Where Rivers Meet

Geoarchaeology and Geophysics at Catholme – an addendum to the Geoarchaeology Report

David Jordan 1 July 2005

Part 1 - Modelling at Catholme

The Catholme geoarchaeology study had two parts:

1 a conventional geoarchaeology study which discusses the origins and properties of the archaeological and natural deposits. This was designed to help the archaeologists understand their site.

2 a study of the relationship between the geophysical properties of the site and the distribution and origin of soil components within it.

This was designed to help us understand the archaeological and physical meaning of the surface geophysical survey results gathered by Meg Watters and her team.

In practice, while Mark Hounslow and Vassil Karloukovski concentrated on the magnetic properties of the site, the principal geoarchaeological effort, under this author, went into studying the origins of electrical resistivity distributions and it is this that is discussed in greatest detail in the main geoarchaeology report while Hounslow, Karloukovski and Watters report their own results.

This addendum reports on work carried out more recently which considers how the origins of electrical resistivity behaviour at Catholme could be modelled mathematically – from soil property origin to component distributions, thence to resistivity distributions and finally to ground surface measurements.

We concentrated on resistivity because we think widening the use of techniques other than magnetometry is a priority – and resistivity survey is the obvious initial target because it is the second most common technique in use and because aggregate sites generate strong contrasts in soil drainage behaviour which probably allow equally strong electrical resistivity contrasts to develop. This is similar to the development of strong moisture stresses which cause the early maturing of cereal crops and makes air photography particularly successful over aggregate soils.

Thus electrical resistivity survey may, in principal, be particularly suitable for sites on aggregate if we can work out when and how to detect the maximum resistivity contrast between archaeological remains and the natural soil.

We may be able to do this because we can build archaeological soil resistivity distribution models, to solve this problem of predicting optimum survey conditions, on the basis a great deal of recent research in associated fields and we wanted to test the applicability of this research to archaeology and to bring it to wider attention.

Modelling resistivity

We can "model" the origins of archaeological-soil electrical resistivity (ER) behaviour by digging holes, measuring soil ER at a large number of points, reassembling these data into a forward finite-element model and observing how the outcome relates to real measurements made at the ground surface. Informative though this is, it lacks predictive power because it does not describe the underlying causes of the soil ER distribution and thus does not allow us to relate ER behaviour to what we might know about the landscape in advance – such as soil texture or moisture – from which we might predict how to best carry out survey and interpret survey results at a specific site. If we are to produce more precise *predictive* models of spatial and temporal variations in soil ER around archaeological features we need to bring together models which describe the distributions of several associated, mapped or predictable parameters so as to solve local ER equations.

Soil scientists (Rhoades et al. 1999, Corwin and Lesch. 2003, 2005, Robain et al. 2003) have given us a number of such equations which relate ER (quoted as apparent electrical conductivity, ECa – the inverse equivalent of resistivity) to the conductivity of the key soil conductance pathways.

They have then shown that the conductivity of these pathways can be predicted from simple soil properties which we might be able to predict, in turn, from soil maps and hydrological models.

These equations develop the well-known model for porous rocks proposed by Archie (Archie, 1942)

$$\rho = \rho_f \Phi^{-2}$$

where ρ is the resistivity of the rock minerals
ρ_f is the resistivity of the pore fluid
and Φ is the porosity

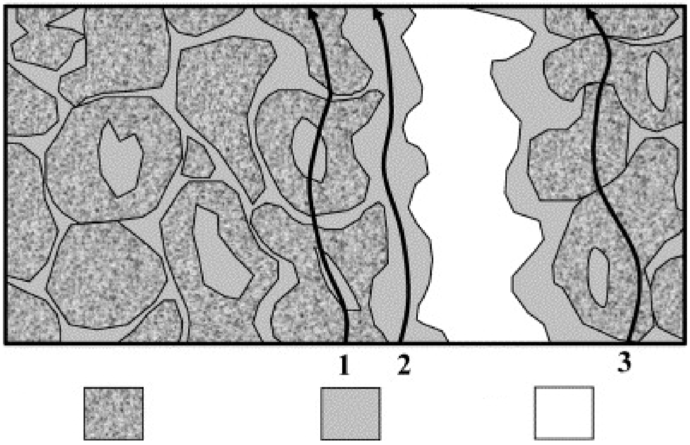
This empirical model both provides a reasonably good estimate of the bulk resistivity of simple porous media and reflects the geometry and properties of the key components. It assumes, however, a simple two-phase system of rock and electrolyte-filled pores which does not hold for most soils. It is, for the same reasons, unlikely to provide a satisfactory model of resistivity distributions in archaeological strata.

