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THE DISCOVERY OF AN ANGLO-SAXON *GRUBENHAUS* AT NEW BEWICK, NORTHERN UK USING ELECTRICAL SURVEYING AND PREDICTIVE DECONVOLUTION*

P. W. J. GLOVER†

Département de géologie et de génie géologique, Faculté des sciences et de génie, Université Laval, Sainte-Foy, Québec, Canada, G1V 0A6

Twin-probe and 33-fold multiplexed Wenner electrical resistivity surveys were carried out at New Bewick, northern UK to examine the extent of crop marks and potential Grubenhäuser (sunken-featured buildings, sunken-floored buildings or SFBs). The twin-probe method was faster, but provided data with a lower spatial resolution. However, the Wenner array data was affected by characteristic 'M'- or 'W'-shaped responses over filled excavations such as those expected to represent a Grubenhaus. The raw Wenner array data have been analysed using one-dimensional and two-dimensional predictive deconvolution in order to remove these artefacts. The deconvolution was carried out using an inverse matrix element method. The filtered results indicate the presence of anomalies consistent with the presence of at least six Grubenhäuser and other anomalies concurrent with the linear crop-marks. One particular anomaly measured about 5 m by 4 m and with a pit depth of 0.6 m below 0.3 m of topsoil. This anomaly was subsequently excavated and a Grubenhaus was discovered at the site. The excavated Grubenhaus measured 4.7 m by 3.9 m with a pit depth of 0.5 m below the base of the topsoil, confirming the electrical survey results.

KEYWORDS: RESISTIVITY, NEW BEWICK, SUNKEN-FEATURED BUILDING, DIGITAL FILTERING, DECONVOLUTION, GRUBENHAUS, WENNER, TWIN-PROBE

INTRODUCTION

Earth resistivity surveys were carried out on a site with archaeological potential in northern England in the summer of 1984 but the results were not published other than partially in an MSc thesis Glover (1985). The purpose of this paper is to publish the data fully, together with new digital filtering techniques that have been used to analyse the data.

Three different types of resistivity meter and two different survey types were used. There were three main archaeological objectives and two technical objectives associated with the instrumentation and survey method.

The primary archaeological objective was to determine the extent to which large numbers of crop marks seen on aerial photographs were due to archaeological features. One particular type of crop mark, appearing as small, light-coloured, sub-rectangular areas, was thought to represent the sites of *Grubenhäuser* from the Anglo-Saxon period. These buildings are common in mainland Europe and are well documented in settlements of the Anglo-Saxon period in southern Britain (e.g., Marshall and Marshall 1993; Karkov 1999; James 2002; Tipper 2004) and northern Europe (Welch 1992; Guélat and Federici-Schenardi 1999; Hamerow 2002). However, at the time of the survey none had been documented north of the Vale of

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†Corresponding author: email paglover@ggl.ulaval.ca

Pickering in North Yorkshire (Cramp 1983) except for some atypical examples at Yeavering, Northumberland (Hope-Taylor 1977; Karkov 1999) and possible sites identified by aerial photography at Sprouston and Milfield (St. Joseph 1982; Karkov 1999).

There are now a large number of *Grubenhäuser* sites, defined by their distinctive crop marks [e.g., Mucking, Essex (Clark 1993), and Radley Barrow Hills, Oxfordshire (Chambers and McAdam 2007)], which have been subsequently excavated. It is now possible to be quite confident that the distinctive crop marks on many other sites (not investigated by excavation) are also evidence of *Grubenhäuser*. Furthermore, many *Grubenhäuser* have been identified in the Vale of Pickering in recent years by their distinctive geophysical anomalies (principally by fluxgate gradiometry), and several sites have subsequently been excavated (Tipper 2004). The similarity of some crop marks at New Bewick to those representing the confirmed *Grubenhaus* at Yeavering indicated strongly that the New Bewick crop marks also represented *Grubenhäuser*.

The second archaeological objective was to investigate numerous linear features that are also found on the aerial photographs, which were thought to be enclosures, boundary ditches or pit alignments. The site is badly affected by periglacial frost-cracking which often provides patterns that give the impression of being anthropogenic. Hence, the third archaeological objective was to examine the extent to which resistivity measurements could distinguish between the periglacial frost cracks and the linear archaeological features.

Both technical objectives were related to the improvement of archaeometric resistivity measurements. The first was to carry out a comparison between the twin probe method and the Wenner method in the search for buried *Grubenhäuser* (Gaffney 2008). It was expected that the Wenner method would provide a higher resolution but be affected by a characteristic signal shape that depends upon the properties of the buried feature. A second objective was to develop and test a method for removing such artefacts in a focused manner. That is to say, with a signal analysis method that isolates the target feature from the background resistivity values.

Electrical resistivity was chosen as a tool for investigation as it could be used to probe the ground for archaeological remains and natural discontinuities swiftly, relatively easily, and without recourse to laborious, expensive and invasive excavations, as reviewed by David (1994).

The most common array used in archaeological prospecting is undoubtedly the twin-probe configuration (Gaffney 2008). Its success arises from two advantages: first, the speed with which it can be used to survey large areas of ground; and, second, that it produces a single response; either a peak for high resistance, or a trough for low resistance, without transient behaviour (Gaffney *et al.* 1991; Gaffney 2008) but with a relatively low resolution compared to certain other probe arrangements. We used a standard RM15 twin-probe instrument.

The Wenner array was probably the most common array before it was supplanted by the twin-probe array (Garrison 2003). Its use requires much more time than the twin-probe array because it requires the planting of four electrodes for each measured point, compared with two electrodes for the twin-probe array; however, some time may be saved by planting a set of 33 electrodes at one time and using a multiplexer to make 30 measurements in swift succession before the whole line is moved forward once again (Mojica *et al.* 2006). The results of the Wenner array are affected by a characteristically shaped response if the array crosses a buried feature perpendicularly, and the shape of the response depends upon the size and resistivity of the buried feature (Telford *et al.* 1990; Garrison 2003). However, it can provide results which have a greater resolution than the twin-probe because the current is injected into the ground locally, rather than remotely (usually greater than 30 m away). A large (31-electrode) multiplexed Wenner array was used to measure data in 30 m × 30 m blocks.

It should also be noted that fluxgate gradiometry is generally far quicker, and generally (but not always) produces an excellent result with the identification of *Grubenhäuser* (although it was not quite so effective when the data presented in this work were obtained). It is probably the method of choice at present (Schmidt 2007).

THE SURVEY SITE

The New Bewick site (UK Grid reference NU 061 206) occupies a field 1 km west of New Bewick farm in Northumberland, UK. It is situated on the edge of a plateau of glacial sands about 30 m above the river Breamish/Till which is approximately 200 m to the northeast. The topsoil is light and sandy. The elevation of the site is 94 m above the present mean sea level. Figure 1 and Figure 2 show the position of the site and its relationship to other archaeological and topographic features. The most important archaeological feature in the vicinity is the Iron Age hill fort of Old Bewick (UK Grid reference NU 075 215) and its cup and ring-marked rocks (Bradley 1997; Beckensall 2002), which is 1.8 km to the northeast.

The closest Anglo-Saxon remains to the site are all extremely important Anglo-Saxon sites in themselves. They comprise the Anglian palace settlement of Milfield (Hope-Taylor 1977; Gates and O'Brien 1988), the settlements at Sprouston (St. Joseph 1982) and Thirlings (O'Brien and Miket 1991), and the seventh century royal settlement at Yeavering (e.g., Hope-Taylor 1977; Karkov 1999), which are all to be found approximately 16 km to the northwest, and also occupy sites near to the River Till, or its tributary, the River Glen. Hope-Taylor's excavations of the royal palace or *villa regia* at Yeavering produced evidence of substantial timber halls, and a single *Grubenhaus*, at the highest level of society (Hope-Taylor 1977).

Figure 3 shows one view of the crop marks at the site. The diffuse, light-coloured patches are large areas of aeolian deposits which overlie all other crop marks. There is evidence of recent agriculture in the form of tractor tram-lines, drainage patterns and the traces of an old field boundary. Many of the other light, linear crop marks with a seemingly random distribution are caused by periglacial frost-cracking. The major archaeological features are also shown diagrammatically on both Figures 2 and 3. The most prominent is a thick, linear, light-coloured 'L'-shaped feature that has since been excavated to reveal the remains of a boundary ditch (Gates and O'Brien 1988). One of the arms of the 'L'-shaped ditch continues towards the south for approximately 200 m before turning abruptly towards the west for 120 m and then turning towards the northwest until it leaves the present-day field. It has an intermittent quality and has been attributed to a linear pit alignment (Gates and O'Brien 1988). At least 12 solid, sub-rectangular marks distributed between the enclosures have been postulated as *Grubenhäuser* by comparison with similar marks at Milfield and Thirlings, but never confirmed by excavation.

THE SURVEY METHODS

The area of the survey is shown in Figure 2, which also shows a satellite photograph of the site. The topsoil at the site is light and sandy, and was planted with winter wheat which was several centimetres high at the time of the Wenner survey and about 6 cm high at the time of the twin-probe survey. The Wenner survey took place in May 1984 after a period of relatively dry weather, while the twin-probe survey required a weekend in June following a more extended period of dry weather.

