# Development of Geoelectrical Techniques for Investigation and Monitoring of Landfills

**Andrew George**

**2006**

**A Thesis in Part Fulfilment of the Doctor of Philosophy Degree Scheme**

**School of Earth, Ocean and Planetary Sciences, Cardiff University**

# Summary

A review of geophysical applications to investigation and monitoring of landfills identified that the geoelectrical methods, such as ERT, SP and EM, are ideally suited because much information can be inferred from the electrical characteristics of landfill waste. The review identified scope for further development due to constraints of geophysical surveying along the ground surface. In particular, the ERT method suffers a loss of data accuracy and resolution with increasing depth of investigation. These constraints have provided the main focus for interest during this research project. A field test site was examined on a reconnaissance basis using a multi-method geophysical approach to obtain the best possible sub-surface characterisation and interpretation in the absence of intrusive calibration data. On the basis of results obtained a model was produced showing combined geoelectrical response, which may be used to plan further detailed investigations including conventional intrusive site examination. It is further demonstrated that the effectiveness of ERT in a landfill setting lies with the arrangement of measurement electrodes and application of specialised electrode address configurations. In an active landfill setting, basal electrodes installed within the cell drainage medium prior to waste emplacement were used in conjunction with ground surface electrodes and the address configuration applied across the array pair. Delineation of basal leachate accumulation and differentiation from perched tables within the waste profile was possible. In a closed landfill setting, where restorative capping and leachate extraction was scheduled, a system for ERT monitoring was established by installing vertical electrode arrays during routine drilling and emplacement of gas wells. In this setting, baseline sub-surface geoelectrical characteristics were identified against which the effects of landfill capping and leachate extraction were assessed through variance in model resistivities and percentage resistivity change. This research has provided recommendations for geophysical monitoring best practice, which may help site stakeholders to achieve a more effective management of leachate control systems, to assess the effectiveness of restorative strategies, and to demonstrate legislative compliance with a greater degree of certainty.

# Acknowledgements

I would like to thank the staff and research students of The Department of Earth, Ocean and Planetary Sciences, Cardiff University, UK, who have provided inspiration, support and advice in all aspects of this research; in particular Prof. Charles Harris, Dr. Peter Brabham, Dr. Tim Jones, Dr. Emma Paris, Dr. Simon Wakefield, Neil Ross and Sarah Ling.

This research project has been made possible by collaboration with landfill site stakeholders for which acknowledgement must be made. Cardiff Council provided access to the active Lamby Way domestic landfill and the restored Ferry Road site. Considerable inspiration and technical support has been given by Cardiff Council, in particular by Mrs. Jo Taylor-King, Andrew Barnett, Jonathan Hutchins, Andrew Williamson, and by Colin Crookes of Parsons Brinkerhoff who was the appointed engineer at Lamby Way. Amgen Cymru Ltd have enabled access to the closed Nantygwyddon landfill in Rhondda Cynon Taff and considerable support was provided by personnel of Encia Consulting Ltd acting on behalf of Amgen, in particular Nigel Brinn, Lee Foulkes and Jeremy Jones.

Acknowledgement must be made to Dr. Rob MacDonald, Dr. Jonathan Thomas and Nick Russill of Terradat (UK) Ltd for providing access to geophysical survey equipment and extensive training in its use. Terradat have also given advice and guidance in the commercial practices of geophysical surveying.

I would like to thank Mrs. Viv Davies of the Central Register of Air Photography in Wales, Welsh Office, for her time and efforts in finding site desk study material.

I have considerable appreciation of my two great friends Clive Elsbury and Avril Owen for their constant encouragement, help and advice over the past three years.

I would like to thank my parents Glyn and Diana George and my family for their appreciable support, encouragement, patience and interest during my academic career.

This project was sponsored by Biffaward (ENTRUST project no. 689198.018/A/013).

# Table of Contents

## List of Figures — Page Number

## List of Tables — Page Number

# (1)
# Introduction

## 1.1. Research Aims and Objectives

The aim of this study is to provide new applications of geoelectrical sub-surface characterisation techniques for the investigation and monitoring of active and closed landfill sites. Applicable geoelectrical ground survey methods will be identified by undertaking a review of published case studies and research literature indicating the scientific mechanisms, limitations and scope for development of the techniques. Adaptations of geoelectrical methods will be applied to suitable test sites that are typical of the nature of landfills encountered in the UK. The effectiveness of adapted geoelectrical ground characterisation methodologies will be assessed by comparison with conventional investigation and monitoring techniques. It is anticipated that the research outcomes will provide a firm basis for recommendations of geophysical best practice aimed at landfill development stakeholders and geophysical consultants.

## 1.2. Context of Research

Geophysical survey techniques are increasingly being applied to environmental ground investigations, in particular the characterisation of landfill sites and contaminated land. Through the deployment of geophysics, large-scale reconnaissance surveys may be performed ahead of a more detailed intrusive site investigation. Alternatively, geoelectrical acquisition equipment may be installed into the sub-surface, as with borehole geophysics, to enable regular detailed monitoring of a specific environmental problem.

Most of the geophysical survey methods being applied to environmental ground investigations have their origins in mineral and groundwater exploration. Techniques such as electrical resistivity tomography, electromagnetics and self-potential may be utilised during landfill characterisation studies to provide information on the occurrence and distribution of electrically-conductive leachates, the performance of engineered barrier systems, occurrence of rainwater ingress, and migration of contaminant plumes.

Conventional geophysical surveys deployed along the ground surface have the advantage of being non-destructive. However, limitations arise mainly regarding the use of non-invasive electrical resistivity surveys whereby data resolution and accuracy is rapidly decreased with increasing depth of investigation. These limitations mean that important aspects of landfill design and function, such as the permitted accumulation of leachate above an engineered barrier system, would not be reliably assessed with non-invasive geophysics. Therefore, there is a requirement for adaptation and development of existing geoelectrical techniques to enhance data reliability through a landfill waste-mass.

A further constraint exists with the investigation of closed and restored landfills when it is not desirable initially to deploy widespread conventional intrusive drilling, trial pitting and sampling due to disruption of clay capping systems and risk of exposure to contaminants. In this situation, reconnaissance-scale non-invasive geophysical surveying is frequently required; however, only one or two methods may be deployed often resulting in an inadequate understanding of site conditions. A non-invasive landfill characterisation would be greatly enhanced through the use of multi-method geophysical surveys providing an optimal site interpretation.

There is no legislative requirement for the implementation of geophysical surveying and monitoring during the stages of a landfill development. However, from the perspective of the environmental regulatory bodies, geophysical monitoring may provide additional assurance that a landfill is performing as designed. This is particularly relevant to *special wastes sites*, whereby geophysical monitoring of leachate accumulation, barrier performance, etc, may be recommended as an extra compliment to conventional monitoring.

## 1.3. Thesis Outline

Following the introduction, Chapter 2 provides a review of applicable geoelectrical ground survey techniques for the investigation and monitoring of active and closed landfills. The known geoelectrical characteristics of landfill waste and leachate are also examined. Three landfill test sites are described in Chapter 3, which includes a review of the geology, hydrogeology, historical land use, nature of wastes, monitoring measures to date, and environmental concerns for each site. Chapter 4 describes a multi-method geoelectrical approach to the non-invasive characterisation of a lined hydrocarbon disposal cell constructed within a restored landfill. Chapter 5 provides a methodology for geoelectrical waste-mass characterisation during development of an active disposal cell. In Chapter 6, a methodology is provided for assessing the variation in geoelectrical sub-surface characteristics resulting from restoration at a closed landfill. Chapter 7 provides recommendations for geophysical best practice aimed at landfill development stakeholders and geophysicists. Research conclusions and potential for further work are presented in Chapter 8.

# (2)

# A Review of Geoelectrical Applications to the Investigation and Monitoring of Landfills

## 2.1. Background and Objectives of the Review

At an early stage in the research project it was necessary to review the current available geoelectrical technologies, with particular regard to the selection of appropriate methods for practical application to field test sites. Of the various geophysical technologies currently used both for research and commercial projects, the geoelectrical methods are ideally suited to sub-surface characterisation and regular monitoring of landfill and contaminated land. By reviewing published research and discussing current methodologies with practicing professional geophysicists, it is apparent that a number of geoelectrical methods are particularly relevant to environmental ground investigation and include the following:

- Electrical Resistivity Tomography (ERT)
- Borehole ERT
- Self-Potential (SP)
- Electromagnetic Induction (EM)

There exists a wealth of published information on these techniques and much has been written about the scientific theory and practical application to ground investigation. It was therefore anticipated that the above methods could be utilised for this research project, whereby they would be applied in combination and/or further advanced in landfill and contaminated land settings. Accordingly, a review of available literature and published case studies has been compiled in this section of the thesis and is based on the following objectives:

- Provide an account of the geoelectrical characteristics of landfill waste, leachate and typical landfill contaminants.

- Identify relevant modern geoelectrical techniques, with particular regard to those methods that could be combined, adapted, improved or advanced through the application to environmental ground investigation and monitoring.

- Outline the scientific principles of each method and the available modern equipment developed to utilise these mechanisms for sub-surface characterisation.

- For each geophysical technique, provide an account of the accepted and conventional field survey protocol and the capabilities for data handling and presentation of results.

- Demonstrate, with reference to case studies, the requirement for geophysical data calibration by integration with conventional site investigation means.

- Identify, within the context of this research, the accepted limitations and scope for further development of the techniques selected.

## 2.2. Geoelectrical Characteristics of Landfill Waste and Leachate

Geoelectrical characteristics of landfill waste are increasingly being studied for the purpose of site delineation and detailed investigation. With the advent of automated electrical resistivity survey equipment and use of multi-electrode arrays, large-scale ERT surveys are often deployed across old closed landfills to distinguish the waste-mass from background natural geology on the basis of variation in electrical resistivity/conductivity. Furthermore, the elevated conductivities encountered within landfills enable the use of electromagnetic mapping surveys, particularly for locating the boundaries of closed sites and to detect migrating leachate plumes.

Elevated conductivity within landfill waste and sometimes observed extending into background geological deposits is attributed to the presence of leachate. As described in Christensen et al. (2001), leachate is generated by excess rainwater percolating through the waste layers of a landfill. Combined physical, chemical and microbial processes in a landfill waste-mass act to transfer pollutants from the refuse material to the percolating water. In general, landfill leachates contain very high concentrations of dissolved organic matter, inorganic macrocomponents, together with heavy metals and xenobiotic organic compounds (XOC's), (Christensen et al. 2001). The elevated ion content, which may be a factor 1000-5000 higher than uncontaminated groundwater, results in a strong electrical conductivity, or reduced resistivity. Table 2.1 indicates the typical composition of landfill leachate.

With the use of electrical resistivity tomography sub-surface imaging, it is generally possible to distinguish leachate-saturated wastes from drier material on the basis of variation in resistivity. With detailed ERT across a typical domestic landfill, a broad range in resistivities is encountered. It is possible to subdivide a range in resistivity values according to the conditions in the landfill, mainly attributed to variation in moisture content and the nature of materials deposited. However, this requires calibration by comparison to moisture content and hydrogeochemical analysis obtained from boreholes, trial pits and observation wells. Typical resistivity values encountered within domestic and industrial landfills are shown in Table 2.2.

Unsaturated landfill wastes are distinguished from zones of leachate saturation by the higher resistivity values observed. Landfill waste is typically comprised of rubble, wood, plastics, rubber, scrap metals, glass, textiles, etc (Ove Arup and Partners, 1995). In its bulk form, this material is electrically non-conducting, so will exhibit a high to very high resistivity.

Table 2.1: *Typical composition of landfill leachate (Christensen et al. 2001).*

| **Parameter** | **Range** |
|---|---|
| pH | 4.5 – 9 |
| Specific conductivity (µS $cm^{-1}$) | 2500 – 35000 |
| Total solids | 2000 – 60000 |
| | |
| ***Organic matter*** | |
| Total organic carbon (TOC) | 30 – 29000 |
| Biological oxygen demand ($BOD_5$) | 20 – 57000 |
| Chemical oxygen demand (COD) | 140 – 152000 |
| $BOD_5$/COD (ratio) | 0.02 – 0.80 |
| Organic nitrogen | 14 – 2500 |
| | |
| ***Inorganic macrocomponents*** | |
| Total phosphorous | 0.1 – 23 |
| Chloride | 150 – 4500 |
| Sulphate | 8 – 7750 |
| Hydrogencarbonate | 610 – 7320 |
| Sodium | 70 – 7700 |
| Potassium | 50 – 3700 |
| Ammonium nitrate | 50 – 2200 |
| Calcium | 10 – 7200 |
| Magnesium | 30 – 15000 |
| Iron | 3 – 5500 |
| Manganese | 0.03 – 1400 |
| Silica | 4 - 70 |
| | |
| ***Inorganic trace elements*** | |
| *Arsenic* | 0.01 – 1 |
| Cadmium | 0.0001 – 0.4 |
| Chromium | 0.02 – 1.5 |
| Cobalt | 0.005 – 1.5 |
| Copper | 0.005 – 10 |
| Lead | 0.001 – 5 |
| Mercury | 0.00005 – 0.16 |
| Nickel | 0.015 – 13 |
| Zinc | 0.03 – 1000 |

*Note: All values in mg/l except specific conductivity.*

Table 2.2: *Typical resistivity values encountered within domestic and industrial landfills.*

| **Parameter** | **Resistivity (Ωm)** |
|---|---|
| Leachate saturation [a] | 2 – 10 |
| Weak / dilute leachates [a] | 10 – 20 |
| Surface drainage / ingress [b] | 10 – 50 |
| Damp, unsaturated wastes [a] | 20 – 200 |
| Dry wastes [a] | 200 – 2000 |
| Uncontaminated groundwater [c] | 100 – 200 |
| Free-phase LNAPLs, e.g. fuel oil [c] | 400 |
| DNAPLs, e.g. PCE, TCE [d] | 650 – 850 |
| HDPE liners [a] | >2000 |

The above ranges are based on: [a] George (2002), [b] Reynolds (1997), [c] Godio and Naldi (2003), [d] Goes and Meekes (2004).

Landfill liner and capping membranes, such as high-density polyethylene (HDPE) and low-density polyethylene (LDPE) act as electrical insulators preventing current flow through them (George, 2002). This may be problematic for the use of geoelectrical survey methods, particularly where LDPE capping membranes have been emplaced during restoration of closed landfills. Otherwise, a basal HDPE liner system may be identified by the high resistivities observed.

Uncontaminated, non-saline groundwater has a typical resistivity range of 100 – 200 ohm.meter (Godio and Naldi, 2003). As landfill leachate exhibits a much lower resistivity range (2 – 10 ohm.meter) it is often possible to delineate the spread of migrating leachate plumes from a waste-mass into natural background geological deposits. For this purpose, a two-dimensional ERT profiling survey, with spatial EM conductivity mapping over the ground surface may provide favourable results.

Current landfill regulations do not permit the co-disposal of domestic refuse with *special wastes*, which include organic hydrocarbon contaminants. In older landfills, organic contaminants are often encountered and may be distinguished from other waste-types, from leachate, or from uncontaminated groundwater by the resistivity values exhibited. Oil contamination, such as diesel fuel, kerosene and gasoline are known as *light non-aqueous phase liquids* (LNAPLs) and are electrically insulating where they exist perched above groundwater and leachate bodies. However, when LNAPL contaminants become dissolved into uncontaminated groundwater during biodegradation and emulsification, the production of organic acids leads to dissolution of mineral ions in the groundwater body resulting in an increase in conductivity / decrease in resistivity (Cassidy et al. 2001), (Godio and Naldi, 2003), (Sauck et al. 1998). Other commonly encountered organic compounds, such as trichloroethylene (TCE) and perchloroethylene (PCE) occur within groundwater bodies and are known as *dense non-aqueous phase liquids* (DNAPLs). These contaminants exhibit a higher resistivity than the background lower bulk resistivity of a saturated groundwater aquifer (Goes and Meekes, 2004) or leachate body and may be detected on this basis.

Table 2.3: *Applications of geoelectrical ground survey methods to landfill investigation and monitoring (adapted from Brabham et al. 2005).*

| Geophysical Technique | Potential application to landfill investigation |
|---|---|
| Electrical Resistivity Tomography (ERT) | Characterise the general composition of landfill material.<br>Differentiate waste-mass from background geology.<br>Distinguish between dry inert fill and saturated waste.<br>Monitor the generation and migration of leachate.<br>Examine the integrity of cap and liner systems. |
| Cross-Borehole ERT | Identification of leachate with depth through waste.<br>Monitor the distribution of dry and saturated fill.<br>Assist in the management of leachate re-circulation.<br>Delineation of leachate flow pathways through waste. |
| Electromagnetic (EM)<br>*For example: EM31, EM38* | Delineation of migrating leachate plumes.<br>Identify buried metal objects, e.g. chemical drums.<br>Delineation of landfill boundaries.<br>Spatial mapping of wet & dry areas. |
| Self Potential (SP) | Identify and map seepage problems across a landfill.<br>Determine the integrity of capping materials.<br>Identify contamination plumes derived from landfills. |

The electrical characteristics of landfill waste are therefore very responsive to geoelectrical ground survey techniques, which may be deployed on a large scale to locate old landfills (*for example*: Lanz et al. 1998., George, 2002), or on a smaller scale to monitor specific problems (*for example*: George, 2002). The applications of geoelectrical ground survey methods to landfill investigation and monitoring are indicated in Table 2.3.