A more realistic model of soil conductivity is described by Rhoades et al (1999) based primarily on studies in the US. This describes three conductance pathways which act in parallel:

1 conductance through alternating soil particles and soil solution (pore-water containing ions in solution, forming an electrolyte) which envelopes and separates the particles. This forms a solid-liquid pathway coupled in series.

2 conductance through continuous soil solution in pores – a continuous liquid pathway.

3 conductance through or along the surface of soil particles in direct and continuous contact – a continuous solid pathway.



After Rhoades et al., 1999

In moist soils conductance is principally through the soil solution in the larger pores (pathway 2) while conductance along particle surfaces and through particles has a smaller role which becomes more significant as the soil dries. It has been shown (Rhoades et al, 1976, Shainberg et al, 1980, Bottraud and Rhoades, 1985) that surface conductance is essentially a constant for any given soil and largely independent of the soil solution, though coupled to it in series.

Conductance through solid mineral matter is minimal and can be largely ignored under most circumstances since most mineral grains are insulators. Clay minerals, on the other hand, play a crucial role in providing charged surfaces for ion exchange, delivering cations and buffering the soil solution as well as determining much of the soil physical structure (which determines the distribution of insulating fissures) and water-retention characteristics (which determines the availability and characteristics of the conductance pathways).

The geoarchaeological study at Catholme discussed the conductance pathways and considered how the differences between the parent fluvioglacial deposits and the archaeological feature fills affected the distribution of these pathways and resulted in the resistivity values which we measured. We can now consider a more formal, mathematical statement of these differences and their consequences.

This equation consists of two terms, the first describing conductivity in the solid, microporous fine matter of the soil and the second in the open pores.

$$EC_a = \left[\frac{(\theta_{ss} + \theta_{ws})^2 EC_{ws} EC_{ss}}{(\theta_{ss} EC_{ws}) + (\theta_{ws} EC_s)} \right] + \theta_{wc} EC_{wc}$$

Adapted from Rhoades et al. (1999) **Equation 1**

Where θ_{ss} is the proportional volume (cm^3cm^{-3}) of the solid, wet, microporous fine matter phase which conducts by surface charge exchange, θ_{ws} the proportional volume of water in this phase, θ_{wc} the proportional volume of water in open pores and the terms ECss, ECws and ECwc are the conductivities of the microporous phase and the pore water in this phase and in the open pores.

The equations to calculate ECa developed by Rhoades et al (1999), Corwin and Lesch (2005), Robain et al (2003) and others are based on an underlying understanding of how soils conduct electricity but they do not provide a means of calculating conductivity on their own. They must be accompanied by a further set of adjustment calculations which allow us to put figures, for specific soils, into the ECa equation. These have been derived empirically by fitting equations to the measured behaviour of very large numbers of soils.

Thus Corwin and Lesch (2003) have shown empirically that the terms for θ and EC can be derived from soil wetness, bulk density, slurry water saturation and "soil saturation extract" conductivity – the conductivity of water extracted from a soil slurry (since measuring actual pore water conductivity is often difficult and unreliable).

The important matter here is that these, in turn, can be reasonably predicted for many soils and thus it may be possible to build reliable predictive models of soil resisitivity distributions based on this type of equation, and thus to predict survey behaviour in order to decide if survey is likely to succeed. Our reasonable scepticism that such complex systems can be modelled to produce useful predictions (which require a good degree of reliability if they are to be useful) can be balanced by two considerations:

1 the empirically derived adjustments have been shown to fit soil behaviour well

2 our principal need is to predict whether a sufficient resistivity contrast will exist between a buried archaeological feature and its surroundings to be able detect the feature, given the performance of the equipment being used. Thus our model has to provide us with a reliable prediction of the relative resistivity of the feature and the natural soil around but – at least for this purpose – it need not give us the same degree of absolute accuracy in these predicted resisitivities. This simplifies matters because there are some key soil properties (such as the ionic concentration and thus the conductivity of pore water) which will often be in equilibrium between the soil and feature, and may allow us to calculate relative resistivity reliably, even where absolute calculations might be much less so.

