CHARACTERISING SAND AND GRAVEL DEPOSITS USING ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT): CASE HISTORIES FROM ENGLAND AND WALES

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Abstract

Electrical Resistivity Tomography (ERT) is a rapidly developing geophysical imaging technique that is now widely used to visualise subsurface geological structure, groundwater and lithological variations. It is being increasingly used in environmental and engineering site investigations, but despite its suitability and potential benefits, ERT has yet to be routinely applied by the minerals industry to sand and gravel deposit assessment and quarry planning. The principal advantages of ERT for this application are that it is a cost-effective non-invasive method, which can provide 2D or 3D spatial models of the subsurface throughout the full region of interest. This complements intrusive sampling methods, which typically provide information only at discrete locations. Provided that suitable resistivity contrasts are present, ERT has the potential to reveal mineral and overburden thickness and quality variations within the body of the deposit.

Here we present a number of case studies from the UK illustrating the use of 2D and 3D ERT for sand and gravel deposit investigation in a variety of geological settings. We use these case studies to evaluate the performance of ERT, and to illustrate good practice in the application of ERT to deposit investigation. We propose an integrated approach to site investigation and quarry planning incorporating both conventional intrusive methods and ERT.

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Introduction

Electrical resistivity tomography (ERT) is a ground imaging tool, which can complement conventional point sampling approaches by providing fully volumetric information on ground conditions. Todate, ERT has not been routinely applied by the minerals industry to sand and gravel deposit investigation due, in part, to unfamiliarity with the technique and a lack of demonstration studies. Here we describe a programme of research, which was established to begin the process of developing ERT specifically for sand and gravel reserve assessment. Our principal aims and objectives have been to:

- design and carry out controlled field-tests at well-characterised sites to prove the suitability of ERT as a rapid, cost effective tool for non-invasive imaging of sand and gravel deposits,
- determine how ERT methods can be integrated with conventional site investigation methodologies,
- estimate the likely cost benefits of using ERT,
- develop good practice guidance for the use of ERT,
- facilitate knowledge transfer and raise awareness within the minerals industry of the benefits of apply ERT technology.

Overview of Electrical Resitivity Tomography (Ert)

ERT is used to generate models of subsurface electrical property distributions, from which subsurface geological structure and hydrogeological variations can be identified (Chambers *et al.*, 2002; Kuras *et al.*, 2008). This technique is analogous to medical imaging techniques, such as MRI and CT, which are used to image the internal structure of the body. The principal benefits of ERT are that it is a rapid non-invasive method, which employs highly portable lightweight field equipment (Figure 1), that can provide fully 2D & 3D spatial models of the subsurface at the site scale. This is in contrast to intrusive sampling methods, which typically provide information only at discrete locations. ERT is sensitive to compositional variations in the subsurface, and can therefore be used to distinguish between different lithologies, e.g. clean gravels (high resistivity) and clay (low resistivity) bedrock or overburden, and can also be used to spatially map 3D quality variations within the mineral deposit (e.g. resistivity typically reduces with increasing clay content). When used in time-lapse mode (i.e. repeated measurements) ERT is very sensitive to changes in moisture content (i.e. resistivity decreases with increasing moisture content) and the electrical conductivity of groundwater (which is usually a good measure of water quality). Due to the high temporal and spatial resolution of the technique it can be used to monitor not only slow seasonal changes, but also rapid changes, including drawn down surfaces that could be associated with quarry dewatering.

One of the earliest references to the use of 2D ERT for sand and gravel resource studies is by Barker (1997), in which he describes a survey from the Trent Valley, UK. Other published examples are rare, but include Beresnev *et al.* (2002), Hill (2004) and Lucius *et al.* (2006). There are currently no published examples of the use of 3D ERT for this application.

Case Studies

A set of 18 field sites for controlled testing were chosen to include a range of geological settings and geological complexity (Figure 2). Most of the sites were associated with existing sand and gravel quarries and all were well characterised with ground truth data (e.g. boreholes, trial pits) used to calibrate and assess the ERT models.