## 2.3. Electrical Resistivity Tomography (ERT)

### 2.3.1. Background to the Resistivity Method

Electrical resistivity surveying is a commonly used geophysical technique for sub-surface characterisation of landfills and contaminated land in the UK. Resistivity surveying has origins in mineral and groundwater exploration, but in recent decades it has increasingly been applied to environmental and engineering investigations of the shallow sub-surface. Traditionally resistivity investigations involved the application of electrical current to the ground across a pair of metal electrodes, whilst the voltage difference across an adjacent electrode-pair was measured simultaneously, thus giving a determination of ground resistance, as illustrated in Figure 2.1. In the early stages of development, these tests were often conducted to investigate soil moisture properties or clay content. Electrical Resistivity Tomography (ERT) surveying is a recent development of the resistivity technique, whereby multi-electrode arrays are used to acquire many data points through the sub-surface. Raw data is subjected to inversion producing a two-dimensional image or tomogram of sub-surface resistivity variation with distance and depth beneath a survey traverse. Recent applications of resistivity surveying to landfill investigations have included the delineation of old disposal sites (Lanz et al. 1998) and characterisation of leachate saturated zones prior to remediation (George, 2002).

### 2.3.2. Resistivity Measurement Theory

Ground resistivity surveys involve the measurement of resistance by introducing an electrical current across a pair of grounded metal electrodes (AB) and measuring the voltage potential between an adjacent electrode-pair (MN). This concept is illustrated in Figure 2.1.

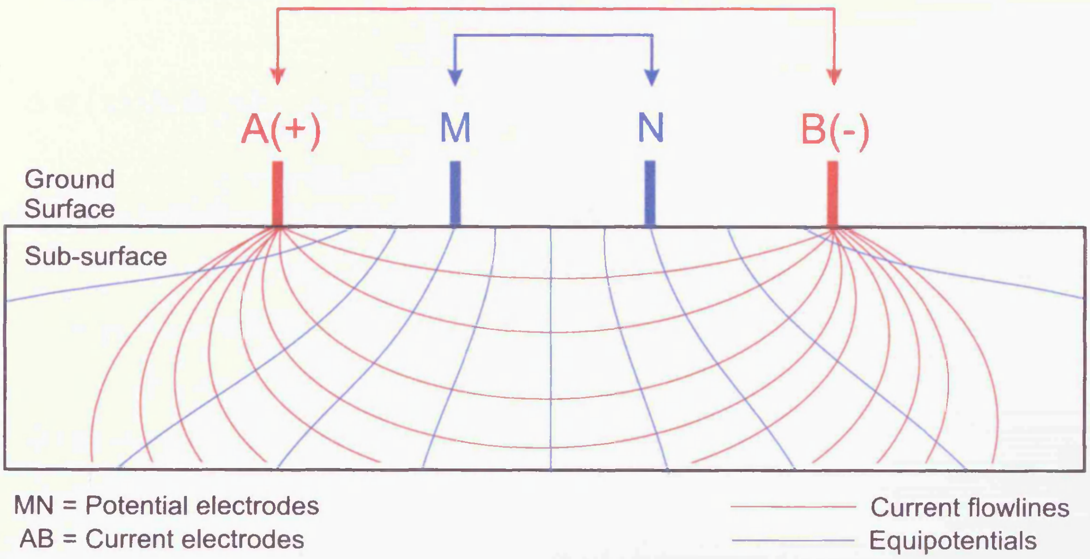



Figure 2.1: *A diagram illustrating the basic theory of ground resistivity measurement by introducing electrical current and measuring voltage potential.*

A good account of resistivity survey theory has been discussed in Hauck (2001). An equation for the potential distribution due to a point current source $\boldsymbol{I_s}$ located at point $\mathbf{x_s}$ can be derived from:

*Ohm's law:*

$$j(x) = \sigma(x)\, e(x) \tag{2.1}$$

and the *divergence condition:*

$$\Delta \cdot j(x) = I_s\, \delta(x - x_S) \tag{2.2}$$

where **e** is the electric field (in V/m), **j** is the current density (in $A/m^2$), $\boldsymbol{\sigma}$ is the conductivity of the medium (in S/m) and $\mathbf{x} = (x, y, z)$ (Keller and Frischknecht, 1966). The time independent form of the first Maxwell equation, $\boldsymbol{\Delta} \times \mathbf{e} = 0$, implies the existence of a scalar electric potential:

$$e\,(x) = -\Delta\, \Phi\,(x) \tag{2.3}$$

which may be combined with Eq. (2.1) and Eq. (2.2) to give:

$$\Delta\, \sigma\,(x) \cdot \Delta\, \Phi\,(x) + \sigma\,(x)\, \Delta^2\, \Phi\,(x) = I_s\, \delta\,(x - x_s) \tag{2.4}$$

Assuming a homogenous half-space Earth model, the first term on the left hand side of equation (2.4) is not used and the potential caused by a current source located at $\mathbf{x} = (0, 0, 0)$ is given by:

$$\Phi\,(x) = \rho\, I_s\, 1 \,/\, 2\, \pi\, [x] \tag{2.5}$$

where $\rho = 1 / \sigma$ is the resistivity and [x] is the distance from the origin. So, the boundary conditions $\boldsymbol{\Phi} = 0$ for $[x] \rightarrow \infty$ and $\boldsymbol{\Phi} \rightarrow \infty$ for x = (0, 0, 0) are applied.

Since potential functions can be added arithmetically, the total potential at one observation point may be calculated by adding the potential contributions from each source. The potential difference between two potential electrodes (MN) induced by a pair of current electrodes (AB) is then given by:

$$\Phi_M - \Phi_N = \Delta\, \Phi = \rho\, I_s / 2\pi\, (1/AM - 1/BM - 1/AN - 1/BN) \tag{2.6}$$

where *AM* denotes the distance between current electrode A and potential electrode M. So, the minus sign for two of the distance terms arise since one of the current electrodes in a normal two-electrode current must have a negative sense of current flow compared to the other.

When $\sigma$ is allowed to vary over a full 2D or 3D half-space Earth model the first term in Eq. (2.4) does not vanish. Integrating over volume $V$ and applying Green's theorem:

$$\iint_S \sigma(\mathrm{x}) \, [\partial \Phi(\mathrm{x}) / \partial \mathrm{n}] \, dS = I(\mathrm{x}) \tag{2.7}$$

where **n** is the unit vector normal to the surface.

Using the finite-difference discretisation of Dey and Morrison (1979) this leads to a matrix equation of the form:

$$\mathbf{G} \, \mathbf{\Phi} = \mathrm{I} \tag{2.8}$$

where **G** is the conductance matrix consisting of the discretised conductivities and **Φ** are the discretised potentials. The generally sparse conductance matrix **G** can be inverted using a sparse matrix solver to give the potentials over the whole 2D or 3D model grid.

During DC resistivity surveys, the quantity that is actually measured is *potential difference* between the two potential electrodes (MN). For a homogeneous Earth, Eq. (2.6) can then be used to calculate the *resistivity* (*ρ*), so the terms can be rearranged to obtain:

$$\rho = \mathrm{K} \, (\Delta \Phi / I) \tag{2.9}$$

where ***K*** is called the *geometric factor* combining the effect of electrode separation distances (Keller and Frishknecht, 1966).

If the sub-surface is non-uniform, the so called *apparent resistivity* (**$\rho_a$**) is determined from Eq. (2.9).

### 2.3.3. Electrode Array Geometries

Resistivity ground surveys were primarily developed using the four-electrode system comprising two current and two potential electrodes. However, modern ERT acquisition systems utilise multi-electrode arrays, whereby it is possible to use between 18 and 72 electrodes connected along a single traverse with multi-core cables. Multi-electrode acquisition systems were developed to minimise the time spent during field data acquisition and to enable resistivity variations to be determined over significant distances and depths. A four-electrode configuration can be applied to a multi-electrode survey traverse by a range of different geometries. The most widely used electrode array geometries, the *Wenner*, the *Wenner-Schlumberger*, and the *Double-Dipole*, are described and illustrated in Figure 2.2.

In the Wenner array geometry, current is applied to the outer electrodes with potential difference being measured across the inner pair. When this geometry is applied to a multi-electrode array, greater depths and distances are progressed by increasing the spacing between electrodes, whereby the spacing increase is always a multiple of the minimum spacing (*a* in Figure 2.2). If the Wenner array geometry is used during field data acquisition, the number of readings is relatively small; therefore this array configuration can minimise the time taken to run a survey. However, the resolution is only suitable for analysing vertical layered changes and small scale lateral heterogeneities often remain unresolved.

In the Double-Dipole geometry, two 'dipoles' are established comprising the current pair (AB) on one side of the array and the potential pair (MN) on the other side. When this array geometry is applied to a multi-electrode traverse, the spacing (a) of the dipoles remains constant and always equal or less than the spacing between the dipoles (na). Data acquisition is progressed vertically and horizontally by increasing the spacing between the dipoles (na). The Double-Dipole configuration results in a larger number of measurements than the Wenner array and horizontal resolution is good, however this is at the compromise of decreased depth penetration.

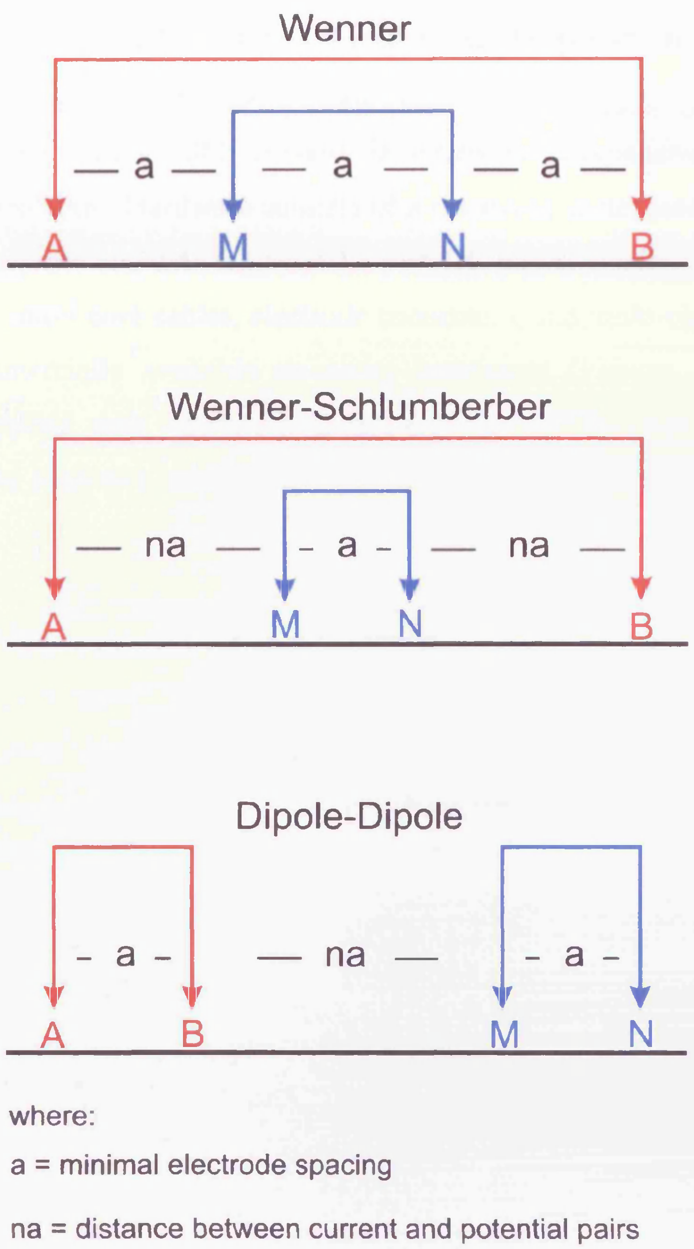



Figure 2.2: *Schematic representations of the commonly used Wenner, Wenner-Schlumberger, and Double-Dipole electrode array geometries (after Hauck, 2001).*

In the Wenner-Schlumberger array geometry, current is applied to the outer electrode pair whilst potential difference is measured across the inner pair. The difference between this and the standard Wenner array is that the midpoint spacing between the potential electrodes (a) is kept constant and the spacings between AM and NB are increased logarithmically. This results in an enhanced data resolution and with a slightly increased number of spacings, but not as many as the Double Dipole array.

## 2.3.4. ERT Instrumentation and Field Data Acquisition

Equipment utilised during ERT surveys is relatively inexpensive, portable and commercially available. Hardware consists of a resistivity meter integrating a multi-channel switching unit and data logger, a 12 Volt DC power supply, a set of stainless steel electrodes, multi-core cables, electrode connectors, and multi-channel cable link nodes. A commercially available resistivity instrument (Figures 2.3, 2.4) would normally be supplied with interface software enabling the operator to compile and upload electrode sequence address configurations and to download raw data for processing.

Figure 2.3 illustrates a modern commercial resistivity meter and external 12 Volt DC supply. In this photograph, the IRIS Instruments® SYSCAL 72-Switch is illustrated and was used during this research programme. Figure 2.4 illustrates an ERT survey traverse in operation during a geophysical site characterisation.

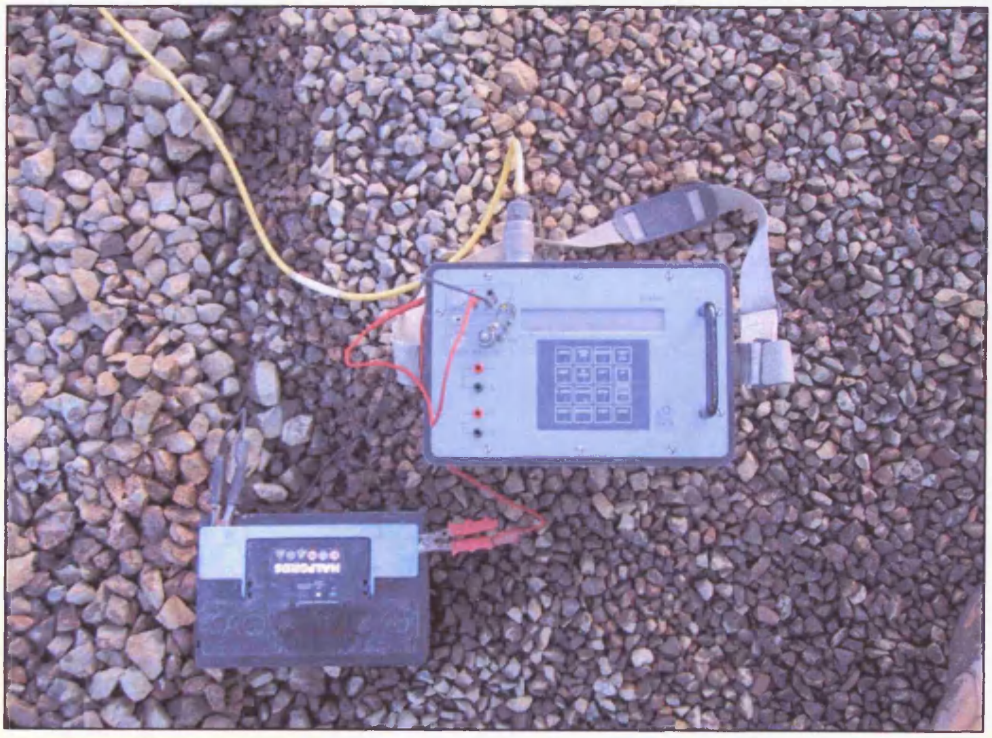


Figure 2.3: *A photograph illustrating a modern commercial resistivity meter and external 12 Volt DC supply (author).*

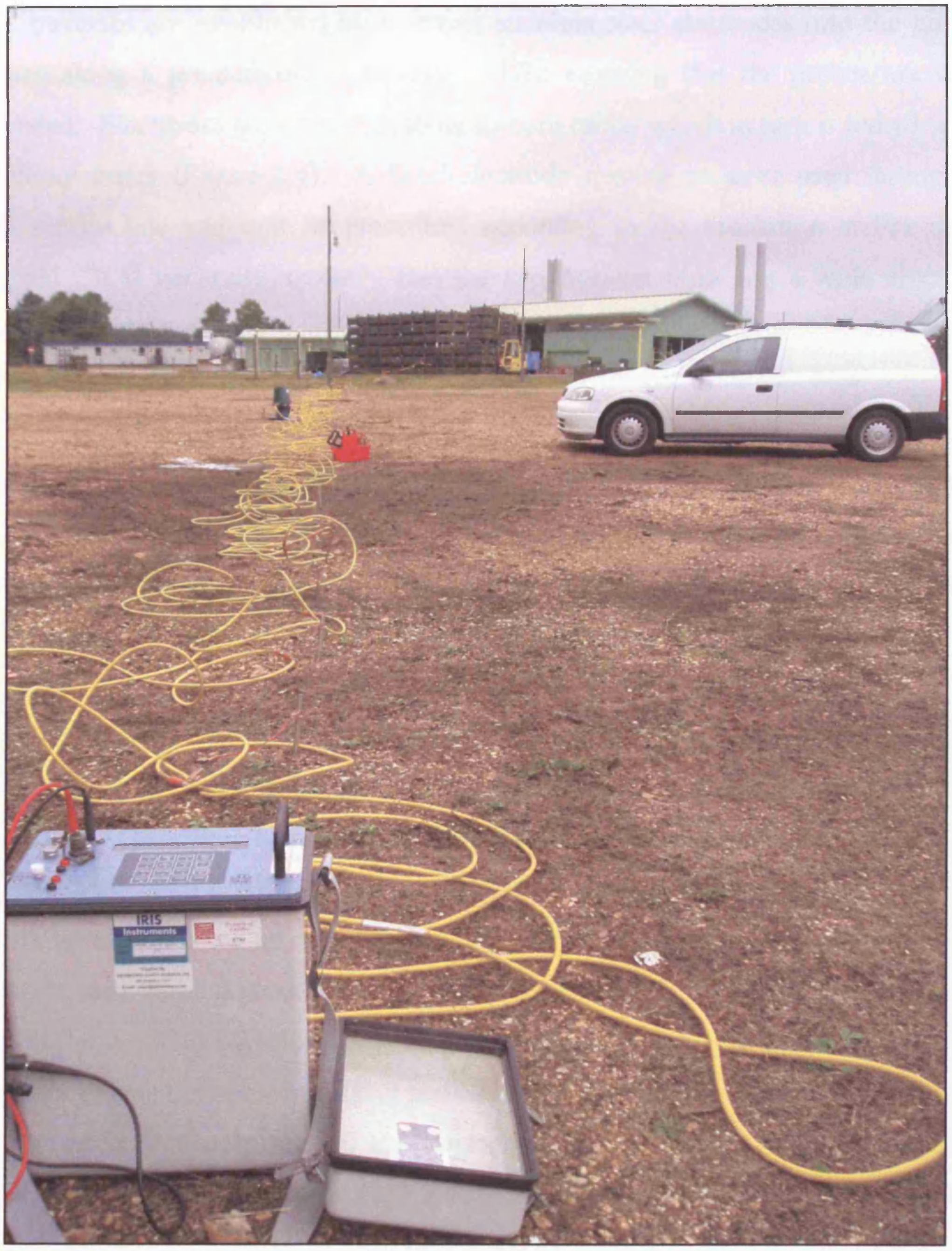


Figure 2.4: *A photograph illustrating ERT data acquisition during a geophysical site characterisation (author).*

An ERT survey is usually planned by collaboration between the geophysical contractor and client according to information relating to sub-surface targets or possible anomalies obtained from desk study research. A survey plan of the site will show ERT profile traverse positions, the start and end electrode locations, and electrode spacing.

