Determining Reserves of Aggregates by Non-invasive Electrical Tomography (DRAGNET): MIST Project MA/6/1/008

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In partnership with

BRITISH GEOLOGICAL SURVEY

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Determining Reserves of Aggregates by Non-invasive Electrical Tomography (DRAGNET): MIST Project MA/6/1/008

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) in partnership with the Minerals Industry Research Organisation (MIRO), Lafarge, Hanson, Cemex and Tarmac. The research was funded by Mineral Industry Sustainable Technology Programme Grant MA/6/1/008, and in-kind contributions from the industrial partners.

Acknowledgements

Of the many individuals who have contributed to the project we would particularly like to thank Duncan Wardrop (Lafarge), Stephen Penn (Cemex), Malcolm Keeble (Hanson), Eddie Bailey (formerly Tarmac) and Rob Palmer (Tarmac) for their willingness to participate in the research, and for the provision of advice and guidance. Stephen Penn deserves special thanks for chairing the DRAGNET project meetings. In addition, we would like to extend our gratitude to Chris Dunn (Hanson), Kirk Blackburn (Lafarge) and Gareth Burdell (Lafarge) for their assistance during the fieldwork phase of the project.

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Executive Summary

Three-dimensional electrical resistivity tomography (3D ERT) is a geophysical imaging technique that has developed rapidly in recent years. The great strength of the technique is that it is a relatively low cost non-invasive method of providing high-resolution spatial information that reveals the structure of the subsurface. Despite its obvious suitability, 3D ERT has not yet been applied by the minerals industry to the investigation of sand and gravel deposits. The DRAGNET project was therefore established to begin the process of researching and developing 3D ERT for sand and gravel reserve assessment. More specifically, we have demonstrated the technique at UK extraction sites, we have sought to establish procedures to integrate 3D ERT with conventional investigation methods, we have developed best practice guidance for the future use of the technique in this area, and we have begun to consider the economics of the 3D ERT for minerals surveys.

The DRAGNET demonstration studies were carried out at Marfield Quarry, North Yorkshire, and Bull's Lodge Quarry, Essex. These sites were selected due to their challenging geologies. The Marfield Quarry site comprised extremely coarse gravels, which have proved to be nearly impossible to drill, whilst the Bull's Lodge test area had overburden to mineral thickness ratios of as much as 2:1, with in excess of 10 m of till overburden. Integrated models were generated for both sites to demonstrate our methodology for 3D data fusion, visualisation and interpretation using combined 3D ERT and conventional data sets.

The 3D ERT model of the Marfield Quarry site was used to identify the distribution of overburden, depth to bedrock and quality variations within the gravels. Operationally relevant information derived from the Marfield 3D ERT model was presented in a form that could be directly used by minerals industry geologists for reserve calculations.

The Bull's Lodge 3D ERT model successfully defined the overburden, but was not able to resolve the base of the mineral. The failure of ERT in this case was due to the unfavourable overburden to mineral ration, and the very low resistivity of the till, and highlights the limitations of the technique. Synthetic modelling studies carried out as part of this project were used to determine the range of overburden to mineral rations over which 3D ERT would be successful, and to trial a new survey strategy that has the potential to resolve thin mineral layers buried beneath thick overburden. The results from the synthetic modelling and the case studies represent an invaluable resource with which to inform the planning of future minerals surveys, and have provided a foundation on which to begin developing best practice guidance.

The key elements of our best practice guidance for 3D ERT mineral reserve assessment surveys are as follows: (1) Overview of ERT; (2) Limitations of ERT; (3) Survey planning and design (including array type, vertical and lateral resolution); (4) Data collection; (5) Data processing and interpretation (including inversion and visualisation); (6) Data quality assessment; (7) Case studies.

Based on our experience during the project, and other published sources, we assess the likely cost benefits of applying 3D ERT to sand and gravel investigations. Due to the limited scope and resources available to us this assessment is necessarily qualitative. We consider the relative costs of ERT (particularly compared to drilling), its effectiveness for sand and gravel deposit investigations, and the added value that it can provide to site operators. It is probable that 3D ERT will be most suited both to the investigation of complex deposits with significant lateral heterogeneity, and those sites that are difficult to drill. In such situations 3D ERT can be used to reveal the structure of the deposit between intrusive sample points, it can provide targets for drilling, and can potentially reduce the number of intrusive sample points required.

1 Introduction

1.1 PROJECT OBJECTIVES

The objectives of the project were:

1. To design and carry out controlled field-tests at two well-characterised aggregate extraction sites to prove the suitability of electrical resistivity tomography (ERT) technology as a rapid, cost effective tool for non-invasive 3D volumetric imaging of sand and gravel deposits.
2. To evaluate in consultation with major aggregate producers the suitability of 3D ERT for accurate quantification of workable reserve (product) and overburden volumes and as an aid for targeting extraction work more accurately, thereby minimising waste, and reducing the amount of drilling required.
3. To build on the state-of-the-art in aggregate evaluation and determine how ERT methods can be integrated effectively with existing methodologies.
4. To estimate the likely cost benefits to industry, regulatory bodies and other site planners of using ERT.
5. To disseminate the results of the research widely on a pre-competitive basis to the UK aggregates industry and research and regulatory organisations so that they can evaluate the usefulness of ERT and improve best practice where necessary.

The project results are also expected to help realise further medium to long-term objectives:

6. To increase the efficiency of sand and gravel resource assessment and extraction programme planning at site and regional level.
7. To minimise any adverse environmental impacts of aggregate extraction, including waste generation and damage to ecosystems.

1.2 PROJECT PARTNERS

1.2.1 Research provider and lead partner

Partner 1: British Geological Survey (BGS)

BGS provided the technical lead for the project through its Electrical Tomography Programme (ETP), which was set up within the BGS Environment and Hazards Directorate to provide a research-led consultancy service to industry. BGS has an outstanding record of innovation and pioneering research in the field of ERT (see www.bgs.ac.uk/etp). This coupled with extensive BGS resources, including state-of-the-art laboratories, IT infrastructure and broad corporate experience across all of the geoscientific disciplines, means BGS was well qualified to undertake the proposed research.

1.2.2 Sponsors and steering group

Partner 2: Lafarge Aggregates Ltd

Lafarge is the world leader in building materials and holds top-ranking positions in all three of its divisions: Cement, Aggregates & Concrete, and Gypsum. A majority share in the former Roofing division was recently divested. Cement is the largest of these worldwide and the Group places much importance on research and technical innovation of this material through a dedicated research centre near Lyon.

In the UK all three divisions are represented. Gypsum with a modern plasterboard factory in Avonmouth and a new site at Cotham in Nottinghamshire; Aggregates and Concrete through the former Redland Aggregates and Ennemix; and Cement by the acquisition in 2001 of Blue Circle Cement.

Bulk construction materials are not often seen as being prime areas for research but Lafarge Aggregates Ltd have participated in several valuable MIRO coordinated research projects in recent years. The technical circumstances surrounding resource identification, environmentally acceptable quarrying and the quest for production efficiencies are areas where there is still room for greater knowledge.

Lafarge employs 80,000 people in 76 countries and posted sales of €16.0 billion in 2005.

Partner 3: Hanson.

Hanson is one of the world's largest suppliers of heavy building materials to the construction industry. Its products fall into two categories: aggregates (crushed rock, sand and gravel, ready-mixed concrete,asphalt and cement related products) and building products (concrete pipes, precast products, concrete pavers, tiles and clay bricks). They employ over 27,000 people, primarily in North America, the UK and Australia, with further operations in Asia Pacific and Continental Europe.

Their UK aggregates division produces crushed rock, sand and gravel, asphalt, slag cement and ready-mixed concrete from over 400 sites and has an annual turnover in excess of £850 million.

Partner 4: CEMEX UK Operations Ltd

CEMEX is a leading global producer of cement, readymix concrete, aggregates and other building materials. It combines a deep knowledge of local markets with a global network and information technology systems to provide world-class products and services to its customers, from individual homebuilders to large industrial contractors. In the UK, through its acquisition in 2005 of RMC, CEMEX is the leading producer of readymix concrete and the second-largest manufacturer of aggregates. It is the third-largest cement and asphalt producer, with a significant share of the roof tile, concrete-block paver and concrete block markets. CEMEX is the leading supplier of concrete sleepers to the UK's rail industry and a dominant supplier of PFA cement additives. CEMEX operates more than 300 readymix concrete plants, over 130 quarries, four cement plants, seven terminals and more than 150 other operating units ranging from asphalt, mortar and recycling plants to pre-cast concrete and specialist product factories. It also operates a fleet of dredgers through its marine aggregates business.

Partner 5: Tarmac

Tarmac Limited is the leading supplier of aggregates in England. Tarmac operates 82 quarries throughout the country supplying sand & gravel and crushed rock aggregates. Production of sand & gravel in England is in the order of 12m tonnes per annum. Tarmac also produces secondary aggregates from iron and steel slag and recycled aggregates from construction and demolition waste. Marine dredged sand & gravel is supplied through a joint venture company.

As well as the extraction and supply of aggregates Tarmac has significant related manufacturing interests. Tarmac Limited is one of only four companies in England producing cement, from a new £100m+ state-of-the art plant at Buxton, Derbyshire and is also the single largest producer of lime for industrial and environmental uses in the UK. Tarmac Limited is also the biggest producer of asphalt in England and is amongst the top three suppliers of ready mixed concrete. Tarmac also has a market leading presence in the manufacture of concrete products – blocks, pre-cast structures, flooring, railway sleepers and paving materials.

1.2.3 Project administration

Partner 6: MIRO

MIRO, the Mineral Industry Research Organisation is a UK-based international CLG set up by major minerals industry companies to manage innovative R&D for its members with external funding and is staffed by minerals industry experts with successful R&D management records. MIRO provided day to day administration for the project, controlling work cost and time limits as required by DEFRA and the industrial partners and providing material for dissemination of the project findings. It acted as Project Contact Point, submitted progress and final reports on behalf of the team partners and compiled and published this Final Project Technical Report and organised the dissemination of the project results.

1.3 PROJECT WORK PLAN

The key tasks of the work plan can be summarised as:

Task 1: Test Site Data Review (BGS, Lafarge, Hanson, MIRO)

Two sites have been chosen to demonstrate the use of 3D ERT as a means of providing operationally relevant survey information on known aggregate resources. These two sites contain features which limit the reliability of current intrusive methods for predicting the content and extent of the aggregate resource and for accurate planning of extraction operations.

Marfield near Masham, North Yorkshire, is a sand and gravel quarry, operated by Lafarge, where production started in 1961 and has been in continuous operation ever since. In the 1980s, plans were formulated to move extraction to land north of Marfield Wood. Several attempts were made to determine the form of the complex deposit by conventional borehole drilling. These attempts were both expensive and of only limited success, and in no case was the full thickness of the glacial deposits penetrated. The gravel deposit at Marfield displays a very wide range of particle sizes from small boulders to fine sand, it can be excess of 30 metres thick, and is complicated by the presence of a stiff glacial till with further granular material beneath. Limited trial pits identified that this latter material appeared to act as a confined or semi-confined aquifer. An accurate assessment of the volume and nature of a sand and gravel deposit is necessary for several reasons. To the commercial operator it is important to determine the financial viability of an extraction site, to design a safe and practical mining operation, and to design a suitable and deliverable restoration scheme. To the students of geology it is important to elucidate a complex and multi-episode glacial history in this part of Yorkshire.

Bull's Lodge near Colchester in Essex, is a sand and gravel deposit over London clay and covered by boulder clay. The site is operated by Hanson. High geological variability towards the edge of the deposit has previously led to poor production. A previous MIST project (MA/3/1/001) has been conducted at an area of this site to demonstrate the use of a mobile magnetometer array for survey work. Extensive data therefore already exists for parts of the site and use within this project will provide a lead-on from this previous work. Hanson has conducted a close spaced pre-production drilling operation within the study area; these data have allowed us to make a comparison between 3D ERT and the best achievable results from intrusive surveying.

The industrial partners provided access to these test sites so that the ability of the ERT method to image lithological structures and hydrogeological properties could be tested against existing geological ‘ground truth’ data. Hence, the geology at each site had already have been investigated in some detail and was represented by borehole and grading data. The industrial partner will make this site data available to the project as an in-kind contribution.

Task 2: Design of Field-Testing Programme (BGS, Lafarge, Hanson)

An individual survey plan was designed for each test site, which was controlled by site-specific factors such as lateral extent, cover, vertical and lateral heterogeneity and depth of investigation, as determined from the data review for each site. In addition survey design drew upon existing BGS expertise developed over many years of research in the field of ERT, and design parameters determined from the synthetic modelling studies. Electrical data have been collected along surface grid lines to provide high-resolution ERT data sets.

Task 3: ET Field Surveys and Intrusive Sampling (BGS, Lafarge, Hanson)

Electrical surveys were carried out consecutively at the two field sites. The field crew consisted of three people, and the measurements were undertaken using a highly portable multi-channel resistivity imaging instrument.

Additional intrusive samples were collected at one of the sites with the aim of providing improved geological control and ground-truth data sets that were contemporaneous with the ET surveys. In addition to conventional drilling and trial pitting, cone penetration tests were undertaken. This method is relatively cheap and rapid, and can provide direct resistivity measurements of the subsurface that will be enormously beneficial for validating the ERT models.

Task 4: 3D Modelling, Data Integration and Interpretation

Electrical models were generated using state-of-the-art 3D forward modelling and inversion software. BGS has developed procedures to display ERT data in a virtual 3D GIS environment alongside other relevant site-specific contextual information, such as lithological and geophysical borehole logs. BGS has considerable expertise in this area and has many relevant datasets that could be integrated with the electrical and intrusive site data.

Integration of 3D ERT images alongside other ground-truth data was used to constrain the interpretation and provide a robust assessment of model accuracy. Key indicators of ET model quality as assessed against ground-truth included overburden thickness, product thickness, depth to bedrock, depth to water table, and sand and gravel properties (grain size, clay content). This component of the project drew upon the findings of a parallel DTI Technology Progamme funded project (started in November 2006) which aimed to develop a software system capable of providing knowledge from ET images in a form that is easily usable by non-specialist quarry operators and is compatible with existing minerals industry software (e.g. LSS).

Task 5: Compilation of Best Practice Guidance Document and Cost Benefit Analysis

BGS has produced a ‘best practice’ guidance document and a ‘cost benefit analysis’ in consultation with all other project partners. These documents were be reviewed at a project workshop attended by project partners (BGS, Lafarge, Hanson, CEMEX, Tarmac, MIRO).

Task 6: Final Reporting and Dissemination of Results

BGS was responsible for final reporting in conjunction with MIRO, who were responsible for hard copy distribution and web publication. Dissemination activities will be undertaken by MIRO and BGS.

2 Context

2.1 OVERVIEW OF ERT

2.1.1 Background & rationale

ERT is probably the most significant geophysical methodology to have emerged in the last decade. It is used to generate models of subsurface electrical property distributions, from which subsurface geological structure and hydrogeological variations can be identified. This technique is analogous to medical imaging techniques, such as MRI and CT, which are used to image the internal structure of the body. In unconsolidated materials, such as sand and gravel, there is generally a relationship between grainsize and resistivity (with coarser materials being more resistive), and between water content and resistivity (with saturated materials being less resistive).

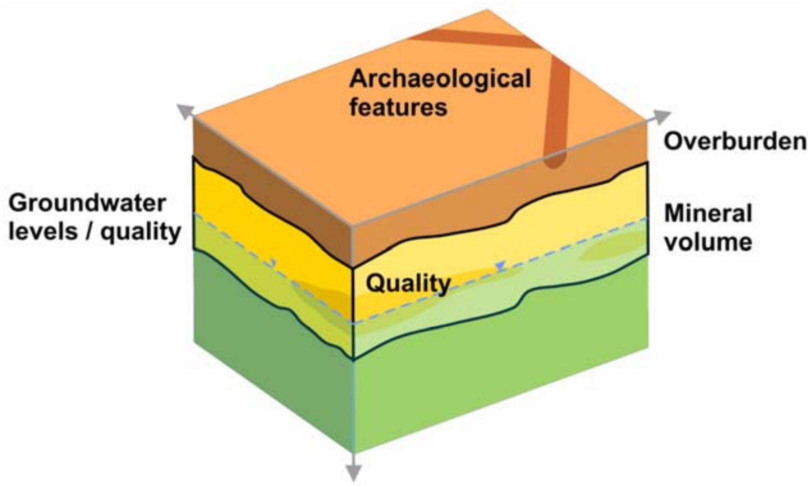

Figure 1. ERT imaging targets associated with sand and gravel deposits.

ERT is increasingly being used for environmental and engineering site investigations, but despite its suitability and potential benefits it has yet to be applied by the minerals industry to sand and gravel resource definition and assessment. The principal benefits of ERT are that it is a cost-effective non-invasive method that can provide fully 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 intervals, and other geophysical mapping techniques such as the EM31/34 or RM15, which cannot provide detailed depth information. The additional 3D spatial information provided by ERT will therefore enable an improved understanding of the deposit to be mined. We anticipate that 3D ERT has the potential to provide information of the thickness of overburden and the mineral deposit (if a sufficient resistivity contrast exists between the overburden, sand and gravel, and bedrock), quality variations within the body of the deposit, and information on the level and quality of groundwater (Figure 1).

2.1.2 Data collection & processing

Examples of ERT data collection and processing methodologies are given by Chambers et al. (2006), Slater et al. (2002), Chambers et al. (2002), and Dahlin et al. (2002), so only a brief description is provided here. ERT surveys involve making a large number of four-point electrical measurements (consisting of a current, C1-C2, and a potential, P1-P2, dipole) using computer controlled automated measurement systems and multi-electrode arrays (e.g. Figure 2). These data are used to produce 2D and 3D models of subsurface electrical property distributions, from which subsurface geological structure and hydrogeological variations can be identified. ERT surveys are entirely scaleable, and can be used to cover areas ranging from a few square meters to many hectares. For site-scale surveys (e.g. hectares) a typical field crew will consist of between two and five people. The equipment is lightweight and portable and can be deployed from an estate car or 4×4 vehicle. Most of the costs associated with ERT field surveys are due to staff time.

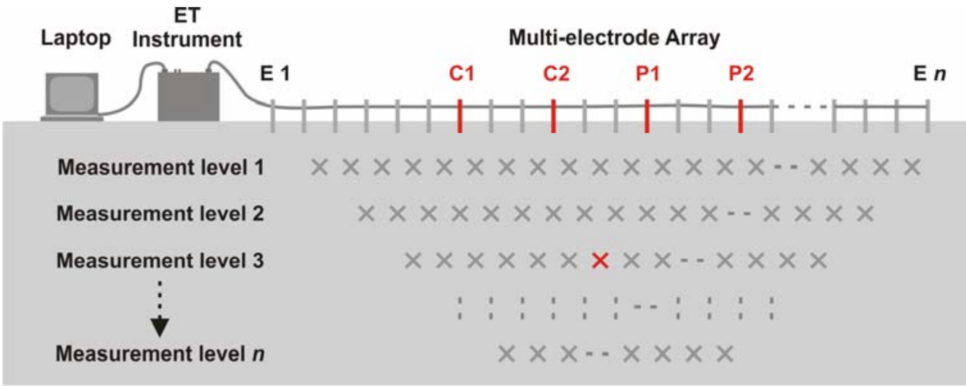

Figure 2. Schematic illustration showing the basic components of an ERT surface survey.

To generate resistivity models, or *images*, from the field measurements data inversion is undertaken; this is typically achieved by using regularised nonlinear least-squares algorithms (Loke and Barker, 1996) in which the forward problem is solved using either finite element or finite difference methods. In brief, the aim of the inversion process is to calculate a model that satisfies the observed data. A starting model is produced, e.g. a homogeneous half-space, for which a response is calculated and compared to the measured data. The starting model is then modified in such a way as to reduce the differences between the model response and the measured data; these differences are quantified a misfit error value. This process continues iteratively until acceptable convergence between the calculated and measured data is achieved, or until the change between misfit values calculated for consecutive iterations becomes insignificant.

2.1.3 Application to sand & gravel

Prior to the development of ERT, DC resistivity investigations of sand and gravel deposits were undertaken using 1D resistivity soundings and traverses. Auton (1992) and Crimes et al (1994) provide examples of 1D resistivity methods. Auton (1992) describes the use of 1D soundings for studying drift sequences in northeast Scotland, for which he concluded that the technique was a useful adjunct to conventional sampling. Crimes et al (1994), however, concluded that the accuracy of the technique was too poor to be of general use for sand and gravel exploration; they studied a range of sites in England and Wales and found that overburden thickness and depth to bedrock were overestimated by 39 % and 34 % respectively, and mineral thickness was underestimated by 29 %. In general, 1D resistivity methods have not been widely adopted by the minerals industry due to the significant uncertainties associated with data interpretation; in particular, 1D soundings tend to be more severely affected by the problems of non-uniqueness, three-dimensional features and small-scale heterogeneities described in Section 2.3.

It is curious to note that despite significant development in ERT over the past two decades, 1D soundings and traverses are still referred to in Smith and Collis (2001) and the most recent code of practice for site investigation (British Standards Institution, 1999) as being the principal DC resistivity methods for site investigation; ERT is mentioned only in passing, and in the case of Smith and Collis (2001) is described as being “almost completely superseded by electromagnetic conductivity surveying”. It is clear in this instance that there is a significant lag between developments in the research community and awareness and take-up by both industry and geoscientists from other disciplines. This problem has probably been compounded by the relative lack of published case studies; this is perhaps been due to the focus of ERT research tending towards environmental, archaeological and engineering applications, rather than minerals.

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. Baines et al. (2002) applied 2D ERT with the stated aim of assessing its use for investigating aggregate resources, and in particular sand and gravel channel belts and valley fills. They considered sites in the Netherlands, United States and Canada. Beresnev et al. (2002) also sought to develop 2D ERT for sand and gravel prospecting, and used test sites in Iowa, United States to study glacio-fluvial deposits occurring as terraces and point bars. More recently the USGS have released a report titled "An Introduction to Using Surface Geophysics to Characterize Sand and Gravel Deposits (Lucius et al., 2006), which includes a brief assessment of ERT for deposit evaluation; examples of 2D ERT models are presented.