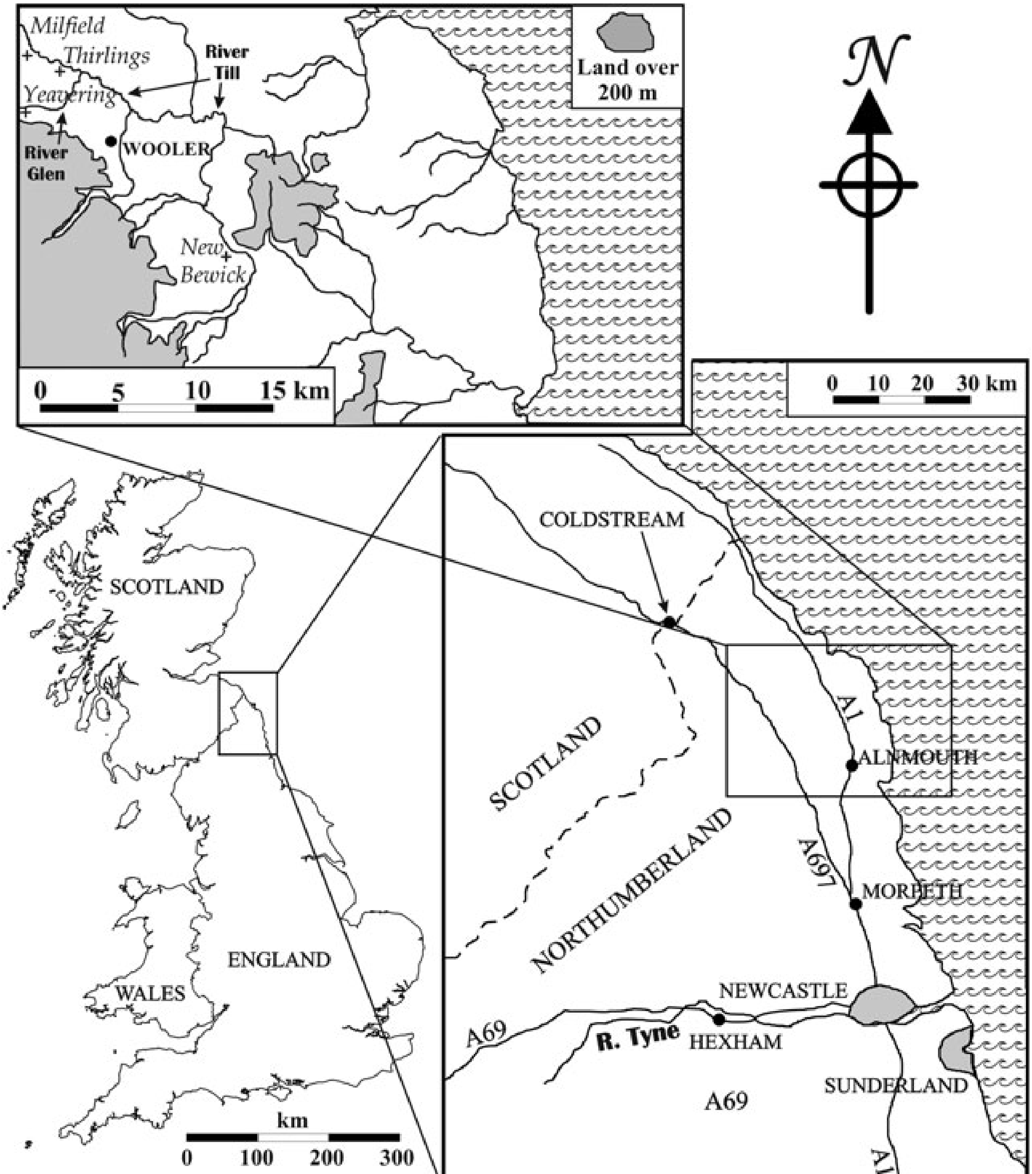

Figure 1 *The general location of the New Bewick site.*

The multiplexed Wenner survey covered an area of 10 140 m^2 (1.014 ha). The data were acquired in blocks of 30 m by 30 m, which were pre-surveyed and marked with lines. Each block consisted of 31 lines that were 1 m apart and perpendicular to the direction 009°. Each line consisted of 30 measurement points 1 m apart by multiplexing 33 electrodes into 4 electrodes using a switch-box and a multi-core cable. Each electrode was planted to a depth of 20 cm with a 1 m spacing. Hence, a 1 m spacing Wenner configuration was applied at each

Figure 2 *The New Bewick site: satellite photograph (©Google Earth), crop marks and location of the surveys.*

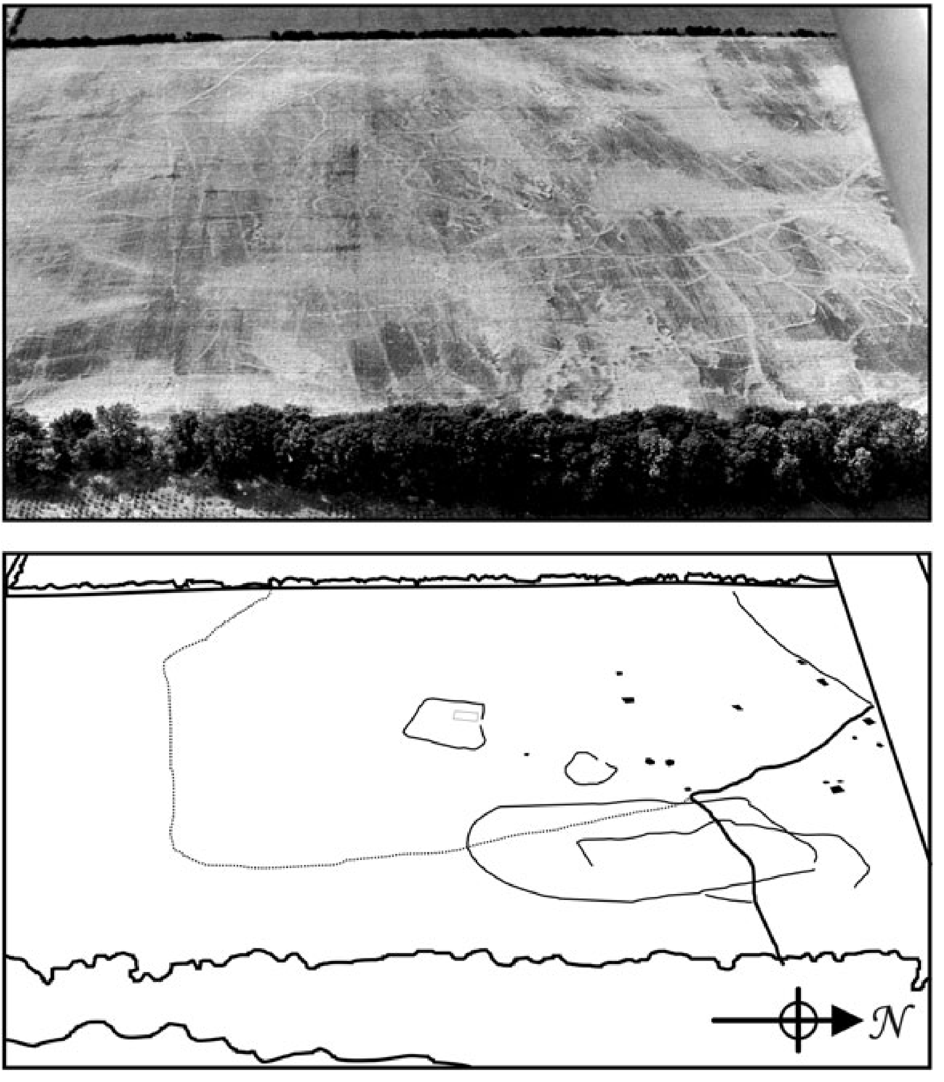

Figure 3 *Aerial photograph of the site and an interpretation of the main crop marks. [Aerial photograph from the Museum of Antiquities of the University and the Society of Antiquaries of Newcastle upon Tyne (A/064486/36), ©Prof. Norman McCord.]*

grid location. The experimental arrangement is shown in Figure 4. Measurements were made only in one direction (i.e., multiplexed lines perpendicular to the direction 009° rather than two sets, one perpendicular to 009° and the other to 099°) because of the length of time required to carry out this type of survey. The Wenner survey required two people for eight full field days during good weather, of which 1 day was needed to survey and lay out the site.