It is interesting to note that equation 1, and the factors from which its terms may be derived, bring in considerations of soil texture, ion availability and charge exchange behaviour which show that soil resistivity is not *only* about how wet and stony the soil is as archaeological surveyors have sometimes assumed. Variations in other factors will also have a significant effect. Wetness and stone content are clearly important but ECa is primarily a measure of the content of dissolved electrolyte present in a unit-volume of soil (Rhoades et al. 1999). The availability of exchangeable ions is clearly essential here although wetness is certainly the main *seasonal* factor which causes variations in soil resistivity. This can also be modelled using such equations in order to predict when, and not just where, survey may succeed.

There are reasons to think that these equations are as valid for most archaeological deposits as they are for natural soils, although we must test this on a range of sites to see whether this is true. If we consider, for example, the structure and components of a rural, prehistoric ditch-fill such as those at Catholme, we find that it is almost entirely derived from the adjacent parent soil and that a secondary soil profile has formed in it since the site went out of use. Artefacts and ecofacts are usually present in only low concentrations and they may have little effect on the way the deposit conducts electricity. Thus, while the distribution of the soil components may well be different between the fill and the soil around (it is usually much more mixed), its behaviour can be modelled using equations like that above because the same mechanisms and pathways of conduction will occur – and thus, while the values that we put into the equation will be different, the equation itself probably does not need to be altered.

This may not hold true for some urban deposits where complex electrochemistry and distributions of strongly reducing conditions, high pore-water ion concentrations, spontaneous potentials and alternative conduction pathways (such as through masses of decaying bone or metal artefacts) can complicate our understanding of soil conductive behaviour. But resistivity survey is often a poor way to investigate such deposits in any case because their complexity is almost impossible to resolve and because there are too many other sources of interference.

If we may be able to model resistivity contrasts using the proposed model we need now to investigate the actual distribution of resisitivities in archaeological features. Predicting the detectability of features, however, requires that we also predict the distribution of the variables which affect conduction and this requires both that we measure these (and the resistivity values they cause) at a lot of sites and build a better theoretical understanding of how they come about, as we started to do at Catholme.

It is this author's experience that there are consistent and potentially predictable relationships between the fills (or components, for solid features like walls and road surfaces) of many features and the soil around them which might allow us to predict their relative resisitivity behaviour, at least approximately – and thus predict our ability to detect them. This needs to be developed and tested by gathering existing data on feature fills from excavation and survey records and by measuring actual values, in 3-dimensions on real sites and soils.

The example of Catholme is useful because, given some knowledge of the soil profile, we would probably have been able to predict that the fills in Field B would have been more mixed, finer and more water-retentive than the bulk of the parent material around, whereas the opposite would be true in Field F – as we found.

There are several other matters which we need to consider:

1 Feature-soil resistivity contrasts, and their behaviour through the year, will depend on the amount and distribution of water in the ground. Soil hydrology and its influence on the distribution of other soil components has been widely studied because it is crucial to our understanding of crop growth, catchment water flow and pollution movement.

   Thus, from a combination of empirical and theoretical studies we know quite a lot about how wet soils are in different parts of the country, how water is partitioned in the soil, how it changes through the annual cycle and the way it moves under the influences of rainfall, recharge and evapotranspiration. We also have a large body of work to draw on which describes the movement of dissolved and fine-particulate matter.

   Modelling the relative resistivity of archaeological features requires that we apply this knowledge through models which represent the texture and structure of archaeological deposits within soils – and the effect of this on their water content under different soil water states. Existing soil hydrology models provide a well-tested basis for this (Sanford, 2002).

2 Archaeologists tend to measure soil electrical resistivity by detecting potential difference, in-phase with a single input frequency around 130Hz. Multi-frequency survey (electric spectroscopy) and the comparison of resistivity response at various phase-angles has been shown to be valuable in the analysis of porous rocks (Scott and Barker, 2005) but we believe that little such work has been done in archaeology.

It may be possible to better distinguish archaeological features using other frequencies and phase-angles, or some combination. This possibility arises because the differences in pore structure and ion-surface exchange properties means that charge-relaxation (induced polarisation) behaviour, which influences quadrature conductivity and response at different frequencies, may be quite different within many archaeological features and the soil around, even where their in-phase conductivity at a single frequency is indistinguishable. New multi-frequency EM instruments may also be helpful here although the meaning of the readings they give is understood only very approximately, for soils at least.

Likewise, the electrochemical contrasts between feature fills and their surroundings may make it worth our while revisiting the use of Spontaneous Potential survey for archaeology, despite its problems, in those specific sites where we are concerned about electrochemical changes reflecting active decay through, for example, changing redox conditions.