In addition to work focussed specifically on sand and gravel aggregate resource assessment, a number of researchers have considered ERT for the more general, but nevertheless relavent, application of investigating unconsolidated Quaternary deposits (e.g. Froese et al., 2005; Kilner et al., 2005; Revil et al., 2005; Turesson et al., 2005)

2.2 UK SAND AND GRAVEL

2.2.1 Types & occurrence

Information relating to UK sand and gravel deposits can be gathered from a wealth of sources. Of particular interest is the Geological Society publication, titled 'Aggregates: Sand, gravel and crushed rock aggregates for contruction purposes' edited by Smith and Collis (2001), in which can be found a thorough overview of the types and occurrences of sand and gravel resources of the UK; much of the information in section is based on this publication. Other useful reviews at a regional and national level are given by Merritt (1992), and are contained in the British Geological Survey (BGS) sheet memoirs (e.g. Bristow, 1990) and regional geology series (e.g. Sumbler, 1996). More detailed descriptions at the 1:25,000 scale are provided in the 'Sand and Gravel Resources – Mineral Assessment Report' series (e.g. Hawkins, 1981), which covers the key sand and gravel extraction areas in the UK and contains information regarding the quality and quantity of deposits. The more recent 'Mineral Resource Information in Support of National, Regional and Local Planning' series (e.g. Harrison et al, 2003) also contains useful summary information of sand and gravel deposits, in this case at a county level.

The most significant on-shore sand and gravel sources are found within unconsolidated superficial drift deposits, and in particular, those of a fluvial origin, such as alluvial and river terrace deposits. Glacial drift is also a crucial source of aggregates in certain areas. Coastal deposits such as beach gravel or raised beaches are of lesser importance. Likewise, solid formations, though being of local importance, contribute relatively little to the overall UK supply of sand and gravel aggregates.

Sand and gravel is a low value bulk mineral; consequent local sources will be used whenever possible to reduce transport costs. Fortunately, UK sand and gravel aggregate deposits are widespread, as summarised in following paragraphs and in Figure 3.

2.2.1.1 FLUVIAL DEPOSITS

Fluvial deposits include river channel or alluvial deposits, river terraces and alluvial fans. In general these deposits have relatively little overburden, and are more consistent with lower fines content than glacial deposits. Water levels will vary depending on their location, e.g. those in existing river valleys typically have high water tables.

Perhaps the most significant river channel deposit in the UK is the Kesgrave Formation, which extends across large areas of Suffolk. Strategically important river terrace deposits include those of the Thames and Trent valleys.

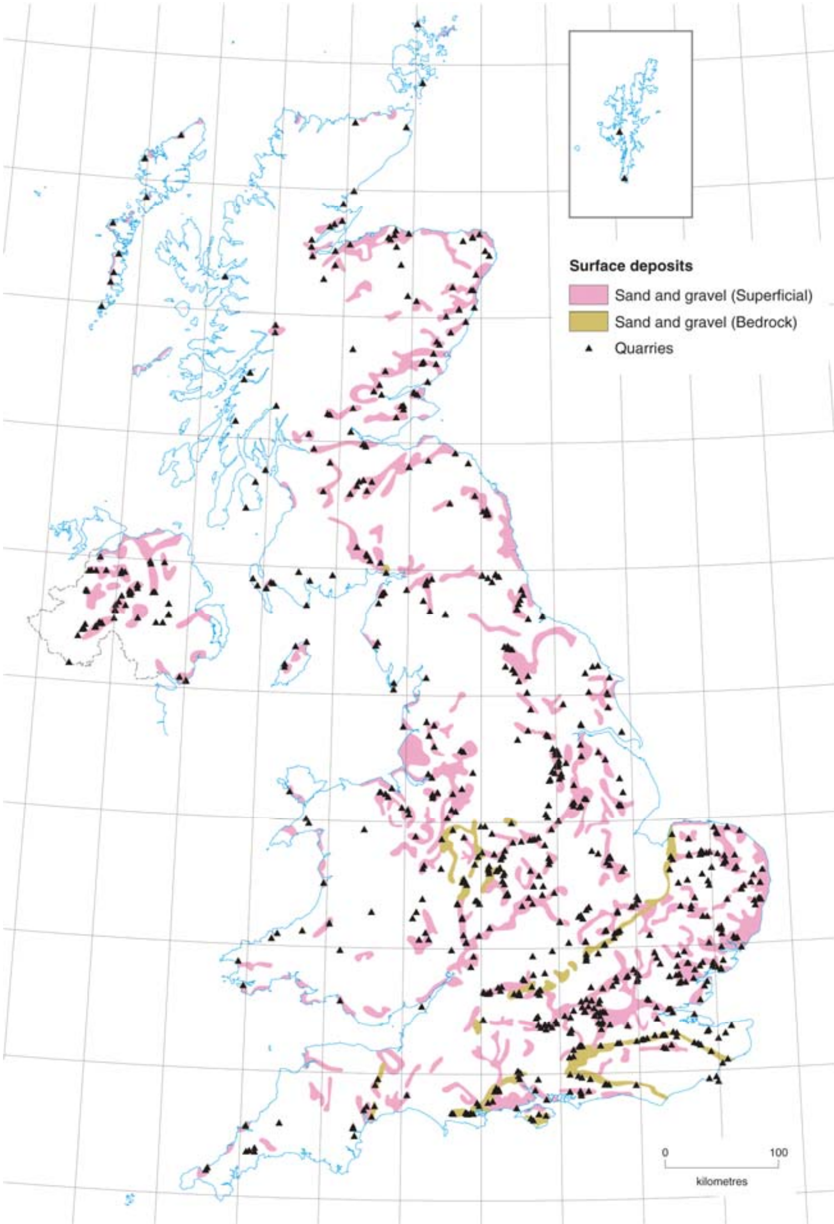

Figure 3. Distribution of sand and gravel in the UK (BGS © NERC 2008).

2.2.1.2 Glacial Deposits

Glacial deposits are typically heterogeneous, with greater potential for variations in particle size, shape and composition, and in deposit thickness and extent. Glacial deposits from outwash plains (sandars) and kames, eskers and kame terraces tend to provide the most significant opportunities for sand and gravel extraction. Till and morainic drift are of lesser importance.

Examples of economically significant esker and kame systems are found in the Carstairs area, Lanarkshire, whilst glaciodeltaic deposits are found throughout the Scottish Highlands (e.g. Brackletter, near Fort William). Glaciofluvial sandar and fans can be found in upland (e.g. Wrexham, Clwyd) and lowland areas such as the Midlands and East Anglia. Moreover, the large spreads of 'Plateau Gravel' in central southern England probably includes a glaciofluvial component. Other glacial sand and gravel sources worthy of note are periglacial deposits, which are generally found beyond the southern limits of the Devensian glaciation, and head deposits, such as the Downwash Gravel, near Aldershot and the gravely head near Chelmsford, Essex.

2.2.1.3 Coastal Deposits

Coastal deposits are defined as having been laid down between low tide and the storm beach of permanent water bodies. Existing deposits, such as ridges and bars, must be exploited with extreme caution to prevent unwanted consequences, such as an acceleration or deleterious change in prevailing patterns of coastal erosion.

Raised beaches and deltas, no longer associated with the present day coastal system, are less problematic and can present useful sources of aggregates. Raised beaches are particularly common in Scotland, due to the uplift of the landmass resulting from the melting of the glacial ice. Late glacial beaches can be found in the firths of Tay and Forth, Ayrshire, whilst deltaic deposits are found in areas such as Beauly, Inverness-shire. In England, examples of raised beach deposits are found in the Fens, e.g. Market Deeping, Lincolnshire and March, Cambridgeshire.

2.2.1.4 Solid Formations

The most useful solid formation sources of sand and gravel aggregate come from deposits laid down during periods of regression and transgression, and from deltas and fans. Transgressive episodes have produced basal pebble beds, such as the Tertiary Blackheath Beds, North Surrey. On the other hand, beach plain gravels as exemplified by the Pliocene Westleton Beds, Suffolk, were laid down during periods of regression. Other significant solid formation aggregate sources include the 'Bunter' Pebble Beds of the north Midlands, and the Budleigh Salterton Beds of Devon, both of which are Triassic in age and were formed as deltas or fans.

2.2.2 Thickness

Information on sand and gravel thickness is contained in the individual reports of the 'Sand and Gravel Resources – Mineral Assessment Report' and 'Mineral Resource Information in Support of National, Regional and Local Planning' series, as well as numerous publications including journal papers, BGS memoirs and site investigation reports. However, to the best of our knowledge there is no summary of deposit thickness variations for UK sand and gravel deposits. Therefore, we have conducted a review of the reports comprising the 'Mineral Resource Information in Support of National, Regional and Local Planning' series to extract and summarise thickness variations for the various deposit types found in the UK by region (Appendix 1). In brief, of those deposits for which depth information was collected 70 % were less than 10 m thick, and 92 % were less than 20 m thick. River terrace deposits fall almost entirely within the 'less than 10 m' thickness range. Glaciofluvial deposits are generally thicker, with a majority of deposits being characterized by thicknesses in the '10 to 20 m' range, with a lower occurrence of those in '0 to 10 m' range. Only a few deposits fell within the '20 to 30 m' and 'greater than 30 m' ranges.

2.2.3 Electrical properties

In his paper on the application of electrical methods to sand and gravel resource assessment in Scotland Auton (1992) makes the very valuable point that for the correct interpretation of resistivity data good geological control is required. Indeed, it is likely that the resistivity values of sand and gravel deposits across the country will vary significantly depending on the geology of the source area. Auton's own results demonstrate that sand and gravel from southern Britain often tends to be less resistive "…being derived from ice that moved across ground underlain by soft argillaceous bedrock, rather than hard gritty igneous and metamorphic rocks as in Grampian region" (Auton, 1992, p26).

Data for the UK linking the geology and electrical properties of sand and gravel deposits with economic potential are relatively sparse, and so at present we have relatively little information to help us determine the likely resistivity ranges that we are likely to encounter for sand and gravel, bedrock and overburden material in different parts of the country. This information is critical in helping us predict the likely usefulness of ERT as a tool for sand and gravel resource assessment. To bring together the currently available information we have undertaken a review of published and unpublished literature that deals with the resistivity sand and gravel. Our review is however limited to those references concerned with UK deposits of known economic potential; in general these deposits will consist of relatively clean sand and gravel with a low fines/clay content; uneconomic deposits with high fines contents would generally be characterized by lower resistivities and are not considered in this report. Due to the paucity of resistivity data for many important sand and gravel resources in the UK we have also undertaken a number of pre-validation field trials to assist us in validation site selection, and to increase our knowledge base of UK sand and gravel electrical properties.

2.2.4 Conventional evaluation

Potential sand and gravel reserves are evaluated by the minerals industry using conventional methods, which include desk studies, direct investigation using boreholes and trial pits, and material testing to establish particle size distribution and lithology.

The aim is to provide an accurate geological model of the site which details:

- The thickness and type of overburden
- The thickness and type of mineral
- The depth to the base of the mineral
- The quality of the mineral
- The position of the watertable

Overburden and mineral thickness are normally modelled to provide isopachyte maps and the accuracy of these, and therefore subsequent volume calculations, depends upon the quality of the information used to provide the base data. Direct methods, such as boreholes provide accurate depths to the relevant lithological interfaces at widely spaced points. Current practice is to provide borehole data on a 100 m grid, with additional boreholes in some cases. However the modelling usually assumes a consistent gradient on the interface between the data points. This can provide an oversimplified or at worst inaccurate model of the interfaces and lateral variations across the site. Consequently the essential volume calculations based on these models can be unreliable.

An accurate assessment of the volume of overburden and mineral, and their distribution across the potential extraction area, is an essential pre-requisite for a mineral reserve assessment and therefore additional information to improve the accuracy and reliability of the geological model can be invaluable.

2.3 PREVIOUS STUDIES

2.3.1 1D soundings

Resistivity data from the Grampian region of Scotland, produced from the interpretation of 1D resistivity soundings, are presented by Auton (1992) and Auton et al. (1988). The bedrock in the study area consisted of Dalradian metasediments and Old Red Sandstone sediments. These were characterized by resistivities of 400 to 10 000 Ωm, with mean resistivities of between 1000 and 2000 Ωm. The fluvio-glacial and glacial sand and gravel of the area displayed a similar resistivity range, with a mean resistivity of approximately 2000 Ωm. The till/morainic drift had saturated resistivities of 18 to 60 Ωm, and unsaturated resistivities of 100 to 300 Ωm. Auton (1992) also presented data from a number of unspecificied locations in the West Midlands (Wolstonian in age) and in East Anglia (Anglian in age). The data showed for both areas a significant difference, of approximately one order of magnitude, between the sand and gravel and the associated till; sand and gravel resistivities were generally a few hundred Ωm, whilst till resistivities were a few tens of Ωm.

Crimes et al. (1994) described resistivity sounding data collected in the Warwick-Leamington area. Model resistivity values interpreted from 1D sounding curves for the sand and gravel were generally above 100 Ωm; the marl bedrock was characterized by resistivities of less than 25 Ωm.

A geophysical investigation of a potential sand and gravel site is described in a University of Leicester MSc thesis by Chambers (1997). The site was situated between Fairford and Cricklade in the Thames Valley. A typical geological section through the site consisted of less than a metre of soil overlying 1 to 3 m of River Thames sand and gravel, which rested on Oxford Clay. The First, Second and Third Terrace sand and gravel were present within the study area. The water table was observed to vary between 0.8 and 1.9 m below ground level across the site. Overburden resistivities ranged from 16 to 61 Ωm, with an average of 37 Ωm. Sand and gravel resistivities varied between 69 and 325 Ωm, with an average of 183 Ωm. The Oxford Clay displayed a narrow range of resistivities of 8.6 to 14.5 Ωm, with an average of 12 Ωm.

2.3.2 2D ERT

Barker (1997), in his review of a number of applications of ERT, presented a 2D ERT section through a sand and gravel deposit at Hoveringham in the Trent Valley. The ERT line was located adjacent to an operational sand and gravel quarry. Borehole data indicated a local sand and gravel thickness of approximately 6 m, below which was an indeterminate thickness of Triassic Mercia Mudstone bedrock. Sand and gravel resistivities varied from approximately 150 to more than 500 Ωm; Mercia Mudstone resistivities were generally below 100 Ωm.

2D resistivity surveys of a site a few kilometres to the north of Chelmsford are described by Hill (2004) and Jeffrey et al. (2005); this work was funded by the 'Mineral Industry Sustainable Technologies' fund and industrial partners. The site was adjacent to an operational sand and gravel quarry. The sand and gravel, which was between 5 and 10 m thick, was covered by 0 to 15 m of Boulder Clay, and was underlain by London Clay. No information was provided on the depth to the water table. The 2D resistivity sections indicated that sand and gravel resistivities varied from 150 to 500 Ωm. The Boulder Clay and London Clay displayed very similar resistivities, both less than 50 Ωm, with an average of approximately 20 Ωm.

Several 2D ERT surveys were conducted by the BGS as part of TARGET, a parallel project to develop a non-invasive visualisation and evaluation technique for complex sand and gravel deposits. This was funded by a grant from the DTI Technology Programme and contributions from industrial partners. Five different sites were chosen throughout East Anglia and the East Midlands that represented a range of geologies associated with typical UK sand and gravel deposits (Chambers et al., 2008a). The results of the surveys are summarised below.

2.3.2.1 INGHAM, SUFFOLK

The Ingham Sand and Gravel (pre-Anglian) is underlain by the Upper Chalk and overlain by Boulder Clay (Anglian), glacial sand and cover sand. This site represents a relatively complex geology for an economic aggregate deposit, with overburden and mineral thickness varying substantially over small distance. Furthermore, the level of Chalk bedrock surface varies significantly within the site. Borehole logs indicate that the water table is located somewhere within the sand and gravel.

The resistivity of the sand and gravel varies from 150 to 300 Ωm (Figure 4). The Boulder Clay resistivity ranges from 15 to 50 Ωm, whilst the Upper Chalk displays resistivities of 50 to 100 Ωm.

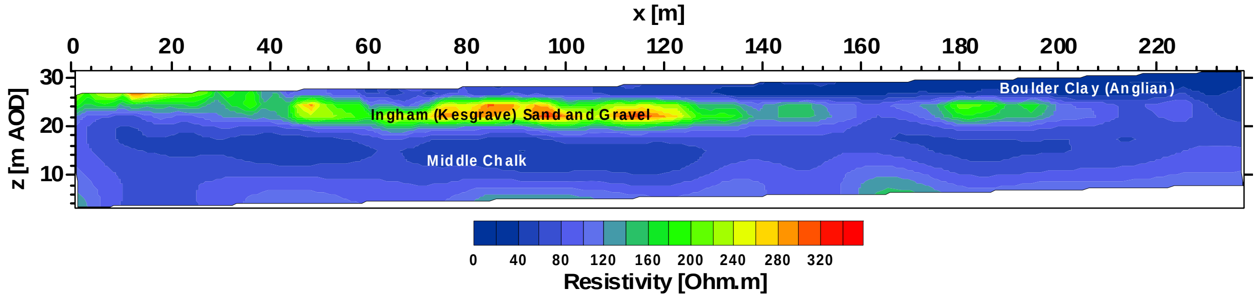

Figure 4. Ingham 2D ERT section, misfit error 0.9 % rms (TARGET project).

2.3.2.2 Norton Disney, Lincolnshire

The Norton Disney site is underlain by Lower Lias Clay bedrock (Late Triassic / Early Jurassic), over which are Quaternary River Terrace Sand and Gravel deposits. The site represents an *ideal* sand and gravel deposit, due to its regular nature. Groundwater level data from nearby boreholes indicate that the water table at the site is likely to be towards the base of the sand and gravel.

The 2D ERT section (Figure 5) reveals a bedrock resistivity of 15 to 30 Ωm, whilst the sand and gravel shows a range of resistivities from 500 to 1200 Ωm.

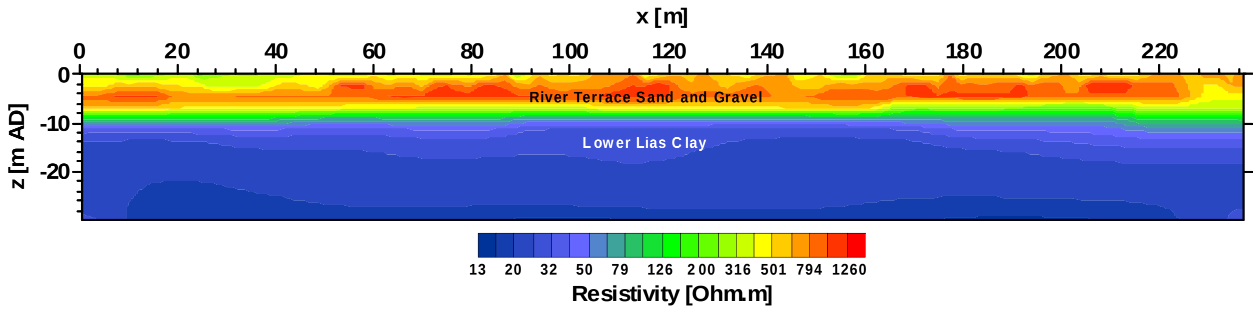

Figure 5. Norton Disney 2D ERT section, misfit error 2.5 % rms (TARGET project).

2.3.2.3 Broom, Bedfordshire

The Broom sand and gravel (Pleistocene) is glacio-fluvial in origin, with little variation in thickness across the survey area. The overburden consists of a few tens of centimetres of topsoil. The sand and gravel is underlain by an indeterminate thickness, thought to be several meters, of Oxford Clay (mid-late Jurassic), which in turn is underlain by the early Cretaceous Woburn Sands Formation (previously referred to as 'Lower Greensand'). The water table recorded nearby boreholes is within the sand and gravel at between 2 and 4 m below ground level.

Bedrock resistivities ranged between 12 and 25 Ωm, indicating that the model resistivities are dominated by the response of the Oxford Clay, rather than the Woburn Sands. Sand and gravel resistivities vary from 100 to 400 Ωm.

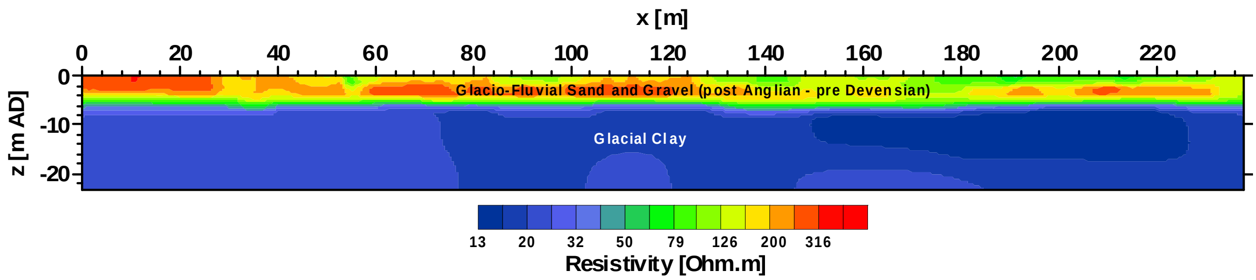

Figure 6. Broom 2D ERT section, misfit error 2.7 % rms (TARGET project).

2.3.2.4 WIMBLINGTON FEN, CAMBRIDGESHIRE

The Wimblington Fen site was covered by a few tens of centimetres of peat, underneath which is the March Gravel (Quaternary), and the Ampthill Clay (Jurassic). The water table at the site was less than 1.5 m below ground level, as indicated by the water levels in the drains. The 2D ERT section indicated an undulating bedrock surface.

The Ampthill Clay bedrock was characterized by very low resistivities of 5 to 10 Ωm. Likewise, the sand and gravel also displayed low resistivities of 30 to 85 Ωm, possible indicating the presence of a significant proportion of clay minerals.