ERT traverses are established by inserting stainless steel electrodes into the ground surface along a pre-determined traverse, whilst ensuring that the probes are well-grounded. Electrodes are connected to multi-core cable, which in turn is linked to the resistivity meter (Figure 2.4). A fixed electrode spacing must be used throughout each survey line and will be prescribed according to the resolution and/or depth required. It is generally accepted that the geophysicist must use a wide electrode spacing to obtain greater depths of investigation, but at the compromise of vertical and horizontal resolution, which is greater using smaller electrode spacings.

Prior to an ERT survey, an electrode sequence address file is uploaded from PC onto the resistivity meter. A sequence address file contains a list of configurations instructing the instrument to apply electrical current and measure potential difference according to the electrode array geometry used for a given number of electrodes.

Poorly grounded electrodes and/or very dry soil conditions will undoubtedly result in a low signal to noise ratio and inaccurate readings of resistance and apparent resistivity. Therefore, care must be taken prior to data acquisition to ensure all electrodes are well-grounded and to perform a contact resistance test. Modern resistivity meters have an in-built function to test the contact resistance between electrode pairs and the ground surface prior to a survey. High contact resistances (>4 kΩ) can be rectified by improving the ground contact. In cases where high contact resistances persist, a suitable contact can be obtained by application of saline water to the ground immediately around the electrode. It is widely accepted that contact resistances should be less than 4kΩ across all electrodes in a traverse in order to optimise the signal to noise ratio and obtain accurate readings of apparent resistivity.

On completion of data acquisition the readings are downloaded to PC using interface software, which will enable the operator to assess the quality of the raw data in the field, remove erroneous data points, and export the results in a format suitable for inversion.

### 2.3.5. Tomographic Inversion – RES2DINV®

Following the acquisition of resistance and/or apparent resistivity data points from the sub-surface during an ERT survey, an inversion routine must be performed to produce a two-dimensional image tomogram, which is a model of the difference between measured and calculated apparent resistivity values.

Apparent resistivity raw data acquired from all field test sites during this research was subject to inversion using the RES2DINV® software (Geotomo Software, 2002). This software incorporates a forward modelling sub-routine to calculate the apparent resistivity values and a non-linear least-squares optimisation technique for the inversion routine (deGroot-Hedlin and Constable, 1990; Saski, 1992; Loke and Barker, 1996).

The smoothness-constrained least-squares inversion method used by RES2DINV® is based on the following equation (Geotomo Software, 2002):

$$(J^TJ + uF)d = J^Tg \qquad (4.10)$$

where $F = f_x f_x^T + f_z f_z^T$

$f_x$ = horizontal flatness filter

$f_z$ = vertical flatness filter

$J$ = matrix of partial derivatives

$u$ = damping factor

$d$ = model perturbation vector

$g$ = discrepancy vector

As described in Geotomo Software (2002), RES2DINV® incorporates a new implementation of the least-squares method based on a quasi-Newton optimisation technique (Loke and Barker, 1996a). This technique is more than 10 times faster for large datasets than the conventional least-squares method and requires less processing memory. A further advantage of this method is that the damping factor and flatness filters can be adjusted to suit different types of data.

RES2DINV® uses a two-dimensional model to divide the sub-surface into a number of rectangular blocks, the purpose of which is to determine the resistivity of the blocks that will produce an apparent resistivity pseudosection that agrees with the actual measurements. An optimisation method used by the program attempts to reduce the difference between the calculated and measured apparent resistivity values by adjusting the resistivity of the model blocks. A measure of this difference is given by the root-mean-squared (RMS) error. It is important to note that the inversion model with the lowest RMS error can sometimes show large and unrealistic variations in the model resistivity values and may not always be the best model from a geological perspective. In general, the most prudent approach is to choose the model at the iteration after which the RMS error does not change significantly - usually between the 3$^{rd}$ and 5$^{th}$ iterations.

The effectiveness of resistivity data inversion and the quality of tomographic interpretation is highly dependent on accuracy, resolution and equivalence, a description of which is provided in Hauck (2001). In order to estimate the quality of the inversion results, the model *resolution* and *accuracy* must be analysed. Both quantities are strongly influenced by the number of model parameters; that is the number of model blocks in a tomographic inversion. If many model parameters are selected the accuracy of these parameters may be low, whereas the resolution of the inversion result is high. If only a few model parameters are selected the accuracy is high but the resolution is low. In effect, there is a compromise between accuracy and resolution in choosing the number of model parameters for a given data set.

Non-invasive ERT is restricted to acquisition of measurements from the ground surface, which usually results in a decrease of the sensitivity of the model parameters to the data with increasing depth. One possibility is to increase the model block size with depth leading to fewer model parameters and higher accuracy at larger depths. At shallow depth, where the sensitivity is usually largest, a higher resolution is often achievable.

A further problem of uncertainty sometimes arises from the principle of *equivalence*, which implies that two highly resistive anomalies with slightly different resistivities and dimensions may show the same response if the product of their thickness and resistivity values ($z$ ρ) is the same. Furthermore, two highly conductive bodies will give the same response if the ratio between their thickness and resistivity values ($z$ / ρ) is the same.

It is essential that non-invasive ERT results must not be relied upon solely and should be calibrated by comparison to results from conventional site investigation information, such as moisture content and hydrogeochemical analysis obtained from boreholes, trail pits and monitoring wells (Section 2.7).

### 2.3.6. Data Presentation and Interpretation

Tomographic inversion, using a program such as RES2DINV®, produces a two-dimensional colour-scaled image of resistivity variation with distance and depth beneath the survey electrode profile. Modelled apparent resistivity data can be viewed as a numerical block image, or alternatively data points can be contoured, and in both cases a scale of resistivity in ohm.meter (Ωm) from low to high is provided.

Interpretation of modelled apparent resistivity may be qualitative, which involves visual inspection of resistivity variation and anomalous occurrences. It is advisable to compare the resistivity image produced with a geological or conceptual model of the perceived ground characteristics. For example, a landfill site would be expected to contain leachate within the waste-mass and possible migration into the background geological deposits and as these liquids are electrically conductive, zones of low resistivity may be inferred to be characteristic of leachate. This approach may be adequate for initial reconnaissance ground investigations, but must be calibrated by comparison to observation well data, geological logs and intrusive sampling.

Occasionally, resistivity surveys are repeated in a temporal sense by acquiring raw data along a fixed array of electrodes on an hourly, daily, or monthly basis. On this basis, the acquisition of multiple data sets from the same electrode profile will permit qualitative interpretation involving timelapse inversion. This can be performed using the RES2DINV® program. Several apparent resistivity data sets can be inverted simultaneously to produce an ERT image of the first data set acquired, followed by subsequent images of resistivity variation between specified time intervals. A timelapse processing approach is particularly useful for analysing resistivity changes within bulk background resistivity values, whereby variations may be caused by increased saturation, desaturation, or the migration of conductive saline groundwater or contaminated plumes.

## 2.4. Borehole ERT Techniques

### 2.4.1. Background to the Borehole ERT Principle

Borehole electrical resistivity tomography techniques were primarily developed for near-surface environmental and engineering investigations to overcome problems of poor accuracy and resolution often encountered with increasing depth when employing conventional ground surface ERT surveying. Resistivity measurements using borehole electrode arrays were initially attempted to perform groundwater investigations and controlled tracer injection experiments in natural geology (Binley et al. 1995; Slater et al. 1996., 1997). Further applications have since included the characterisation of DNAPL-contaminated ground (Goes and Meekes, 2004), single-hole ERT monitoring of landfills (Tsourlos et al. 2003), and monitoring of in-situ contaminated land remediation (Ramirez et al. 1995; Newmark et al. 1998).

Borehole ERT involves the same underlying theory as conventional ground surface techniques, however the electrode arrays are emplaced vertically into the sub-surface after intrusive drilling. Electrical current is introduced to the sub-surface through a pair of current electrodes (AB), whilst potential difference is measured across potential electrodes (MN), thus permitting the calculation of resistance and apparent resistivity values.

Borehole ERT methods are perhaps best suited to detailed investigation and temporal monitoring following reconnaissance-scale surveying. Anomalous zones or areas of concern, such as contaminant and leachate plumes, would normally be targeted by conventional intrusive investigative methodology, which represents an ideal opportunity to install borehole ERT equipment for regular monitoring. The main advantages of borehole ERT are that the measurement electrodes are permanently installed within the ground allowing frequent repeated measurements to be recorded with a high level of positional accuracy. Furthermore, borehole electrodes are installed with increasing depth through the sub-surface, often utilising the entire length of casing and this permits the recovery of data with consistent accuracy and resolution with depth. Some constraints are noted, perhaps the most significant being that the boreholes utilised for ERT cannot be widely-spaced as resolution and accuracy would be anticipated to decrease with increasing borehole separation.

It is relatively inexpensive to install and operate borehole ERT acquisition systems, mainly because the technique can be used when boreholes are being drilled routinely without having to prescribe costly drilling especially for geophysical monitoring.

### 2.4.2. Borehole ERT Measurement Theory

The arrangement of electrodes in borehole surveys is different from conventional ground surface investigations because borehole ERT involves emplacement of vertical electrode arrays into the sub-surface and measurement of resistivity in two-dimensions across the plane of ground between a pair of arrays. As described in Geotomo Software (2002), the geometric factor for sub-surface electrodes is different from that used for ground surface arrays. If the C1, C2 and P1, P2 electrodes are located at $(x_1, z_1)$, $(x_1, z_2)$, $(x_1, z_3)$, $(x_1, z_4)$ respectively, the geometric factor $k$ is given by:

$$k = 4pi/(1/r_1 + 1/r_1') /(1/r_2 + 1/r_2') \qquad (4.11)$$

where $r_1 = sqrt\,(dx^2 + dz^2)$

$r_1' = sqrt\,(dx^2 + Dz^2)$

$dx = x_1 - x_2$

$Dz = z_1 + z_2$

$dz = z_1 - z_2$

$r_1 = \text{sqrt}\,(dx^2 + dz^2)$

$r_1' = \text{sqrt}\,(dx^2 + Dz^2)$

$dx = x_3 - x_4$

$Dz = z_3 + z_4$

$dz = z_3 - z_4$

## 2.4.3. Electrode Array Geometries

A four-electrode configuration (AB and MN) can be applied to multi-electrode borehole arrays by a range of various geometries depending on the nature of the investigation. As discussed in Goes and Meekes (2004), the most commonly used borehole electrode geometries include the cross-hole dipole-dipole, the circulating dipole-dipole, and the cross-hole tripole-pole. A further geometry based on the cross-hole tripole-pole has been developed, known as the 'Meekes' configuration (Goes and Meekes (2004). These four geometries are discussed and illustrated, with reference to the work of Goes and Meekes (2004).

In cross-hole dipole-dipole geometries, each borehole contains two electrodes and the considered configurations of the four-electrode pattern are AB-MN, AM-NB, and AB-MN (Figure 2.5). In the AB-MN configuration, the potential and current electrodes are situated in separate boreholes, so compared to the other two configurations (AM-NB and AB-MN) the distance between the current and potential electrodes is relatively large. The AB-MN configuration can result in many low or zero potential readings, which are easily obscured by background noise (Bing and Greenhalgh, 2000). Furthermore, there is a risk that part of the current flows through the fluid in the borehole instead of through the subsoil, because both current electrodes are situated in the same borehole.

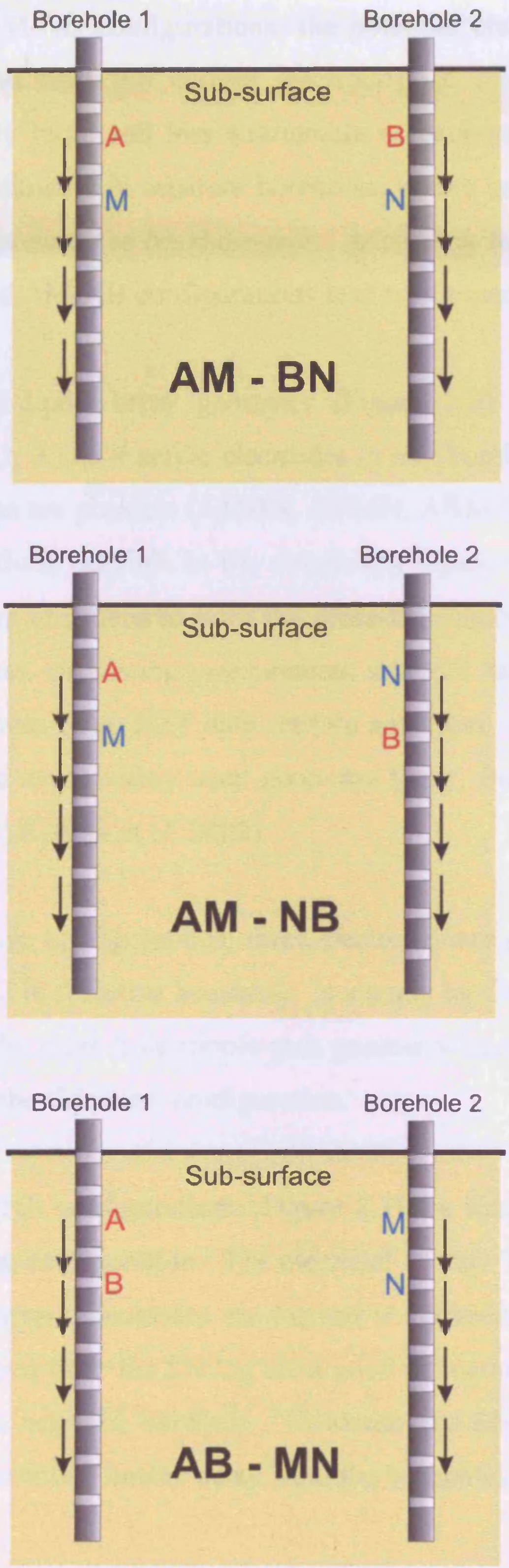



Figure 2.5: *A diagrammatic representation of the three electrode configurations of the cross-hole dipole-dipole borehole ERT array geometry (after Goes and Meekes, 2004).*

In the AM-BN and AM-NB configurations, the potential electrodes are situated in different boreholes and near the current electrodes, so the potential differences measured will be fairly large and less susceptible to background noise. Also, the current electrodes are situated in separate boreholes, so the current flow has to flow through the sub-soil between the borehole-pair. According to Bing and Greenhalgh (2000), the AM-BN and AM-NB configurations lead to comparable results

The circulating dipole-dipole array geometry (Figure 2.6) consists of individual measurements with 1, 2, 3 and 4 active electrodes in one borehole, so many different electrode configurations are possible (AMBN, ABMN, ABM-N, AB-MN, etc). With some of the configurations possible in the circulating dipole-dipole geometry, (AB-MN), the disadvantages encountered with the cross-hole dipole-dipole patterns may still apply. Nevertheless, circulating measurement schemes have been recommended to guarantee completeness of an ERT data set (Xu and Noel, 1993) and in published case examples it is the most widely used geometry ( e.g., Sullivan and LaBrecque, 1998; Slater et al. 2000; Kemna et al. 2002).