2D ERT

2D ERT surveys were undertaken at thirteen sites, including Washington (West Sussex), Clifton (Worcestershire), Blashford (Hampshire) and Borras (Flintshire). These surveys were intended to demonstrate 2D ERT as a rapid sand and gravel reconnaissance tool, and to extend our knowledge of the electrical properties of the deposits and bedrock in these areas. In all cases 2D ERT was successful in imaging the sand and gravel due to the clear resistivity contrasts between the sand and gravel, overburden and bedrock materials (Figure 3). The bedrock materials in each case were more clay rich than

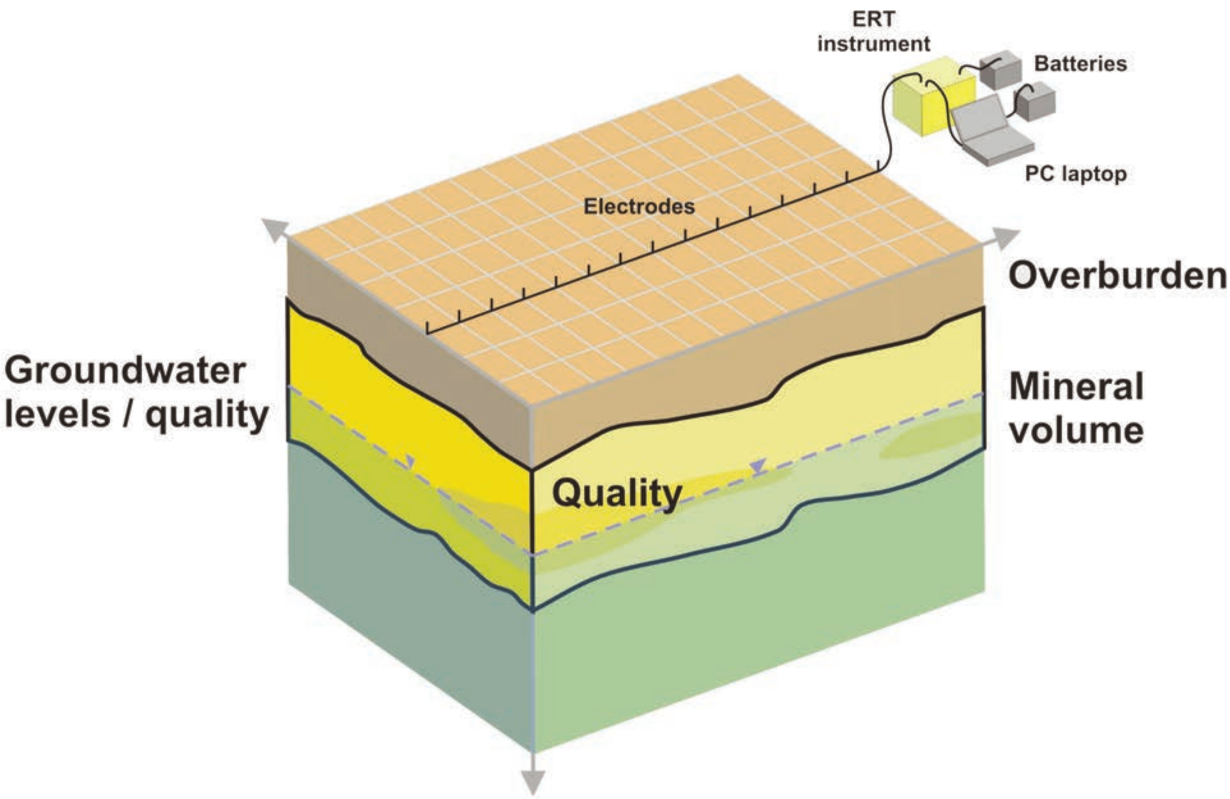

Figure 1. *Schematic illustration showing the basic components of an ERT imaging survey, and targets associated with sand and gravel deposits. A 3D survey comprises a network of survey lines (i.e. a grid of electrode positions), whilst a 2D survey is carried out using a single line of electrodes. ERT has the potential to distinguish between mineral, bedrock and overburden, identify quality variations in the mineral (e.g. high concentration of fines shown as shaded areas within the mineral), and monitor the level and quality of groundwater.*