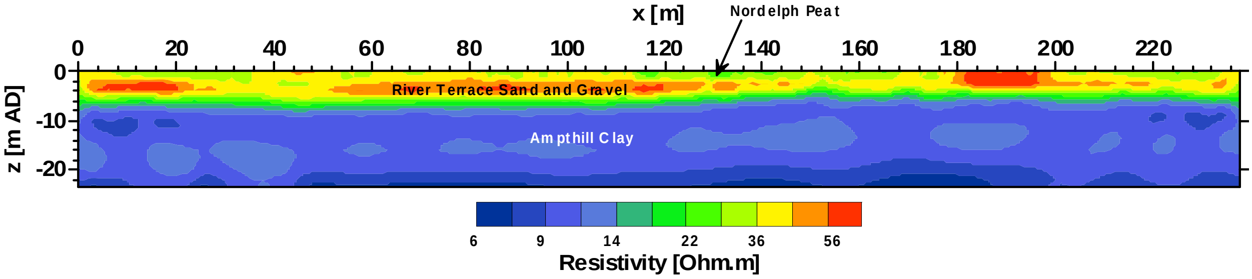

Figure 7. Wimblington Fen 2D ERT section, misfit error 0.9 % rms (TARGET project).

2.3.2.5 TRAFFORD ESTATE, NORFOLK

The Trafford Estate is underlain by Upper Chalk (Cretaceous) bedrock. The sand and gravel consists of Pleistocene glacial-fluvial deposits with Norwich Brickearth interburden. Part of the survey area has a cover clays silts and sands described as Quaternary Brickearth deposits. The water table at the site is thought to be within the Chalk, below the level of the sand and gravel.

Upper Chalk resistivities ranged from 50 to 100 Ωm. The sand and gravel displayed a range of resistivities from 200 to 700 Ωm. The overburden was characterized by resistivities of 15 to 100 Ωm.

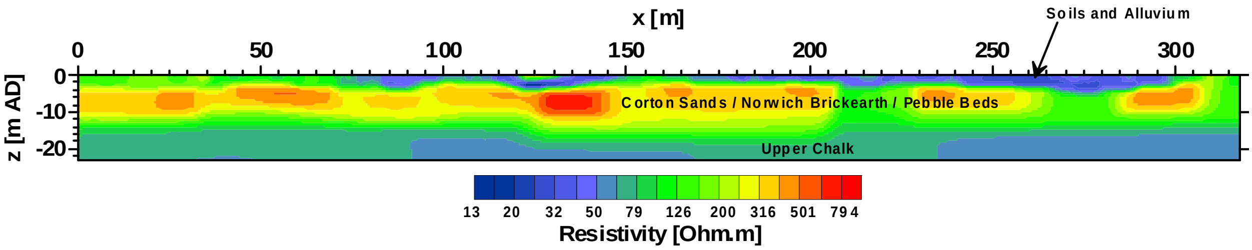

Figure 8. Trafford Estate 2D ERT section, misfit error 2.8 % rms (TARGET project).

2.3.3 3D ERT

2.3.3.1 HOLME PIERREPONT, NOTTINGHAM

The BGS undertook a number of ERT surveys at a sand and gravel quarry, near Holme Pierrepont, Nottingham during 2003; the investigations were designed to assess the usefulness of ERT for determining sand and gravel thickness at the site. The surveys were located in an area of the quarry where the overburden had already been stripped. Due to pumping at the site, the water table was known to be below the level of the sand and gravel. The sand and gravel were Trent Valley river terrace deposits, and were underlain by Triassic Mercia Mudstone bedrock. Sand and gravel resistivities ranged from approximately 500 to 2000 Ωm. Bedrock resistivities were generally less than 50 Ωm.

2.3.3.2 TARGET VALIDATION SURVEYS

Under the recently completed TARGET project two 3D ERT surveys (Chambers et al., 2008c) were undertaken to validate the TARGET visualisation methodology (see Section 5.4.2). The TARGET visualisation procedure accommodates two approaches, one of which is tailored to the investigation of simple geologies, and the other is designed for use when investigating more complex and heterogeneous subsurface conditions. A site with relatively simple geology (Norton Disney) and a site with significant geological complexity (Ingham) were investigated during the validation phase; hence, both aspects of the visualisation procedure were demonstrated. For both sites visual output in the form of 2D surfaces that defined bedrock/mineral interfaces (and also in the case of Ingham, mineral/overburden interface) was generated in a form that could be directly input into the industry standard terrain modelling software (i.e. LSS).

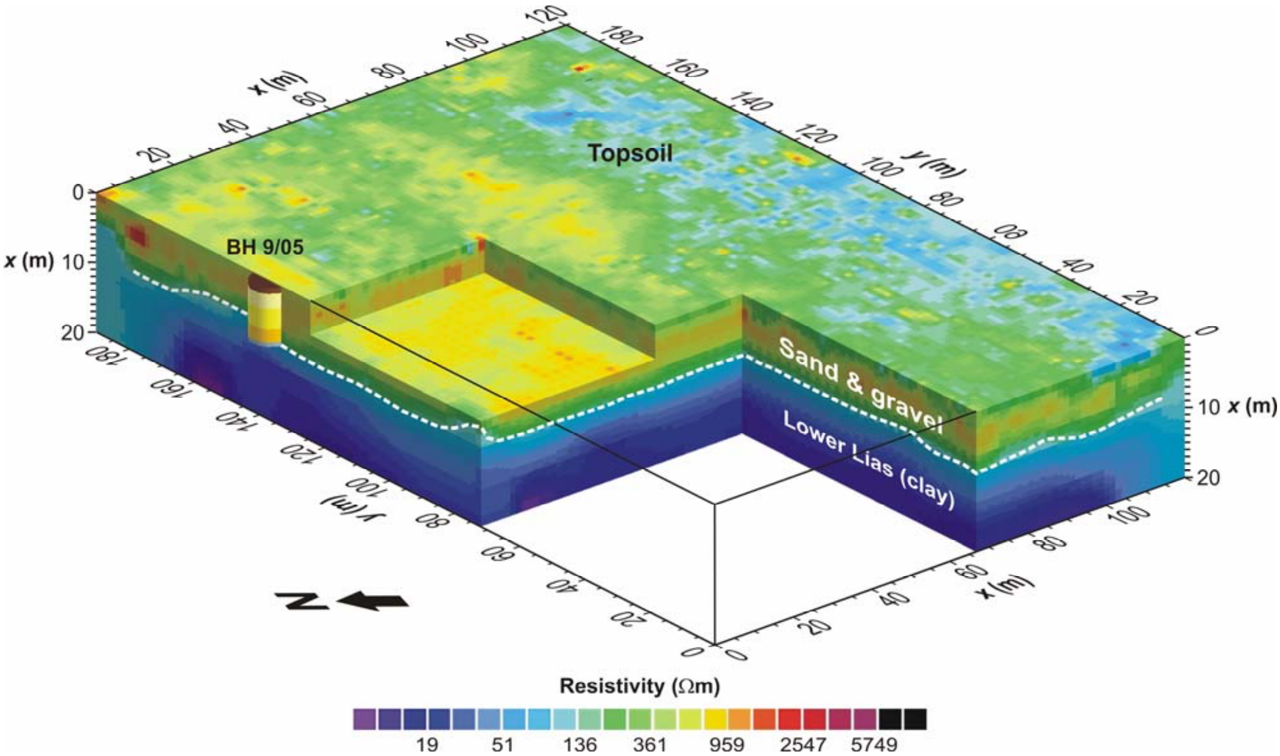

Figure 9. Integrated Norton Disney 3D ERT model.

The Norton Disney survey (Figure 9) was successful in demonstrating the simple TARGET methodology and the use of an automated bedrock detection approach using borehole information to calibrate the electrical model.

Ingham (Figure 10) was a site on which the TARGET approach to the investigation of complex deposits proved to be particularly valuable. Four phases of drilling were required to adequately characterise the geological complexity of the site. The early application of 3D ERT could have significantly reduced the number of holes needed, and would have permitted more effective targeting of any holes that were drilled. We also demonstrated that 3D ERT was able to detect significant structures and quality variations (e.g. channels) that were not detectable using boreholes alone.

The resistivity properties for the deposits at the Ingham and Norton Disney sites are summarised in the descriptions of the 2D ERT reconnaissance surveys described in Sections 2.3.2.1 and 2.3.2.2 respectively.

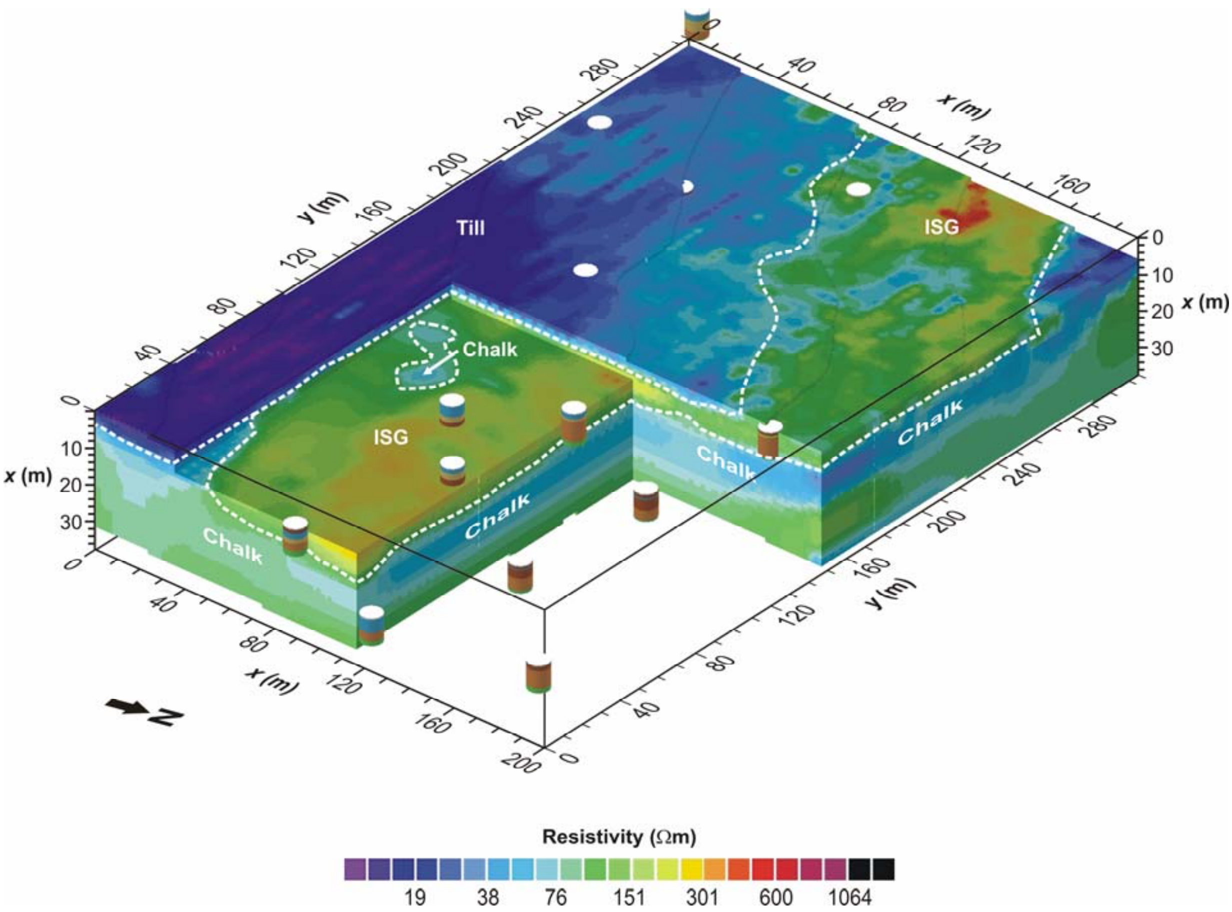

Figure 10. Integrated Ingham 3D ERT model.

3 Case Study – Marfield Quarry, North Yorkshire

3.1 SITE DESCRIPTION

3.1.1 Location and Background

The site is located 2.5 km to the northwest of the village of Masham, North Yorkshire, and is bounded to the east by existing Lafarge sand and gravel workings. The grid reference of the site is 421030 E, 482740 N. The site is currently used as arable land, but forms part of the reserves of Marfield Quarry; consequently, sand and gravel extraction is due to begin at the site in the near future.

Figure 11. Aerial view of the Marfield Quarry ERT survey area (© UKP/Getmapping Licence No. UKP2008/01).

3.1.2 Intrusive Investigations

The land immediately adjacent to the survey area has been worked for sand and gravel for many years, and consequently ground truth data collected in the vicinity of the site, in the form of borehole logs, has been made available to us. This area has posed a particular problem for drilling due to the prevalence of large cobbles and boulders, which often lead to refusals. As a result borehole data is relatively sparse and of variable quality. Nevertheless, drilling of the site has been carried out in a number of phases over the lifetime of the quarry, and includes a location (BB1) a short distance to the northwestern corner of the survey area. Borehole BB1 (Figure 11) reveals the presence of 4.5 m of overburden, beneath which gravel extends to a depth of at least 17 m below ground level; bedrock is not proven. In addition, inspection of the working faces of the quarry a short distance (~20 m) to the east the site has been possible (Figure 12).

A mineral assessment reports also covers the area of the survey (Giles, 1982), and includes additional borehole information.

Cone penetration tests (CPT) were commissioned under the DRAGNET project. These tests were unsuccessful due to extremely poor weather and ground conditions, and refusals caused by cobbles and boulders.

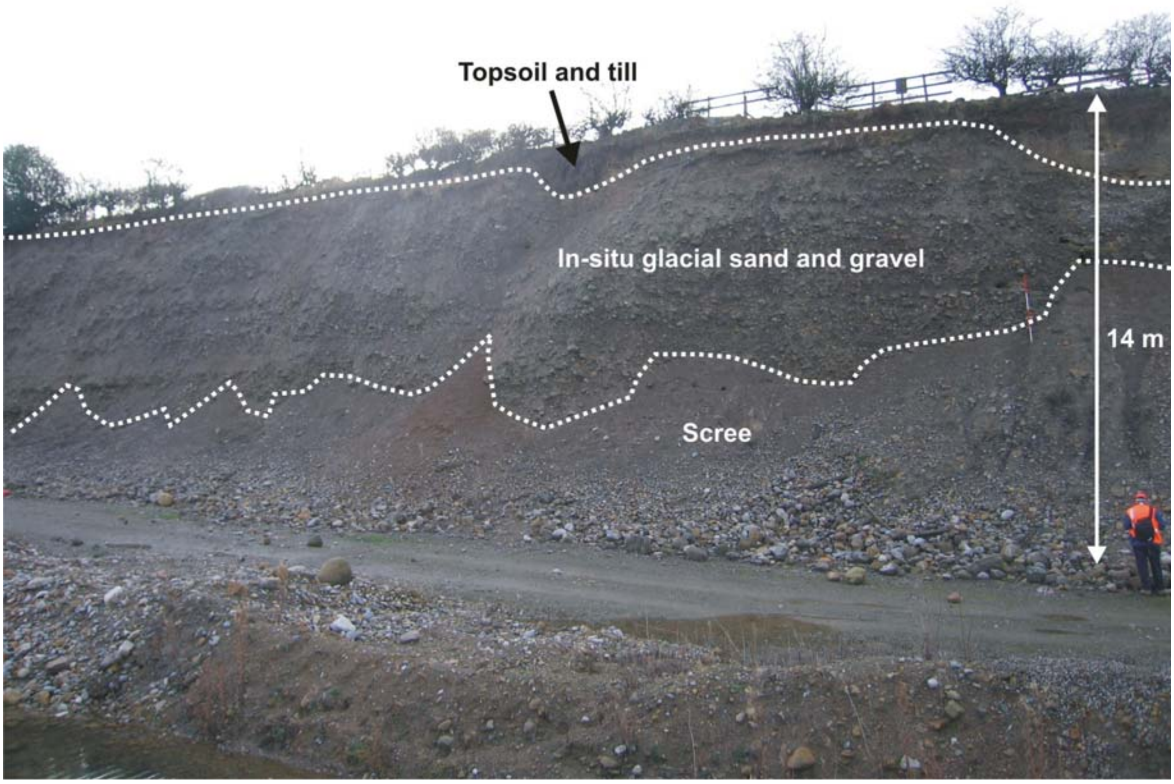

Figure 12. Marfield Quarry working face adjacent to ERT survey area (see Figure 1).

3.1.3 Geology

The bedrock in the area of the survey consists of Namurian sandstone or mudstone formations (Carboniferous). The bedrock is likely to be overlain by a few meters of either till or glacial lake deposits of clay and silt; these deposits are not laterally continuous and so could be absent within our survey area. Nearby boreholes (Giles, 1982, boreholes SW9 and SW11), within 600 m of the ERT survey area, encountered between 2.6 and 3.4 m of tills overlying Namurian Sandstone. Fluvio-glacial sand and gravel overlies the lake deposits and bedrock. In the area of the quarry they appear as pebble and cobble sized gravels with a sand matrix. Giles (1982) reports than sand lenses, cross bedding and channel structures are common within these deposits. The gravels are overlain by a variable cover of clay till. Topsoil appears to be only a few tens of centimetres thick.

3.1.4 Hydrogeology

At the time of drilling BB1 (Figure 11) was recorded as a dry hole, indicating a water level below 17 m below ground level. Communications with the Lafarge geologist for Marfield Quarry (K.

Blackburn) have indicated that in the area of the ERT survey water levels were likely to coincide with the base of the sand and gravel, with flow following the dip of bedrock from west to east.

3.2 FIELD SURVEY

3.2.1 Surface Conditions

At the time of the 3D ERT survey the surface of the site (Figure 13) was covered in turnip stubble, and the site was clear of trees and established bushes. The topsoil was moist and was ideal for the installation of ERT electrodes.

3.2.2 Survey Design

The 3D ERT survey was carried out within an area of 120 m by 260 m (2.27 hectares); we refer to the short axis of the survey area as x, and the long axis as y. A summary diagram of the survey grid is shown in Figure 11, with the ERT lines shown in blue. The origin ($x = 0$ m, $y = 0$ m) of our local ERT survey area was located in the top eastern corner of the field (Figure 11). The survey lines were 260 m long, striking in a southeasterly direction, and were positioned at 10 m intervals, resulting in a total of thirteen lines. An along-line electrode separation of 5 m was used for all survey lines.

The dipole-dipole array with dipole sizes (a) of 5, 10, 15, 20 and 25 m, and dipole separations (n) of $1a$ to $8a$ was used; full sets of reciprocal measurements were collected for each line.

Figure 13. Photograph of Marfield Quarry site during the November 2007 ERT survey. Looking north-north-west.

3.2.3 Field Operations

A pre-survey visit to the site was completed on the 31st October. The purpose of the visit was to establish the corner points of the grid, which were marked using wooden stakes, and to undertake a high resolution topographic survey (i.e. 20 m grid) of the area. A Leica SmartRover GPS was used for this survey work.

The field survey was completed on the 5th and the 6th November 2007, with a field crew of three (J E Chambers, A L Weller and J Williams). Tape measures strung between the stakes were used to mark out our survey lines. Individual electrode positions were read directly from the tape measures. The field procedure can be summarised as follows:

(a) Position tape measure for survey line 1 (L1);
(b) Install electrodes at 5 m intervals;

(c) Connect multi-core cable to electrodes;
(d) Connect multi-core cable to AGI Sting ERT instrument;
(e) Perform contact resistance test to identify electrodes with poor contact with ground;
(f) Check electrodes with poor ground contact (i.e. reposition electrode or re-clip electrode);
(g) Run predefined measurement set;
(h) Whilst measurement set for L1 is being collected position tape measure for line 2 (L2);
(i) Upon completion of measurement set for L1, move line (cable & electrodes) to position L2;
(j) Repeat stages (e) to (i) until survey is completed.

Weather conditions were good during the survey with no significant rainfall and moderate wind.

The field ERT survey time (i.e. total time on site) was 16 hours. The measurement time (i.e. time taken for ERT instrument to collect the data) was 10 hours. The difference between the field survey time and the measurement time is due to the time taken to survey in the survey area, set up ERT survey lines and to run contact resistance tests. Field survey time for this survey design could be slightly reduced by using a larger field crew (e.g. four members) and additional cable sets, although efficiency in terms of area covered per man day would not be improved; measurement time could only be reduced by using a different ERT system with more than eight measurement channels, of which there are very few on the market, or by altering measurement parameters, which would reduce data quality.

3.3 DATA PROCESSING

3.3.1 Data Editing

The combined dataset from the thirteen survey lines comprised a total of 17 420 reciprocal pairs. Reciprocal measurements provide the most effective means of assessing data quality and determining reliable and quantitative data editing criteria. Reciprocal error is particularly effective for assessing error due to high contact resistances, random errors arising from the resistivity instrument and sporadic errors due to background noise (Slater et al., 2000). For a normal 4-electrode measurement of transfer resistance (R_n) the reciprocal (R_r) is found by interchanging the current and potential dipoles. Reciprocal error $|e|$ is defined here as the percentage difference between the normal and reciprocal measurement.

$$|e| = 100 \times \frac{2|R_n - R_r|}{R_n + R_r}$$

Analysis of the reciprocal errors showed that more than 94 % of the normal and reciprocal measurement pairs had an associated error of less than 5 %. Measurements with a reciprocal error of more than 5 % were removed; the remaining reciprocal pairs were averaged prior to inversion.

Contact resistances recorded during the field survey typically ranged from 1 to 5 kΩ. These represent relatively high contact resistances. The consequence of high contact resistances is that less current can be injected into the subsurface, which can reduce signal-to-noise.

3.3.2 Numerical Inversion

Edited survey data collected from the individual lines were concatenated into a single data set comprising 16 362 individual apparent resistivity measurements.

The 3D ERT field data were inverted using the L_1-norm implementation (Loke and Lane, 2002) of the regularized least-squares optimization method (Loke and Barker, 1996), in which the forward problem was solved using the finite element method, so that topographic data could be incorporated into the inversion process.. The L_1-norm (robust) optimization method minimizes the sum of absolute values of the changes in model resistivity and was used in preference to the L_2-norm (smoothness constrained) method, which minimizes the sum of squares, as it provides significantly better results for situations where there are sharp boundaries (Loke et al., 2003). In this case the geology was dominated by the relatively sharp interface between the resistive sand and gravel and the more conductive basal deposits and bedrock.

The final resistivity model consisted of 24 cells in the *x*-direction, 52 cells in the *y*-direction and 11 layers in the *z*-direction, resulting in a total of 13 728 model cells. Good convergence between the observed and model data was achieved after 6 iterations, as indicated by absolute error of 1.7 %.