In cross-hole tripole-pole configurations, three electrodes are placed in one borehole and the fourth is located in the other borehole. In a study by Goes and Meekes (2004) two configurations of the cross-hole tripole-pole geometry have been tested: the 'well log' configuration and the 'Meekes' configuration.

The MNA-B and A-MNB configurations (Figure 2.7) are based on the short-normal (SN) resistivity well log configuration. The electrical current has to flow through the sub-soil because the current electrodes are located in different boreholes. Apparent resistivity values obtained from the SN log are a good indication of the real resistivity values of the sediment near the borehole. However, the SN log does not provide information on the resistivities further away from the boreholes.

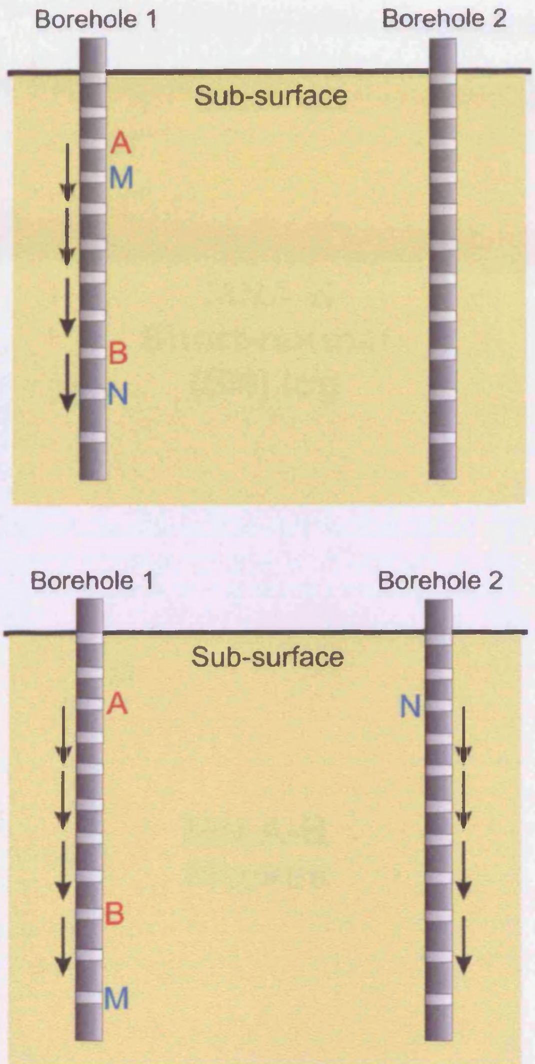



Figure 2.6: *A diagrammatic representation of the circulating dipole-dipole borehole electrode geometry, of which many configurations are possible (after Goes and Meekes, 2004).*

In the 'Meekes' (A-MN B and MN A-B) configurations, which have been applied to the study of resistive DNAPL layers in the sub surface (Goes and Meekes, 2004), the current electrodes are always situated in different boreholes and are always fixed in such a position that the direct line between the electrodes has a large angle compared to the horizontal layers in the sub-soil (Figure 2.7). The reasoning behind this is that the current flow is influenced strongly because relatively many flow lines between the current electrodes are distorted if a thin resistive layer is present between the boreholes.

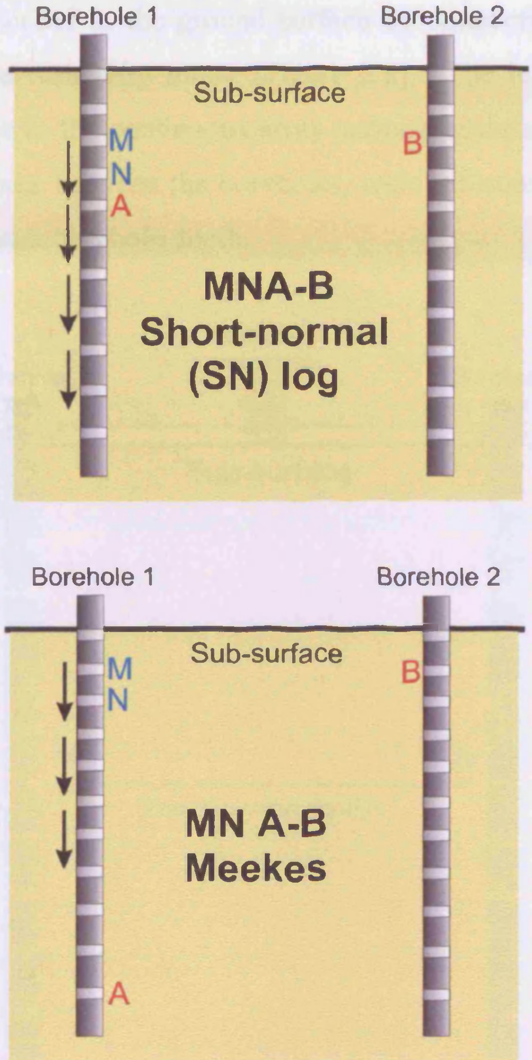



Figure 2.7: *A diagrammatic representation of the short-normal (SN) well log and 'Meekes' configurations of the cross-hole tripole-pole electrode geometries (after Goes and Meekes, 2004).*

## 2.4.4. Instrumentation and Field Data Acquisition

A commercially available resistivity instrument (Figures 2.3, 2.4) can be utilised to perform borehole ERT data acquisition and would normally be supplied with software enabling the operator to compile and upload electrode sequence address configurations. Measurement electrodes are emplaced within the sub-surface following intrusive drilling and should be pre-fabricated to fit prescribed borehole depths. Vertical electrode separation may vary in individual boreholes, but is usually less than 1 metre.

Measurements are recorded at the ground surface by connecting a pair of borehole electrode arrays to the resistivity meter (Figure 2.8). The instrument will apply a configuration sequence to the continuous array permitting data recovery from a two-dimensional spatial plane between the boreholes, which is constrained by the ground surface and the maximum borehole depth.

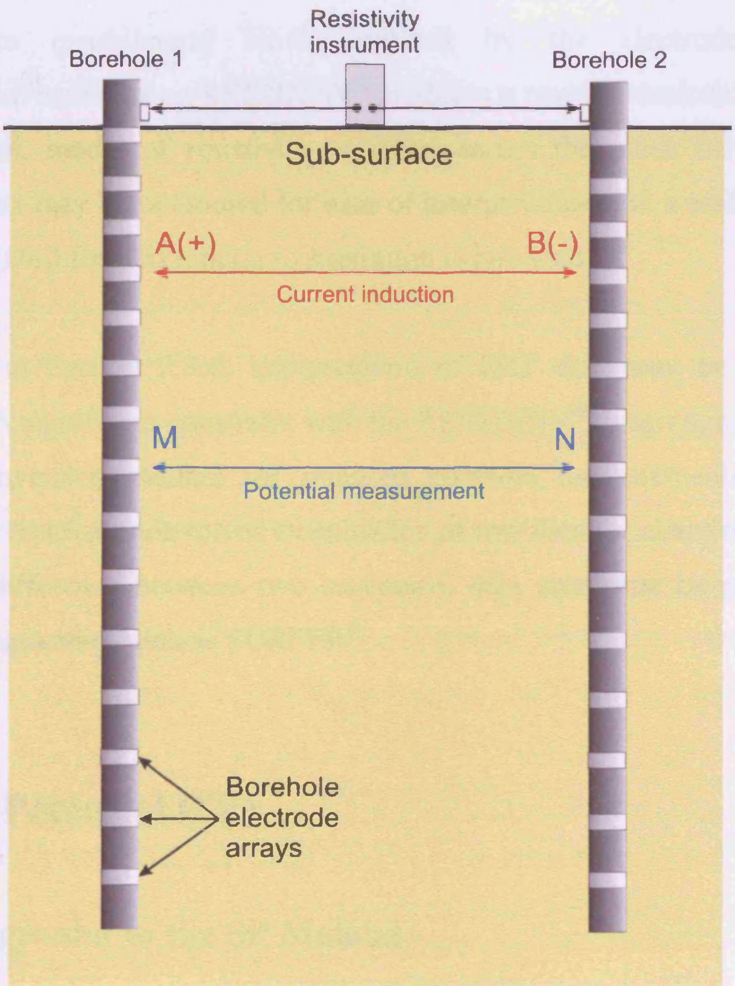



Figure 2.8: *A diagrammatic representation of ERT data recovery from a pair of adjacent boreholes (after Binley et al. 1996).*

It is desirable to perform a contact resistance test immediately prior to a data recovery, as discussed in Section 2.3.4. It is unlikely that any high contact resistance readings (>4kΩ) can be rectified after electrodes have been emplaced in borehole installations; therefore the positions of high readings must be known prior to data recovery to allow editing of erroneous data points prior to inversion.

### 2.4.5. Tomographic Inversion, Data Presentation and Interpretation

Processing techniques for the inversion of electrical resistivity sub-surface measurements are described in detail in Section 2.3.5. Raw data acquired from borehole ERT surveys may be inverted using the RES2DINV® programme (Geotomo Software, 2002). Inversion will sub-divide the sub-surface plane between the boreholes into quadrilateral blocks defined by the electrode separations. Tomographic inversion using RES2DINV® produces a two-dimensional colour-scaled numerical block model of resistivity variation across the plane between the two boreholes. Data may be contoured for ease of interpretation and a scale of resistivity in ohm.meter (Ωm) from minimum to maximum is provided.

As described in Section 2.3.6, interpretation of ERT data may be qualitative or quantitative. A significant constraint with the RES2DINV® programme is the lack of a timelapse inversion method for repeated borehole measurements. Therefore, quantitative interpretation involves examination of raw data for changes in resistivity, whereby the difference between two successive data sets must be plotted using a contouring programme, such as SURFER®.

## 2.5. Self-Potential (SP)

### 2.5.1. Background to the SP Method

Self-Potential (SP) surveying involves the measurement of naturally occurring electrical potentials developed in the near-surface by electrochemical actions between minerals and fluids, or by electrokinetic processes involving the flow of ionic fluids (Sharma, 1997). Application of the passive SP technique differs from other active geoelectrical methods, such as electrical resistivity tomography and electromagnetics, which require the induction of artificially created currents from the ground surface. SP has its origins in mineral exploration, whereby significant natural potentials in the range of a few millivolts (mV) to over 1 Volt are found to occur over base-metal sulphide deposits in the presence of groundwater (Sato and Mooney, 1960; Kilty, 1984; Becker and Telford, 1965). Environmental applications have included the detection of groundwater seepage through earth dams and reservoir floors (Ogilvy et al. 1969; Butler and Llopis, 1990), and more recently during the investigation of contaminated land and landfill (Coleman, 1991; Hämmann et al. 1997; Sauck et al. 1998; Nyquist and Corry, 2002).

Self-Potential surveys can be deployed rapidly and by using inexpensive measurement equipment and are generally undertaken to compliment other geophysical techniques. Field equipment consists of a pair of non-polarising electrodes connected to a high impedance voltmeter and may be operated by a single person (Figure 2.9). Data processing may be undertaken rapidly using commercial contouring programmes and generally involves qualitative assessment, although quantitative analysis of anomaly source geometries and depth may also be attempted.

## 2.5.2. Sources of Natural Potentials

Natural potentials are established in the sub-surface through a range of possible mechanisms. These have been discussed by Sharma (1997) and are listed below:

- **Electrofiltration potential.** Flow of fluid through a capillary or porous medium may generate an electric potential in the direction of the flow path. The potential is generally positive with descending ingress of fluid from the ground surface and negative with ascending ingress at depth.

- **Thermoelectric potential.** A potential difference may appear across a unit of ground where a temperature gradient is maintained and may be measured in areas of geothermal and volcanic activity.

- **Electrochemical potential.** Potential differences may be established in the sub-surface due to the mobility of anions and cations of different concentrations in groundwater.

- **Mineralisation potential.** Strong potentials generally occur over base-metal deposits, particularly where a mineral body straddles the water table.

Generally, the mechanisms of interest during landfill investigations are the electrofiltration and electrochemical potentials and the two may occur simultaneously, particularly where conductive leachates migrate through the subsurface (electrofiltration potential) and mix with groundwater (electrochemical potential), which has been observed during studies by Coleman (1991). Electrofiltration and electrochemical potentials have also been observed with the migration of electrically-conductive dissolved phase LNAPL plumes (Sauck et al. 1998) and with the flow of leachate derived from organic refuse (Nyquist and Corry, 2002).

As discussed in Sharma (1997), SP data acquired during environmental investigations, particularly in urban environments, are generally of low amplitude and often affected by electrical noise. Noise interference tends to be derived from changing soil conditions and levels of saturation, electrically grounded machinery and buried metal objects, power lines and reinforced concrete. Modern voltmeters contain filters to suppress electrical noise; nevertheless recognition of noise potentials is important to avoid their misinterpretation as anomalies of interest.

## 2.5.3. Self-Potential Acquisition Equipment and Survey Procedure

Field equipment for recording natural potentials is relatively simple and inexpensive, consisting of a pair of non-polarising electrodes connected to a voltmeter (Figure 2.9). A non-polarisable electrode is a metallic probe immersed in a solution of one of its salts, for example copper in copper sulphate. The electrode and solution is contained in a receptacle (usually an unglazed ceramic pot) with a porous base allowing very slow permeation of the liquid onto the ground surface. Non-polarising electrodes must be used because unlike steel they do not generate electrical fields when placed in the ground.

Figure 2.9: *A photograph illustrating the non-polarising electrodes and voltmeter used during Self-Potential surveys (author).*

As described by Sharma (1997), measurement of natural potentials can be made along survey traverses or in grids by two possible configurations. In the dipole configuration (Figure 2.10) two electrodes and a voltmeter are connected with wires of fixed length and are moved successively together from one measurement station to the next. After the potential difference is measured the two electrodes are advanced along the traverse with the trailing electrode occupying the station of the previous electrode. To maintain consistent polarity and reduce errors the negative voltmeter lead is always connected to the trailing electrode and the positive lead to the leading electrode, as illustrated in Figure 2.10. An alternative and preferred method is the fixed-base configuration (Figure 2.11), which uses a stationary electrode and a moving electrode connected via the voltmeter and a cable reel. In this configuration the negative lead of the voltmeter is connected to the stationary base electrode, which should be positioned outside the survey grid, whilst the positive voltmeter lead is connected to the mobile electrode, which is moved along the survey traverse or grid. The fixed-base electrode configuration has a major advantage over the dipole method because of the lower level of cumulative error and reduced possibility of mapping spurious anomalies of short wavelength (Sharma, 1997).

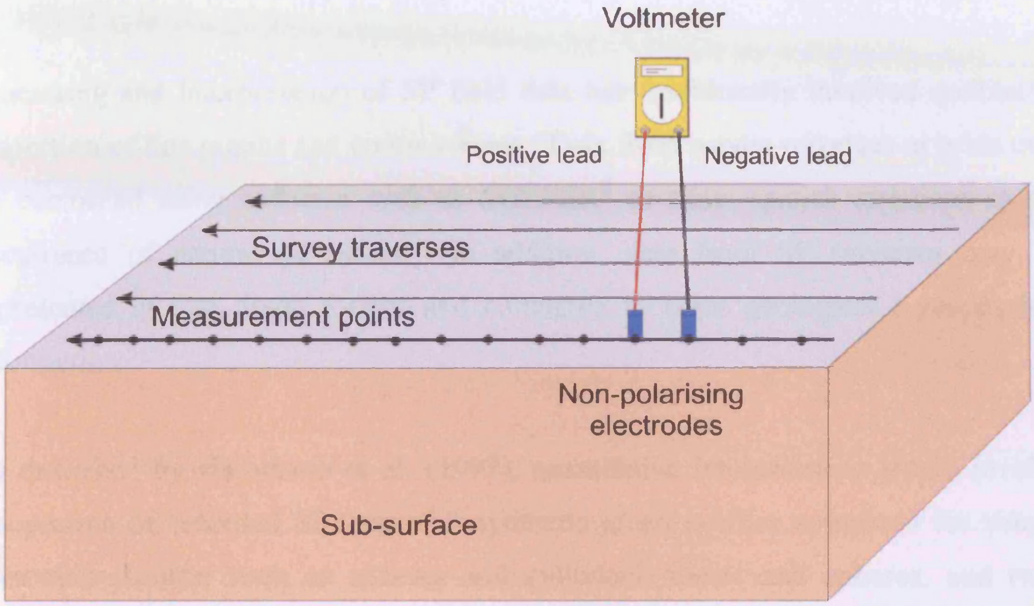



Figure 2.10: *A diagram illustrating the electrode arrangement and procedure for detecting natural potentials with the dipole configuration (after Sharma, 1997).*

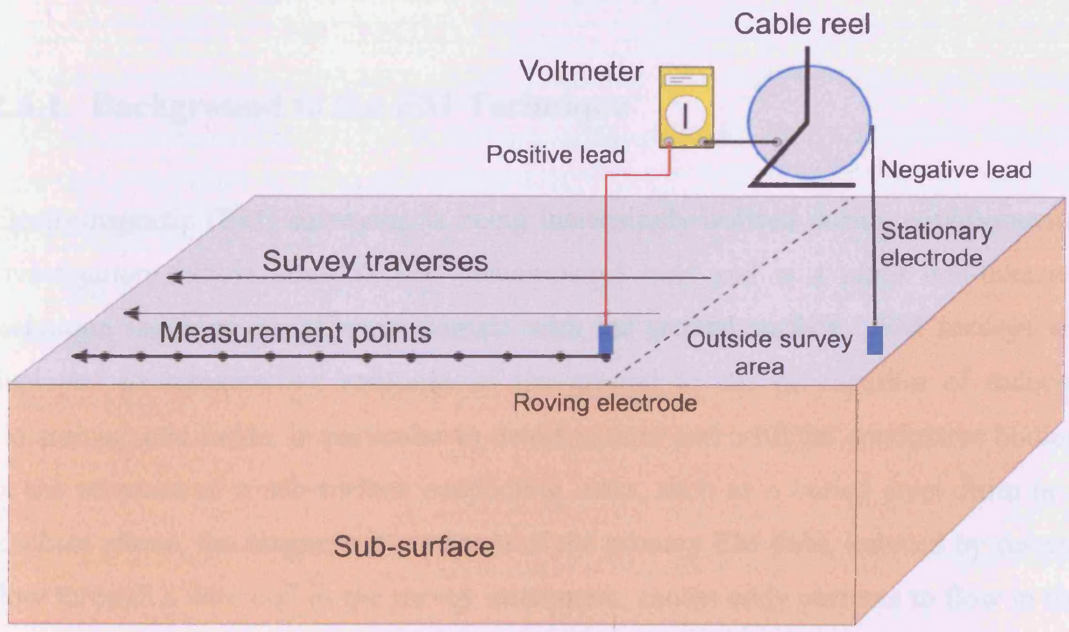



Figure 2.11: *A diagram illustrating the electrode arrangement and procedure for detecting natural potentials with the fixed-base configuration (after Sharma, 1997).*

### 2.5.4. Data Processing, Interpretation and Presentation

Processing and interpretation of SP field data has traditionally involved qualitative inspection of line graphs and contour maps. Data from survey traverses or grids may be contoured using software such as SURFER® to show spatial variations in the occurrence of natural potentials. In addition, data from SP traverses may be represented in line graph format and compared to other geological / geophysical information.