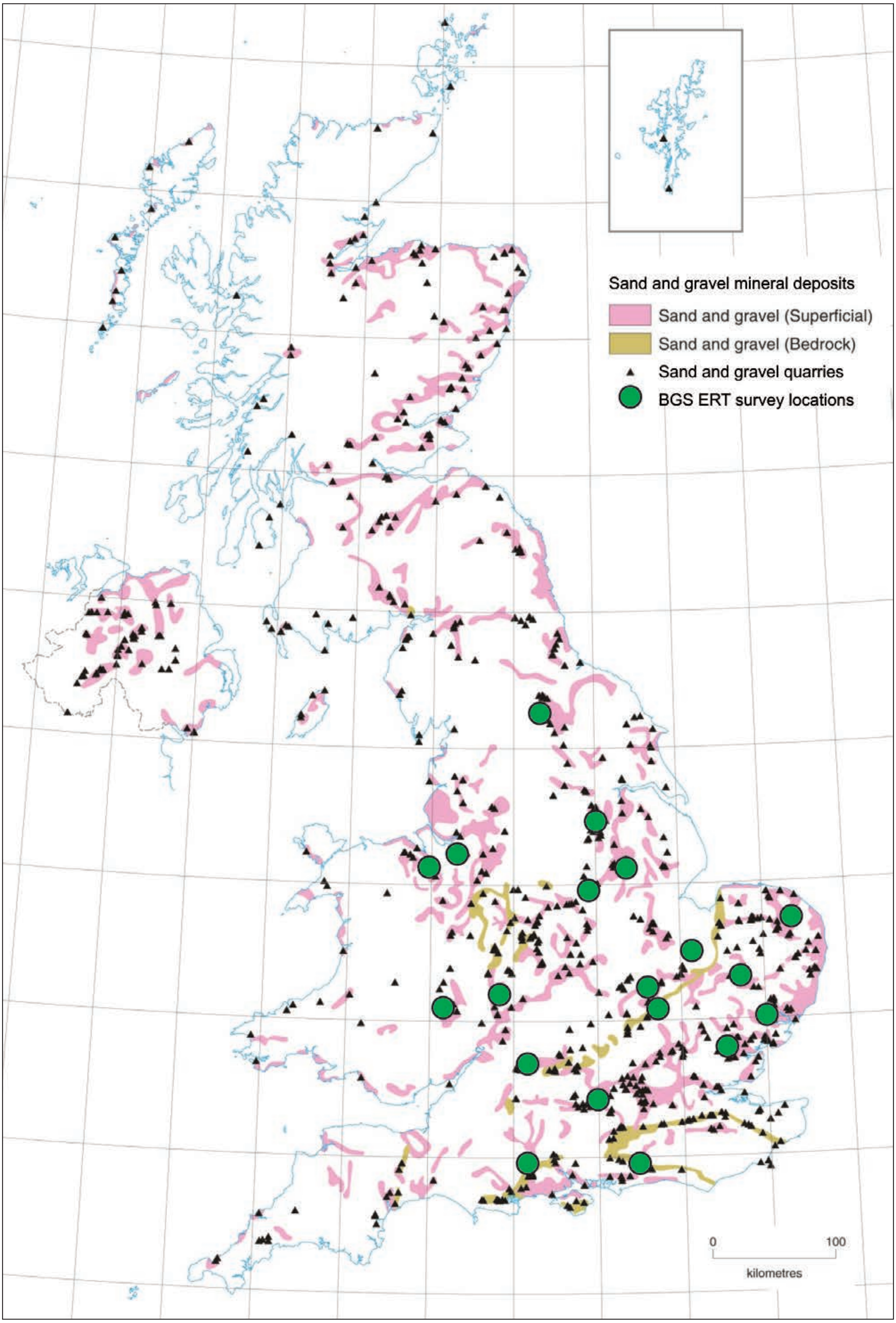

Figure 2. *BGS ERT sand and gravel survey sites (green circles).*

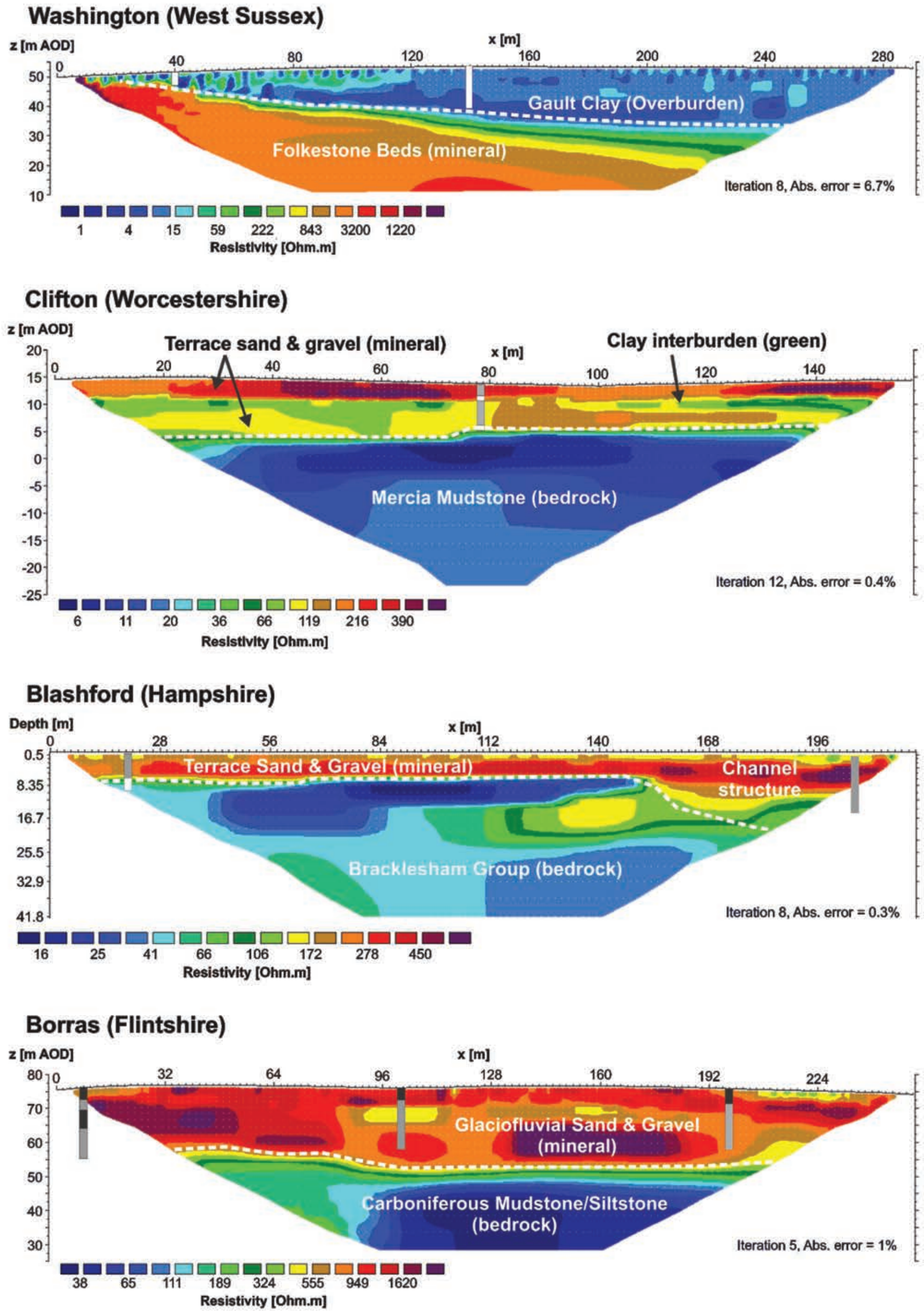

Figure 3. *A selection of 2D ERT images from 4 study sites in England and Wales. The dashed white lines show the inferred interfaces between mineral and bedrock, and mineral and overburden. Elevation is given as either depth below ground level or metres above Ordnance Datum (AOD).*

the sand and gravel, resulting in a lower resistivity.