3.4 VISUALISATION & INTERPRETATION

3.4.1 Integrated 3D Display

The Marfield Quarry 3D resistivity model output from RES3DINV has been gridded using a node spacing of 1.25 m in the *x, y* and *z* directions, resulting in a model comprising 885 900 voxels. Interpolation was carried out using an inverse-distance method, by which a weighted average of the closest data point from each 90^{o} sector around each node was calculated.

RockWorks2006 has been used to display the gridded and interpolated 3D model. A 3D view of the model, with cut-outs and annotation is shown in Figure 14. Aerial photographs and site plans have not been included, because in this case they would not assist in the analysis and interpretation of the model. Similarly, groundwater level data has not been shown as not enough sample points were available with which to plot a groundwater surface.

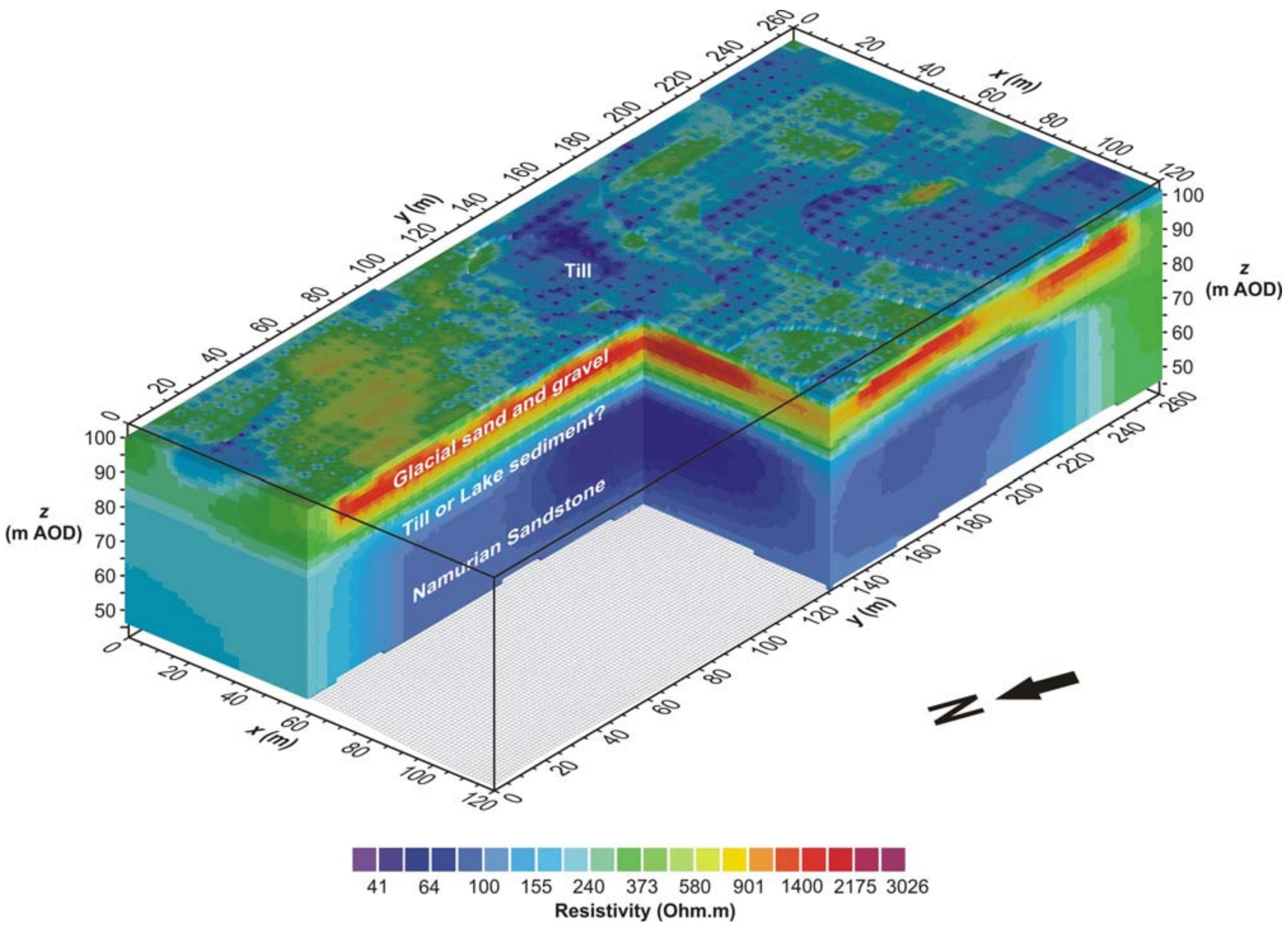

Figure 14. Integrated Marfield Quarry 3D ERT model.

We have also included a number of figures showing sections through the 3D model: a surface drape and horizontal sections at 95 and 80 m below ground level are shown in Figure 15; vertical sections that are parallel to the y-axis, are shown in Figure 16. These sections have been selected to display key features of the model, which are discussed in Section 3.4.2 'Analysis and Interpretation'.

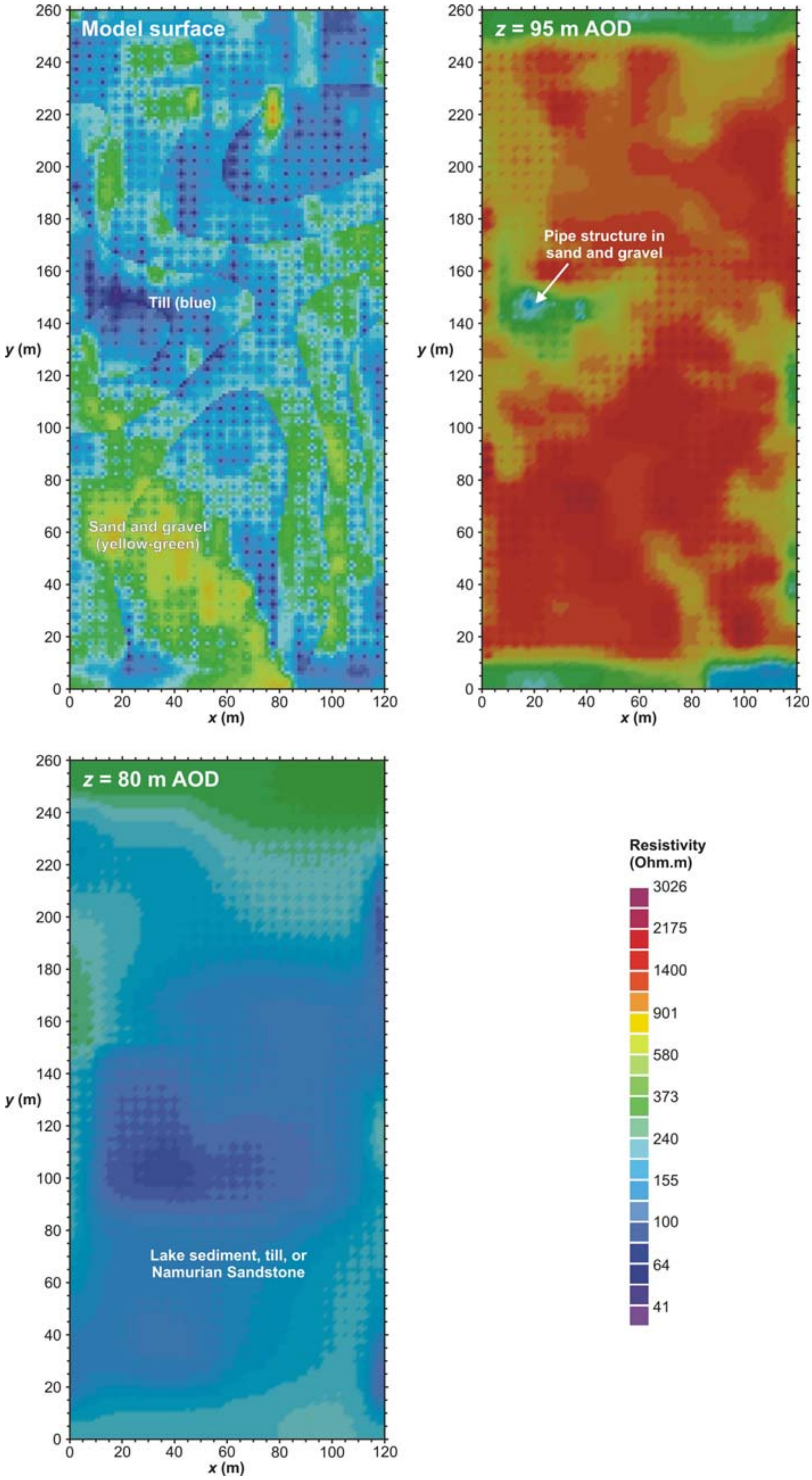

Figure 15. Horizontal sections through the Marfield Quarry 3D ERT model

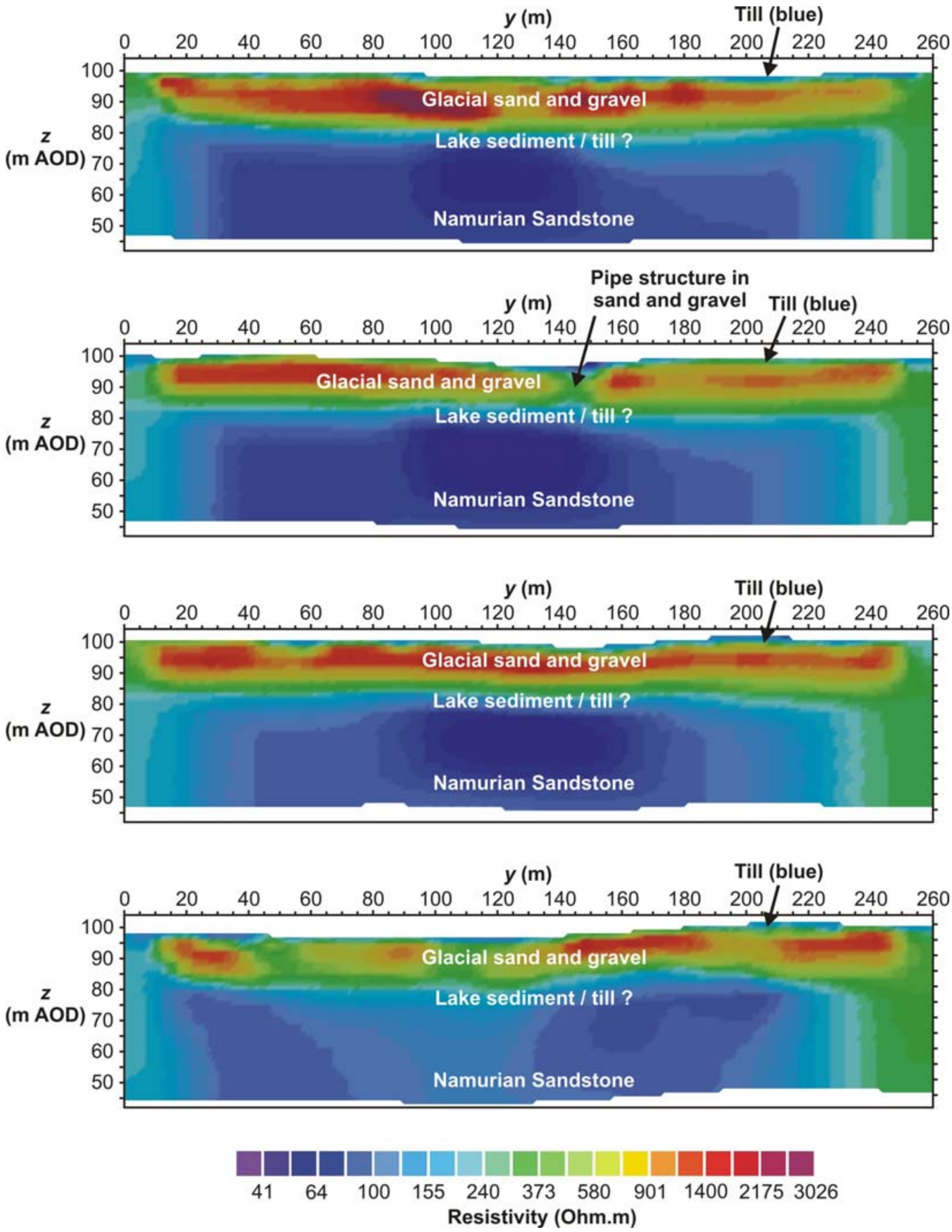

Figure 16. Vertical sections, parallel to the *y*-axis, through the Marfield Quarry 3D ERT model.

3.4.2 Analysis & Interpretation

The principal geological units known to underlie the site are clearly reflected in the 3D ERT model. The resistive gravels dominate the upper part of the model (red to yellow), before giving way to more conductive tills, lake sediments and Namurian Sandstone (blue). The good resistivity contrast between the gravels and the underlying material allow us to clearly identify the base of the mineral. The methods by which we calculate the position this interface are discussed in Section 3.4.3.

The uppermost layers of the model reveal a patchy distribution of resistivities across the surface. We have interpreted the more conductive areas as till, whereas the more resistive zones are likely to indicate the absence of till cover, with gravel at the surface. The relatively high contact resistance from the survey indicates that the till and top soils are not particularly rich in clay: instead silt and fine sand probably dominate.

The fluvio-glacial gravel is seen as an essentially tabular structure, though significant internal structures are apparent. The most obvious of these is a pipe-like feature centred on x = 18 m, y = 147 m. This feature is persistent with depth and displays a markedly lower resistivity than the surrounding gravels, indicating the presence of a more conductive material such as clay or peat. Other channel-like features (e.g. Figure 15, x = 80 m, y = 30 m) also be observed, again distinguishable as resistivity lows relative to the main body of the gravels.

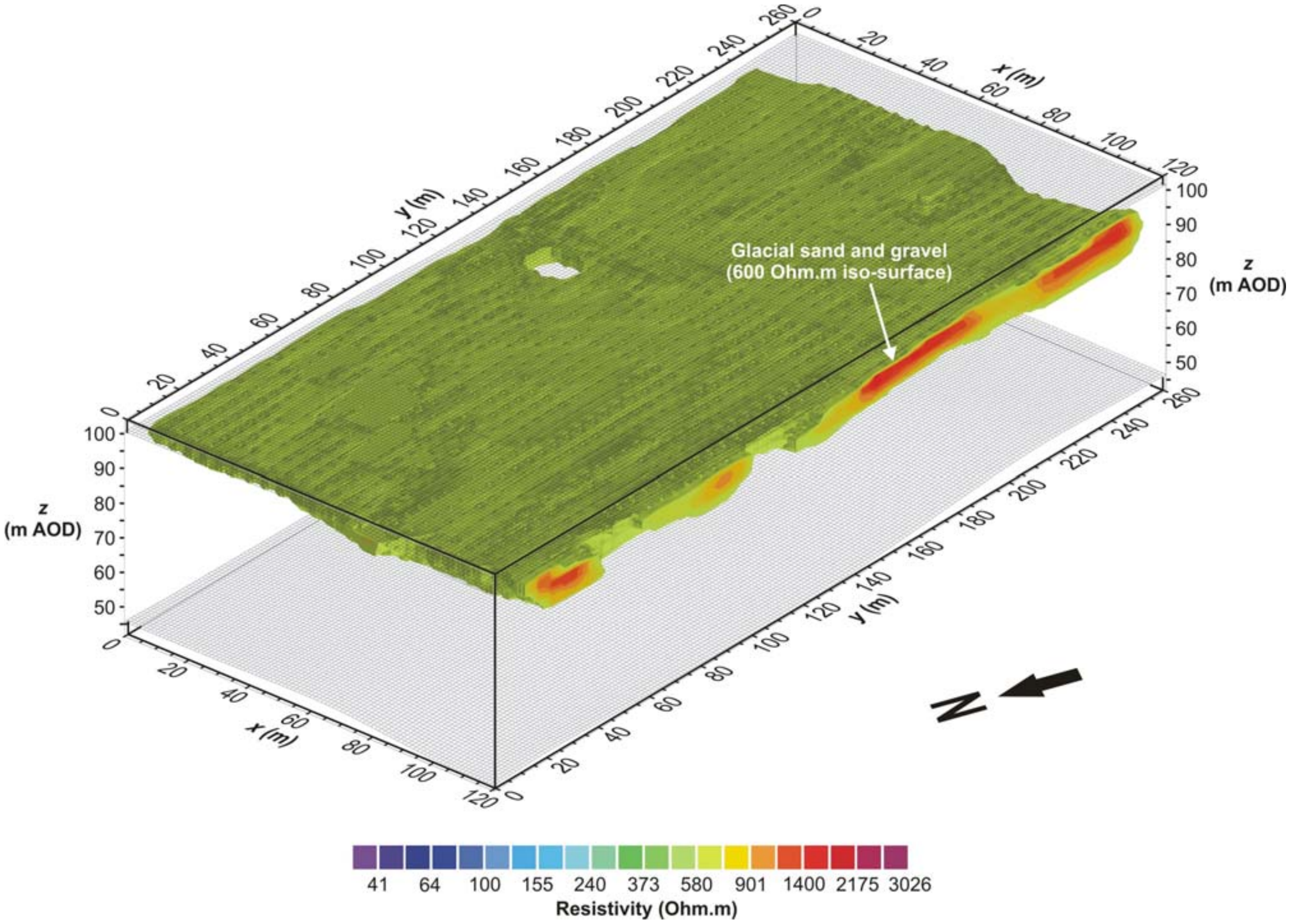

Figure 17. Marfield Quarry 3D ERT model: opaque volume defined by the 600 Ωm iso-surface.

Beneath the gravel, low resistivity dominates indicating more clay rich materials. Moreover, it is likely that the formations below the gravels are saturated. The low resistivities lend weight to the hypothesis that the lake deposits are present, due to their expected relatively high clay content. Moreover, given that the Namurian deposits in this area are likely to be sandstones, which would generally be expected to be more resistive, the presence of lake sediment is even more likely.

3.4.3 Determination of Geological Boundaries

Resistivity data, ρ, were extracted from the 3D model as a function of elevation, z, for each surface position (x, y). Following previous work on vertical resolution in ERT images of layered structures (Chambers et al., 2008a), an interpolating curve was fitted through $\rho(z)$ for each (x, y) point. In that study, each $\rho(z)$ curve had only eight data points, and so a shape-preserving interpolant was used to represent the form of the data more accurately near the sharp bedrock interface. But this type of interpolation does not generally have a smooth first derivative, a fact which has since been found to cause unrealistic discontinuities between the steepest gradients at neighbouring (x, y) points. For this reason, and also since there are eleven data points per curve in this case, smoother cubic spline curves were used instead. An example set of $\rho(z)$ data and its interpolating spline function is shown in Figure 18.

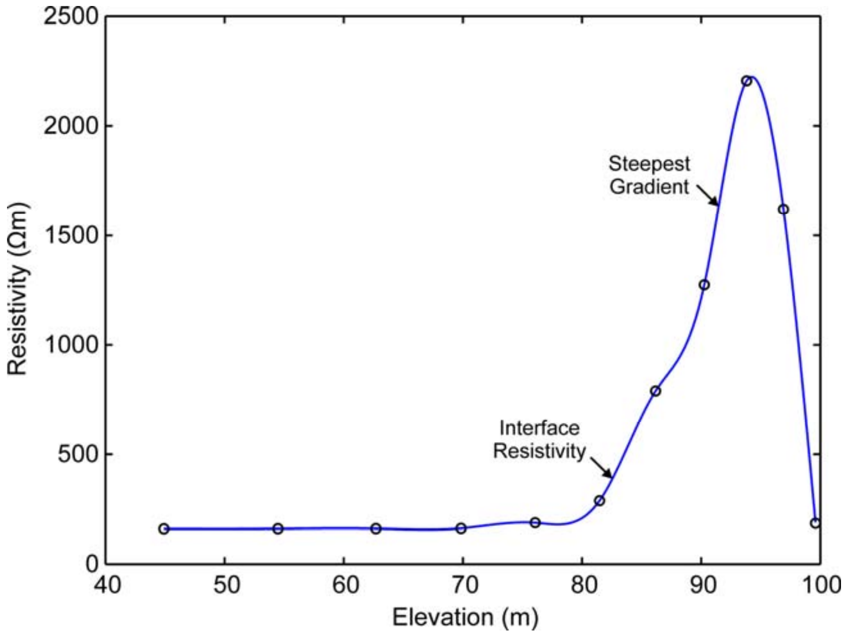

Figure 18. Resistivity data (circles) and interpolating curve (blue line) as a function of elevation. The points of steepest gradient and where the curve crosses the interface resistivity value are indicated.

Two methods were used to determine the elevation of the bedrock interface for each (x, y) point across the survey area (see Figure 18). The first involves finding the elevation where the resistivity varies most rapidly (the steepest gradient). This approach can be used in the absence of any prior information, such as borehole logs. The second method uses a known bedrock elevation from a borehole log. The average model resistivity at this elevation in the vicinity of borehole is denoted ρ_i. The second method finds the bedrock elevation simply by calculating where each curve crosses the line $\rho = \rho_i$.

The results of each approach are shown in Figure 19. Despite using a smooth interpolant, the steepest gradient method still gives an interface surface which, in places, varies sharply by up to 5 m in elevation over 2 m horizontally (Figure 19a). Compared to the bedrock elevation of ~83 m, estimated from the borehole at (x = 160 m, y = -2 m), this method has significantly overestimated the interface elevation by ~7 m. This is consistent with the results of previous synthetic and field studies (Chambers et al., 2008a).

The average interface resistivity value at an elevation of 83 m was estimated from four vertical resistivity curves in the region of (x = 95 m, y = 25 m). Although these are not the closest curves to the borehole, care had to be taken to avoid the corners of the resistivity model where the image resolution is poor. The interface resistivity was found to be ρ_i = 357 Ωm. The results of the interface resistivity method using this value are shown in Figure 19b. Here the elevation of the bedrock varies much less rapidly with position. This layer is shown in the 3D model in Figure 20. It is worth noting that sharp unrealistic changes occur at the corners of the bedrock interface layer when using either method. This is because the data density, and hence the image resolution, is lowest in the corners, leading to unrealistic vertical resistivity profiles in these areas.