Two resistivity meters were used. The first was a commercially available ABEM Mk II Terrameter. The second was a resistivity meter specifically designed for archaeological surveying which was built in the Department of Geophysics and Planetary Physics of the University of

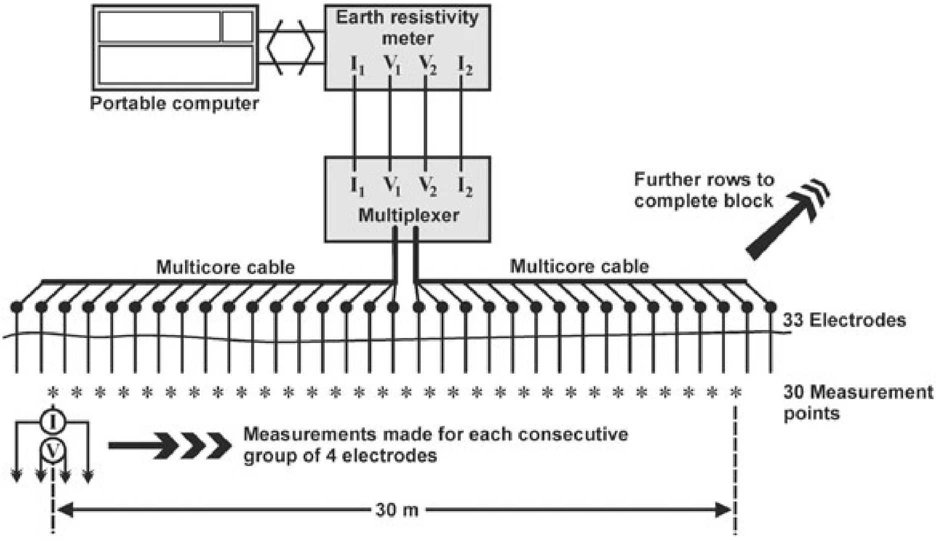

Figure 4 *The measurement arrangement for the Wenner resistivity survey.*

Newcastle upon Tyne by the author (Glover 1985). The arithmetic means of five measurements were taken at each grid position. The data were transferred to a portable computer either by hand (for the ABEM instrument) or automatically by RS-232 link (for the in-house machine). All the data were compiled and normalized. In particular, the blocks were stitched together digitally using a 4 m interpolation. However, the peripheral resistivity values of all blocks were very similar to those in the adjoining blocks in all cases. Digital filtering techniques were used subsequently to remove the characteristic response of a Wenner configuration, as described in the Results section.

The twin-probe survey covered an area of 12 100 m^2 (1.21 ha). The entire survey area of 110 m × 110 m was pre-surveyed and marked with fluorescent lines and measurement tapes. The data were then acquired in strips in the direction 009°, walking back and forth in a serpentine fashion while planting the twin-probe head every 1 m to a depth of 20 cm and making a stack of five electrical measurements, until the whole block was covered. The whole procedure was then repeated in the 099° direction. The full survey required two people for seven full field days during good weather (it would have been about 5 days for a survey in one direction only). At least two people are required to lay out the survey grid, which required 1 day, and although only one person is required to operate the instrument at any one time, two people provides relief for the monotony and physical effort of repetitively planting the electrodes.

A standard Geoscan Research RM15 was used to make the twin-probe type measurements. Once again the arithmetic means of five measurements were taken at each grid position. All the data were compiled and normalized. In particular, the data from each measurement set were compared for consistency and operator-induced errors. Here we define a measurement set as the data that are taken consecutively without a significant break for food or refreshments or change in operator.

A comparison of the time taken to carry out each type of survey is shown in Table 1. About 1 day was required to survey the site in both cases, and a similar amount of time was used to make measurements (8 days for the Wenner method and 7 days for the twin-probe method).

Table 1 *Comparison of the time required to undertake each survey*

Method	*Multiplexed Wenner*	*Twin probe*
Area covered (ha)	1.01	1.21
Measurement points	10 140	24 200
Stacking	5	5
Number of directions	1	2
Number of meters used	2	1
Number of staff	2	2
Time for surveying (days)	1	1
Time for measurements (days)	8	7
Weather	Sunny, dry, 20% clouds, light wind	Sunny, dry, 30% clouds, moderate wind

However, the twin probe survey area was larger than that of the Wenner survey area (1.21 ha compared with 1.01 ha), and there were twice as many measurements made because the measurements were made in two directions for the twin-probe survey and only in one direction for the Wenner survey. In mitigation, however, it should be said that the Wenner survey made measurements with two types of electrical resistance meter at each point, which also doubles the number of measurements made (although not the number of electrodes planted!). Overall, the twin-probe method is faster, but not overwhelmingly so. The speed of the Wenner measurements was due in part to the automated multiplexer used to make the measurements.

RESULTS

Initial results

Figure 5 shows the variation of the apparent resistivity from each survey in the form of a variable colour map. The apparent resistivity varied from a minimum of 240 Ω.m to a maximum apparent resistivity of 1118 Ω.m for the Wenner survey and from 597 Ω.m to 1300 Ω.m for the twin-probe survey, representing excellent resistivity contrast. In the case of the Wenner survey, the raw data exhibit a striping perpendicular to the resistivity measurement lines, which is an artefact typical of this type of survey if it is carried out only in one direction. The twin-probe type survey is not subject to the striping artefact. It is clear from Figure 5 that the Wenner survey, although affected by the characteristic signature, provides the higher spatial resolution of the two methods.

The data show a number of possible archaeological features. A separate interpretation has been done for each of the surveys, as shown as Figure 5 (c) and Figure 5 (d). A comparison of the data from each survey and their interpretations shows that although the Wenner survey was able to delineate anomalies with a greater precision than the twin-probe survey, most anomalies can be picked out in both surveys, but are sometimes not the same size. The twin-probe results conflate anomalies G and H, and it also includes two extra anomalies (K and L) and a possible unlabelled anomaly near the westernmost boundary of the survey area (Fig. 5 (d)), which are outside the area of the Wenner survey.

The linear features that were interpreted as ditches or post-hole alignments on the aerial photographs are visible in the electrical resistivity data (labelled a, b and c in Fig. 5 (c)). It is

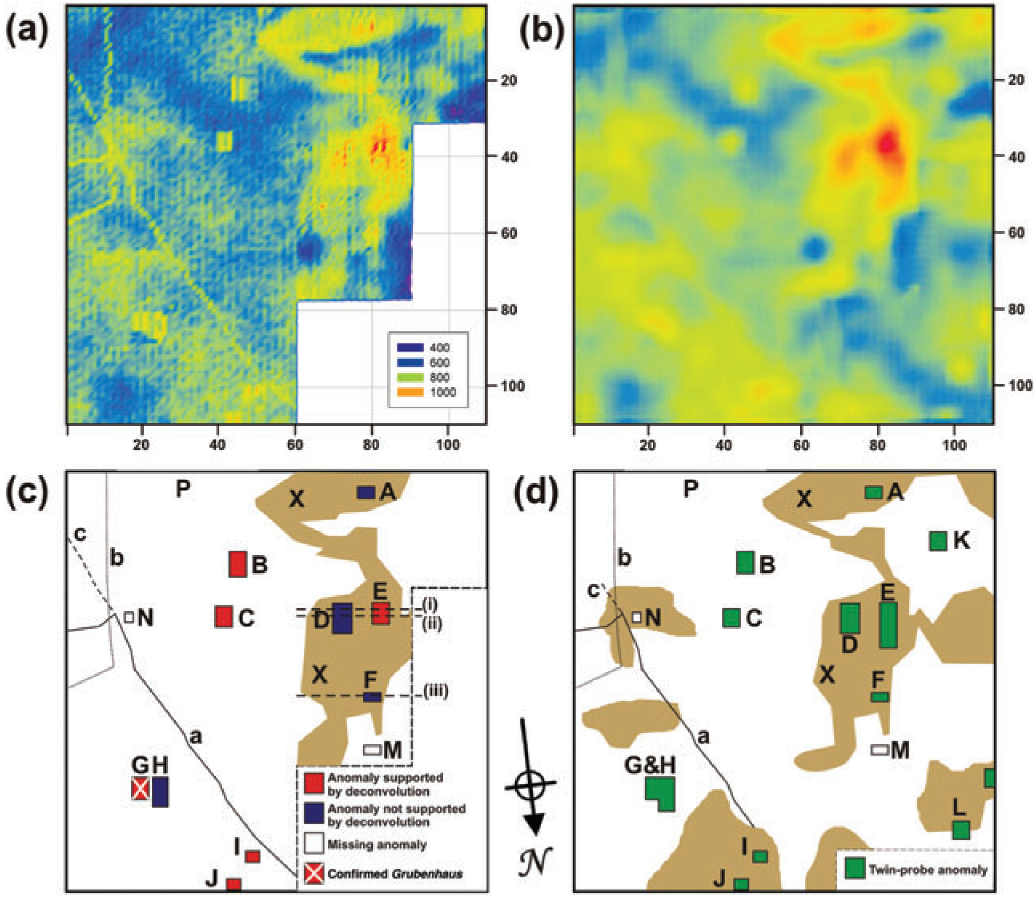

Figure 5 *Apparent resistivity results and initial interpretation for each survey. (a) Apparent resistivity results from the Wenner array survey before digital filtering, together with (c) the initial interpretation of recognized features and the position of the profiles (i) to (iii) that are shown in Figure 9. (b) Apparent resistivity results from the twin-probe array survey, together with (d) the initial interpretation of recognized features.*

fortunate that the features that give rise to these anomalies are sufficiently large or represent a sufficient resistivity contrast. Normally, small ditches and post-hole alignments do not exhibit a sufficiently large anomaly to be detected with a 1 m array. Here, the Wenner array picks out the linear features as a broken line that is well defined, while the twin-proble survey shows an unbroken, but more diffuse anomaly.