The Washington survey included a thickening wedge of clay overburden, which was successfully identified in the resistivity image as a low resistivity zone (<50 Ohm.m). At Clifton, river terrace sands and gravels, including a clay interburden, were imaged above Mercia Mudstone bedrock. The Blashford survey revealed a significant channel structure in the bedrock, which resulted in significant thickness variations in the deposit. The glaciofluvial deposits at Borras were shown to be highly variable, with clean coarse (i.e. lower fines content) areas of the deposit characterised by particularly high resistivities (>1000 Ωm).

3D ERT

Proof-of-concept surveys using 3D ERT were undertaken at Masham (North Yorkshire), Ingham (Suffolk), Norton Disney (Lincolnshire), Chelmsford (Essex), Nottingham (Notts), and Willington (Bedfordshire) (Chambers *et al.*, 2012). Two surveys are described here.

The Masham site represents a relatively simple geology, which consists of Namurian sandstone or mudstone bedrock, overlain by fluvio-glacial sand and gravel, which in turn is overlain by a thin variable cover of clay till. However, it is essentially unproven due to the high proportion of cobbles and boulders in the deposit, which prevent the successful deployment of conventional drilling methods. The 3D ERT survey (Figure 4) was effective in identifying the distribution of overburden across the area and revealing the thickness of the gravel deposit. A surface defining the base of the gravel was calculated from the ERT model; as with other surveys we have undertaken, this surface was in a form that could be directly incorporated into terrain modelling packages for reserve calculation.

Ingham is a complex site difficult to characterise using boreholes, because of the spatial variability of the deposit. 3D ERT was used to image the extent and thickness of till overburden and the sand and gravel deposit (Figure 5). Quality variations were also observed in the mineral, with high resistivities (yellow to red) likely to be associated with coarser materials, and lower resistivities (green) indicative of higher fines content.

Summary

ERT was an effective ground investigation technique for all but one of the 18 sites considered during the projects due to the good resistivity contrasts observed between mineral and bedrock. Economic sand and gravel deposits are by definition relatively clean (i.e. low clay