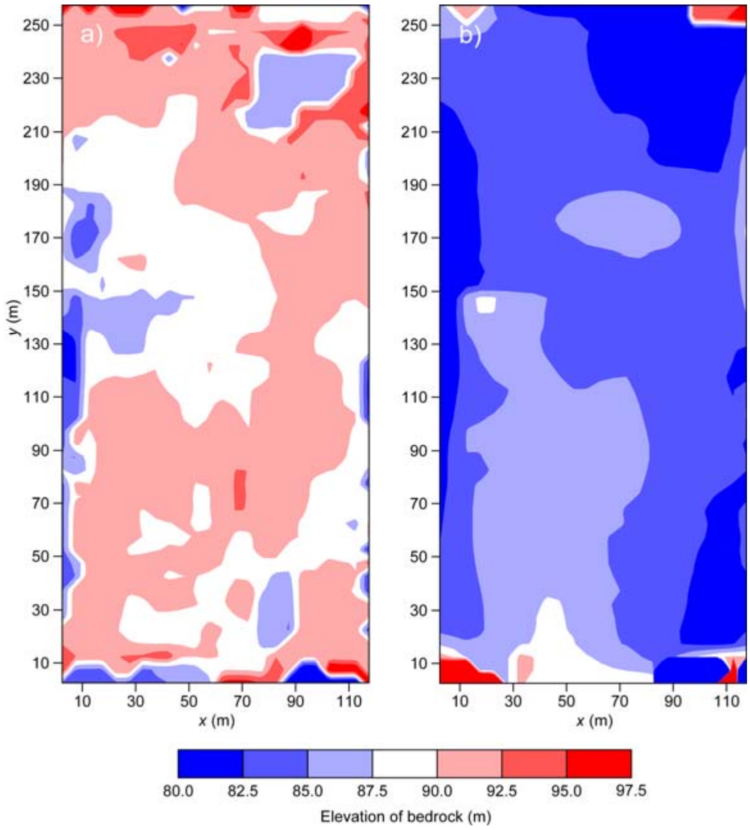

Figure 19. Elevation of bedrock determined by a) the steepest gradient method, and b) the known interface method.

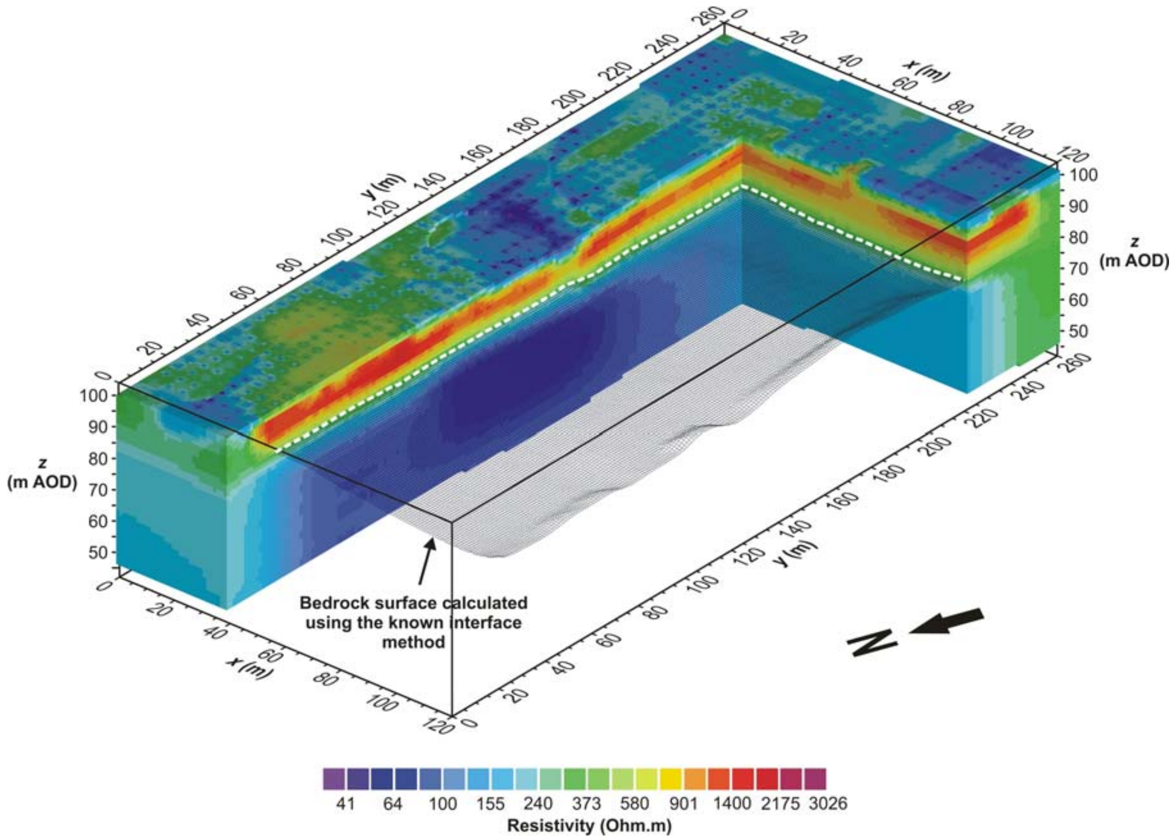

Figure 20. Marfield Quarry 3D ERT model showing bedrock surface calculated using the known interface method.

3.5 CONCLUSIONS

The Marfield Quarry site geology was relatively simple, but was essentially unproven due to the failure of conventional drilling methods to prove bedrock. The 3D ERT survey was successful in identifying the distribution of overburden across the area and revealing the thickness of the gravel deposit. A 2D surface defining the base of the gravel was calculated from the ERT model; this surface was in a form that could be directly incorporated into terrain modelling packages, such as LSS, for reserve calculation. The uncertainties associated with our interpretation of the 3D ERT model could be very significantly reduced with calibration data from even one successful intrusive sample point.

4 Case Study – Bull's Lodge

4.1 SITE DESCRIPTION

4.1.1 Location and background

The Bull's Lodge site is located 6 km to the north east of Chelmsford, Essex. The grid reference of the site is 573600 E, 212100 N. The site, which is a former airfield, is bounded to the south by Bull's Lodge Quarry, and to the east, west and north by agricultural land. The survey area forms part of the reserves at the site, and is due to be quarried.

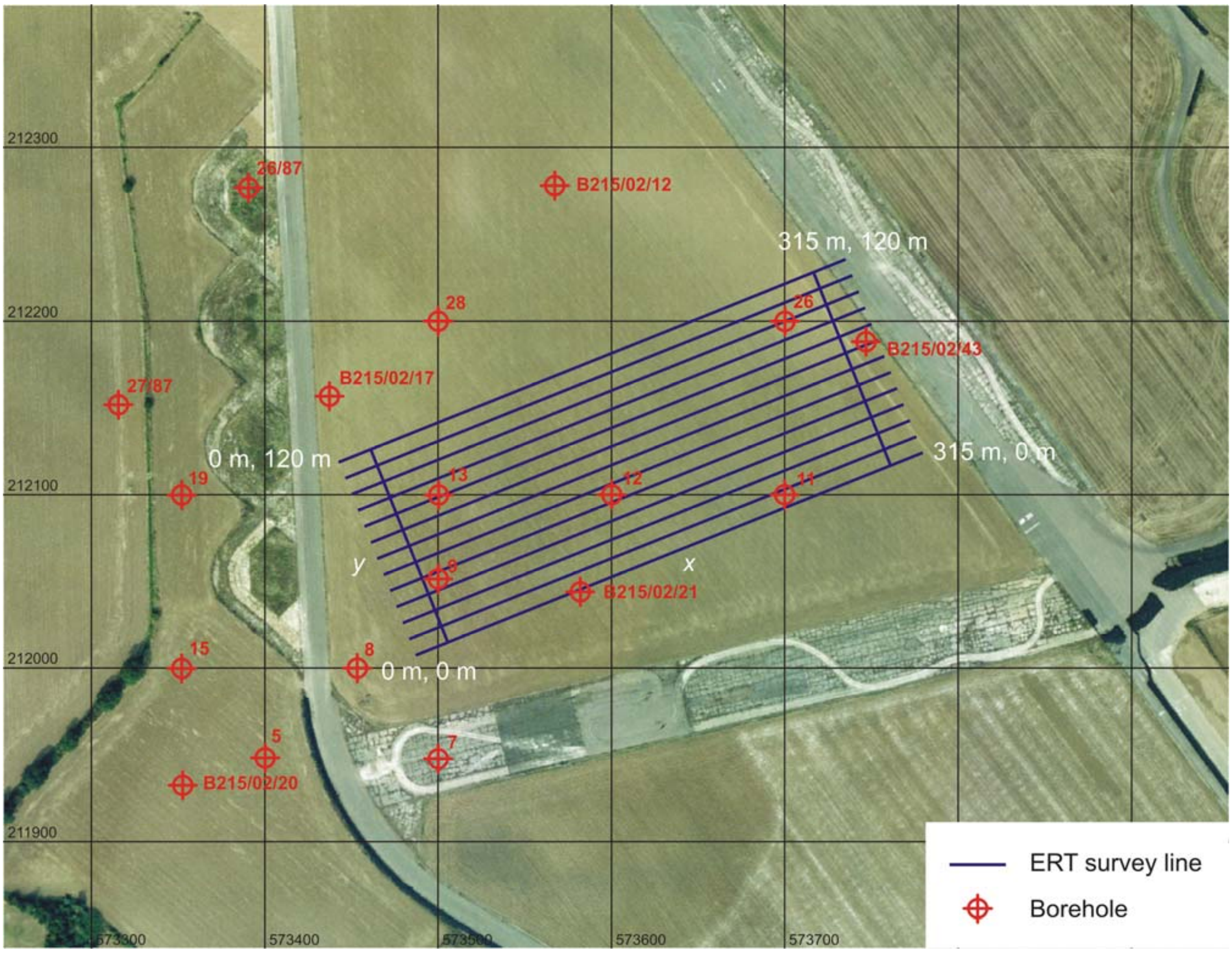

Figure 21. Aerial view of the Bull's Lodge ERT survey area (© UKP/Getmapping Licence No. UKP2008/01).

4.1.2 Intrusive Investigations

Three phases of drilling have been undertaken in and around the 3D ERT survey area in 1987, 2002, and 2007 (Tucker, 2004). The locations of some of these holes are shown in Figure 21.

Geophysical (2D ERT and EM31) surveys were undertaken by Terradat in 2003 in the south-western quadrant of the airfield, directly to the south of the DRAGNET 3D ERT survey. These surveys revealed a good contrast in electrical properties between mineral and overburden, and mineral and bedrock (Tucker, 2004 – Appendix C).

Hill (2004) describes geophysical surveys of the land directly to the south of our survey area using a multi-sensor platform (MSP) survey system, with EM31, EM34 and EM38 sensors. In addition, 2D ERT surveys were undertaken to provide calibration for the EM data. The 2D ERT surveys were particularly successful in identifying the distribution and thickness of overburden and mineral. The sand and gravel was seen to have resistivities of hundreds of Ωm, whilst the bedrock and overburden had resistivities of a few tens of Ωm.

The site also falls within the area of report number 6 of the Assessment of British Sand and Gravel Resources series (Eaton, 1973). This report describes a number of boreholes from the land adjacent to the site.

As with the Marfield Quarry site, a CPT survey was commissioned under the DRAGNET project. Again, testing was unsuccessful due to extremely poor weather and ground conditions.

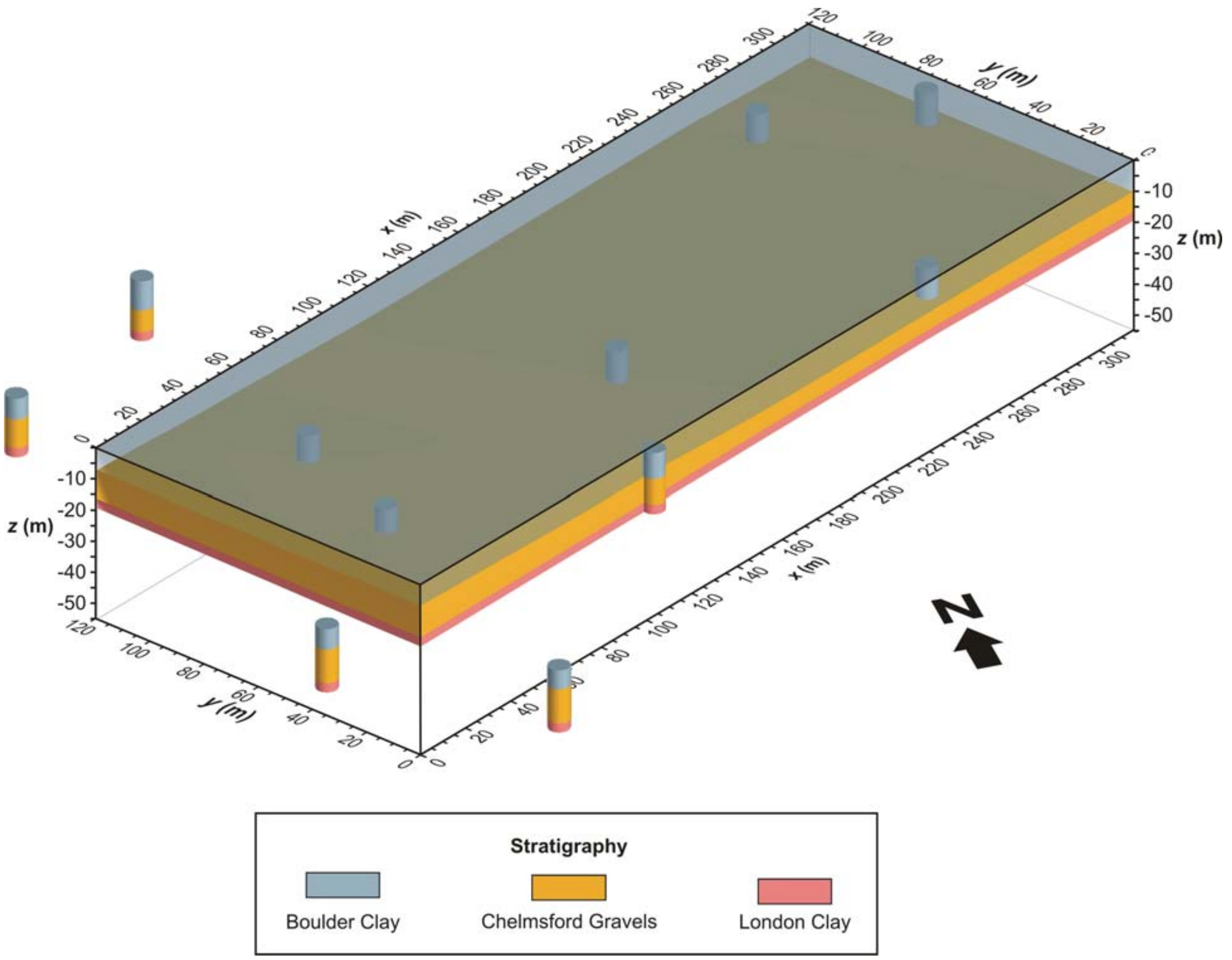

Figure 22. 3D geological model of the Bull's Lodge 3D ERT survey area.

4.1.3 Geology

The general geology of the Bull's Lodge site and surrounding areas is described by Eaton (1973) and Tucker (2004) as consisting of London Clay bedrock overlain by sand and gravel, with a Boulder Clay overburden. A 3D geological model of our survey area that has been produced from borehole data is shown in Figure 22.

BEDROCK (LONDON CLAY)

The London Clay is stiff bluish-grey silty clay. Its thickness in the area of the survey is not known.

SAND AND GRAVEL (CHELMSFORD GRAVELS)

The sand and gravel was formed from glacial outwash deposits from the same ice-sheet that deposited the overlying Boulder Clays. In this area they are known as the Chelmsford Gravels (Clayton, 1957) and consist of angular to sub-rounded flint, quartz and quartzite. Grain size and thickness varies significantly in and around the Bull's Lodge quarry.

BOULDER CLAY (SPRINGFIELD TILL)

The Boulder Clay in the area of the 3D ERT survey consists of the Springfield Till (Clayton, 1957), which is a stiff clay that contains abundant fragments of flint and other erratics.

4.1.4 Hydrogeology

No groundwater data relating to our survey area is currently available. However, the close proximity of the working quarry face and moisture content from borehole from previous drilling campaigns leads us to suspect that much of the sand and gravel is unsaturated.

4.2 FIELD SURVEY

4.2.1 Surface Conditions

The field survey was carried out within an area of stripped overburden. The ground was firm and moist, and electrode emplacement was straightforward; no preparation of electrodes was required, and they could all be installed by hand. The surface conditions at the site were ideal for ERT. We encountered some periods of rain during the survey, but these did not slow survey progress.

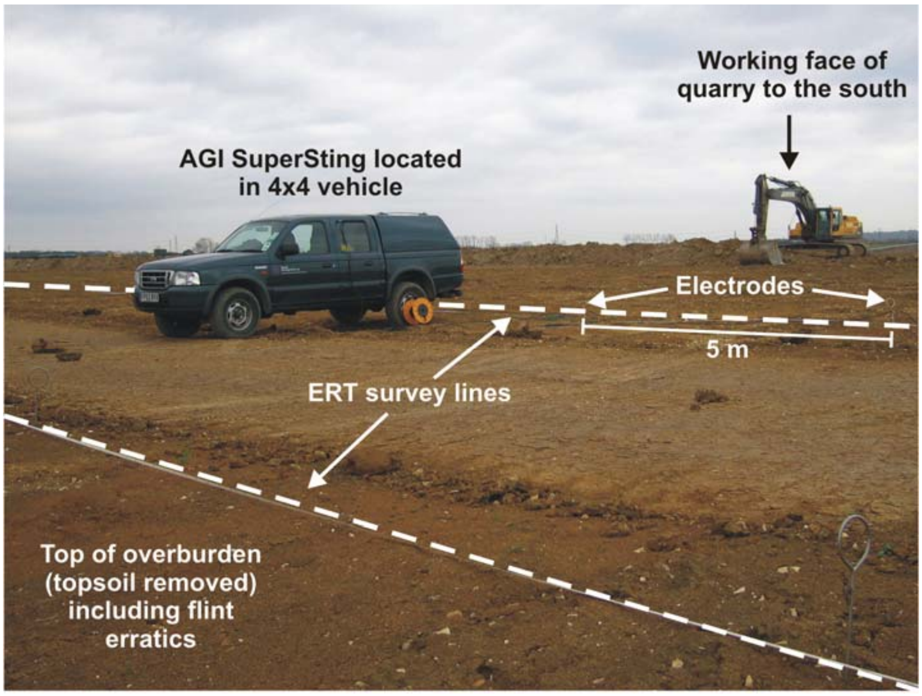

Figure 23. Photograph of the Bull's Lodge northern quarry extension area during the 2007 3D ERT survey. Looking south-east.

4.2.2 Survey Design

The 3D ERT survey was carried out within an area of 315 m (x-axis) by 120 m (y-axis) (3.8 hectares). A summary diagram of the survey grid is shown in Figure 21, with the ERT lines shown in blue. The main survey lines were 315 m long, striking in a west-north-westerly direction, and were positioned at 10 m intervals, resulting in a total of thirteen lines. Two additional survey lines, which were 315 m long, were positioned at y = 20 and 295 m to improve data density at the eastern and western margins of the survey. An along-line electrode separation of 5 m was used for all survey lines.

The dipole-dipole array with dipole sizes (*a*) of 5, 10, 15, 20 and 25 m, and dipole separations (*n*) of 1*a* to 8*a* was used; full sets of reciprocal measurements were collected for each line.

4.2.3 Field Operations

The survey was completed in a three day period between the 7th and 9th November 2007. The field party consisted of three people (A L Weller, J E Chambers, and J D O Williams). The field procedure was similar to that described from the Masham survey (Section 3.2.3).

For the Bull's Lodge survey the total time on site was 19 hours and the total measurement time was 12.3 hours.

4.3 DATA PROCESSING

4.3.1 Data Editing

The combined dataset from the fifteen survey lines comprised a total of 23 569 reciprocal pairs. Analysis of the reciprocal errors showed that more than 98.8 % of the normal and reciprocal measurement pairs had an associated error of less than 5 %. Measurements with a reciprocal error of more than 5 % were removed; the remaining reciprocal pairs were averaged prior to inversion.

Average contact resistances recorded during the field survey were an order of magnitude lower than those recorded during the Marfield Quarry survey. The lower contact resistances are certainly a significant factor in the extremely low reciprocal error of the Bull's Lodge ERT data, and can be attributed to the very low resistivity of the stripped overburden.

4.3.2 Numerical Inversion

Edited survey data collected from the individual lines were concatenated into a single data set comprising approximately 23 279 individual apparent resistivity measurements.

The 3D ERT field data were again inverted using the L_1-norm implementation of the regularized least-squares optimization method (Loke and Barker, 1996), and the forward problem was solved using the finite difference method.

The final resistivity model consisted of 63 cells in the *x*-direction, 24 cells in the *y*-direction and 11 layers in the *z*-direction, resulting in a total of 16 632 model cells. Excellent convergence between the observed and model data was achieved after 6 iterations, as indicated by RMS error of 2.1 %.

4.4 VISUALISATION & INTERPRETATION

4.4.1 Integrated 3D Display

The Bull's Lodge 3D resistivity model output from RES3DINV has been gridded using a node spacing of 1.25 m in the *x, y* and *z* directions, resulting in a model comprising 1.1 million voxels. Interpolation was carried out using an inverse-distance method, by which a weighted average of the closest data point from each 90^{o} sector around each node was calculated.

RockWorks2006 has been used to display the gridded and interpolated 3D model. A 3D view of the model, with cut-outs, annotation and borehole logs is shown in Figure 24. As with Marfield

Quarry, aerial photographs and site plans have not been included, because in this case they would not have assisted in the analysis and interpretation of the model.

We have also included figures showing sections through the 3D model: horizontal sections at z = -5 and -10 m are shown in shown in Figure 25; a vertical section, parallel to the x-axis at y = 40 m, is shown in Figure 26.