As described by Hämmann et al. (1997), quantitative interpretation would involve comparison of recorded SP data with synthetic graph profiles computed for simple geometric models, such as spheres and cylinders, sheets and spheres, and two-dimensional sheet-like structures. Results of curve modelling could allow the locations and dimensions of SP sources to be determined.

## 2.6. Electromagnetic Induction (EM)

### 2.6.1. Background to the EM Technique

Electromagnetic (EM) surveying is being increasingly utilised during environmental investigations across landfills and contaminated land and is a rapid non-invasive technique requiring no physical contact with the ground surface. EM surveys are deployed to measure the response of the ground to the propagation of induced electromagnetic fields, in particular to detect natural and artificial conductive bodies. In the presence of a sub-surface conducting mass, such as a buried steel drum or a leachate plume, the magnetic component of the primary EM field, induced by current flow through a wire coil in the survey instrument, causes eddy currents to flow in the conductor. These eddy currents give rise to a secondary EM field, which are detected by the receiver coil component of the instrument.

EM surveys can be operated in the time domain, involving a continuous primary field source, or in the frequency domain, which involves measurement of the secondary field in the absence of the primary field being induced. The differences between the transmitted and received EM fields will reveal the presence of a buried conductor and provide information of its geometry and electrical properties.

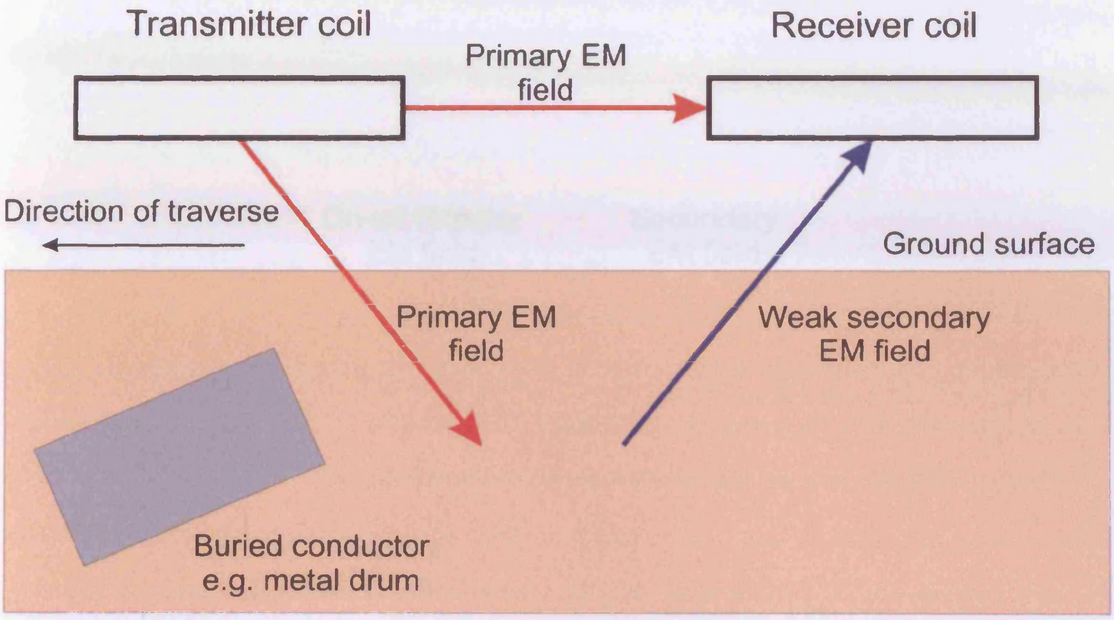
## 2.6.2. Field Equipment and Survey Procedure

EM survey equipment is designed to be highly portable and can be operated by a single person (Figures 2.12 and 2.13). EM instrumentation is relatively simple in construction and consists of a battery powered oscillator supplying an AC current to the transmitter coil, which generates a primary electromagnetic field. A secondary EM field is detected by the receiver coil of the same dimensions as the transmitter. Older EM instruments required manual recording of measurements from an analogue display, whereas modern equipment is commonly used with a digital data logger and GPS recorder.

EM survey equipment operates in either frequency-domain (FDEM) or time-domain (TDEM) format. Frequency-domain techniques operate on the principle that the secondary EM field is measured in the presence of a continuous primary field, as illustrated in Figure 2.14 of the thesis. One drawback with FDEM surveying, as discussed by Keary and Brooks (1991) is that the secondary EM field is measured in the presence of a stronger primary field with an anticipated decrease in accuracy. This problem may be overcome by taking field measurements according to the time-domain principle. During time-domain (TDEM) surveying, the primary field is not continuous but is switched on and off automatically so that the secondary EM field is measured in the absence of the primary leading to a greater degree of accuracy. The principle of time-domain surveying is illustrated in Figure 2.15 of the thesis.

Figure 2.12: *A photograph illustrating the Geonics EM31, utilised for environmental investigations requiring depths of around ~5 metres (photograph by Dr. P. Brabham, Cardiff University).*

Figure 2.13: *A photograph illustrating the Geonics EM38, utilised for shallow environmental investigations to around ~1 metre depth (photograph by Dr. P. Brabham, Cardiff University).*



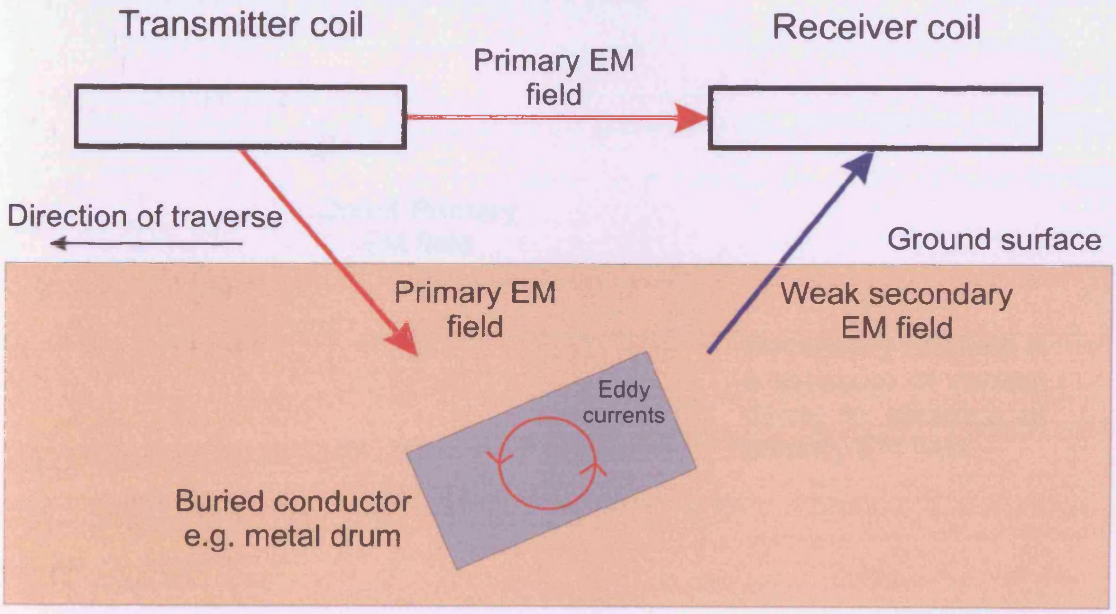




Figure 2.14: *A diagram illustrating the principle of electromagnetic surveying using the frequency-domain (FDEM) technique (after Sharma, 1997).*

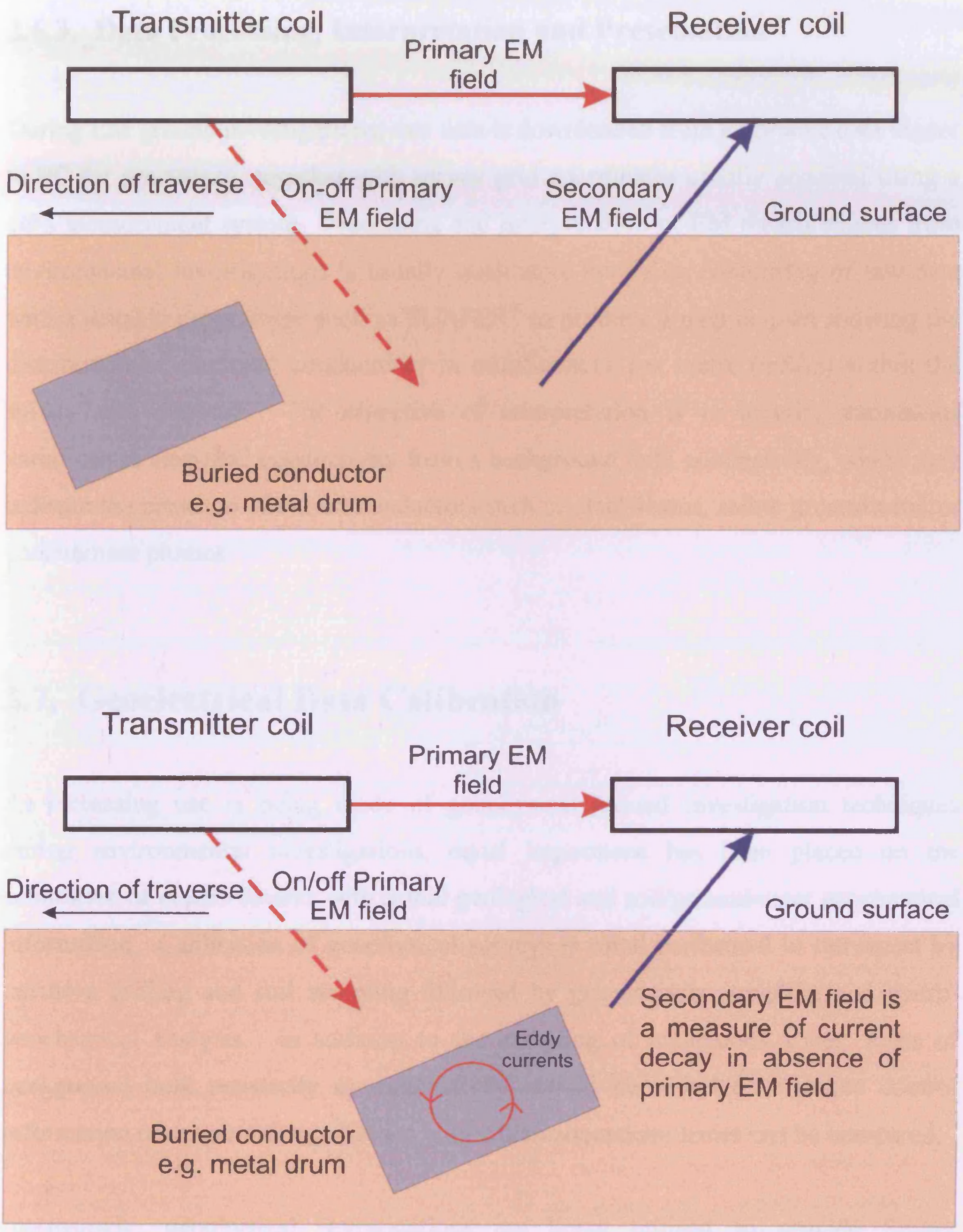



Figure 2.15: *A diagram illustrating the principle of electromagnetic surveying using the time-domain (TDEM) technique (after Sharma, 1997).*

### 2.6.3. Data Processing, Interpretation and Presentation

During EM ground investigations, raw data is downloaded from a portable data logger to PC for processing, together with survey grid coordinates usually acquired using a GPS measurement system. Processing and interpretation of EM measurements from environmental investigations is usually qualitative involving contouring of raw data with a suitable programme such as SURFER® to produce a map or plan showing the distribution of electrical conductivity in milliSiemens per metre (mS/m) within the survey area covered. The objective of interpretation is to identify anomalous variations in electrical conductivity from a background bulk conductivity, which may indicate the presence of buried conductors such as steel drums, saline groundwater or contaminant plumes.

## 2.7. Geoelectrical Data Calibration

As increasing use is being made of geophysical ground investigation techniques during environmental investigations, equal importance has been placed on the calibration of measurements with actual geological and soil/groundwater geochemical information. Calibration of geophysical surveys is often performed in retrospect by intrusive drilling and soil sampling followed by groundwater sampling and hydrogeochemical analysis. In addition to the sampling of anomalous zones, areas of background bulk resistivity or conductivity should be sampled to define control information of uncontaminated zones with which anomalous zones can be compared.

Increasingly, geophysical investigations are being utilised to provide further information of known contaminated sites by complimenting conventional intrusive drilling, sampling and monitoring. Godio and Naldi (2003) utilised resistivity imaging to investigate the extent of dissolved-phase hydrocarbon contamination by deploying ERT traverses across ground where contamination was previously detected in groundwater observation boreholes. The authors used ERT to correlate groundwater conductivity measurements associated with bioactivity in a dissolved hydrocarbon plume.

Nyquist and Corry (2002) utilised Self-Potential mapping to delineate the extent of an organic plume extending from a waste trench, whereby anaerobic zones had previously been identified in groundwater monitoring wells. The authors reported a consistent relationship between high SP values and depleted dissolved oxygen in the groundwater.

By taking a multi-method geophysical approach including the use of SP and EM, Sauck et al. (1998) successfully delineated a dissolved-phase hydrocarbon plume and calibrated the geophysical information with groundwater conductivity measurements taken from observation wells.

During intrusive geoelectrical investigations involving borehole ERT, direct calibration can be performed in parallel with the geophysics. For example, Goes and Meekes (2004) developed a system of borehole ERT measurement for the detection of DNAPL contaminated zones. Calibration was performed by sampling of groundwater and analysis for various organic pollutants (PCE, TCE, etc), whereby the distribution of contaminants corresponded to zones of high resistivity (>200 ohm.m) in the overall intermediate resistivity (20-40 ohm.m) groundwater.

Where possible, geophysical reconnaissance and detailed investigations or temporal monitoring across active and closed landfills should be calibrated by comparison with leachate dip levels, leachate/groundwater conductivity and geochemical analysis. An ERT survey performed across a closed domestic landfill by George (2002) comprised five resistivity traverses, which were deployed taking into account the distribution of leachate observation wells. Zones of low resistivity (<10Ωm) as delineated by the ERT corresponded directly to observation well dip levels and leachate conductivity, whereas zones of higher resistivity (>50 Ωm) matched areas where leachate was absent in observation wells.

## 2.8. Summary of Applicable Geoelectrical Methods, Limitations and Scope for Development

ERT provides a useful tool for non-invasive characterisation of landfills and contaminated land, whereby the perceived investigation targets are near-surface. However, problems of reduced accuracy and resolution arise when ERT is used to locate or investigate sub-surface features at depth. When investigating near-surface geoelectrical characteristics, a narrow electrode spacing is most effective and will provide limited depth extent of data recovery with high resolution and accuracy. A wider electrode spacing must be used to undertake deeper investigations, but at the compromise of accuracy and resolution, which decreases exponentially with greater depth. This has particular implications to the investigation of active and closed landfill sites where non-invasive ERT is attempted.