Linear feature a shown in Figure 5 (c) was excavated after we had carried out resistivity surveying and it was shown to represent a ditch 0.9 m deep and 2.3 m wide that was filled with sandy silts that had accumulated gradually (Gates and O'Brien 1988; Glover in press). The qualities of the other linear features indicate that they, too, are ditches of similar dimensions.

In the Wenner array data there are 10 small, high-resistivity anomalies which are sub-rectangular and have the characteristic 'M'-shaped response from the Wenner array. These anomalies are labelled A to J in Figure 5 (c). Each anomaly may represent the remains of buildings; however, the Wenner array signature confuses their representation in the raw data.

The digital deconvolution, described subsequently, has shown that anomalies B, C, E, G, I, J are consistent with the presence of a *Grubenhaus* while anomalies A, D, F and H are not. It should be noted that those anomalies that are not consistent with the presence of a *Grubenhaus* may represent the remains of other types of structure. Not all of the anomalies shown up by the Wenner array data would be picked out on the twin-probe data because the resistivity highs are too diffuse. Anomalies F, G, H, I and J would not be noticed in an interpretation of the twin-probe data carried out separately. However, a joint interpretation of the two sets of data shows that the twin-probe data are consistent with the Wenner array data.

Locations M and N show crop marks that are similar to those that represent *Grubenhäuser* (Figs 2 and 3), but for which there is no evidence in the raw apparent resistivity data from either method. Similarly, there is crop-mark evidence for part of an enclosure at location P, but no indication in either set of resistivity data.

Additionally, there is a complex, diffuse, high-resistivity area to the west of the survey area, which surrounds some of the other anomalies (shaded in Fig. 5 (c) and Fig. 5 (d)). This area is well represented in the data from both types of survey. There is no clear initial interpretation for this anomaly, although it has been associated with the compaction of the subsurface due to the passage of people.

Resistivity array signatures

The apparent resistivity measurements are striped perpendicular to each measurement line. This is an artefact of the Wenner method. Traversing a lateral discontinuity of soil resistivity with a Wenner array produces two separate signatures, depending on whether the array is traversed across the discontinuity longitudinally or transversely. If the array is traversed across the discontinuity transversely (i.e., all the electrodes cross the strike of the discontinuity at the same time), then the apparent resistivity varies smoothly from the resistivity on one side of the discontinuity to that on the other side. However, if the array is traversed across the discontinuity longitudinally (i.e., perpendicularly to the strike of the discontinuity, such that electrodes cross the discontinuity one at a time), there are perturbations in the transition due to the disturbance of the potential field by the discontinuity. The imposition of topsoil modifies the absolute apparent resistivities that are measured, but leaves the shape of each signature essentially unaltered.

A filled-in pit representing a *Grubenhaus* consists of two vertical discontinuities. If the filling material is of higher resistivity than the surrounding material, the sum of the two longitudinal signatures forms a characteristic 'M'-shape, while the two transverse signatures form a smooth and broad maximum (Fig. 6). If the filling material is of lower resistivity than the surrounding material, the sum of the two longitudinal signatures forms a characteritic 'W'-shape, while the two transverse signatures form a smooth and broad minimum.

The shape of the signatures depends upon the difference between the two soil resistivities, the physical dimensions of the in-filled pit and the array spacing. An array spacing of 1 m is sufficient to allow the method to penetrate sufficiently into the soil to recognize the buried pit, i.e., between 0.3 and 1 m, with a 1 m lateral resolution. Unfortunately, this spacing also produces the 'M'- and 'W'-shaped signatures when crossing buried structures between 3 and 5 m wide, which can obscure the feature in the data. Fortunately, the signature may be removed from the data by using digital filtering if the dimensions of the buried feature are known.

It is extremely important to be able to predict the signature function accurately. One method of doing this would involve the creation and measurement of a full-size or scaled physical model. Instead, we have carried out numerical modelling in 3D using the finite element

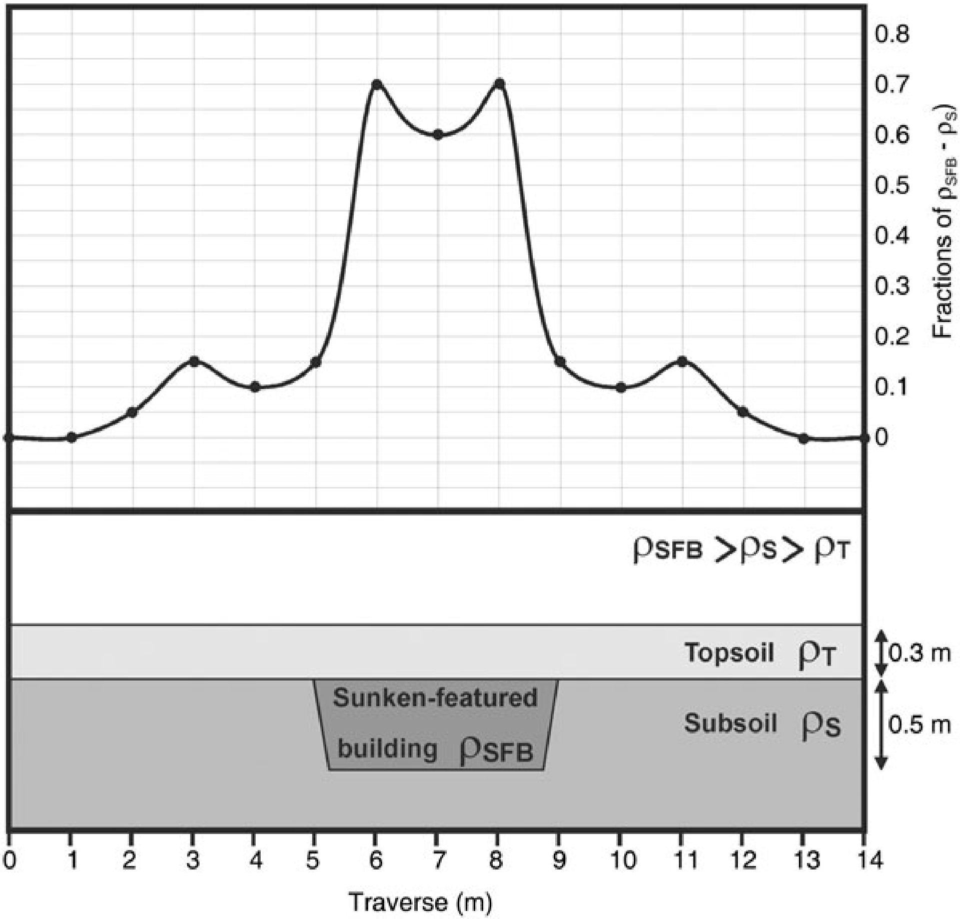

Figure 6 *A 2D resistivity/depth model (signature function) for a* Grubenhaus *and the apparent electrical resistivity response that it generates. The dimensions used for this example are those measured by Gates and O'Brien (1988) during their excavation of a* Grubenhaus *at the New Bewick site.*

package FEMLab. The software was used to solve the partial differential equations representing the electrical problem in 3D over a semi-infinite 2D model of a buried feature with variable width, depth and depth of topsoil. This modelling provided several signature functions for features of different widths, depths and geometries.

Digital filtering

Signatures such as those from the Wenner configuration can be removed from the apparent resistivity data using the process of predictive deconvolution (Kanasewitch 1975). The geological application of such a procedure is rarely satisfactory because the geometry of the target feature is complex and unknown, and must be predicted. Consequently, there are an infinite number of possible solutions. However, the procedure may be applied successfully and reliably in the search for archaeological remains because they are more predictable. It is sufficient to know the physical dimensions of the *Grubenhaus* (width and depth) to be able to calculate its electrical resistivity signature. It should be noted that it is not necessary to know the apparent resistivities of the topsoil, the fill or the surrounding soil, nor is it necessary to know the thickness of the topsoil, providing it is constant. Figure 6 shows an example response for a filled *Grubenhaus* of width 4 m, with a depth of 0.5 m and a topsoil thickness of 0.3 m.

Once the electrical signature has been found, it may be removed from the data by the process of deconvolution. If the predicted dimensions match those of the buried structure, the resulting data will represent the position, dimensions and depth of the target feature more accurately than the raw data. However, if the predicted dimensions do not match those of the buried structure, the deconvolution process will tend to smooth the data, removing useful information.

For example, the application of the signature shown in Figure 6 to a set of data containing a line of raised values representing, for example, a narrow (1 m wide) filled ditch will result in the line of raised values being transformed into a line of values slightly greater than those of the background resistivity, spread over a width of at least 4 m, and hence most probably overlooked in the interpretation. Hence, when the filtered results are interpreted, it is important for the scientist to know and take into consideration what filtering has been applied.

A modified form of the predictive deconvolution method described by Tsokas *et al.* (1991) has been used. The deconvolution procedure, which depends upon matrix operators, is relatively mathematically complex and need not be described in detail in this contribution.