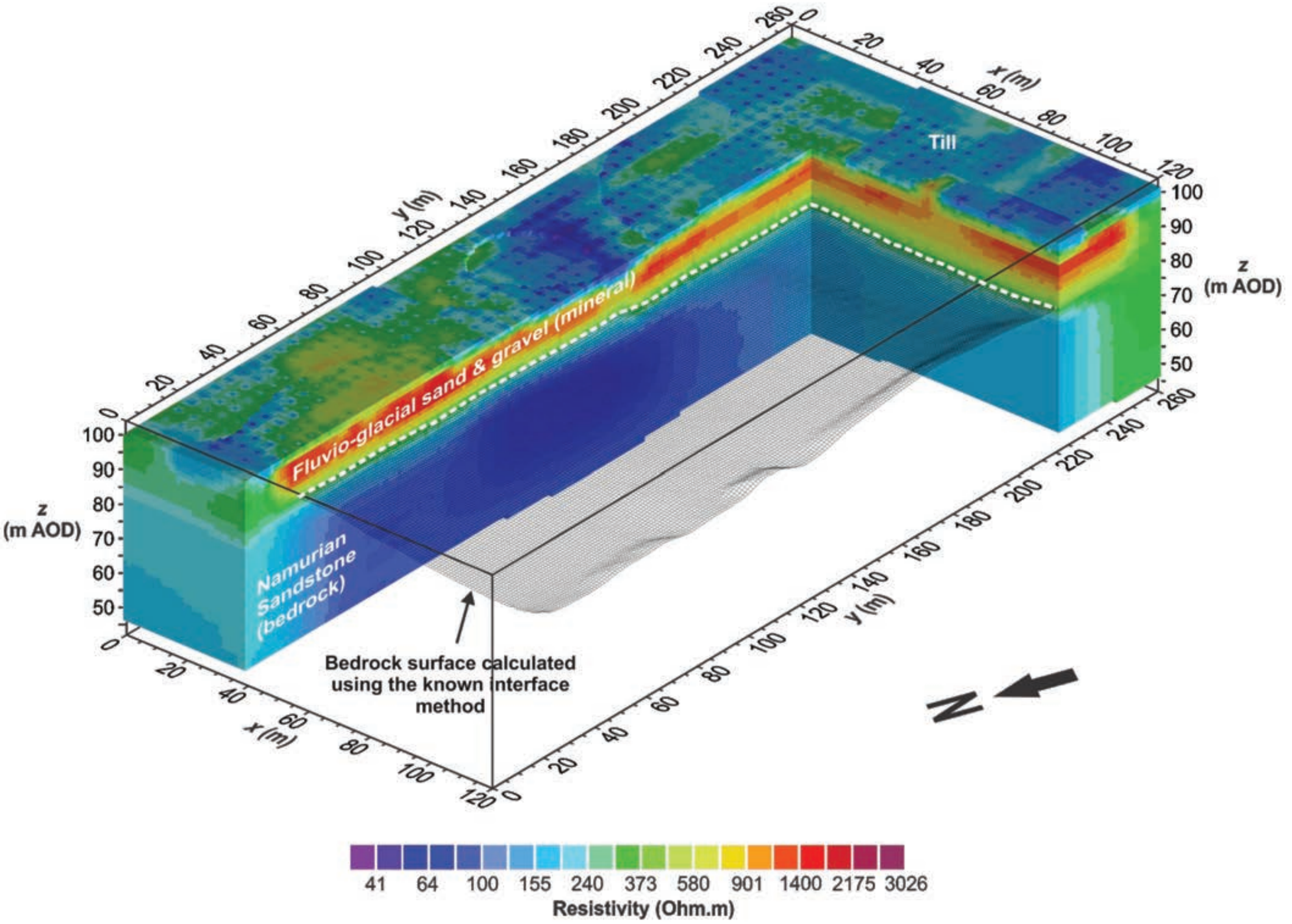

Figure 4. *Masham 3D ERT model, including calculated bedrock surface. The interface between the mineral and bedrock is shown by a white dashed line. Elevation is given as metres above Ordnance Datum (AOD).*