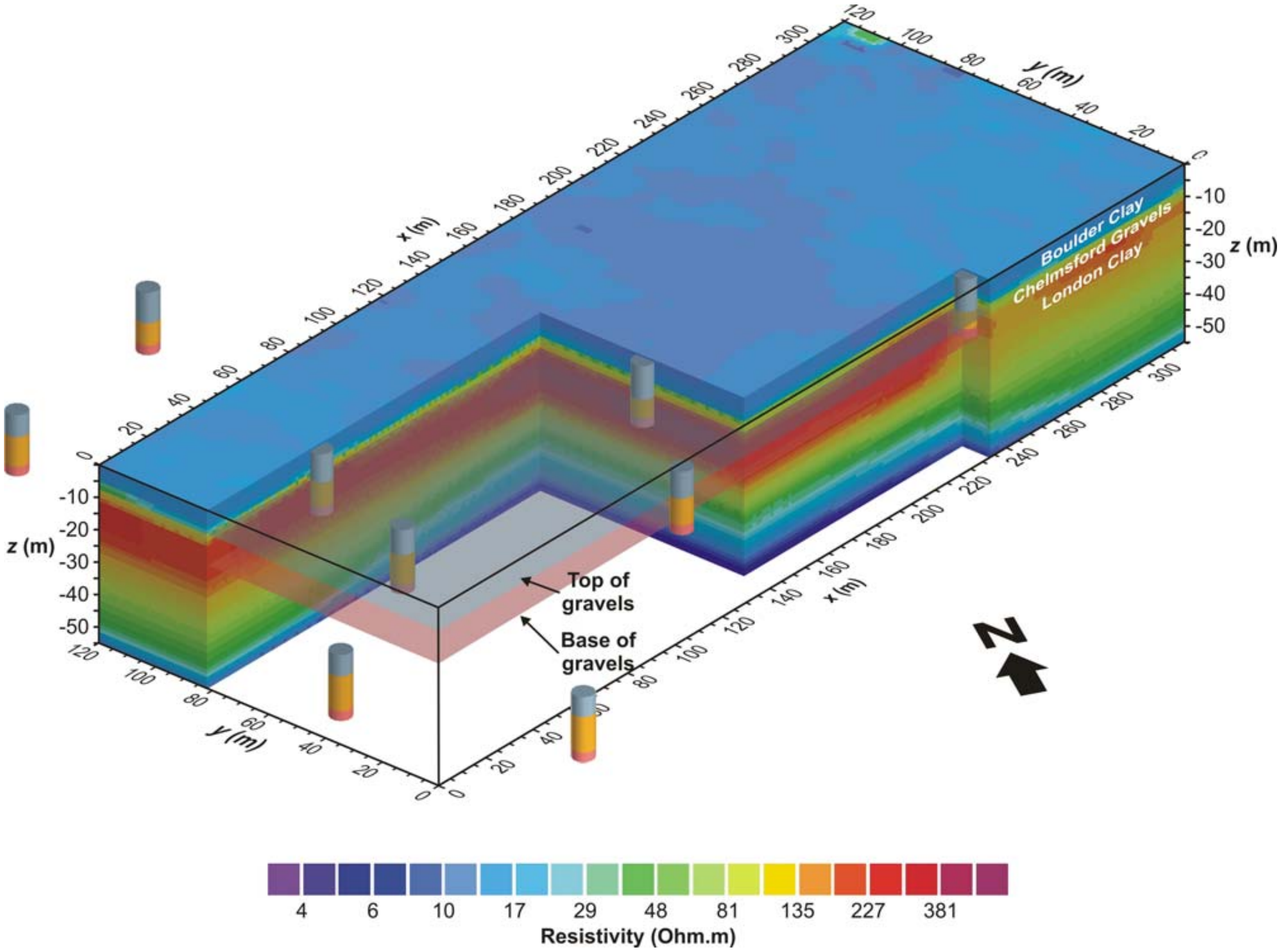

Figure 24. Integrated Bull's Lodge Quarry 3D ERT model.

4.4.2 Analysis & Interpretation

The three main geological units known to underlie the site are distinguishable from the 3D ERT model. The Boulder Clay overburden appears as a homogeneous layer of low resistivity material (< 10 Ωm, blue). The underlying sand and gravel appears as a more resistive feature characterized by resistivities of hundreds of Ωm (red). Towards the base of the model bedrock resistivities appear to be lower than those of the sand and gravel, as would be expected of the London Clay.

The interface between the overburden and mineral appears to be well resolved. The horizontal sections at z = -10 m in Figure 25 shows that the variations in thickness of overburden, as indicated from the borehole data, are broadly reflected in the 3D ERT model. In particular the high resistivity zones from x = 0 to 130 m, and the wedge shaped feature at x = 200 to 280 m and y = 20 to 120 m are areas in which overburden is thinnest.

Inspection of Figure 24 and Figure 26 reveals that the lower interface, between the mineral and bedrock, has not been adequately resolved in the model. The thickness of the relatively thin layer of sand and gravel appears from the 3D ERT model to be grossly overestimated when compared to the geological model and borehole data. We have attributed this to the presence of the thick conductive overburden, a hypothesis that we discuss in detail in the following section.

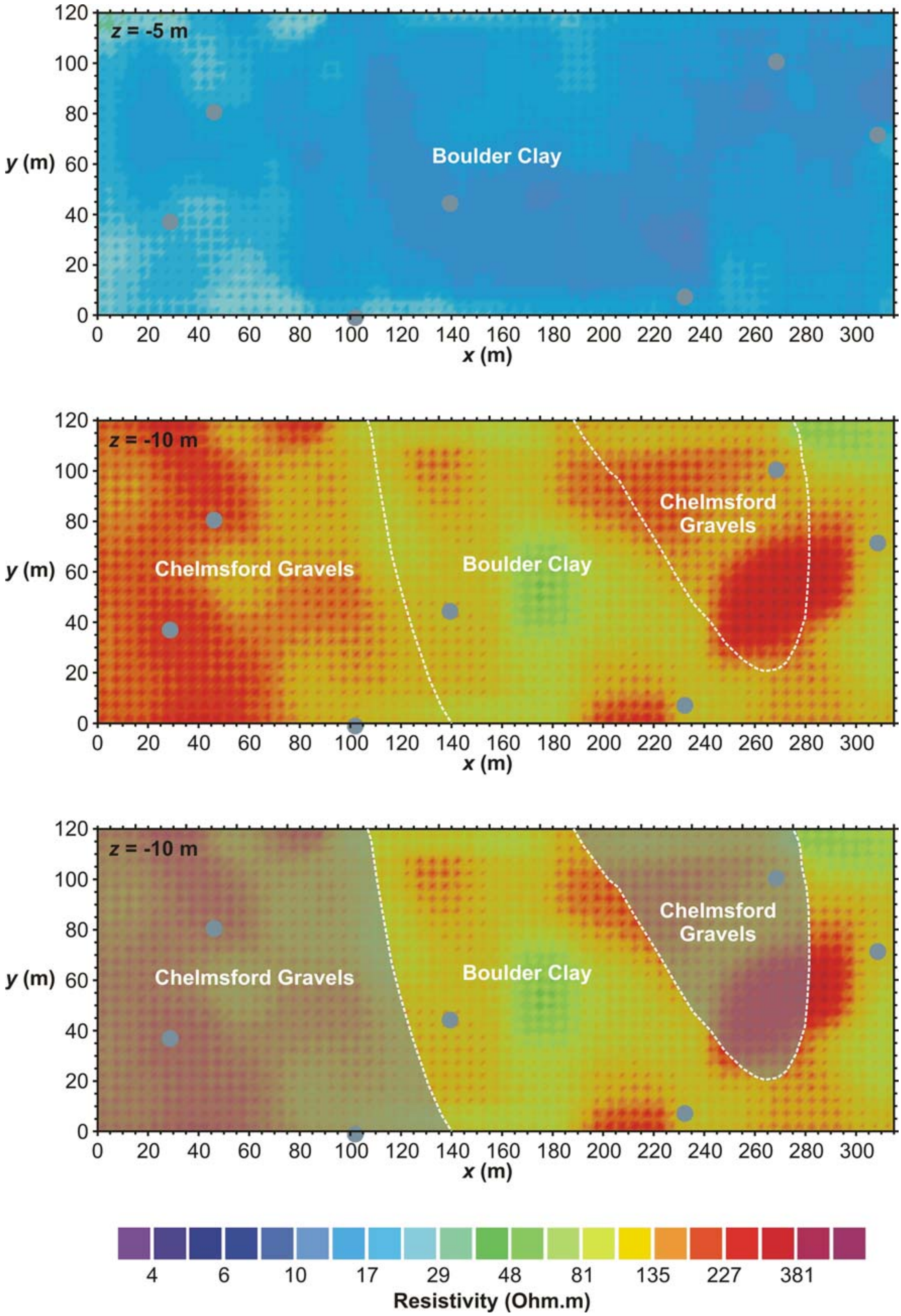

Figure 25. Horizontal sections through the Bull's Lodge 3D ERT model.

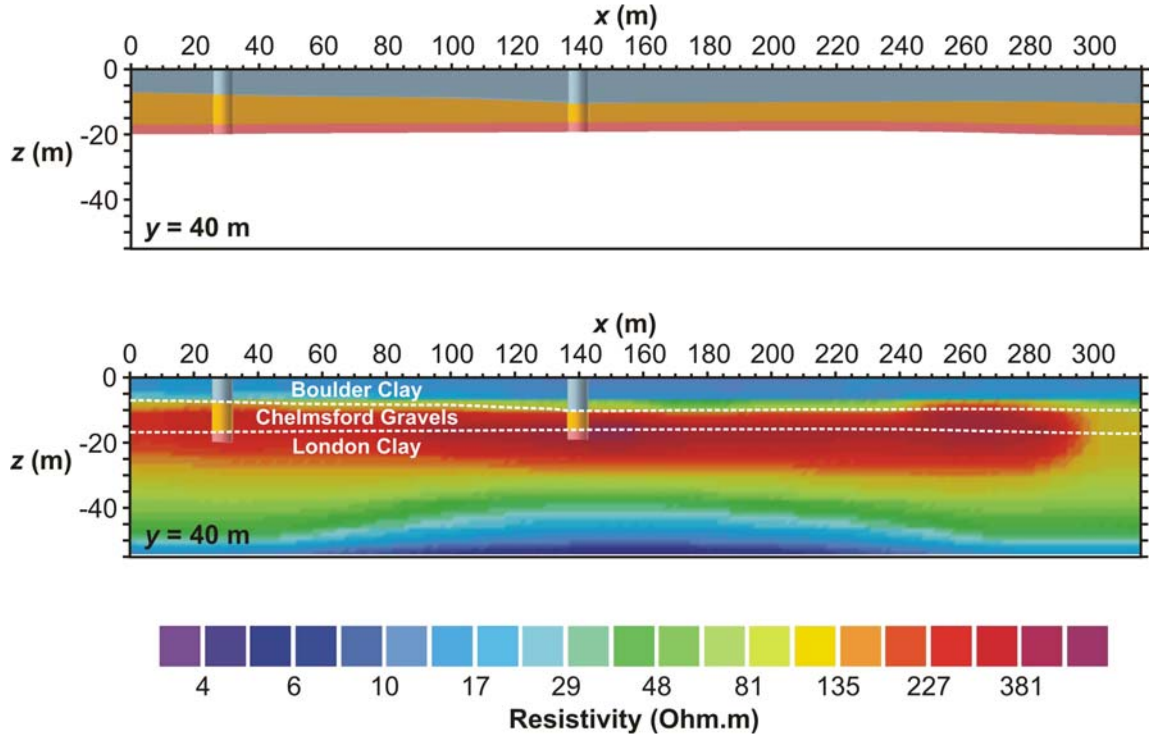

Figure 26. Vertical section through the Bull's Lodge 3D geological model (top) and 3D ERT model (bottom) at $x = 40$ m.

4.4.3 Effect of conductive overburden on bedrock interface determination

To help understand the poor resolution of the bedrock interface in the Bull's Lodge model, the effect of a conductive (e.g. clay) overburden of varying thickness was simulated. Figure 27a shows the resistivity model that was used, which comprised a clay overburden of thickness h_1 and resistivity $\rho_1 = 15$ Ωm, an aggregate layer of thickness $h_2 = 6.6$ m and resistivity $\rho_2 = 500$ Ωm, and an infinitely thick bedrock of resistivity $\rho_3 = 10$ Ωm. There were 64 electrodes in the model at 5 m spacings, giving an overall length of 315 m. Synthetic data for a dipole-dipole array, with dipole lengths $a = 5$ m – 25 m and dipole spacings of $n = 1 – 8$, were calculated from an analytic expression for the potential on the surface of a three-layered earth (Wait, 1982). The data were inverted using Res2DInv with an L_1 smoothness constraint preferentially weighted by a factor of 3 to favour horizontal features. The results of the inversions for each value of h_1 are shown in Figure 27b. When the overburden thickness is ≤ 7 m, the aggregate layer is reasonably well resolved. But for $h_1 > 7$ m, there is a rapid decrease in the sharpness of the bedrock interface. This is quantified in Figure 27c by comparing the depth to bedrock determined by the maximum gradient method (see Section 3.4.3) against the actual interface depth ($h_1 + h_2$). This shows that the maximum gradient depth is with 1-2 m of the actual depth if $h_1 \leq 7$ m. If the interface is deeper than this, the error in the depth increases rapidly. Therefore it seems that, in general, surface ERT will be unable to recover the depth to bedrock accurately if there is a conductive overburden which is significantly thicker than the electrode spacing.

This failure to delineate the bedrock interface is due to current flowing preferentially in the conductive overburden. A possible way to improve the results would be to include data where the current is injected directly into the bedrock. This could be achieved by placing extra current electrodes in boreholes beneath the interface and measuring potentials at the surface. Figure 28 shows an inversion of dipole-dipole data as above, augmented by data measured between all surface potential dipoles of length 5 m when current was injected between the two sub-surface electrodes (shown by white dots in the bedrock at a depth of 20 m). The data were generated from a Res2DMod model with $h_1 = 10$ m, and inverted as above but with extra 0.5 m thick model layers included between depths of 18 m and 22 m so that the currents from the borehole electrodes could be accurately represented. Although the results show considerable artificial variation in the structure of the bedrock, the maximum gradient depth for the image in Figure 28 is 18.0 m, much closer to the actual depth of 16.6 m than was found using surface data only (23.9 m, see Figure 27c). Although this technique needs further study before it can be recommended, if suitable boreholes were already available at the site of interest, it could provide valuable data at little extra cost.

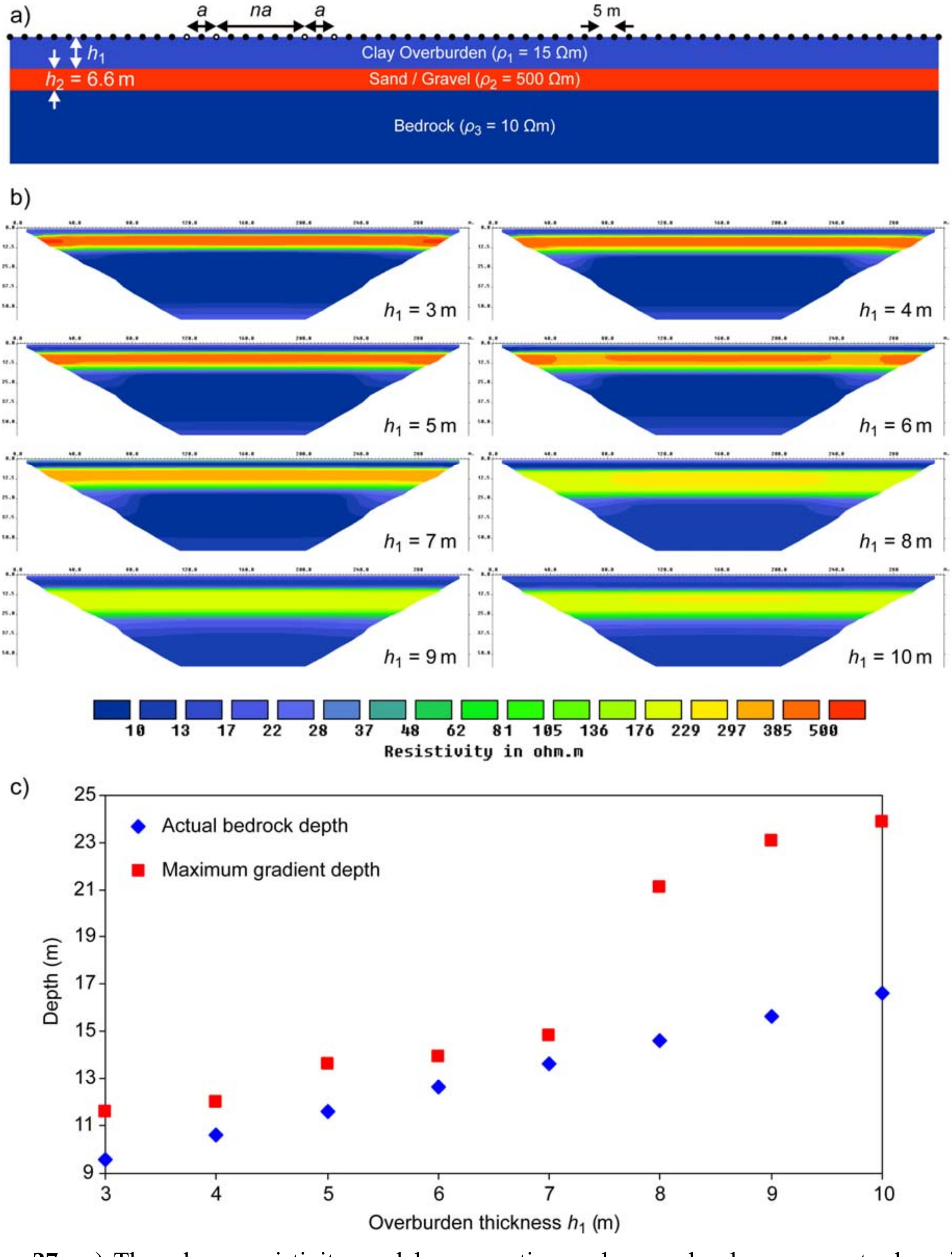

Figure 27. a) Three-layer resistivity model representing a clay overburden, aggregate deposit and bedrock. b) Resulting resistivity images for overburden thickness h1 = 3 m – 10 m. c) Comparison of actual depth and depth determined by the maximum gradient method.

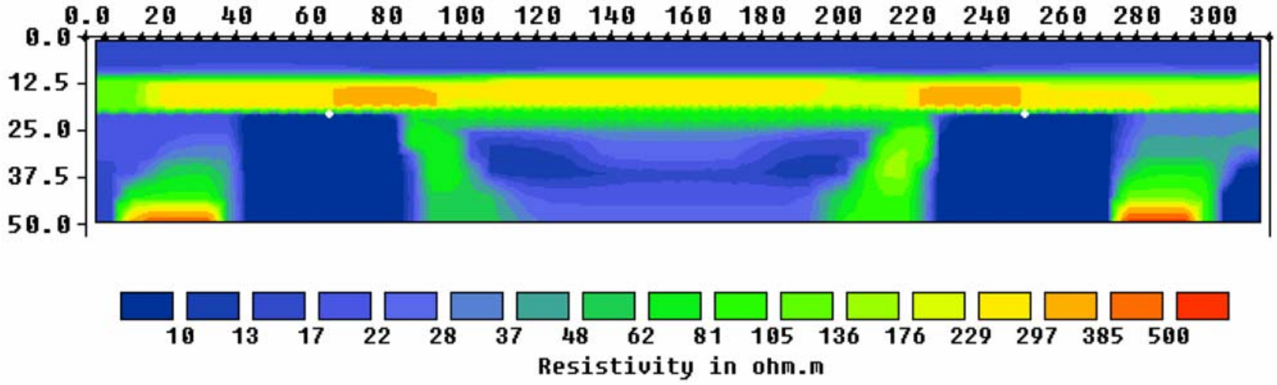

Figure 28. Resistivity image obtained for an overburden thickness h1 = 10 m using surface dipole-dipole data combined with gradient data from currents injected at two subsurface electrodes (white dots).

4.5 CONCLUSIONS

The Bull's Lodge site geology was relatively simple with good available ground truth data. All the relevant data streams were combined in virtual 3D space, and our approach to data integration, 3D display and interpretation have been demonstrated. In this case 3D ERT was effective in determining the thickness of the Boulder Clay overburden, but failed to resolve the base of the sand and gravel. This failure was due to the unfavourable overburden to mineral thickness ratio within the survey area, and the highly conductive nature of the overburden, which caused current to be channelled and focussed in the upper layer, resulting in poor resolution of the sand and gravel. The overburden to mineral ratio at which 3D ERT would be effective at the Bull's Lodge site has been determined from synthetic modelling studies, thereby providing a useful resource with which to inform survey design for future surveys at similar sites. Furthermore, a new survey design concept involving the use of a buried current dipole has been trialled, again using synthetic models, that has the potential to resolve even relatively thin mineral layers beneath thick conductive overburden.

5 Best Practice Guidance

The application of 3D ERT to sand and gravel resource assessment is still in its infancy; consequently, best practice guidance is currently unavailable. Moreover, to the best of our knowledge such guidance has not been developed for any application of 3D ERT. Although specific guidance for this application has not been developed we can turn in the first instance to a number of sources that provide more general guidance on the role of geophysics in ground investigations. Sources include the Geological Society of London, the Construction Industry Research and Information Association (CIRIA), the US Geological Survey (USGS) and the British Standards Institution (BSI). We have described some of the most significant publications in the following paragraphs, in order of increasing significance.

In 1988 a working group of the Geological Society Engineering Group published a report titled ‘Engineering Geophysics’ (McDowell et al., 1988). The report covered general topics such as the planning of surveys, the applicability of geophysical methods, as well as specifics targets and applications. This publication predates the advent of electrical imaging, but mention was made of sand and gravel prospecting using 1D resistivity soundings. An updated version of the report, titled ‘Geophysics in Engineering Investigations’, was published in 2002 (McDowell et al, 2002). This report benefited from an increased focus the professional use of geophysical techniques, and contained a wider range of potential applications. Again, sand and gravel investigations were considered, and on this occasion, with a fleeting mention of the use of resistivity imaging. However, the report did not include guidance on the application of 3D ERT to this or any other application.