The Wenner signature can be described by a discrete one-dimensional signature function $R(x)$ as shown in the top panel of Figure 7. The position and strength of each sub-surface feature that gives rise to each signature can be described by a discrete strength function $D(x)$ as shown in the middle panel of Figure 7. Convolution is the summation of each element of the signature matrix at each position and at each strength defined by the strength function for each of its elements. If the discrete signature matrix $R(x)$ is convolved with the discrete strength function $D(x)$, the result is a matrix that contains the values that would be measured in the field, which we will call the field observation $T(x)$, according to the equation $T(x) = D(x) * R(x)$, where * is the convolution operator. This process is shown diagrammatically in Figure 7, where the top panel $R(x)$ shows the response of the earth to a buried feature with given dimensions, and the middle panel shows the discrete strength function $D(x)$, which represents the location of five buried structures, each with a different strength; three positive and two negative. In the context of the problem, the size of the peaks that comprise the discrete strength function $D(x)$ represent the difference between the apparent resistivity of the filling material and that of the surrounding medium; a positive strength indicates that the apparent-resistivity of the filling material is greater than that of the surrounding medium, and a negative strength represents the opposite. It is clear that the $R(x)$ function contains all of the dimensional information (width, length, depth, depth of topsoil), while the $D(x)$ function contains the location and relative resistivity information in the model. The bottom panel shows what would be the resulting field observation.

The digital filtering of the archaeological data requires the inverse process; that of deconvolution. In this process the field observation $T(x)$ is known; it is the measured data. We require to calculate the discrete strength function $D(x)$ from the field observation by deconvolving it with our prediction of the signature function $R(x)$. The simplest way of doing this is to convolve the field observation $T(x)$ with the inverse of the predicted signature function $\bar{R}(x)$, according to $D(x) = T(x) * \bar{R}(x)$, where $R * \bar{R} = \theta$ and θ is the identity matrix. The details are given in Tsokas *et al.* (1991) and Kanasewitch (1975).

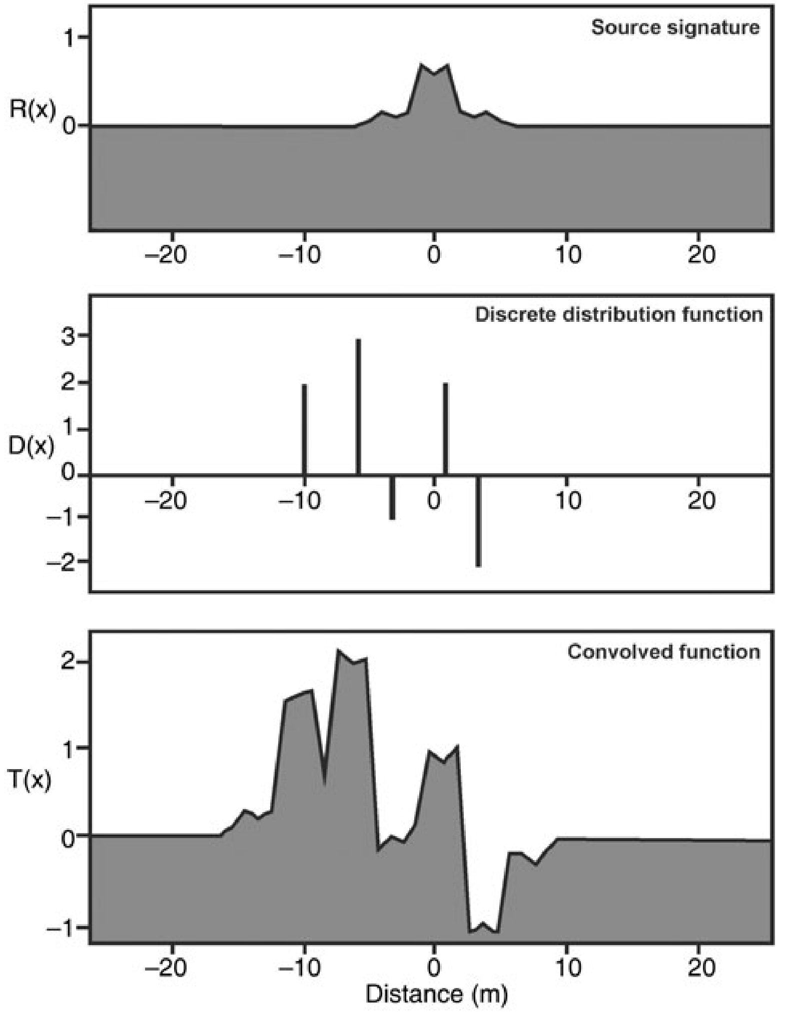

Figure 7 *The process of convolution: The source signature* R(x) *describes the response of the earth to the presence of a single feature. The discrete strength function* D(x) *describes the position of each feature along a profile and the strength of each feature. When* R(x) *is convolved with* D(x) *the result is the actual measurement* T(x). *In this example, the source signature for a buried* Grubenhaus *given in Figure 6 is convolved with an arbitrary discrete strength distribution to give a synthetic measurement. The process of deconvolution is the inverse of this process.*

It is possible to create an inverse signature function $\overline{R}_\delta(x)$ which produces a single spike (delta function) at the centre of the deconvolved feature on each profile, with an amplitude that describes the discrepancy between the resistivities of the filling material and that of the surrounding subsoil. Figure 8 shows this for two variations of the process: one which we will term delta-function deconvolution and the other which we will label boxcar-function deconvolution. The delta-function deconvolution provides the location and intensity of any anomaly, but not its extent, whereas the boxcar-function deconvolution provides the location, intensity and extent of the anomaly.

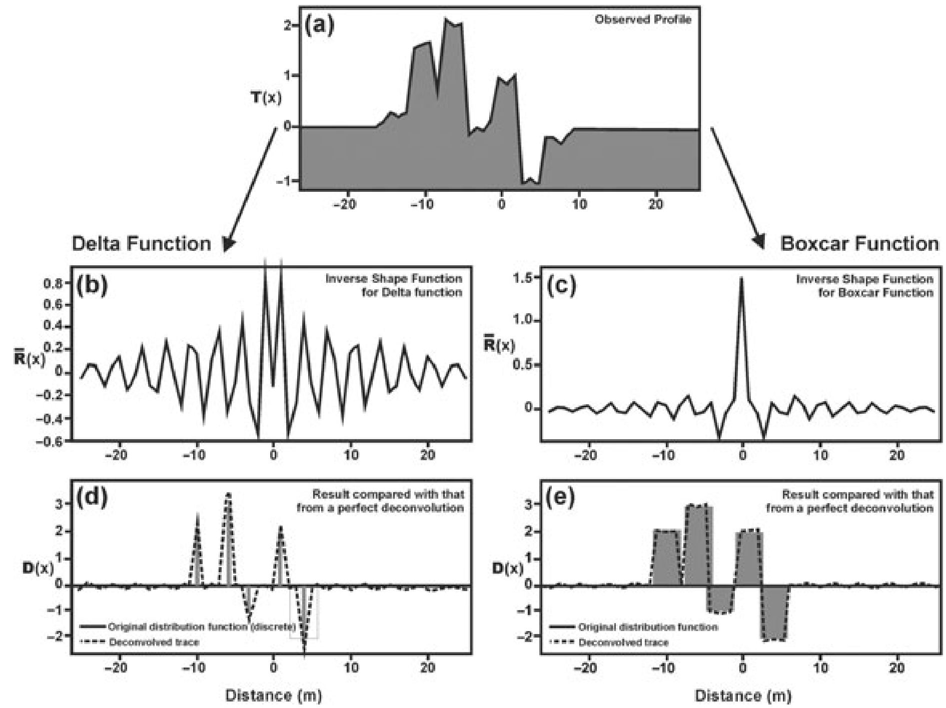

Figure 8 *The process of delta-function and boxcar-function deconvolution. (a) The 'observed' profile* $T(x)$ *which is the synthetic profile constructed in Figure 7 is the starting point for both processes. (b) The inverse filter* $\bar{R}_\delta(x)$ *that reproduces the final discrete strength function* $D_\delta(x)$ *in the form of delta functions (as in Fig. 7) when it is convolved with the observed profile. (c) The inverse filter* $\bar{R}_{bx}(x)$ *that reproduces the final discrete strength function* $D_{bx}(x)$ *in the form of boxcar functions (as in Fig. 7) when it is convolved with the observed profile. (d) The delta-function deconvolved result compared with the initial discrete strength function, and (e) the boxcar-function deconvolved result compared with the real position and extent of each feature.*

The top panel is the field observation $T(x)$ and is common to both processes. We have used the profile created in Figure 7 as synthetic field test data.

The process of delta-function deconvolution is shown by panels (a), (b) and (d) in Figure 8. Panel (b) shows the inverse filter $\bar{R}_\delta(x)$, while panel (d) shows the result of convolving $\bar{R}_\delta(x)$ with $T(x)$, which is formally the same as the process of deconvolving $R(x)$ from $T(x)$ and multiplying the result by a delta function $\delta(x)$. The result, which is shown in Figure 8 (d), indicates that the discrete strength function $D_\delta(x)$ has been recovered well. In other words, the position and the amplitude of the resulting peaks agree with the discrete strength function $D(x)$ that was used to create the synthetic data in Figure 7 in the first place.