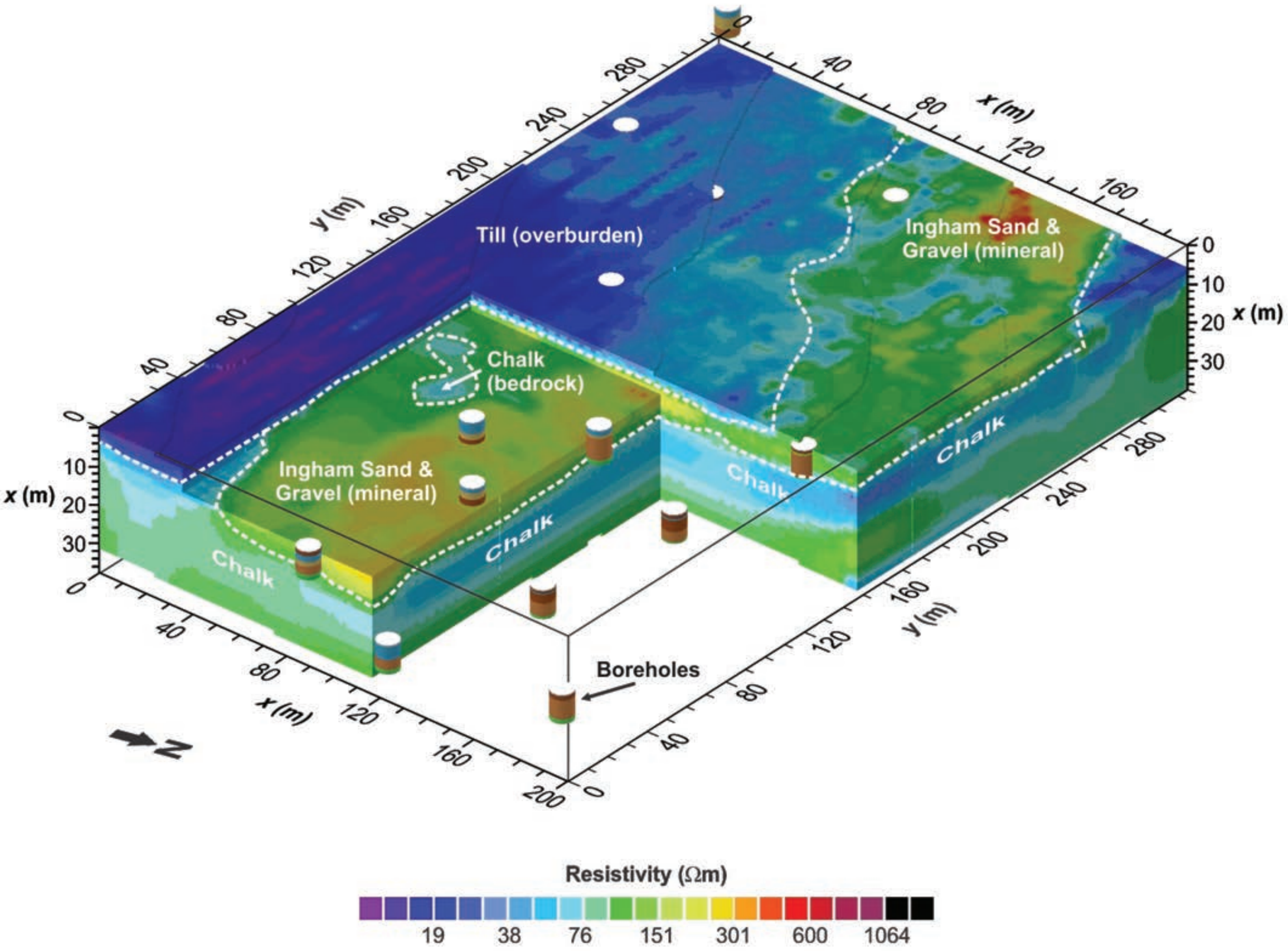

Figure 5. *Ingham 3D ERT model. The dashed white lines show the interfaces between the mineral and overburden, and mineral and bedrock. Elevation (x) is given in metres below ground level. Mineral quality variations are indicated by the resistivity variations, i.e. high resistivities (yellow to red) are likely to be associated with coarser materials, whilst lower resistivities (green) indicate a higher fines content.*

content), and are therefore typically more resistive than weathered mudstone (e.g. Mercia Mudstone Formation), chalk, and clay (e.g. Oxford & London Clay) bedrock that underlies many important UK deposits. The success of ERT in the diverse range geological settings considered so far greatly increases our confidence that it will be more generally applicable to UK sand and gravel resources.

It should be noted that the ERT has a number of limitations (also see Chambers *et al.*, 2008). In particular, ERT provides indirect (non-invasive) information in the form of images, which can contain distortions caused by resistivity variations in regions adjacent to the survey line or area; consequently, some intrusive investigations are always required for verification and sample analysis. It provides smoothed images in which precise interface locations can sometimes be difficult to determine, and also displays a decreasing resolution with depth. ERT surveyed should therefore by undertaken by suitably trained operators, with the results interpreted alongside other appropriate forms of subsurface information.

Initial comparisons have shown that ERT survey costs are likely to be broadly similar to those of drilling (assuming a ≤100 m spaced grid of boreholes), particularly for complex deposits or sites that are difficult to drill (Chambers *et al.*, 2011). Whilst ERT should not replace drilling, it has the potential to reduce the number of intrusive sample points required, and will enable better targeting of boreholes. Moreover, by revealing the structure of the deposit between intrusive sample points it can provide additional information that cannot be identified from borehole data alone.

The modes of ERT field deployment (i.e. 2D and 3D imaging) provide for significant flexibility in terms of survey design and survey objectives. 2D ERT is a best applied as a rapid reconnaissance tool for characterising geological structures over large distances, whereas 3D ERT is ideally suited to detailed high-resolution investigations for reserve assessment. Both 2D and 3D ERT data can be translated directly into operationally relevant information (e.g. bedrock surfaces) for use by minerals geologists and planners.

A framework for good practice guidance for 3D ERT mineral reserve assessment survey has now being developed, based on previous studies, and from the findings and experience gained during this and other research (e.g. Chambers *et al.*, 2011).

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