It may be perceived by landfill engineers and geophysicists that non-invasive ERT may be utilised to locate leachate bodies within the waste-mass on the basis that leachate is electrically conductive. This may certainly prove successful in locating leachate at shallow depth, however a persistent situation is encountered whereby ERT has been ineffective in delineating perched leachate bodies and liquids lying above a basal liner at depth. This situation is attributed to the decrease in resolution and accuracy with depth arising from the use of wide electrode spacings often used during reconnaissance landfill investigations and monitoring. Also, the problem of equivalence arises, whereby several adjacent horizontal or vertical leachate bodies of a similar electrical conductance may give the same overall response and are not individually distinguished. Instances of electrical noise often arise from poor electrode contact at the ground surface and can cause erroneous measurements that must be deleted from a raw data set, which further reduces the resolution and accuracy. Therefore, it is important that electrodes are effectively grounded and that a contact resistance test is performed prior to data recovery, whereby contact values should be <4kohm.

There appears to be little scope for development to improve the accuracy and resolution of non-invasive deep ERT surveys. Therefore, caution must be exercised to select an optimal electrode spacing to suit the desired depth extent of investigation and every effort must be made to obtain the best possible data quality. There is potential, however, for a system of ERT monitoring at active landfills, whereby electrode arrays are permanently installed along the base of a new cell and used in conjunction with surface arrays during cell infilling. On this hypothesis, data is recovered from the ground between a pair of electrode arrays, maintaining resolution and accuracy through the waste-mass. It may, therefore, be possible to overcome accuracy, resolution and equivalence problems associated with non-invasive ERT and so detect and distinguish individual perched leachate bodies and liquids at depth. Applications of this principle would include the monitoring of leachate generation within the waste-mass; the delineation of leachate above an engineered liner system and performance of basal drainage measures; assessing the extent and progression of waste compaction; and monitoring rainwater ingress and the effectiveness of temporary/permanent capping.

Borehole ERT provides an effective tool for detailed characterisation of the sub-surface, whereby accuracy and resolution are maintained with increasing depth. One of the most significant constraints with this technique is that resolution and accuracy is expected to decrease with widely spaced boreholes. As detailed in Ramirez et al. (1995), the distance between boreholes used for ERT should be less than the depth of the boreholes and ideally half the distance of the borehole length. According to Ramirez et al. (1995), if the depth / distance ratio is less than 1.5, accuracy is only optimal in close proximity to the borehole electrodes.

There exists potential for the application of borehole ERT to landfill monitoring studies enabling the effective characterisation of perched leachates with depth and assessment of seasonal variation. Borehole ERT systems would be installed within active and closed landfills during routine gas / leachate well emplacement thus reducing the cost of electrode installation. A further application may be made to HDPE-capped landfills, whereby the insulating effects of the plastic membrane cap would not permit conventional surface ERT measurements. Most significantly, borehole ERT systems provide a means of repeated data recovery during long term seasonal monitoring and in-situ site remediation.

Self-Potential surveying has a number of advantages in that it involves inexpensive equipment that can be deployed rapidly over large areas. It can be applied to large scale reconnaissance surveys or smaller scale detailed investigations. There are, however, several limitations mainly regarding the obscuring of weak signals by electrical noise and poor understanding of SP mechanisms. There is scope for development of the SP technique to temporal monitoring at landfill sites using permanent arrays of non-polarising electrodes, which may be installed internally, or along the ground surface. Repeated measurement of natural potentials may help to characterise the generation and migration of leachates and the effectiveness of landfill drainage. SP surveys could also be used to monitor liquid drawdown around gas and leachate pumping wells on landfills to assess the effectiveness of such systems.

Electromagnetic ground surveying is a favourable tool for widespread mapping of conductivity variations across landfills and contaminated land and has the major advantage of being rapid and non-invasive; therefore the costs of surveying can be significantly lower than with other geophysical methods which require direct contact with the ground, such as ERT. The only significant limitation with modern EM equipment, such as the Geonics EM31 and EM38 is that they operate in the frequency-domain, which may result in a weak secondary EM response of the ground, which may be more susceptible to noise. Furthermore, because the distance between the transmitter and receiver coils is normally fixed, measurements of conductivity variations with depth can only be obtained by raising or lowering the height of the instrument above the ground, or by using different instrument polarisations, such as in the vertical or horizontal mode (Hauck, 2001). This could, however, be overcome by developing EM monitoring systems for installation in boreholes and observation wells.

# (3)
# Field Test Sites

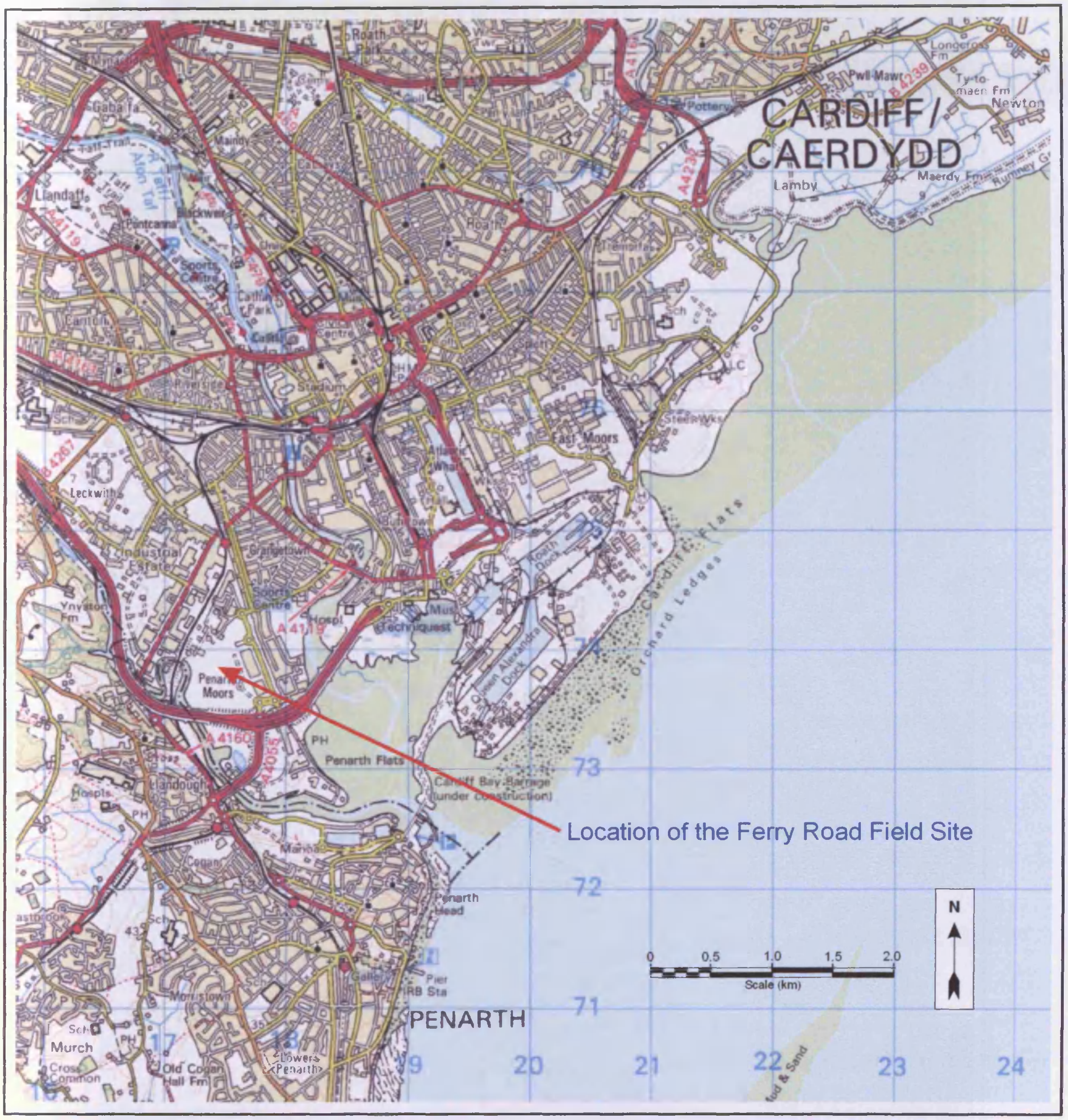
## 3.1. Ferry Road, Cardiff Bay

### 3.1.1. Site Location and Description

Ferry Road landfill, which was closed and restored from 1996 to 1999, is centred on National Grid reference ST 173 377 and is situated approximately 3.5 km to the southwest of Cardiff City Centre on the edge of Cardiff Bay (Figure 3.1). A recent aerial photograph of the study area shown in Figure 3.2 illustrates that the landfill is bounded to the north by the former Grangetown Gasworks site, to the east by the Cardiff Bay Retail Park, to the south by the A4232 Peripheral Distributor Road, and to the west by the River Ely.

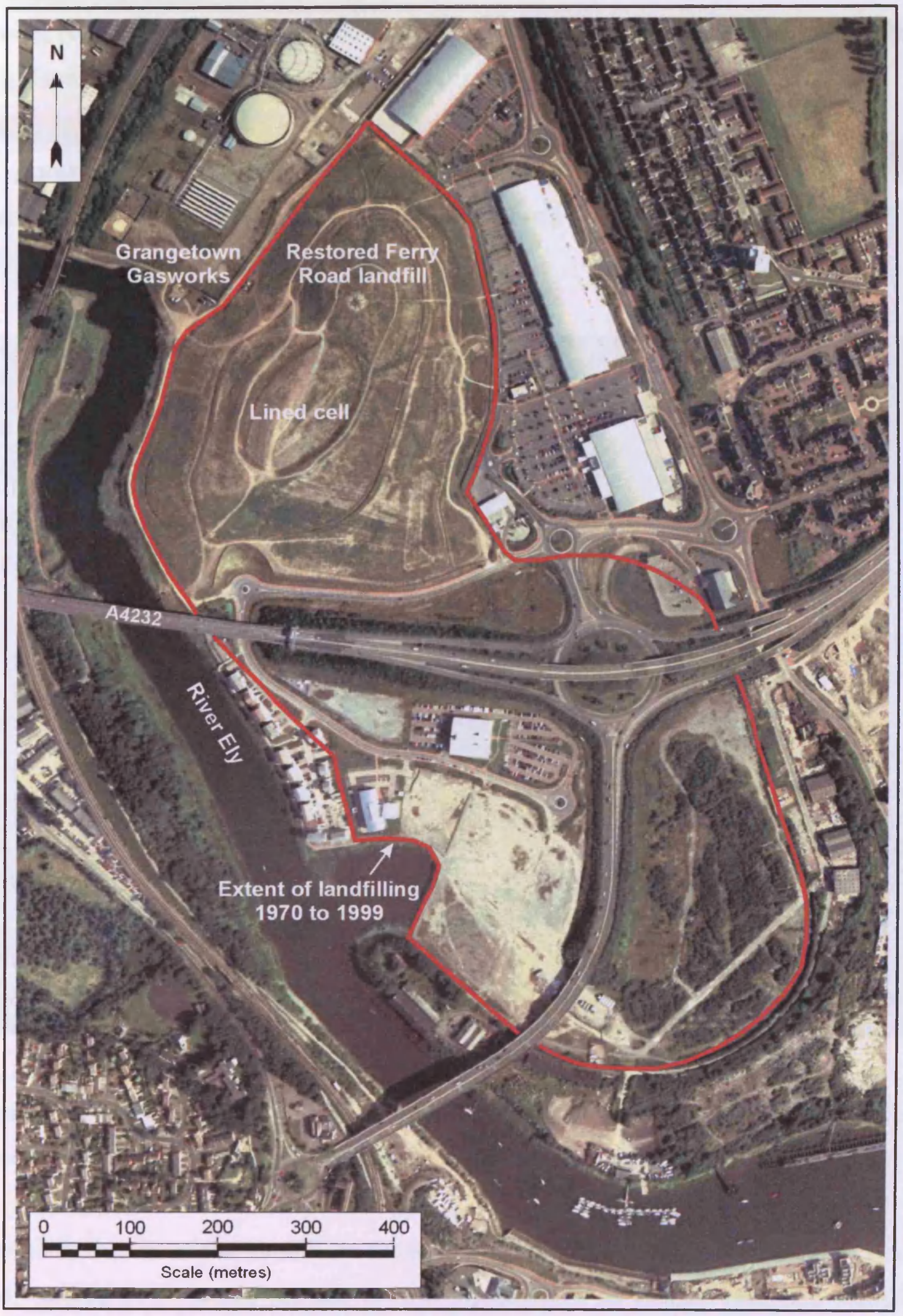
Landfill waste disposal commenced at Ferry Road following artificial realignment of the tidal River Ely in 1969 where the drained river meanders were utilised together with an expanse of surrounding salt marsh. During the 1980's the A4232 carriageway and A4065 Cogan Spur roads were constructed on embankments and piers across part of the southern end of the site.

In 1998 the tidal estuary where the River Taff and River Ely enter the Bristol Channel was impounded by construction of the Cardiff Bay Barrage, whereby a freshwater lake with a stable and constant water level was created. Landfill site operations continued until 1999, followed by restoratorive works and site capping undertaken by Cardiff Bay Development Corporation.




(Taken from the OS 1: 50 000 Landranger Series, Sheet 171)

Figure 3.1: *An OS map extract of Cardiff illustrating the Ferry Road field site location.*




Aerial photograph source: Getmapping (2000)

Figure 3.2: *A year 2000 aerial photograph of the study area with the extent of landfilling between 1970 to 1999 clearly marked in red line.*

During reactivation, waste arisings from areas of the landfill that were disturbed during redevelopment construction work at its margins were re-deposited within the site (Stanley, 1995).

A quantity of contaminated ground removed during construction of the Cardiff Bay Retail Park was also relocated to a purpose-built lined disposal cell constructed on top of the older Ferry Road landfill (Stanley, 1995).

Figure 3.3: *A photograph of the restored Ferry Road landfill in Cardiff Bay, which is now used as open recreational parkland (author).*

Reactivated areas of the landfill, to the north of the A4232 carriageway, were capped and restored by 1999 and the site is now characterised by a large vegetated mound visible from much of southwest Cardiff (Figure 3.3). At present, elevation across the study area ranges from +5 m AOD at the River Ely, to + 40 m AOD at the top of the landfill mound.

### 3.1.2. Geological Setting and Hydrogeology

Solid and superficial deposits underlying the restored Ferry Road landfill site are described as follows:

- **Triassic Mercia Mudstone Group.** Bedrock beneath the study area comprises mudstone of the Triassic Mercia Mudstone Group (Waters and Lawrence, 1987). The mudstones, which usually exhibit a fractured and weathered top surface, are generally compact and occur in bedding units of between 0.5 and 4.0 metres thickness. The mudstones contain minor gypsum deposits in the form of veins and nodules.

- **Fluvioglacial sands and gravels.** These Quaternary-period deposits are found to lie above the bedrock and consist of pebble- to cobble-sized gravel in a slightly clayey sandy matrix with some silt (Waters and Lawrence, 1987).

- **Estuarine Alluvium.** Holocene deposits lie above the sands and gravels and comprise clay layers with occasional silt, sand, gravel and peat.

- **Made Ground.** Deposits of anthropogenic fill and made ground are laterally extensive over urban parts of southern Cardiff and commonly comprise soils, demolition rubble, slag, ash, ceramics, timber, textiles, stone, glass, plastics, and rubber, with a range in grading from clay particles to boulders (Ove Arup and Partners, 1995). Domestic and industrial fill emplaced within the former Ferry Road Tip to the south of the Gasworks boundary may be considered as made ground.

The made ground and fluvioglacial sand and gravel units are perched aquifers in the hydrogeological sense, i.e. their permeability is such that significant flow occurs within them (Ove Arup and Partners, 1995). Underlying Triassic bedrock may be subject to some limited movement of groundwater within its stratum, but for practical purposes its weathered top can be taken as an impermeable base to the groundwater system throughout the area.

A regional groundwater flow towards the southeast was recorded for both the made ground and gravel units prior to impoundment of Cardiff Bay by the barrage, whereby the hydraulic gradient was recorded as 1:1000 (Thomas, 1997).
Perched groundwater conditions exist within the made ground deposits, however vertical leakage through the alluvium and into the underlying gravel aquifer is insignificant due to the very low ($10^{-10}$ m/sec) hydraulic conductivity of the clay (Ove Arup and Partners, 1995).

Surface water hydrology of the study area is dominated by the River Ely and River Taff, which form Cardiff Bay at the estuary mouths. Surface water drainage from the Ferry Road landfill is directed into the River Ely through a series of channels and culverts. Long term effective rainfall for the Cardiff Area (total rainfall minus actual evapotranspiration) has been calculated at 509.9 mm (Ove Arup and Partners, 1995).