The process of boxcar-function deconvolution is shown by Figures 8 (a), 8 (c) and 8 (e). This process requires a different inverse signature function $\bar{R}_{bx}(x)$, which produces a series of elevated values (boxcar) that are centred on the deconvolved feature and are of the same width as the deconvolved feature on each profile. The amplitude of the boxcar describes the discrepancy between the resistivity of the filling material and that of the surrounding subsoil, while its width is that of the original buried feature. Figure 8 (c) shows the inverse filter $\bar{R}_{bx}(x)$. Panel (e) shows the result of convolving $\bar{R}_{bx}(x)$ with $T(x)$, which is formally the same as the process

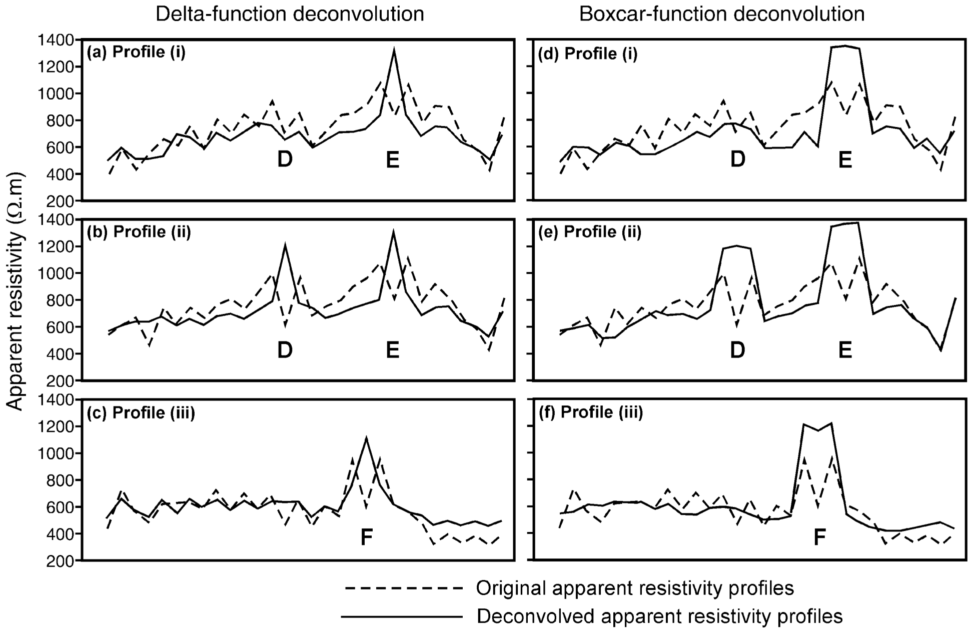

Figure 9 *One-dimensional testing of the deconvolution process on three profiles across the raw resistivity data (the position of each profile is shown in Fig. 5 (c)). (a–c) Delta-function deconvolution with* w *= 4 m, d = 0.5 m and* h *= 0.3 m, and (d–f) boxcar-function deconvolution with* w *= 4 m,* d *= 0.5 m and* h *= 0.3 m.*

of deconvolving $R(x)$ from $T(x)$ and then multiplying the result by a boxcar function of the same width as the buried feature. The result, which is shown in Figure 8 (e), indicates that the discrete strength function $D_{bx}(x)$ has been recovered well. In other words, the centre position and the amplitude of the resulting boxcars agree with the discrete strength function $D(x)$ that was used to create the synthetic data in Figure 7, and their widths describe that of the feature well (i.e., 4 m).

Although the process seems conceptually complex, it is relatively simple to create programs to carry it out. The deconvolution program was tested with the same synthetic data that have been used to explain the procedure above (Figs 7 and 8). We have varied the input parameters across a wide range and found the deconvolution procedure to be both accurate and robust.

Filtered results

Initial testing of the method was carried out in one dimension on profiles through the dataset. Figure 9 shows the results of some of this testing on three profiles, whose positions are shown as lines (i) to (iii) in Figure 5. Each profile has been subjected to both delta-function and boxcar-function deconvolution. In each case it is clear the the ‘M’-shaped signatures in the raw data have been located by the deconvolution process. The location of the ‘M’-shaped anomaly is represented by a single raised apparent resistivity value whose intensity is proportional to that of the original anomaly for delta-function deconvolution and by a series of raised values that are proportional to that of the original anomaly and centred on it for the boxcar-function deconvolution. It should be noted that both approaches smooth data that do not have the key signature. The deconvolution process can be viewed as a type of automatic pattern recognition that amplifies occurrences of a given pattern and smoothes all other data.

It is clear that analysis in one dimension is insufficient. Figure 10 shows deconvolution of the data in two dimensions using the boxcar function and three different anomaly widths, compared with the unfiltered Wenner data and the twin-probe data.

Figure 10 (a) contains the raw data and is provided for comparison with the deconvolved results. Panel (b) shows the result of a deconvolution with an anomaly 3 m wide. The process has sharpened and delineated anomalies B, C, E, G, I, J, but not anomalies A, D, F or H. Anomalies I and J are particularly sharp with this width of filter, and probably represent *Grubenhäuser* that are 3 m wide. Anomalies A, D and F have become part of a large-scale diffuse anomaly labelled X in Figure 5, while the linear features, which were clear in the raw data have been smeared out by the deconvolution process.

Figure 10 (c) shows the results with a deconvolution filter that represents a 4 m wide anomaly. Anomalies B, C, E, G, I, J are exceptionally well delineated with this filter width and probably represent *Grubenhäuser* that are 4 m wide. Anomalies I and J are less well delineated at this filter width, which is consistent with them representing narrower *Grubenhäuser*. Anomalies A, D and F have merged further with the background and the linear features are even more diffuse.

Figure 10 (d) shows all anomalies as broader and more diffuse than their raw counterparts, indicating that no 5 m wide features are present in the sub-soil. No evidence was found to support the crop marks labelled N and M in any of the filtered data. Anomaly H appeared in both the raw, 3 m amd 4 m results, it was difficult to quantify and initially interpreted as having a complex structure that would not respond well to the deconvolution treatment.

The results of filtering with a 5 m wide filter show the greatest similarity to the twin-probe data, indicating that the twin-probe data have a similar spatial resolution to that of the 5 m filtered data. However, the twin-probe data have a much better bandwidth than the filtered data. Ironically, despite the higher bandwidth, it is easier to pick out some anomalies (e.g., anomalies B, C, G and H) on the 5 m filtered Wenner data than the higher bandwidth twin-probe data.

It is worthwhile noting that the application of wider filters has the result of progressively smoothing the 'no signal' data and tends to remove linear striping that is natural (e.g., tractor tramlines) or an artefact of the resistivity method. Figure 11 shows the apparent resistivity frequency distributions for the raw data, and the same data after applying the three width filters used in Figure 10. It is clear that the operation of deconvolution is taking a near-Gaussian raw frequency distribution and extracting hidden structure, including the presence of high resistivity anomalies as indicated. The smallness of these 'feature peaks' should not be interpreted negatively; they represent approximately 144 m^2 in a total survey area of 10 140 m^2 (i.e., 1.4% of the site). It is a testament to the combination of the power of the deconvolution method and the efficacy of the human eye that these small structures can be picked out of the filtered data so easily.

EXCAVATION AND DISCUSSION

A trial excavation was subsequently carried out at the site in 1986 (Gates and O'Brien 1988; Glover in press), which demonstrated beyond doubt that the sub-rectangular crop mark that correlates with anomaly G represents the remains of a *Grubenhaus*. Figure 12 shows the excavation plan next to the results of each electrical survey.