Smith and Collis (2001) in their ‘Aggregates: sand, gravel and crushed rock aggregates for construction purposes’ have useful chapter on the ‘Field investigation of deposits’. This section provides a detailed overview of the main stages of deposit evaluation, from desk study through to presentation of field and test results. Within this chapter ground geophysics are discussed, including resistivity soundings and traverses. Resistivity imaging is only obliquely referred to in the section on resistivity traverses in the form of a reference to the paper on 2D ERT by Griffiths and Barker (1989), and is dismissed as having been ‘almost completely superseded by electromagnetic [EM] conductivity surveying’. This comment is unfortunate given that EM mapping and ERT are complimentary techniques that provide very different types of subsurface information. EM mapping is useful for rapidly mapping the near surface, and provides little depth information; ERT is more time consuming, but can provide 2D and 3D images of the subsurface to depths of tens of meters. Needless to say, Smith and Collis (2001) provide no guidance as to the correct use of ERT for sand and gravel surveys.

Of perhaps most relevance to this work is the CIRIA publication “Rapid characterization of contaminated sites using electrical imaging” (Onions et al., 1996). Although the authors are concerned with 2D rather than 3D imaging and they assess its use for contaminated land rather than minerals, their general approach is useful. Furthermore, this document appears to be almost unique in that it is exclusively focussed on the use of ERT and not other geophysical techniques; consequently, we are provided with a more thorough assessment of the use of ERT than can be found in the documents mentioned in the preceding paragraphs. It should also be mentioned that many of the site investigation concerns of those investigating contaminated sites are similar to those of the minerals geological, e.g. depth to bedrock, water table, and deposit heterogeneity. The report comprises sections on ERT theory, survey design and site conditions, interpretation and case studies.

The scope and resources of this project do not permit us to develop a comprehensive guidance document for the application of ERT for sand and gravel resource assessment. Instead we propose a framework, consisting of the key considerations for the geophysicist engaged in this type of survey. The structure of this framework is as follows: (i) technique overview; (ii) benefits and limitations; (iii) survey design and execution; (iv) data processing and interpretation; (v) quality control; (vi) case studies. Although this project is primarily concerned with 3D ERT, we have also included 2D ERT in our framework. This is because the two techniques are very closely related, and it is clear that 2D ERT is also potentially useful technique for sand and gravel assessment.

5.1 OVERVIEW OF ERT

Resistivity has long been used as a prospecting method by geophysicists. Consequently, basic resistivity theory is covered in many text books (e.g. Telford et al., 1990). The extension of the technique to 2D imaging has just about made it into the text books (e.g. Reynolds, 1997), but is dealt with at a relatively superficial level. We must therefore turn to other sources of information. One of the most comprehensive overviews of 2D and 3D ERT is provided by Dr M H Loke in his 'Tutorial: 2-D amd 3-D electrical imaging surveys' (Loke, 2004). Other published sources include journal papers, conference proceedings, and reports (e.g. Onions et al., 1996; Dahlin and Bernstone, 1997; Chambers et al., 2002). Given the wealth of information on basic resistivity theory and the fundamentals of electrical imaging we will not repeat it here.

5.1.1 Limitations

Any introduction or overview of ERT should consider the limitations of the technique for the desired application. These must be taken into account when designing surveys and interpreting resistivity models:

1. Data quality: Models are only ever as good as the quality of the electrical measurements. Measured data is subject to error from a variety of sources including that introduced by the measurement device, poor electrode contact or electrode polarization, and other indeterminate external effects.
2. Non-uniqueness & resolution: A range of theoretically equivalent models can always be obtained from field data. The problem of non-uniqueness is exacerbated with increasing depth of investigation since the model in deeper regions is less well constrained by the data. The model that best satisfies the smoothness criterion is therefore chosen. However, smoothness constrained (and even L_1-norm) inversion produces models characterized by smoothed and gradational changes in resistivity, even when the data arises from situations where sharp changes in resistivity occur in the subsurface; the ERT models can, therefore, provide only an approximate guide to the true resistivity and geometry of subsurface features (Olayinka and Yaramanci, 2000).
3. Three-dimensional features: Resistivity variations in the regions adjacent to each side of 2D ERT lines, and along the boundaries of 3D ERT survey arrays, can affect the resistivity model even though these features may be offset from the survey line or outside the survey area. This is because 3D structures cannot be accurately modelled by 2D inversion or at the boundaries of 3D models.
4. Small scale heterogeneities: High-contrast heterogeneities in the subsurface that are small compared to the model cell-size cannot be accurately modelled, and so can hinder convergence between measured data and the resistivity model [*image*] during the inversion process.
5. Calibration: ERT provides direct information on only the resistivity of the subsurface, and not lithological variation. Calibration is required for the resistivity images to be meaningfully interpreted. Consequently, ground truth data or some other form of a priori information is required. 3D ERT is therefore complimentary to conventional intrusive methods, and will never entirely replace them.

5.2 SURVEY PLANNING & DESIGN

At the centre of any ERT survey design strategy is the trade-off between image resolution and survey time (i.e. cost). Clearly, the best resolution is achieved using small electrode separations, and very dense measurement sets. However, as electrode separations reduce and the number of electrode configurations increases, costs increase and the survey becomes less and less economically viable due to the increased time that is required to deploy the electrodes, and undertake the electrical measurements. The art of survey design is to devise a strategy that provides sufficient resolution for the problem in hand, whilst using the largest electrode separation and smallest set of measurement configurations possible.

In this section we seek to determine broad guidelines and approaches to ERT survey design of sand and gravel investigation. To undertake this task we consider all available relevant information (Figure 29), including the preceding review data (which outlines deposit types and characteristics), the results of synthetic modelling studies, and published ERT survey design research.

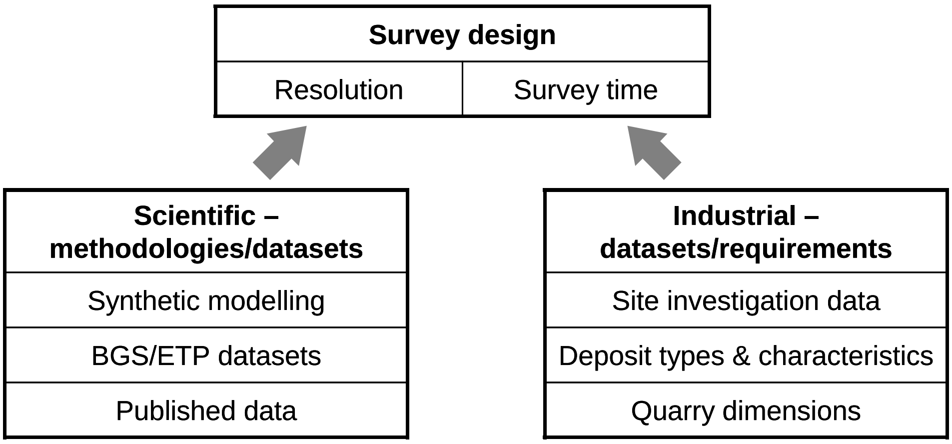

Figure 29. Survey design – input parameters and methodologies

5.2.1 Electrode array types

There are many arrangements of current and potential electrodes that have been used successfully for resistivity imaging. Each type of arrangement has specific strengths and weaknesses (Dahlin & Zhou, 2004). The dipole-dipole type has been used throughout this study. It exhibits lower signal strengths than most of the other commonly used types, and therefore the data it returns can be prone to contamination by environmental noise. However, most modern resistivity instruments have very good noise rejection circuitry and so, providing that reliable electrical contact can be made with the ground, very good results can be obtained. The advantages of the dipole-dipole array include: excellent image resolution (comparable to that obtained by specially optimised arrays, Wilkinson et al, 2006); efficient usage of multi-channel systems; and efficient collection of reciprocal data to obtain noise statistics for QA purposes. If noise does cause a problem at a particular site, then the gradient array (Dahlin & Zhou, 2004) is a useful alternative that provides similar image resolution with better signal-to-noise characteristics. However, it is much less efficient to collect reciprocal data for the gradient array than for the dipole-dipole.

5.2.2 Vertical Resolution (or Depth of Investigation)

The dipole-dipole array is characterised by an intra-dipole spacing, *a*, and an inter dipole spacing, *na*. (see Figure 30a). In general the depth that the current flows into the earth, and therefore the depth of investigation, increases as the spacing of the electrodes increases. It has been shown (Edwards, 1977) that unique median depths of investigation, z, can be defined for each combination of spacings a and na, and that these can be used to determine the rough depth of a subsurface resistivity feature. For the dipole-dipole array the depths of investigation are given in Table 1 as multiples of a. If these tabulated values are not available, it is worth noting that the depths are given approximately by the expression $z \approx (n + 1)\, a / 4$.

Synthetic modelling studies were used to find out how accurately the depth to a horizontal interface (e.g. between a sand / gravel layer and the bedrock) can be determined from a typical dipole-dipole survey. The simulated electrode array had 48 electrodes at 5 m spacings, and dipole-dipole configurations with a = 5 m, 10 m & 15 m, and $n = 1 \rightarrow 8$ were used. The sand / gravel layer was assumed to have a resistivity ρ = 100 Ωm, and the bedrock had ρ = 10 or 20 Ωm, giving resistivity contrasts of 10:1 and 5:1 respectively (Figure 30a). The synthetic dipole-dipole data were inverted to produce electrical images of the interface (Figure 30b).

Resistivity data were obtained from each image and plotted as functions of depth (Figure 30c). The position of the interface was assumed to be at the maximum slope of the resistivity-depth curve. A cubic spline curve was fitted to the resistivity data, and then differentiated to find the point of maximum slope. The differentiated curves also give an estimate of the degree of blurring of the interface (and therefore the uncertainty its depth). The results are summarised in Table 2.

n	***z / a***
1	0.416
2	0.697
3	0.962
4	1.220
5	1.476
6	1.730
7	1.983
8	2.236

Table 1. Median depth of investigation *z*, as a function of inter-dipole spacing *na*.

Actual Interface Depth (m)	**5:1 Maximum Slope Depth (m)**	**10:1 Maximum Slope Depth (m)**
2.5	2.9 ± 0.6	2.7 ± 0.7
3.5	3.8 ± 0.9	3.6 ± 1.0
5.0	4.3 ± 1.1	4.3 ± 1.1
7.0	6.6 ± 1.2	6.6 ± 1.2
10.0	9.5 ± 1.7	9.5 ± 1.7
14.0	12.9 ± 2.2	12.7 ± 2.2
20.0	17.8 ± 3.1	17.4 ± 3.1
30.0	28.2 ± 4.4	27.8 ± 4.5

Table 2. Estimated vs actual interface depth for resistivity contrasts of 5:1 and 10:1.

In all cases the estimated depth is within the uncertainty bound of the actual depth. This uncertainty increases with the depth of investigation. At depths less than the electrode separation (5 m), the interface depth is overestimated. Conversely at depths greater than the electrode separation, the interface depth is underestimated.

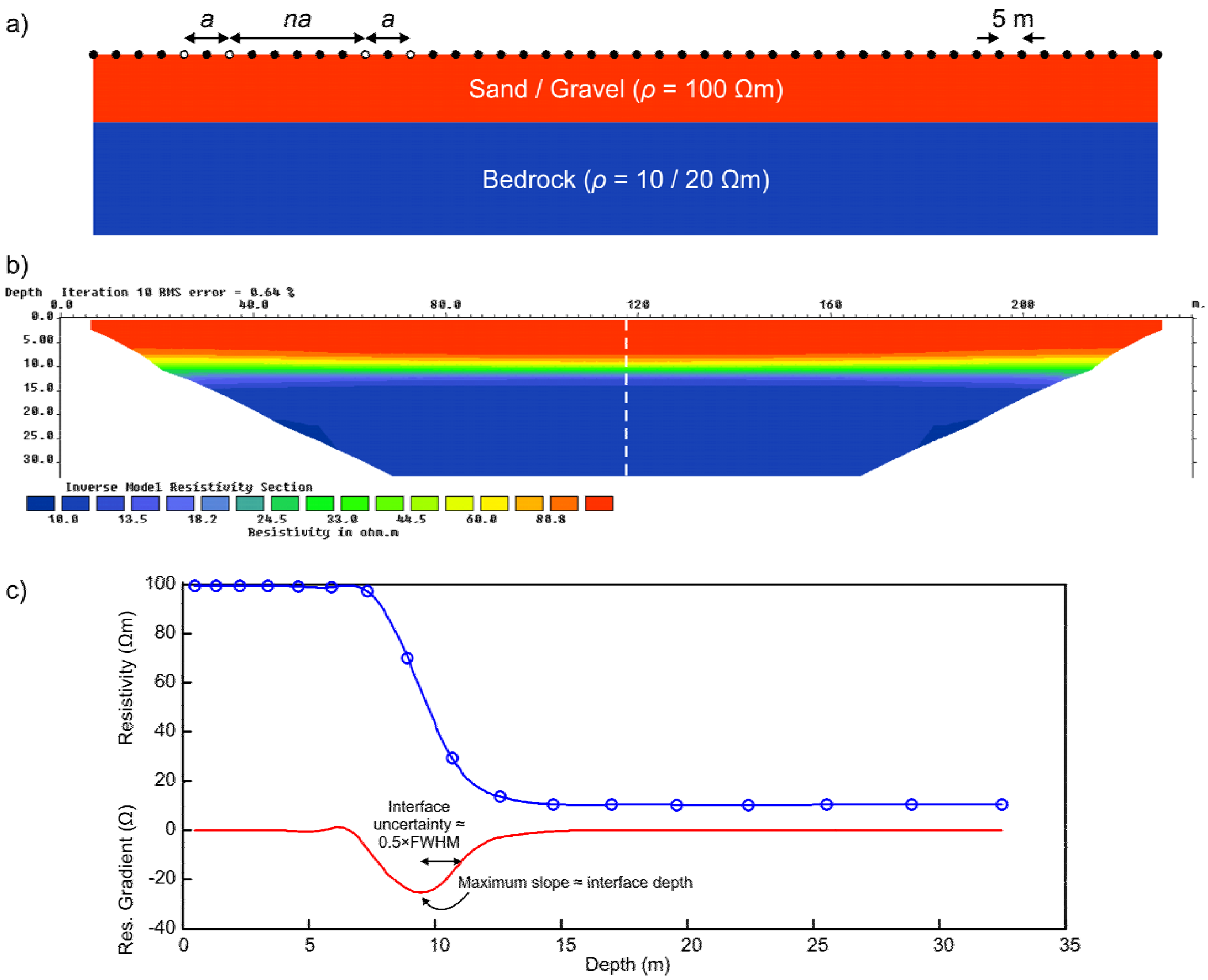

Figure 30. (a) Synthetic model with a resistive sand / gravel layer overlying more conductive bedrock. Also shows an example dipole-dipole electrode arrangement with a = 10 m and n = 3. (b) Inverted image of synthetic data generated from the model. The interface is at a depth of 10 m. (c) Resistivity data as a function of depth (blue circles) taken from the centre of the model (white dashed line). The fitted curve (blue) is differentiated (red) to find the point of maximum slope and to estimate the uncertainty in the estimated interface depth.

5.2.3 Lateral Resolution

3D ERT site investigation surveys are generally carried out using discrete '2D lines' that are migrated across a site at regular intervals (e.g. Bentley and Gharibi, 2004; Chambers et al., 2002; Dahlin et al., 2002). Datasets are then merged and inverted using 3D inversion algorithms. This staged approach is adopted primarily due to limitations associated with the survey equipment and instrumentation. For example, the cable lengths required to address a 3D surface survey grid across an area of several hectares would be unmanageable. In addition, most commercially available ERT instruments are designed to address tens to a few hundred ERT electrodes; again for a single-stage survey covering several hectares many more electrodes would be required. The arguments for undertaking these 3D surveys using a multi-stage line-by-line approach are overwhelming, and this method of undertaking 3D ERT surveys is unlikely to change in the foreseeable future. Given that this is the survey strategy that will be used it is important to determine suitable along-line electrode spacing and line separations. These will depend on the scale of the deposit under investigation. The review in Section 2.2 indicates that economically viable UK sand and gravel is typically relatively shallow with a thickness of < 20 m; the scale of operations is generally many hectares.

5.2.3.1 ALONG-LINE ELECTRODE SEPARATION

The electrode spacing and vertical and lateral resolution are closely linked. Vertical resolution (and depth of investigation) is considered in Section 5.2.2, so here we will focus on lateral coverage. For a 64-electrode system (which is typical of those currently on the market) electrode separations of 2.5 m, 5.0 m and 10 m would give line lengths of 157.5 m, 315 m, and 630 m respectively. Cell sizes in the inverted model typically range between 0.25 to 1.0 electrode spacings; lateral resolution will not be better than the minimum model cell width. For most sand and gravel surveys a line length of 157.5 m may be relatively short compared to the survey area; and a sub-metre lateral resolution will probably be excessive. On the other hand, a line length of 630 m will be practically difficult to handle in the field, and so therefore may not be always feasible, although a lateral resolution of 2.5 to 10 m would probably be sufficient in most cases. It is likely that an along line electrode separation of 5 m will be the preferred option in many cases.

5.2.3.2 LINE SEPARATION AND ORIENTATION

Studies have shown that a significant decrease in resolution can be avoided by using line separations of less than four along-line electrode separations (Chambers et al., 2002; Gharibi and Bentley, 2005; Kuras et al., 2002); e.g. for an along-line electrode separation of 5 m a line separation of 20 m or less should be employed. For sand and gravel surveys it is unlikely that more than one line orientation will be required, as in most cases a single line orientation will resolve features of interest. It is only for very narrow linear features, e.g. a buried pipeline or foundation, that two line orientations may be required. However, a few strategically placed tie-lines (i.e. those line positioned perpendicular to the main survey direction) may be useful in improving resolution at the ends of the survey lines comprising the 3D survey area – this is because resolution diminishes at the end of survey lines due to the decreased coverage, particularly at depth (e.g. Figure 2).

	Example 1	Example 2	Example 3
No. of Crew:	3	3	5
Instrument:	AGI Sting R8	ABEM SAS4000	AGI Sting R8
No. of electrodes/line:	64	64	64
Electrode separation:	5 m	5 m	7.5 m
Line length:	315 m	315 m	472.5 m
Line separation:	10 m	10 m	15 m
Electrode configuration:	Dipole-dipole a = 1-4, n = 1-8	Dipole-dipole a = 1-4, n = 1-8	Dipole-dipole a = 1-2, n = 1-8
Initial setup:	30 mins	30 mins	30 mins
Measurement time/line:	45 mins	75 mins	25 mins
Changeover time/line:	12 mins	12 mins	10 mins
Lines/8hr day:	8	5	13
Hectares/8hr day:	2.2	1.3	8.5

Table 3. Examples of survey parameters and timings for hypothetical ERT surveys.

5.3 DATA COLLECTION

Very often the majority of ERT survey costs are due to the field component of the work. Field surveys should therefore be designed for maximum efficiency. The goal here is to maximize the coverage rate per man day of effort expended. Survey logs should be kept, detailing line position, array type used (e.g. dipole-dipole, Wenner, etc…) dataset names, measurement parameters (e.g. current level; pulse duration), and any other relevant site specific or operation information. Missing or faulty electrode positions should be recorded; these can arise due to human error, or difficult ground conditions that prevent the installation of electrodes.

Inversion and modelling software for 2D ERT data now operates very rapidly (i.e. a maximum of a few minute for a line comprising 64 electrodes), thereby allowing preliminary processing and inversion of datasets in the field. Given that 3D ERT datasets are typically made up of a number of 2D lines this is applicable to both 2D and 3D field surveys. This should be done routinely to assess data quality and to identify problems due to human error (i.e. wrongly connected or disconnected cables and electrodes) or difficult ground conditions (i.e. high contact resistances). If data quality issues are detected remedial actions can undertaken, such as adjusting instrument settings, repositioning and watering electrodes, and repeating measurement sets.

Cable deployment procedures will vary depending on survey design, ground conditions, and the type of field equipment being deployed. Examples of detailed field procedure are given Section 3.2.3 and by Chambers et al. (2008c).

5.3.1 Survey Time

Survey time is influenced by a number of factors:

a. ***Ground conditions*** – surface obstacles, such as boggy ground, vegetation, and man-made structures can impede the deployment of cables and electrodes. Very hard or dry ground may require the electrodes to be hammered into the ground and watered to ensure good electrical contact.

b. ***Field crew*** – in general the addition of crewmembers will lead to a reduction of survey time. It is likely that crews will typically consist of between 2 to 5 members. Crew size should be determined to maximize survey efficiency, and will have to be determined on a case-by-case basis. For example, in some situations the addition of one person to a two-person crew could increase survey speed by more than 33 % and should therefore be considered; conversely, depending on survey design the addition of one person to a five-person crew could lead to no improvement in efficiency, in which case a five-person crew would be preferable. Large crews are particularly useful for long line lengths (i.e. > 300m), or where additional electrode preparation is required.

c. ***Instrumentation*** – a number of ERT systems are available on the market. The most significant consideration for reducing survey time is the number of measurement channels; the more channels a system has the more rapid the data collection will be. For example the ABEM SAS4000 system has 4-channels, whilst the AGI Sting system has 8-channels; therefore, the measurement speed of the AGI system has the potential to be twice that of the ABEM system. Care should also be taking in selecting appropriate instrument settings for the conditions, again with the aim of reducing survey time. For example, in relatively benign conditions with low contact resistances and good signal strengths it may be appropriate to reduce the injected current pulse duration or to reduce the number of current cycles per measurement.

d. ***Survey design parameters*** – the design of the survey (in terms of line length, electrode and line separation, and electrode configuration) exerts the most significant control on survey time. Therefore, particular attention should be given to determining optimal survey design parameters to ensure that redundant data is not collected. Synthetic modelling studies and measurement simulations should be employed when appropriate to refine survey design prior to field measurements.

e. ***Weather*** – ERT surveys can be undertaken in most weather conditions encountered in the UK, with relatively little effect on survey time. However, ERT surveys have to pause during electrical storms to prevent damage to equipment and operators.

f. ***Access*** – although ERT equipment is portable, survey time is kept to a minimum if vehicular access to the survey area can be achieved.