### 3.1.3. Historical Development of the Ferry Road Landfill

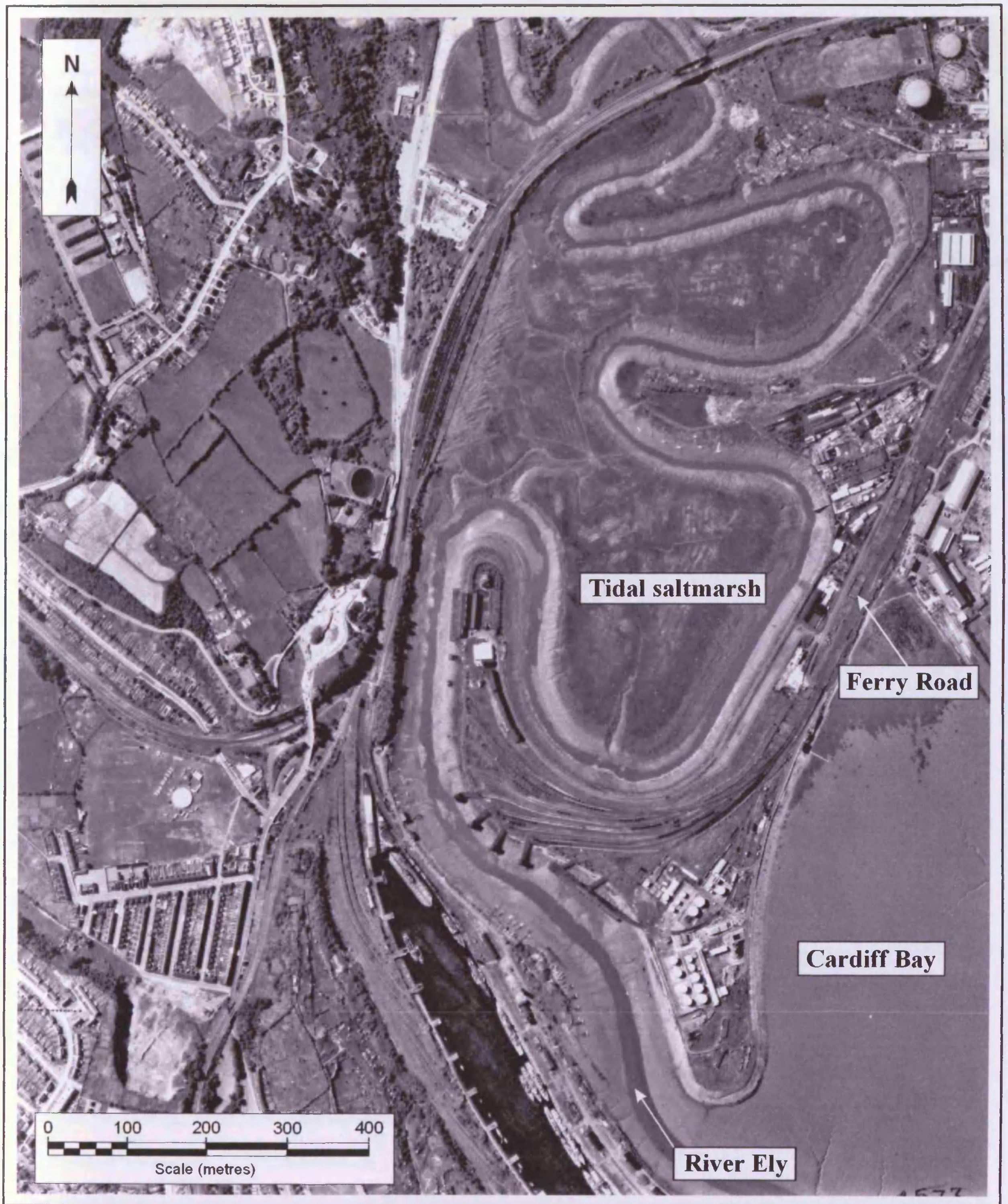
Historical development of the study area can be reviewed with respect to four chronological periods. Each important period is discussed, with reference to the available air photography record, as follows:

- **Pre 1969.** Prior to refuse disposal at the Ferry Road site, the area was characterised by tidal salt marsh and broad sweeping meanders of the River Ely (Figure 3.4). The Grangetown Gasworks site was established in the 19th Century upon an earlier 18th Century ironworks site (Thomas, 1997).

- **1969-1971.** A section of the River Ely was diverted through an artificial excavation made through the superficial deposits (Figure 3.5) and tipping began in the drained river channel void immediately to the south of the gasworks boundary.

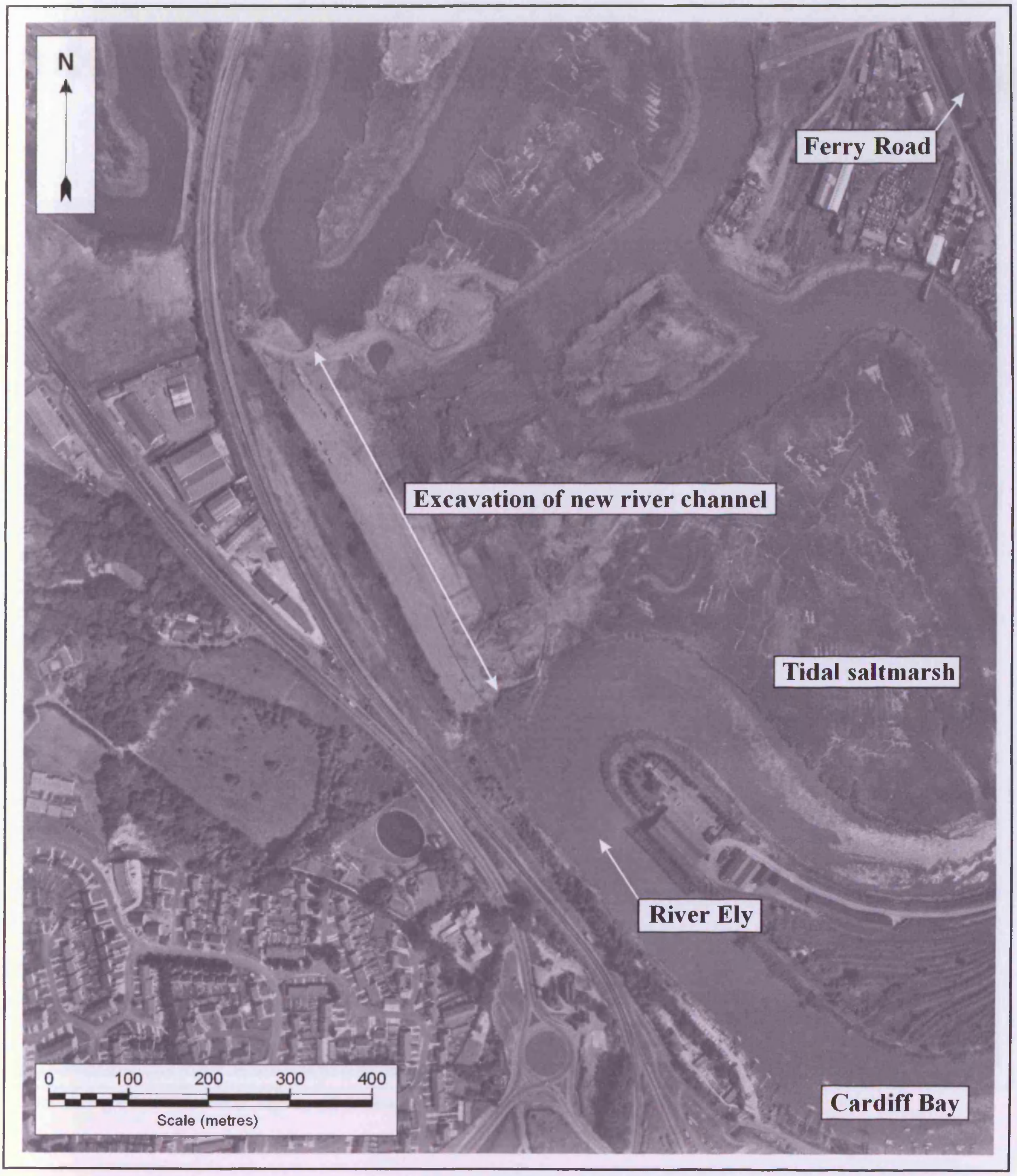
- **1971-1995.** A major period of refuse disposal extending across the tidal salt marsh area resulting in creation of the Ferry Road landfill. Closure of the landfill occurred in 1995 (Figure 3.6).

- **1996-1999.** Over a three-year period the Ferry Road Tip was reactivated in order to receive mature wastes relocated from around the site due to redevelopment of surrounding land. A purpose-built lined disposal cell was constructed during this period for the disposal of hydrocarbon contaminated soils from the location of the Cardiff Bay Retail Park (Figure 3.7).



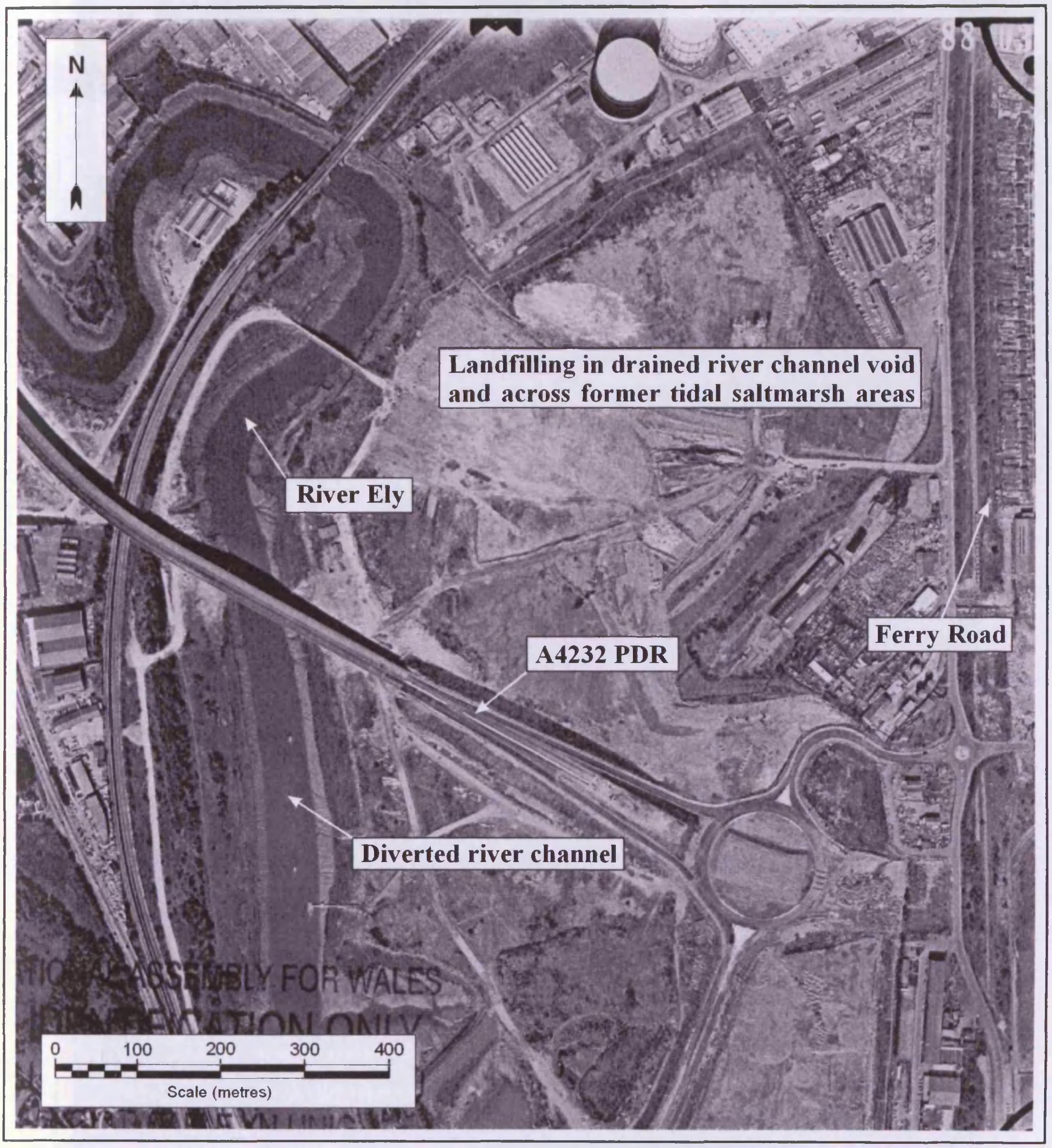

Aerial photograph source: Central Register of Air Photography for Wales

Figure 3.4: *A 1960 air photograph of the Ferry Road area and adjacent docklands prior to landfilling on the site.*




Aerial photograph source: Central Register of Air Photography for Wales

Figure 3.5: *A 1971 air photograph of the Ferry Road area illustrating the excavations made during diversion of the River Ely prior to landfilling.*




Aerial photograph source: Central Register of Air Photography for Wales

Figure 3.6: *A 1988 air photograph of the Ferry Road area illustrating further landfilling to the north of the site and construction of the A4232 PDR.*


Aerial photograph source: Cardiff Bay Development Corporation

Figure 3.7: *An illustrated air photograph of the Ferry Road landfill and adjoining areas showing detail of the site reactivation between 1996 to 1999.*

### 3.1.4. Construction of a Lined Contaminated Soil Disposal Cell

Post-constructional records of the lined disposal cell are not available; however plans were submitted by Ove Arup and Partners (Ove Arup and Partners, 1995) to Cardiff Bay Development Corporation prior to construction of the cell. Detail from these plans has been reproduced in Figures 3.8 and 3.9 and illustrate the construction design of the lined disposal cell in plan view and cross-sectional profiles. It is with reference to these drawings that the construction of the lined cell is discussed.

The lined structure was designed to include a single HDPE liner throughout the spatial extent of waste emplacement. This liner was designed to be anchored over a perimeter leachate bund, but would not extend to a second surface water bund incorporated around the outer limits of the structure. A 1:20 gradient along the liner surface from the centre of the cell towards its margins was considered effective for leachate drainage. Geotextile membranes and drainage blankets were incorporated over the HDPE liner allowing waste emplacement above this in a series of compartments.

Drainage within the extent of the peripheral bund was incorporated with the aim to feed leachate into a collection tank during waste emplacement. Anecdotal evidence indicates that after closure of the cell the leachate drain was diverted into the main leachate collection and disposal system for the Ferry Road landfill. A single peripheral surface water drainage ditch was incorporated into the capping medium immediately around the lined cell structure in order to feed surface run-off via a concealed pipe to the River Ely (George, 2002).

Upon completion of the lined cell construction and subsequent waste emplacement in 1999, the site was capped with a suitable medium in conjunction with restoration of the reactivated Ferry Road Tip mound (Cherrill and Phillips, 2005).

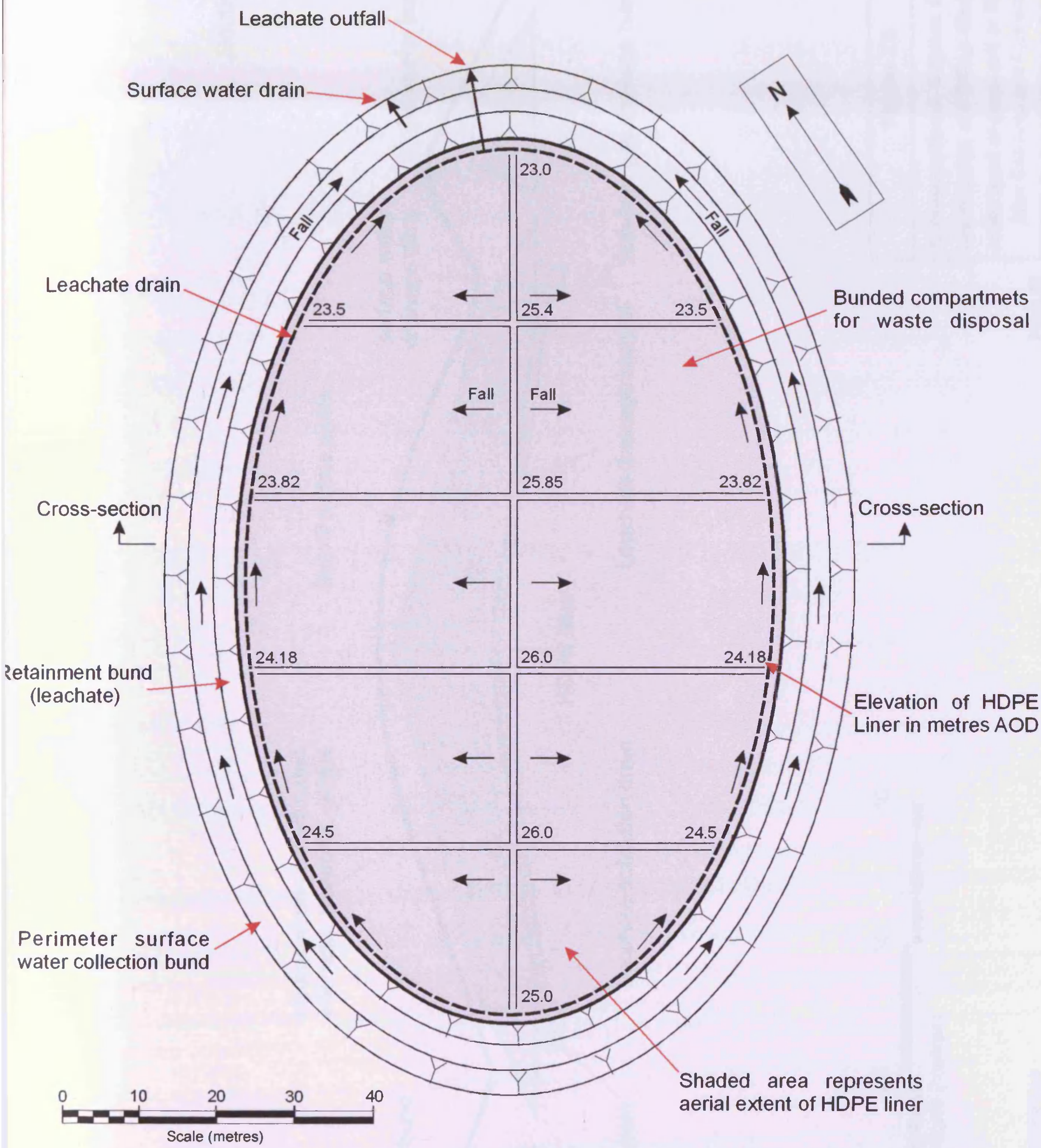



Figure 3.8: *A diagram illustrating construction details of the lined waste cell at Ferry Road (after Ove Arup and Partners, 1995).*