3 the influence of electrically insulating soil macroporosity.

Many soils and archaeological feature fills, which contain a proportion of clay, develop strong pore-structures which, when the soil is dry, divide it into volumes of soil (peds) separated by gas-filled fissures. The effect of this on soil bulk resistivity is profound since it may no longer be controlled mainly by the flow of current through the solid soil but by the arrangement of ped-ped contacts. In the upper part of the soil these may be frequent and the conductive network dense but in the B horizon of even moderately clayey soils the peds can form vertically continuous columns (prisms) divided by deep fissures with infrequent bridges.

This effect is discussed briefly in the main Catholme geoarchaeology report but more recently, to explore its effect further, we measured soil resistivity within prismatic peds and across inter-ped fissures at three sites. We found that, as expected, the resistivity between peds was very much greater than within them – between two and four times as great – suggesting that our assumption was correct and that the macroporosity is having a major influence on the distribution of resistivity in the soil.

Despite the potential significance of this effect on the electrical resistance of archaeological sites it has, we think, been neither recognised nor studied by archaeological geophysicists, although it is discussed briefly by Rhoades et al. (1999) and Pellerin and Wannamaker (2005) emphasise the significance of such inhomogeneity in interpreting EM conductivity surveys for agriculture.

Studies of the propagation of fissures in soil have been carried out using electrical resistivity and this has shown the considerable effect of the fissures on the bulk soil resistivity (Samouelian et al., 2003, 2004) but the emphasis has been on monitoring fissure propagation, rather than the effect of this on resistance networks, and only on re-formed simulated bulk soil samples rather than on real soils.

This matter is significant for archaeology because it is common to find that the fills of cut archaeological features have a significantly different texture – often finer and more clayey - than the surrounding soil. Thus we may expect strong macro-porosity contrasts between fills and the soil around and these will produce equivalent electrical resistivity contrasts when the fissures open under drier, summer conditions when much resistivity survey is targeted. Our picture of soil ER has recognised that texture contrasts lead to differences in ER between fills and the soil around them.

Surveyors have often assumed, however, that finer, more clayey fills will tend to retain water better under dry conditions and thus remain less resistive. But we find sites (such as at Moreton on Lugg. Terra Nova 2002) where, as the soil dries, a clayey fill becomes divided by fissures which make it more resistive even though the peds between the fissures are less resistive than the soil outside the feature cut Such behaviour could explain some puzzling survey results, where expected behaviour is reversed, and emphasises the need to understand much more about the way soils behave geophysically through explicitly associated geoarchaeological research focussing, among other things, on deposit and soil structures.

A model of the Catholme soil resisitivity distribution

As a first step towards testing the model described by the ECa equations, at Catholme, we gathered the data which the model requires. We measured the volume of soil water, soil bulk density, paste saturation % and pore water extract conductivity in order to solve equation 1 for three representative samples and then compared this with actual measurements made in the field. We also assembled the resistivity values, measured on small volumes in excavation, into a forward finite-element model, using the program Res2DMod (Loke, 1995-2005), the outcome of which we also compared with actual survey results in the field.

We did not expect to find a very good correspondence between the model and the measurements because we only had time to analyse a small number of samples in the laboratory and because we expected that the time between the surface survey and the measurement of resisitivity in the soil beneath meant that the values of soil moisture, in particular, are likely to have changed.

Modelled and measured values of conductivity

Table 1 (below) shows the values of the key variables identified in Equation 1, measured on three Catholme samples and a contrasting silty clay from Lower Farm on the Severn Estuary Levels, calculated using the Corwin and Lesch (2003) formulae.

In summary they give a resistivity of 253Ωm for the ditch fill, 270Ωm for the silty sand fill and 521Ωm for the natural sand.

These values correspond quite well with those actually measured on site (200-350Ωm, 150-300Ωm and 400-500Ωm) and, although the estimated resistivity of the natural sand is too high, this is not surprising given the likelihood that the soil dried between the survey and sampling.

We cannot conclude that the model, derived from observations made on a wide range of soil types, necessarily fits reality at Catholme quite so well as these data suggest but we should be encouraged to test the model on other sites.

The predicted ERa of 58Ωm at Lower Farm is significantly higher than the 25Ωm measured on site but this is not surprising, given the small number of analyses and the changes which are likely to have affected the samples. Again, the similarity of the modelled and measured values is encouraging, as is the fact that they differ so significantly from those at Catholme, in the right way and, approximately, to the right extent. It is perhaps not surprising that the formulae derived empirically by Corwin and Lesch (2003) for a wide variety of soils in the US should not fit precisely the behaviour of the wet, temperate soils of the UK.