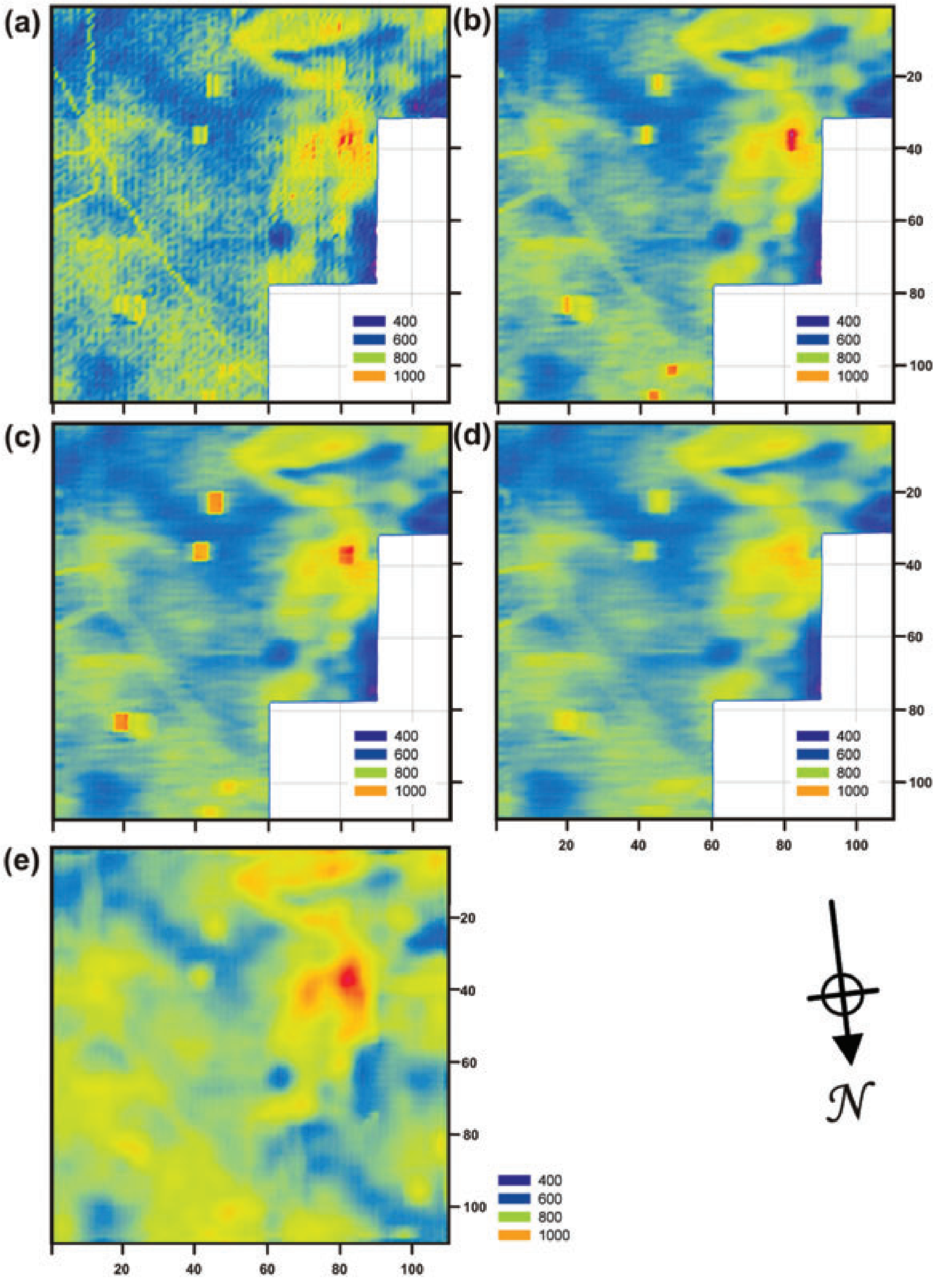

Figure 10 *Two-dimensional boxcar deconvolution as a function of the modelled dimensions of the buried feature. (a) Raw undeconvolved Wenner array data. (b) Wenner array data deconvolved;* w *= 3 m,* d *= 0.5 m and* h *= 0.3 m. (c) Wenner array data deconvolved;* w *= 4 m,* d *= 0.5 m and* h *= 0.3 m. (d) Wenner array data deconvolved;* w *= 5 m,* d *= 0.5 m and* h *= 0.3 m. (e) Results of the twin-probe survey over the same area for comparison.*

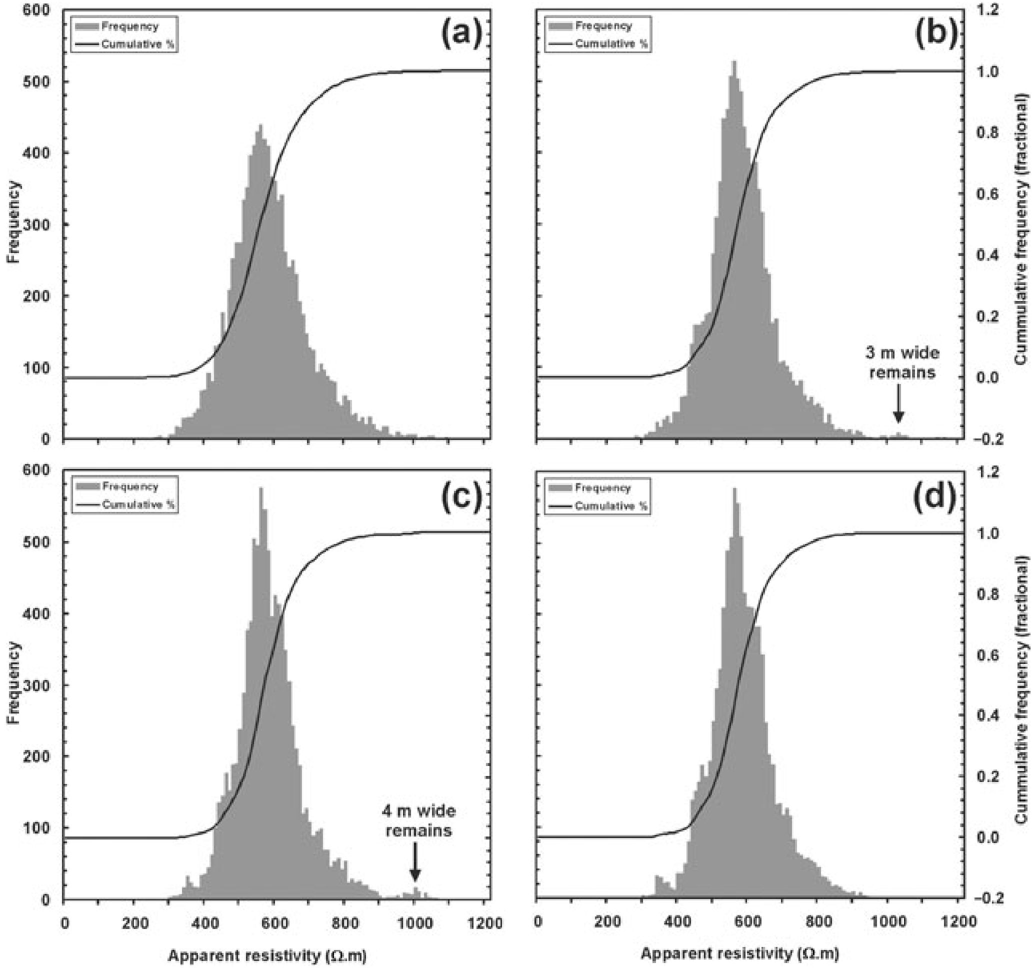

Figure 11 *Frequency distributions and cummulative frequency curves of the raw data (Fig. 5 (a)) and the three deconvolution results reported in Figure 10 (b) to Figure 10 (d). (a) The raw data; (b) deconvolution with a 3 m wide anomaly; (c) 4 m wide anomaly; (d) 5 m wide anomaly.*

For the Wenner array data, the high resistivity areas (shown in red) correspond almost exactly to the location and extent of the excavated *Grubenhaus*. The corners of the electrical data are artificially sharper than they should be, due to the effects of the colour interpolation implemented by commercial imaging software (Sigmaplot) and cannot be surpressed. There is no record of any of the post holes that were found during the excavation, either on the deconvolved data (shown in the figure) or in the raw data (not shown). However, the deconvolved data may be reproducing some of the plough furrows. Anomaly H, which lies just below the *Grubenhaus* in the figure, was too complex to be interpreted from the filtered data. However, the excavation shows it to result from a complex group of pits in the cultural layer, to which no purpose has been ascribed.

The results from the twin-probe survey are less easy to interpret. There seems to be a diffuse area of raised resistivity that corresponds approximately to anomalies G and H, but the

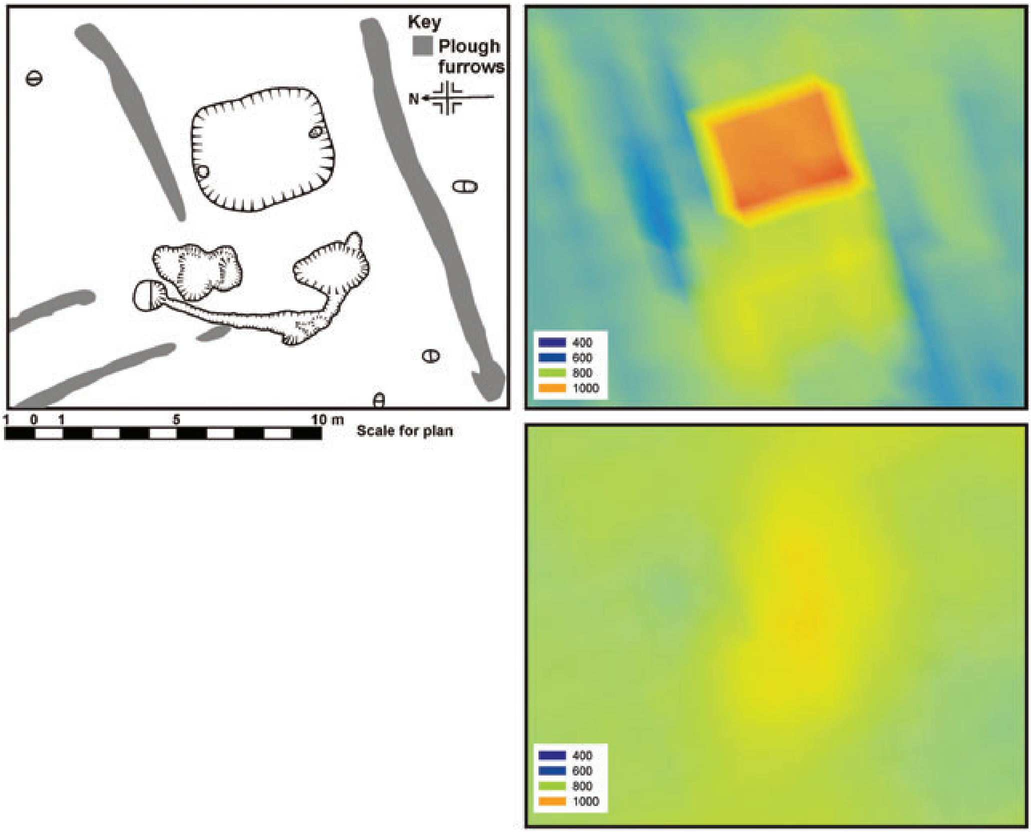

Figure 12 *Comparison of the results of the excavation of anomalies G and H by Gates and O'Brien (1988) with the results of the boxcar deconvolved apparent resistivity data with* w = *4 m,* d = *0.5 m and* h = *0.3 m (upper right) and the twin-probe data (lower right).*

trace of the *Grubenhaus* at G is much inferior to that provided by the 4 m filtered Wenner array data (Fig. 12), or any of the other filtered results (Fig. 5) or the raw Wenner array data (Fig. 5). Once again, there is no trace of post-holes, nor of plough furrows.

