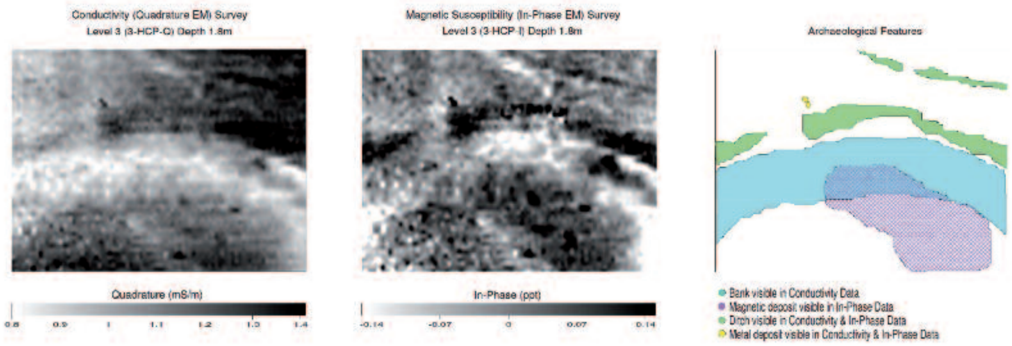
The seasonality surveys returned earth resistance data that corresponded very well with local rainfall and soil temperature records. The effect of rainfall on earth resistance data appears to be delayed by a month (e.g. high rainfall in April has a measurable effect on earth resistance data gathered in May). Seasonality surveys in Bradford, in the United Kingdom (Parkyn 2012), have charted lags of between one and four weeks, depending on the overall weather history of a site. In the case of Kilcloghans it was found that the contrasts between the ditches and the background soils were strongest during March–May. This period experienced reasonably low rainfall and gradually increasing temperatures, which ensured that enough moisture remained in the ditches to create a contrast with the background soils. The poorest contrasts occurred in June and December. In June, low rainfall and high temperatures meant a loss of moisture in the ditches owing to evapotranspiration and no significant contrast existed between the dried-out ditches and the background soils. In December, low temperature and high rainfall had the opposite effect; the ditches and the background soils were both saturated with water, with no significant contrast between them. In general, the ditched enclosures could be seen in all three earth resistance probe arrays throughout the 18-month study period; however, the optimum information from Kilcloghans was gathered in the spring, while the least optimum time was December.

Unfortunately, the seasonality study was carried out during the two wettest summers in recent meteorological history (2011–12); the hoped-for effects of a dry summer could not be easily assessed at the Kilcloghans test site. A clear example of 'seasonality' owing to changes in contrast occurred, however, in the south-east of the country during the summer of 2011 (Illus. 9). During a period of low rainfall and warm weather, very dry soils prevented the carrying out of an earth resistance survey over an enclosure at Davidstown, Co. Kilkenny, owing to an inability to insert the probes into the hard and dry ground. This example of seasonality occurred close to the surface and not within the archaeological features themselves.

An electromagnetic survey, which did not require ground contact, returned very clear and coherent apparent conductivity data, which were used as a proxy for the unobtainable earth resistance data. The conductivity survey indicated the presence of ditches and banks at the enclosure site and was regarded as a suitable alternative to the earth resistance survey in these dry conditions.

Sample density

The manner in which data are collected strongly influences the visualisation of anomalies and their subsequent interpretation. Most magnetometer surveys in Ireland are carried out



Illus. 9—An electromagnetic instrument was used to collect conductivity and magnetic susceptibility data over part of a ditched enclosure at Davidstown, Co. Kilkenny. The survey was conducted on very dry soils (a comparative earth resistance survey failed to obtain satisfactory probe contact at this site). Both the magnetic susceptibility and conductivity data identified an enclosure ditch and an internal bank (University of Bradford).

at a sample resolution of 1 m by 0.25 m (or four readings per m^2), which follows the UK model recommended by English Heritage (David et al. 2008) for general assessments using magnetometer surveys. In Europe, where many geophysical surveys are carried out for research purposes rather than commercial projects, most magnetometer data are collected at twice that rate, a high resolution of 0.5 m by 0.25 m (or eight readings per m^2), for better visualisation of low-contrast anomalies.