We can simulate the effect of groundwater recharge into the profile if we recalculate the ECa and ERa values assuming that nearly all of the pore-space is saturated, as in Table 2. The difference is striking. The contrast between the natural sand parent material and the two contrasting ditch fills is much lower, reflecting the greatly increased volume of the continuous-pore conductance pathway.

The effect of this would be to greatly reduce the contrast between the ditch fill and the soil around it, as we find in winter surveys when the soil is close to field capacity.

Bulk Density	Saturation Extract Conductivity (dS/m)	Total proportional volume of water (cm^3cm^{-3})	Pore Water Conductivity (dS/m)	proportional volume of water in soil conductance path (cm^3cm^{-3})	proportional volume of soil conductance path (cm^3cm^{-3})	Saturation %	EC surface conductance	proportional volume of water in continuous pores (cm^3cm^{-3})	Predicted ECa (dS/m)	Predicted ERa (Ωm)	
ρ_b	Ece	θw	Ecw	θws	θss	Sp	ECss	θwc	ECa	ERa	
					Catholme						
1.7	0.7	0.1	4.17	0.07	0.64	35	0.231	0.03	0.0192	521	1
1.7	0.7	0.16	2.98	0.11	0.64	40	0.326	0.05	0.0395	253	2
1.7	0.7	0.14	3.40	0.10	0.64	40	0.326	0.04	0.0371	270	3
					Lower Farm, Cowhill						
2.1	0.6	0.2	3.78	0.14	0.79	60	0.706	0.06	0.1731	58	4

Table 1 Calculation of expected soil conductivity and resistivity at Catholme and Cowhill based on underlying variables

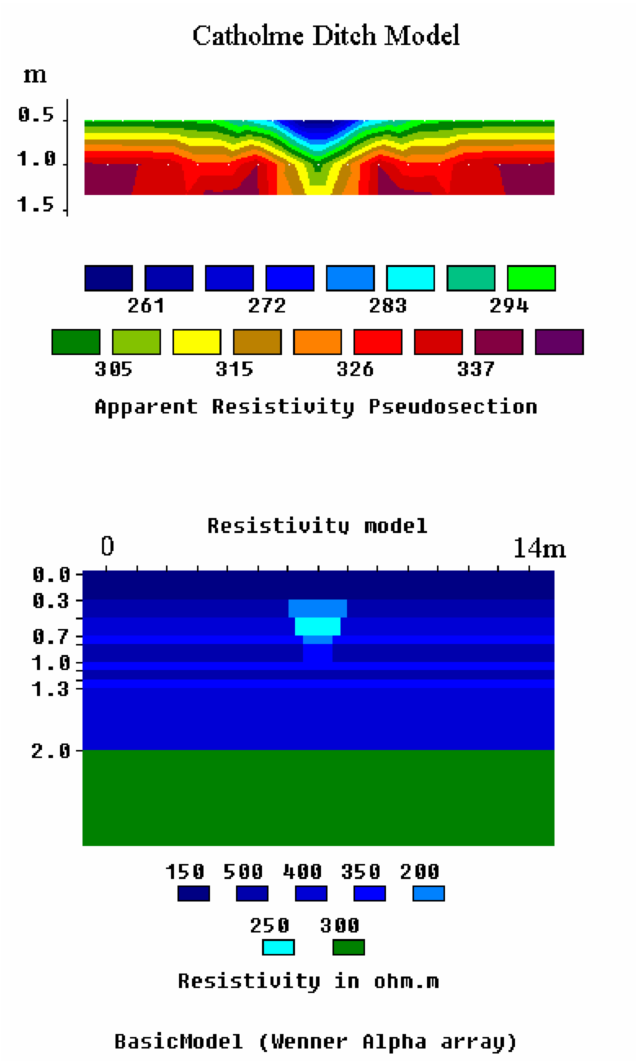
1	B2 natural sand	Catholme
2	B2 Ditch fill	Catholme
3	F1 Ditch fill	Catholme
4	Silty Clay, 50cm	Cowhill