The excavated building was of the type classified by Ahrens (1966) as a *Giebelpfostenhaus* (West 1985; Tipper 2004). In other words, a *Grubenhaus* with the apex of the roof running along the axis of the house on a ridge pole that is supported at either gable-end by one or several posts. It is most probable that other similar sub-rectangular crop marks and resistivity anomalies at New Bewick are also *Grubenhäuser*, as well as those at Milfield and Thirlings (Hope-Taylor 1977; O'Brien 1981; Frodsham 2003; Tipper 2004). It should be noted, however, that there remains a debate over the exact style of superstructure employed in these buildings and several different possible reconstructions have been carried out, and it is not certain that the 'sunken-floor' actually represents a floor or whether a suspended floor was present in some examples of this type of construction.

Grubenhäuser nearly always occur in association with other buildings (e.g., wall-post buildings), such as at the sites of West Stow (West 1969, 1985; Tipper 2004), Catholme (Losco-Bradley 1977; Losco-Bradley and Kinsley 2002; Tipper 2004), Mucking (Clark 1993;

Hamerow 1993), Radley Barrow Hills (Chambers and McAdam 2007), West Heslerton, Chalton (Champion 1977; Karkov 1999), Cowdery's Down (Karkov 1999) and Yeavering (Hope-Taylor 1977; Karkov 1999).

Grubenhäuser may also occur in conjunction with, but at some distance from, larger buildings, such as wall-post buildings or halls. The best example is probably West Heslerton where this does seem to occur, and which has been fully excavated using modern techniques (Powlesland 1999). It may also be the case at Sutton Courtenay, Oxfordshire (Benson and Miles 1974), although Sutton Courtenay is perhaps a poor example because some post-hole buildings may simply have been missed as a result of the excavation technique that was used. The association of *Grubenhäuser* and larger buildings seems also to be the case at Milfield and Thirlings (O'Brien and Miket 1991; Tipper 2004), although I am not aware that any of the *Grubenhäuser* have been confirmed by excavation at Thirlings and none of the crop marks have been investigated at Milfield. Occasionally, *Grubenhäuser* are discovered alone, as at Itford Farm (James 2002), but as these excavations are often in response to a discovery during construction, the wider archaeological context has often not been studied, and may contain the remains of other buildings.

The only traces of Anglo-Saxon occupation in the Northumberland region are those few large and complex timber halls and palaces of the type found at Yeavering and Thirlings (Hope-Taylor 1977; Karkov 1999). The demonstration of *Grubenhäuser* at New Bewick without the apparent remains of any other type of building has been used as an argument for another level in the settlement hierarchy in an area that was previously thought to be sparsely populated (Gates and O'Brien 1988; Passmore *et al.* 2002). This argument is based upon the erroneous interpretation of the role that *Grubenhäuser* seem to have played in the Anglo-Saxon community (Tipper 2004). Whereas it was once thought that *Grubenhäuser* served as dwelling places (Leeds 1947), it is now accepted that, throughout most of northern Europe, these small constructions were no more than outbuildings and workshops (Gardiner 1990; Tipper 2004) and that these constructions would be used by a small community occupying a larger hall nearby. A review of Anglo-Saxon communities in the UK (James *et al.* 1984) has shown that *Grubenhäuser* occur in association with the remains of one or several halls. The general pattern is that of a single or multiple timber-framed halls surrounded by *Grubenhäuser*, where the soil is easily excavated, or by smaller post-built buildings, where the bedrock is close to the surface, such as at chalk downland sites. *Grubenhäuser* that share sites with large post-built halls exist at Milfield (Hope-Taylor 1977; Gates 1982), Thirlings (O'Brien and Miket 1991; Karkov 1999), West Stow (West 1985; Tipper 2004), Catholme (Losco-Bradley 1977; Losco and Kinsley 2002; Tipper 2004), Mucking (Clark 1993; Hamerow 1993), Radley Barrow Hills (Chambers and McAdam 2007) and West Heslerton (Powlesland 1999), although the Milfield and Thirlings sites have not been confirmed by excavation.

Despite the lack of evidence for timber-framed halls at New Bewick, Frodsham (2003) has suggested that the site may represent a newly founded farmstead or hamlet. The lack of the remains of an obvious hall on the aerial photographs of the New Bewick site does not necessarily indicate that one or more were not present. Timber-framed halls constructed using post-holes do not show up well on aerial photographs, and it is quite possible that such a hall might be uncovered if extensive excavations were carried out at New Bewick. There are at least three good examples of sites where remarkably well-preserved remains of post-built and trench-constructed halls have been found by excavation where no previous photographic evidence existed. These include Mucking (Jones and Jones 1975; Jones 1979, 1983a,b; Clark 1993; Hamerow 1993), Radley Barrow Hills (Chambers and McAdam 2007) and West Heslerton (Powlesland 1999). In these cases the excavations were primarily concerned with other aerial photographic evidence or the chance discovery of artefacts. The discovery of the halls was an unexpected addition. Unfortunately, the ephemeral nature of the remains of these halls makes their discovery by further resistivity surveys also very unlikely.

CONCLUSIONS

A mulitplexed Wenner resistivity survey (with two different meters) and a twin-probe resistivity survey (covering 1.014 ha and 1.21 ha, respectively) were carried out in a field at New Bewick farm, Northumberland, UK.

The twin-probe survey acquired data significantly more quickly than the Wenner survey, but with a lower spatial resolution, despite both surveys being carried out on a 1 m electrode spacing. There was no significant difference between the results of the Wenner survey with the commercial MkII Terrameter and the smaller, lighter, in-house designed meter. The Wenner results did show characteristic striping of the data and 'M'- and 'W'-shaped artefacts as expected, which were not present in the twin-probe data. The data resulting from the Wenner survey were subsequently subjected to digital filtering by carrying out predictive deconvolution with various source signatures representing buried *Grubenhäuser*, in order to remove the artefacts and improve the spatial resolution of the Wenner data further.

The raw data in both types of survey showed several indistinct areas of high resistivity, as well as the traces of several linear features, some of which coincided with linear crop marks at the site. One particular linear resistivity anomaly was correlated with the remains of a filled 'V'-shaped ditch that was confirmed subsequently by excavation. In all cases the anomalies appeared sharper in the Wenner data than in the twin-probe data.

The digitally filtered results showed five sub-rectangular resistivity anomalies which probably represent *Grubenhäuser*. One of these anomalies (shown in Fig. 5 as anomaly G) was subsequently excavated (Gates and O'Brien 1988) and confirmed to represent the remains of a *Grubenhaus* with approximately the same dimensions indicated by the resistivity survey. The recognition of the remains of several *Grubenhäuser* at the New Bewick site by the electrical method, and the confirmation of one of them by excavation is indicative that there was a group of *Grubenhäuser* at the site. It would not be correct to assume that other types of buildings were not present at the site. Post-built halls may be present but do not show up well on aerial photographs. They are usually only recognized by excavation.

Although a larger resistivity survey at the New Bewick site would be unlikely to provide evidence for post-built halls, it was thought that magnetic gradiometry might be able to locate hearths that the post-built halls should contain. However, only a small number of post-hole buildings have been excavated with any indication of surviving floors, and with possibly a central hearth. This might, of course, be due to conditions of preservation. Commonly, all that survives are the post-holes defining the wall-lines, which do not show up well on magnetic gradiometry surveys. However, there is also debate as to whether or not post-hole buildings had supported timber floors, hence there would be no evidence for floors and hearths (see Tipper 2004). Furthermore, the site at New Bewick was quite heavily truncated, and therefore it is unlikely that any hearths would have survived anyway.

Grubenhäuser, like ditches, often show up well as magnetic anomalies, and this technique is generally faster and allows much greater area coverage than electrical techniques. Given that settlements of this period are very extensive, fluxgate gradiometry is perhaps a more appropriate technique for sites of this period. The group of pits, to the south of the excavated *Grubenhaus*, was not clearly defined by the resistivity surveys, yet they are quite substantial archaeological features. These might have been defined more clearly by fluxgate gradiometry. Moreover, the excavated SFB (Fig. 12) was not clearly defined by the twin-probe surface electrical survey. However, although it is no longer common to carry out resistivity surveys using the Wenner configuration, we have shown that these types of surveys can provide good results if their data are subsequently processed digitally, and the improvement in spatial resolution may be worth the extra time required to carry out the measurements, especially if used in conjunction with fluxgate gradiometry.

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