Technology is constantly changing and recent research has enhanced the speed at which surveys can be carried out. Some of the latest technology has been used in high-profile international research, such as the Stonehenge Hidden Landscapes Project (Gaffney et al. 2012), which collected high-resolution data (eight readings per m^2) to rapidly identify and define the extent of archaeological features. A bank of 10 magnetometer instruments towed by an all-terrain vehicle (ATV) was able to assess a single large open landscape of more than 200 hectares in just six weeks. Such areas are comparable in size to some of the longest national road schemes in Ireland. Cutting-edge technology such as that used at Stonehenge suggests that higher-resolution data can currently be gathered over large areas in significantly less time than was required in the recent past. It is important to appreciate, however, that the Irish countryside is not amenable to such rapid survey. The likelihood of using ATVs and large banks of magnetometers on Irish road schemes is small, as road corridors represent narrow survey areas that generally traverse multiple irregularly shaped and small fields, frequently over wet, boggy and sensitive landscapes, often covered in tall vegetation. For instance, a 200-hectare magnetometer survey (at four readings per m^2) of the M20 Cork–Limerick motorway required just over six months to complete because the survey equipment had to be disassembled and reassembled for each small field encountered along the road scheme.

Fieldwork carried out for the Research Fellowship at a variety of archaeological site types across Ireland found that the European method of data collection at eight readings per m^2 returned higher-quality data than the four readings per m^2 and greatly increased the chance of identifying both small-scale archaeological features and large features such as ringfort enclosures. The research also found that smaller, human-propelled, cart-mounted banks of multiple magnetometers could be a viable and affordable method of data

Illus. 10—The latest technology allows banks of magnetometers and/or other instruments to be used simultaneously, mounted on a wheeled array. Top: large arrays also incorporate a GPS for enhanced positional accuracy and, for larger landscapes (such as the Stonehenge environs), can be towed by an ATV to increase the speed of data collection. Bottom: for small, irregular fields, such as those at the Carrowmore megalithic cemetery, Co. Sligo, a smaller, human-propelled cart is satisfactory (University of Bradford).

collection on Irish road schemes (Illus. 10). Carts allow a number of magnetometers to collect data simultaneously, which could reduce fieldwork costs and increase data quality, although costs for data-processing are likely to be similar, as the same volume of data is processed.

Conclusions

Between 2001 and 2010 a variety of geophysical survey techniques were commissioned to identify archaeological sites and monuments in advance of the construction of several roads. The geophysical surveys carried out on those projects were extensive and have produced a rich dataset. Subsequent excavations have provided considerable opportunities to assess the suitability of geophysical methods to map and interpret anomalies that are often the product of subtle features. Road schemes are thus an excellent resource for studying the parameters that contribute to a successful identification of a range of features and sites.

Over the last two years, the authors have collated and critically reviewed data gathered from more than 170 geophysical surveys (and their respective excavations) to determine the optimal circumstances for the application of particular techniques. The Fellowship has also carried out new assessments to demonstrate the variations in geophysical results owing to seasonality considerations, assessed novel methods of geophysical survey and created a database of all geophysical survey reports produced for the NRA, which are available on-line.

The influence of the underlying geology is one of the most important factors to consider when commissioning a particular geophysical survey technique. Analysis of the National Roads Authority Archaeological Geophysical Survey Database has shown that magnetometer surveys are not always the most appropriate technique. New and novel technologies should be exploited wherever practical to gain further information about the underlying archaeology. The speed of data collection has increased significantly over the last 10 years, to the point that detailed high-resolution surveys are now practical and affordable for use on most road schemes.

The outcomes of the Research Fellowship will have a significant impact on the way geophysical surveys are commissioned in the future, both in Ireland and abroad. An official review document reappraising geophysical surveys carried out on Irish road schemes will help to ensure that appropriate geophysical methods and techniques are used at locations that have previously been regarded as problematic in terms of the landscape and geology. Some of the key findings regarding the influence of geology on magnetometer data can also be applied to many countries across Europe that share a similar geology. The legacy data of Irish road schemes are available as a resource for future researchers and the general public as an on-line database. The project has sought to enhance the effectiveness of geophysical methods on future NRA-funded schemes. It is likely that the next 10 years of survey on Irish road schemes will be dominated by magnetometer survey owing to its ability to identify rapidly a wide range of archaeological features; analysis of work over the previous decade, however, has revealed the need for a more nuanced approach to specific locations and archaeological site types that will benefit from a multi-method approach.

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