Bulk Density	Saturation Extract Conductivity (dS/m)	Total proportional volume of water (cm^3cm^{-3})	Pore Water Conductivity (dS/m)	proportional volume of water in soil conductance path (cm^3cm^{-3})	proportional volume of soil conductance path (cm^3cm^{-3})	Saturation %	EC surface conductance	proportional volume of water in continuous pores (cm^3cm^{-3})	Predicted ECa (dS/m)	Predicted ERa (Ωm)	
ρ_b	Ece	θw	Ecw	θws	θss	Sp	ECss	θwc	ECa	ERa	
1.7	0.7	0.38	1.10	0.25	0.64	35	0.231	0.13	0.0368	271	1
1.7	0.7	0.2	2.38	0.14	0.64	40	0.326	0.06	0.0438	228	2
1.7	0.7	0.22	2.16	0.15	0.64	40	0.326	0.07	0.0457	219	3

Table 2 Calculation of expected soil conductivity and resistivity at Catholme when the soil is close to saturation – achieved by increasing θw to a value 2% less than the total porosity

The modelled resistivity section

The values of resistivity derived from resistance measurements made during the Catholme excavations can be assembled into a forward finite-element model, such as that below. From this we can determine what we might expect to have detected of the buried features and compare this with reality.



This model was calculated using Res2DMod (Loke, 1995-2005) and represents a very much simplified version of a section through the ring-ditch in field B, as shown in the Catholme geoarchaeology report. The principal simplification is the absence of variation in the distribution of resisitivities in the soil to each side of the ditch. Variations in resistivity distribution within the ditch fill, which were considerable, have also not been represented – though the model shown here represents quite well both the soil and the fill for much of the length of the ditch.

The pseudosection suggests that a surface resistivity survey carried out using a Wenner array of 1m electrode separation would have detected a variation from about 46Ω outside the ditch to about 41Ω within it (about 260 to 290Ωm). Substituting values of 230Ωm and 270Ωm for the ditch fill and the fluvioglacial parent materials to each side (but retaining the lower topsoil resistivity) suggests that a survey under very wet conditions would have detected an anomaly of 10Ω or less.

Taking modelling further

These results are encouraging but we need to build on them by fully testing the model through a more detailed and complete study of at least two contrasting sites – one sandy, one clayey. We could then generalise to other sites using soil map data and hydrological models and see whether the model, adapted if required, gives accurate predictions of resistivity behaviour within them.

To do this we need to carry out resistivity survey, including tomographic profiles, on a number of occasions over two sites (although only 1 Ha need be surveyed in each case) while monitoring soil water content and tension by piezometers and tensiometers.

Test pits within the sites must then be excavated very rapidly (by machine, to avoid drying), sections cleaned by hand with care, resisitivity profiles recorded in section and then sampled in a grid through and to each side of one or two archaeological features. The samples will then be analysed for bulk density, water content, water release behaviour, and soil solution conductivity to provide the variables needed to solve Equation 1 for each volume of the soil.

The outcomes of this would then be compared with the values measured in the field and the grid of predicted resistivity values assembled into a forward model, which would then be compared with the surface survey and tomographic soil resistivity data.

Thin section micromorphological analyses would also be carried out, as at Catholme, in order to understand the origins of the observed resistivity behaviour in the structure of each sample and thus in the distribution of the conductive pathways through the soil and archaeological features.

This detailed study would be followed by a more extensive study in which the key variables (bulk density, water content and soil solution conductivity) will be predicted, for known sites on which survey is anticipated, from soil map and hydrological model data and the prediction compared with survey results.

Similar parallel studies of soil magnetic and dielectric behaviour could usefully run in parallel, using the same sites, excavations and thin-sections, although supplemented by such other analyses as they would require. In this way we may be able to capitalise further on the resisitivity study.

Conclusions

This document describes some first steps towards modelling resistivity survey outcomes based on our study at Catholme – although it does so only very partially and based on only a very limited amount of data. The results are encouraging but need to be followed up by much further work.

What this addendum does not do is relate the properties of the soils and features at Catholme more closely to their geophysical behaviours, although there is a great deal of scope for this to be done within the context of a future project, building on the work reported in the main Catholme geoarchaeology report.

A more detailed and extensive geoarchaeological study and a closer study of the soil physical structure, mineralogy and chemistry at two physically contrasting sites, could be very usefully be combined with a more detailed study of geophysical property distributions with the aim of relating the origins of the archaeological remains to their geophysical representations.

Such a future study could also consider the distribution of soil magnetic and dielectric properties. This Catholme study suggests that it will be worthwhile and, while the challenges of modelling these other geophysical behaviours are quite different, there is a great deal to be gained from pooling the resources of three associated studies of this kind to look at a small number of sites in great detail.

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