Three examples of survey parameters and timings for hypothetical ERT surveys are given in Table 3. These are intended to illustrate realistic for scenarios that could reasonably be expected for sand and gravel reconnaissance surveys.

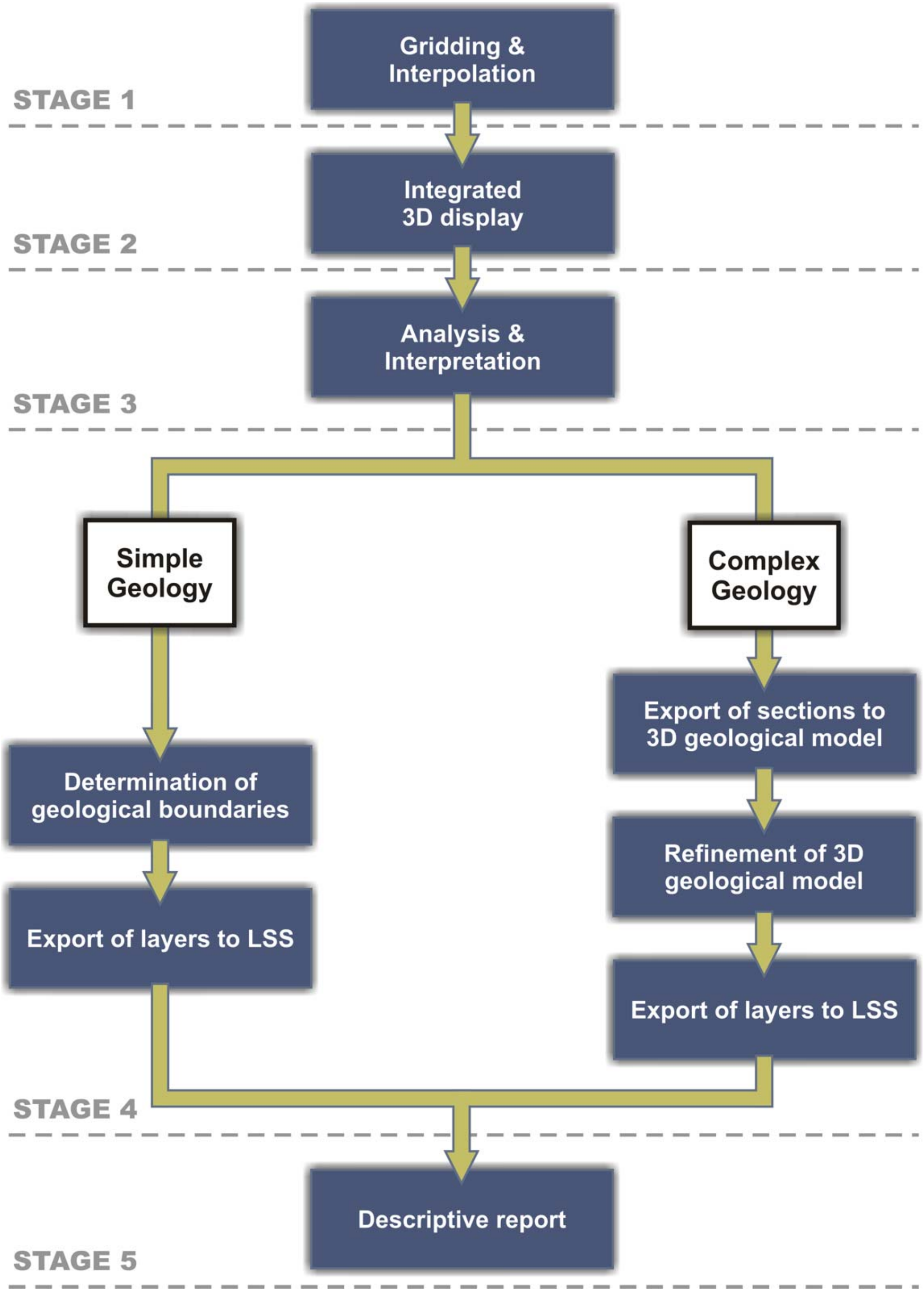

Figure 31. TARGET imaging procedure.

5.4 DATA PROCESSING AND INTERPRETATION

5.4.1 Inversion

Several 2D and 3D resistivity inversion packages are available on the market. Whilst these products may vary slightly in their functionality, the underlying algorithms all work on broadly similar principles. The software used should always be identified in the report, alongside inversion settings, such as model discretisation, types of forward modelling and optimization methods, and types of constraints. All these factors influence the result of the inversion, and must be considered by the geophysicist when interpreting the model. Geophysical model interpretation consequently requires expert input from the geophysicist; this is particularly crucial when identifying artefacts of the inversion process within electrical models, which could easily be interpreted as real properties of the subsurface by a non-specialist.

5.4.2 Visualisation

The imaging procedure used in this report was developed as part of the parallel TARGET project. An overview is given here, and more details can be found in Chambers (2008b). The procedure is divided into five stages. The first three stages and the final stage are common; however, the approach taken in Stage 4 will vary depending on the complexity of the deposit. A flowchart of the procedure is shown in Figure 31. Stage 1 involves representing the 3D model in the form of a regular grid or iso-surfaces. Stage 2 integrates the ERT model with other available site data. At Stage 3, the geophysicist and geologist will be able to assess the heterogeneity of the site, and determine the range of overburden and mineral thickness. This will involve calibrating the model against the available ground truth. If the geology of the site is found to be relatively simple then the depths to key geological boundaries can be determined directly from the calibrated model (Stage 4) and exported directly to LSS, the minerals industry standard package for terrain modelling and 3D visualisation. If the deposit is more complex, the 3D ERT model is used to refine a geological model of the site. The boundaries are then exported from the geological modelling package to LSS. In Stage 5, a descriptive report of the deposit imaging procedure is compiled including calibrated and interpreted 3D images and sections and a description of the methods that were used.

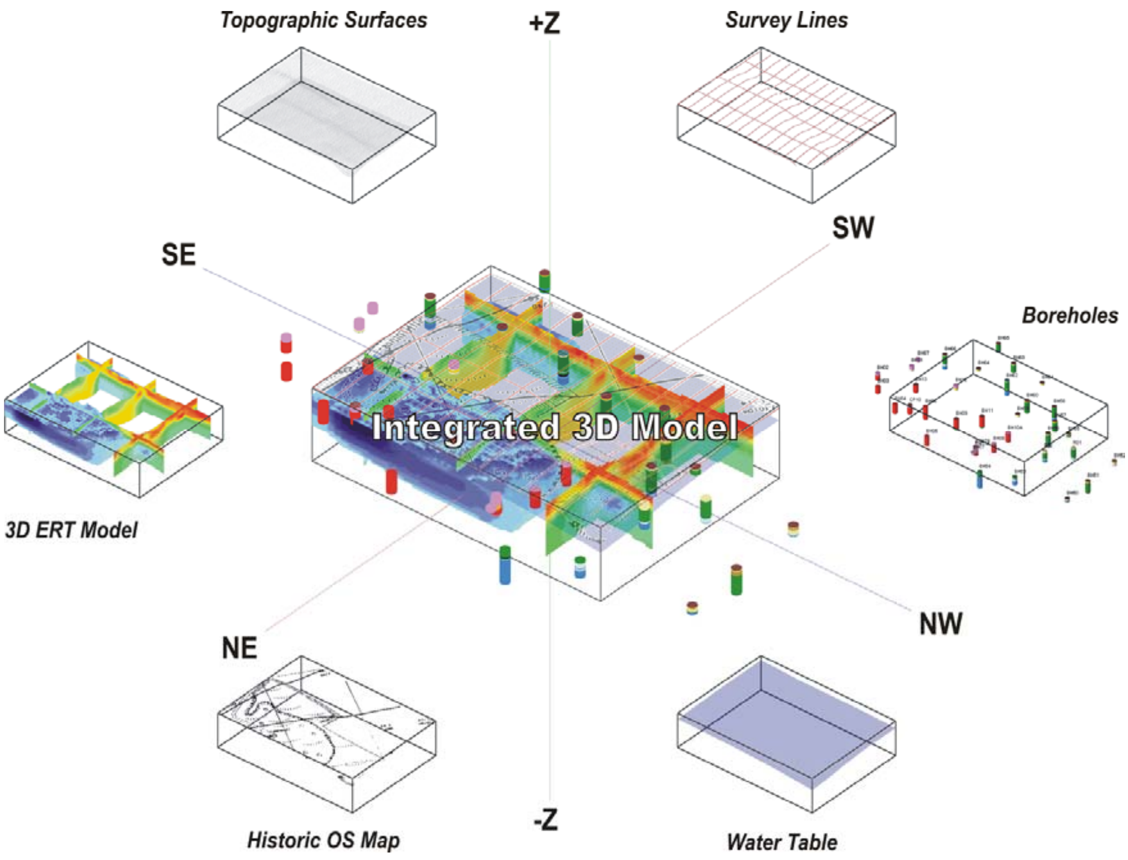

Figure 32. Integrated 3D visualisation of ERT model and conventional investigation data for an old landfill site.

For Stage 2, a range of options for ERT model visualisation are available. The simplest option is to present vertical or horizontal sections displayed within the inversion software. For 3D datasets a more effective option is to use a visualisation package, such as Voxler, RockWorks2006 or GOCAD, to display the model alongside other relevant groundtruth data in virtual 3D space. An example of this type of integrated data visualisation is shown in Figure 32. A 3D ERT image of an old landfill site has been combined with other data, such as the water table surface, historic maps and borehole logs to produce an integrated 3D model that can be interrogated and viewed from any angle.

5.5 DATA QUALITY

Effective quality control touches on all aspects of ERT survey planning, execution and reporting. Of crucial importance is the thorough recording of all aspects of the work. Survey design should be clearly described, and explained and justified based on previous research findings and case histories. Likewise measurement settings should be appropriate for the problem at hand.

A suitable measure of data quality should be selected, and used to quantify the error associated with the measured data. Reciprocal error is a particularly good indicator of data quality. Simply put, the reciprocity theorem implies that if the current and potential dipoles are interchanged then the same apparent resistivity value will be measured. This powerful result holds in very general circumstances, so any differences between data obtained using a particular configuration and its reciprocal are highly likely to be due to noise (either from the environment, the instrument, or both). The percentage reciprocal error between a forward measurement (ρ_f) and its reciprocal (ρ_r) is given by

$$100 \times \frac{|\rho_f - \rho_r|}{\frac{1}{2}(\rho_f + \rho_r)}.$$

The distribution of percentage reciprocal errors gives a good indicator of data quality, and can be used for QA purposes. Typically, if the large majority of data have reciprocal errors < 1 %, the data quality is usually regarded as excellent. Between 1 % and 3 % is good, 3 % – 5 % is acceptable, and > 5 % is likely to cause problems with resolving detail in the associated inverted images.

The inversion process seeks to determine a model with a response that best satisfies the measured data. The level of agreement between the two is quantified as a misfit error. This is a useful indicator of the quality of the model and of the confidence that can be placed in it; good convergence between the modelled and observed data should result in misfit errors comparable with the level of random noise in the data (e.g. the mean reciprocal error). For these reasons, misfit error values should therefore always be displayed alongside ERT models.

5.6 CASE STUDIES

Sand and gravel resource assessment surveys have the potential to encounter a large range of geological settings and ground conditions. Furthermore, the scope and aims of a particular survey will be entirely defined by the specific needs of the client. Given the potential range of ERT survey types, targets and designs, case histories are essential to the geophysicist; they can assist in identifying pitfalls, illustrate the strengths and weaknesses of design strategies, and add to our knowledge of the electrical properties of deposits.

We have noted previously the dearth of good case histories in this area of application. The DRAGNET case studies described above, and those from the parallel TARGET project, have gone someway to addressing this through the work done during the data collection phases of the projects.

6 Cost Benefit Analysis

The application of 3D ERT for sand and gravel resource assessment is still at an early stage of development. This situation presents a number of challenges when trying to quantify the benefits of ERT for this application. In particular the main obstacles are:

1. ***Lack of other published case studies*** - to the best of our knowledge no other case studies describing the use of ERT for sand and gravel assessment appear in the literature. Case studies are essential for assessing how site conditions, deposits types and survey designs can affect the progress, efficacy, and hence, costs of ERT minerals surveys.
2. ***Service provision*** - as yet it appears that the service sector (i.e. geophysical consultancies) do not routinely offer or advertise 3D ERT surveys. This situation will almost certainly change in the near future as demand rises, and take-up of commercially available instrumentation and software increases.
3. ***High end modelling and visualisation*** - the integrated modelling and visualisation of 3D ERT and geological models is still very much at a research and development stage, and consequently cannot be considered a 'near market' component of this project. This aspect of the work is included in Stage 4 of the imaging procedure. Quantification of costs associated with this part of the project is particularly difficult; we have therefore limited our discussion here to the use of Stages 1, 2, 3 and 5 of the imaging methodology, which would include the use of 3D ERT to produce an interpreted 3D geophysical model and descriptive report.
4. ***Unfamiliarity of the 3D ERT to the minerals industry*** - given that this is the case it will take time before we can robustly assess the value that the industry place upon this type of new information. Effective dissemination of results from this project is essential to begin this process.

In view of these challenges we present a general discussion and qualitative assessment of the benefit of ERT for sand and gravel reconnaissance. The three key elements that we consider are the relative costs of ERT surveying, the general efficacy of the technique, and the added value that it can provide relative to conventional methods.

6.1 RELATIVE COSTS

The primary tool for sand and gravel resource assessment is drilling. We have therefore sought to discuss ERT survey costs in relation to drilling. Costs associated with 3D ERT surveys can be divided into those arising from the field component and those due to office based processing and interpretation. In both cases the main cost is staff time. Mobilisation and demobilisation costs are low.

Field costs will depend primarily on survey design, and to a lesser extent ground conditions. Site coverage, in hectares per day (see previous case studies), are at least competitive with drilling; moreover ERT daily rates are likely to be less than that for drilling.

Data processing and interpretation is not strongly dependent on survey size. By employing semi-automated data processing and inversion software large data sets would not ordinarily take longer to analyse than very small data sets. Economies of scale for data processing and interpretation are significant. The production of electrical images (2D or 3D models) and a descriptive report for a typical site would take in the order of 5 to 10 days.

In some cases the cost of an ERT survey could be offset against a reduction in drilling costs due to the information provided by geophysical images. When using boreholes alone, in some cases many tens of boreholes could be necessary to understand the geological heterogeneity of a site. The use of ERT could significantly reduce the number of boreholes required by providing targets for drilling.

6.2 EFFICACY

For ERT to be a viable tool for routine use by the minerals industry there must be evidence to show that in a significant proportion of cases it will provide economically valuable information regarding the structure of the deposit. This will depend primarily on whether a sufficient contrast in resistivity exists between the mineral and overburden, and the mineral and bedrock. These factors are ultimately controlled by the geological setting. Results from both the TARGET and DRAGNET project have indicated that in six out of the seven sites considered 3D ERT is would be a suitable and effective investigative technique.

6.3 ADDED VALUE

Conventional sand and gravel investigations are carried out using drilling. This is a tried and tested method and in many cases provides a cost effective means for robustly assessing the economic potential of the deposit under investigation. This is particularly true for relatively simple deposits that display only limited lateral and vertical heterogeneity. It is our assertion that 3D ERT will provide greater added value for complex deposits where mineral and overburden thickness and quality can vary substantially between even relatively closely spaced boreholes (i.e. 50 to 100 m). In such cases ERT can be an effective means of *filling in the gaps* between intrusive sample points.

7 Future Research, Development & Exploitation

Future Work

Four key interdependent research and development priorities arising from the DRAGNET project have been identified in consultation with industry partners; these are (1) additional case studies, (2) exploitation of existing data, (3) a full demonstration study in which 3D ERT is incorporated into the reserve calculation process from start to finish, and (4) a detailed quantitative cost benefit analysis.

Further case studies are required to demonstrate the capabilities of 3D ERT for a greater range of geological settings. This will allow us to refine survey design strategies, gain additional knowledge of the electrical properties of key deposits (e.g. Thames Valley sands and gravels), and will develop a broader knowledge base from which to develop best practice guidance and better assess the 'value' of ERT for this application.

During the DRAGNET project we have carried out two 3D ERT surveys on sites that will in the near future be excavated as quarry extensions, thereby providing us with a superb opportunity for follow up ground truth that would be impossible for most geophysical surveys. Geological logging of working quarry faces within the 3D ERT survey areas should be undertaken to assess the quality of the electrical models. These additional datasets would provide us with an opportunity to investigate the relationship between mineral grade and resistivity, with the aim of developing 3D ERT of a means of investigating quality variations within deposits.

The TARGET and DRAGNET project have demonstrated 'proof of concept' for the use of 3D ERT as a tool for providing operationally relevant information. However, we have worked on sites where the decision to quarry had already been made, and we have only developed the technique to the point where we can deliver information to minerals geologists. The next step will be to identify a site where the decision to quarry has not yet been taken, and an intrusive investigation program has not yet begun. At such a site we would have the opportunity to fully integrate 3D ERT into the site investigation procedure from the start, thereby allowing a truly integrated approach with the conventional methods. We would then seek to work with minerals geologists to import geophysically derived operationally relevant information into reserve calculation and quarry planning packages such as LSS, and fully assess the *added value* gained from use 3D ERT.

Improved quantification of the costs associated with 3D ERT surveys is required before it will be considered by the industry as a routine site investigation option. At present we know the indicative BGS costs for the research surveys undertaken during the TARGET and DRAGNET projects, but these do not represent competitive commercial rates.

Dissemination & Exploitation

A number of dissemination options are currently being pursued. An abstract has been submitted to the Extractive Industry Geology Conference, which is an excellent forum for raising awareness of the DRAGNET project amongst the wider end-user community. The paper seeks to provide a general overview of the application of ERT to sand and gravel prospecting. The conference paper will be extended and developed for submission to an appropriate journal. By choosing suitable journals we will ensure knowledge transfer to the geophysical consultancies that will utilise the methodologies and guidance that we have developed under DRAGNET. An article is also in preparation for a minerals industry trade magazine; the goal of this article will be to raise awareness amongst end-users of the technology.

Additional funding options for this work are being explored. Preferential routes include the Minerals Industry Sustainable Technologies (MIST) Programme, the Technology Strategy Board (TSB), and EPSRC (in collaboration with an academic partner).

8 Conclusions

8.1 CASE STUDIES

- 3D ERT surveys have been undertaken on two quarry extension sites, at Marfield Quarry, near Masham, North Yorkshire, and at Bull's Lodge, near Chelmsford, Essex.
- The results from these studies were integrated with other pre-existing information and exploration datasets in virtual 3D space to aid analysis and interpretation.

Marfield Quarry

- The Marfield ERT model successfully resolved the key lithologies at the site and was used to identify the depth to bedrock, distribution of overburden, and grain size variations within the deposit.
- Depth to bedrock data was calculated from the ERT model and exported as a 2D surface. The format of this depth to bedrock surface is entirely compatible with industry standard terrain modelling software such as LSS, thereby demonstrating a means of integrating 3D ERT with existing approaches to aggregate reserve assessment.
- Previous investigations at Marfield Quarry met with only very limited success due to the high number of refusals resulting from the extremely coarse nature of the gravels. The success of 3D ERT in this case provides the minerals industry with an alternative approach to the investigation of these types of deposits.

Bull's Lodge Quarry

- The Bull's Lodge 3D ERT model was successful in resolving the thickness of overburden at the site, but failed to adequately resolve the base of the mineral.
- The overburden to mineral thickness ratio within the survey area was approximately 2:1, which due to the conductive nature of the overburden presented too much of a challenge to 3D surface ERT. This case study has therefore been valuable in highlighting the limitations of the technique.
- We have undertaken synthetic modelling studies that have shown the range of conductive overburden to mineral thickness ratios at which ERT is likely to be effective, which will be invaluable for the planning of future sand and gravel 3D ERT surveys. Furthermore, we have proposed a methodology, employing buried electrodes, which could potentially allow 3D ERT to resolve the bedrock interface at the Bull's Lodge site and at other sites with similarly thick conductive overburden.

8.2 BEST PRACTICE GUIDANCE

- A framework for best practice guidance has been established, based on previously published studies and site investigation guidance, and from the findings and experience gained during the DRAGNET project.
- We consider that guidance on the use of ERT for sand and gravel resource assessment should cover the following subjects:
    - Overview of ERT
    - Limitations of ERT
    - Survey planning and design

  - Data collection
  - Data processing and interpretation
  - Quality control
  - Case studies
- The framework that we have proposed is designed as an initial step, which will be developed and refined as more 3D ERT work is undertaken in this field.

8.3 COST BENEFIT ANALYSIS

- Significant challenges still exist before a robust and quantitative cost benefit analysis can be undertaken. These include: a lack of published case histories; limited service provision for both 3D data collection and high-end modelling and visualisation; and unfamiliarity on the part of the minerals industry with 3D ERT. The DRAGNET project has clearly taken significant steps in addressing all of these challenges.
- Despite the afore mentioned challenges we have identified three areas in which we are able to qualitatively assess the benefits of ERT:
  - ERT survey costs are likely to be broadly similar to those of drilling.
  - ERT has been shown to be an effective ground investigation technique for all of the sites considered during the project, which increases our confidence that it will be more generally applicable to UK sand and gravel resources.
  - The potential for 3D ERT to provide ‘added value’ for end-users (i.e. minerals companies) has been demonstrated at the Ingham site, where geological complexity not apparent from borehole data was imaged.
  - The use of 3D ERT has the potential to reduce drilling costs.

8.4 FUTURE DEVELOPMENT AND EXPLOITATION

- Additional case studies are required to demonstrate the capabilities of 3D ERT for a greater range of geological settings.
- Ground truth of completed 3D ERT surveys during quarrying is required to better assess the quality of the existing electrical models.
- A cradle-to-grave demonstration study is required to demonstrate the use of 3D ERT from initial site investigation through to reserve calculation and quarry planning.
- A quantitative cost benefit analysis is required before the minerals industry can determine whether 3D ERT is a viable tool for sand and gravel investigations.
- Knowledge transfer is being actively pursued through the preparation of conference presentations, journal papers, and articles.
- Additional funding will be sought from sources such as MIST, TSB and EPSRC.

9 References

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