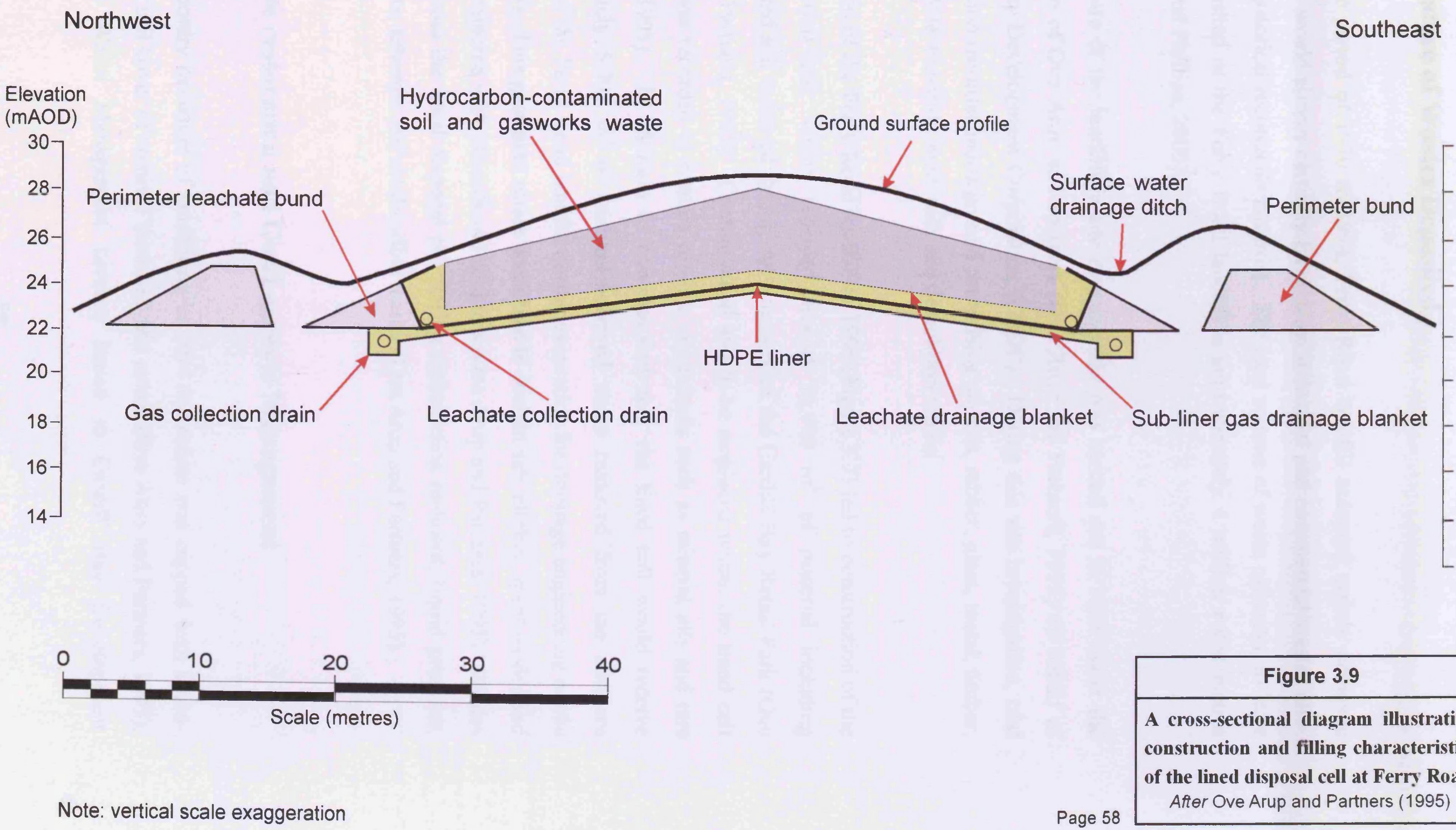



**Figure 3.9**

**A cross-sectional diagram illustrating construction and filling characteristics of the lined disposal cell at Ferry Road.**
*After* Ove Arup and Partners (1995)

## 3.1.5. Nature of Wastes Deposited

During the period of 1970 to 1994, Ferry Road landfill accepted mainly domestic refuse and would almost certainly have taken industrial and commercial wastes also, however historical records do not exist. The total volume of waste estimated to have been deposited in the Ferry Road landfill is approximately 4 million cubic metres (Cherrill and Phillips, 2005).

After closure of the landfill, a site investigation was carried out in 1995 under the supervision of Ove Arup and Partners (Ove Arup and Partners, 1995) on behalf of Cardiff Bay Development Corporation (CBDC). During this site investigation, trial pit excavation recorded made ground comprising plastics, rubber, glass, metal, timber, biodegradable materials, inert soils and demolition rubble.

Reactivation of the Ferry Road landfill in 1996 (Figure 3.7) led to construction of the lined disposal cell, which received around 36,000 $m^3$ of material including contaminated soil removed during development of the Cardiff Bay Retail Park (Ove Arup and Partners, 1995). Contaminated soil to be emplaced within the lined cell structure was recorded to contain organic compounds such as mineral oils and tars (Stanley, 1995). In addition to contaminated soil, the lined cell would receive approximately 5,000 $m^3$ of gasworks-derived waste removed from the northern boundary of the Ferry Road landfill during excavation for drainage engineering works (Figure 3.7). This gasworks waste was noted to contain ash, clinker, spent oxides and soils contaminated with phenols and coal tars (Ove Arup and Partners, 1995). Wastes excluded from the lined disposal cell during construction included; liquid products, free oils/tars, asbestos and combustible matter (Ove Arup and Partners, 1995).

## 3.1.6. Site restoration and Gas/Leachate Management

Upon temporary cessation of landfilling in 1994 the refuse was capped with a non-engineered soil cover of nominal thickness and extent (Ove Arup and Partners, 1995). Under the Waste Management License issued to Cardiff Bay Development

Corporation for the control of site reactivation and subsequent restoration, provision was made for a suitable capping medium to be installed over the area of landfill to become reactivated, not including waste emplaced on Penarth Moors to the south of the A4232 carriageway. During restoration of the site, engineered capping consisted of a 1 m low-permeability clay-rich soil layer laid directly onto the waste and overlain by surface topsoil layer of 0.5 m thickness. A HDPE membrane was not included within the capping design. The primary function of the landfill cap was to reduce rainfall ingress and separate the waste from the surface environment, whilst promoting vegetation growth. A sub-cap drainage system was also installed and connected into the perimeter leachate collection drain in order to intercept any potential zones of surface break-out.

During the main phase of waste emplacement on the Ferry Road landfill between 1970 to 1994 a basic leachate drainage system was provided. This comprised gravity-fed peripheral collection drains discharging leachate directly into the River Ely via four outfalls and indirectly into the River Taff through a surface water sewer (Ove Arup and Partners, 1995). With reactivation of the landfill in 1996, provision was made under the terms of the Waste Management License to install a leachate collection and disposal system. This drainage system comprised a network of stone-filled trenches connected to a perimeter collection drain, whereby leachate is diverted to a treatment facility and discharged under consent to the sewer system (Cherrill and Phillips, 2005).

During restoration of the landfill between 1996 to 1999 a series of leachate pumping wells were installed through the waste-mass along the course of the infilled River Ely channel, as discussed by Cherrill and Phillips (2005). Extraction wells were paired with observation boreholes and extend into the profile of the infilled river channel, where it is perceived that prior to landfilling the natural alluvial clay was breached and the gravel aquifer was exposed. Under the provisions of the Waste Management License granted to CBDC it was intended that groundwater and leachate would be pumped out of the site, therefore limiting off-site migration of contaminants through the gravel aquifer. This concept has been illustrated in the Conceptual Site Models reproduced in Figures 3.10 and 3.11.

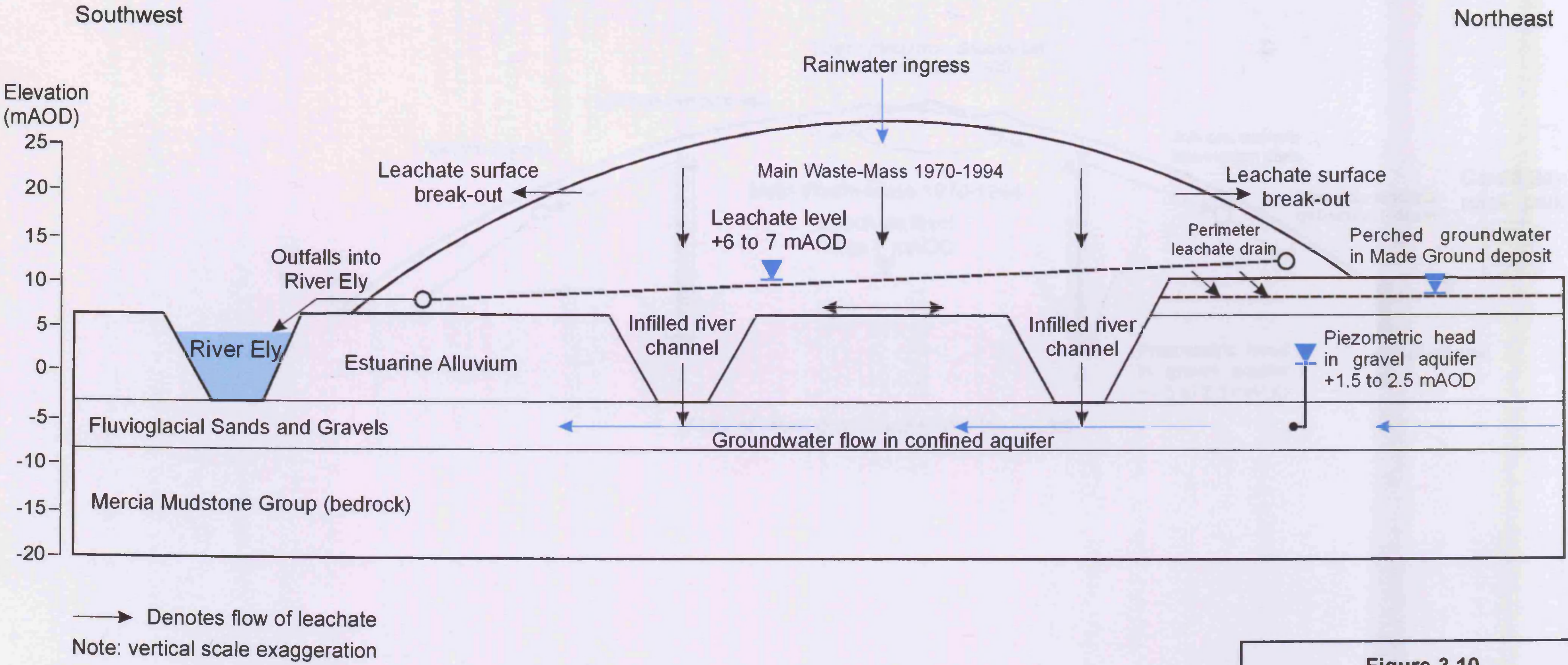



**Figure 3.10**

**A Conceptual Site Model (CSM) of the Ferry Road landfill prior to restoration illustrating the leachate migration pathways**

*After* Cherrill and Phillips (2004)

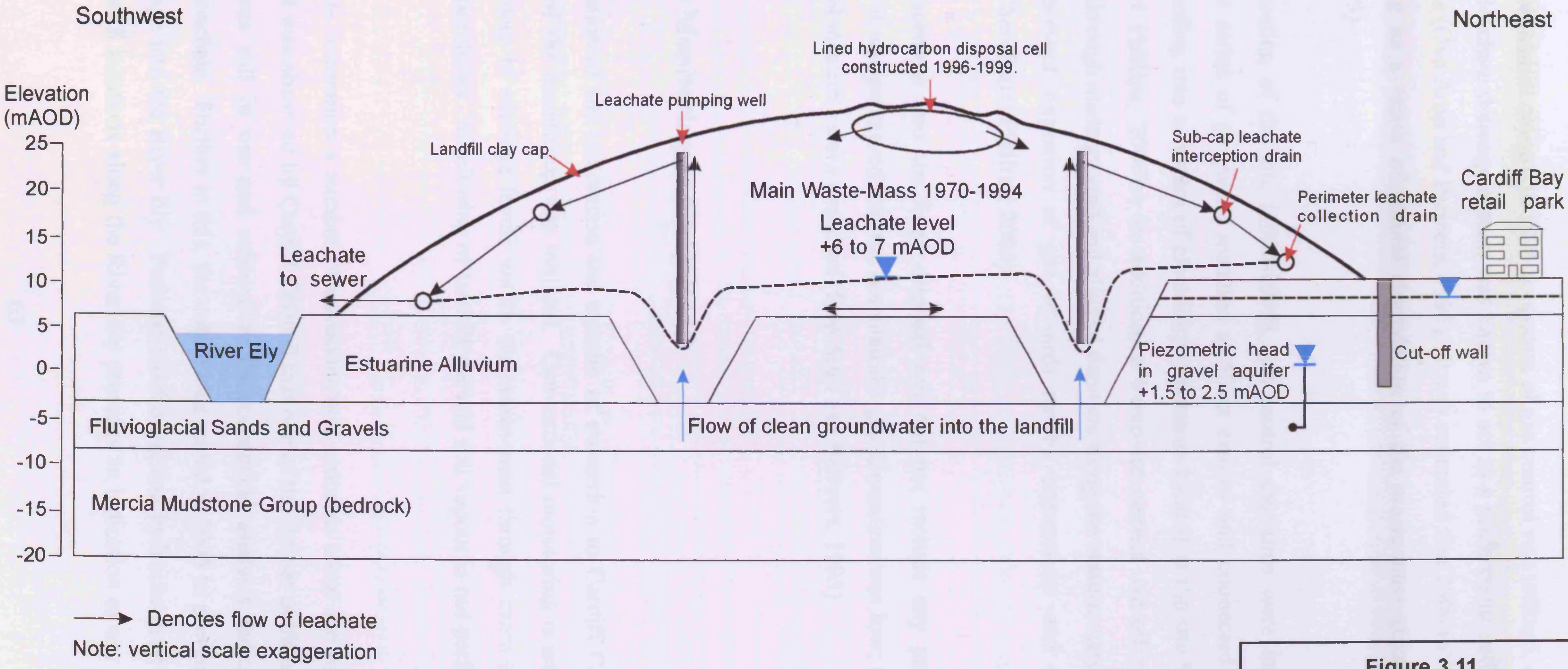



**Figure 3.11**

**A Conceptual Site Model (CSM) of the Ferry Road landfill after restoration illustrating the leachate control measures**

*After* Cherrill and Phillips (2004)

At the time of landfill closure in 1994 no system of gas control was utilized, although the existing leachate drainage system was known to act as a preferential pathway for release of gas (Ove Arup and Partners, 1995). It was estimated that 2500 $m^3$/hr of gas was escaping as a result of natural degradation of the waste-mass (Cherrill and Phillips, 2005).

During restoration of the site (1996-1999), gas control measures were introduced comprising a series of gas wells installed at 50 m centres and connected to three manifolds feeding into a system of electricity generators located at the site boundary (Cherrill and Phillips, 2005). In addition, a bentonite cement cut-off wall was constructed through made ground and alluvial deposits along the eastern margin of the landfill to prevent migration of gas towards nearby commercial and domestic properties (Cherrill and Phillips, 2005).

Waste emplacement into the lined disposal cell did not include any putrescible material and it was perceived that the potential for gas generation was low; therefore no gas control measures were proposed (Ove Arup and Partners, 1995).

### 3.1.7. Site Monitoring at Ferry Road

With completion of site restoration and transfer of ownership to Cardiff Council, a programme of site monitoring was initiated. Conventional monitoring is undertaken by measurement of leachate levels within the waste-mass through examination of observation boreholes. Monitoring of landfill gas and soil vapour is not performed at present.

Following site restoration a number of environmental concerns arose and have been addressed. It was observed by Cardiff Council that one of the former outfalls into the River Ely was still in use and subsequent hydrochemical analysis indicated the presence of leachate. Further to this, the outfall was sealed in 2004 to prevent further leachate escape into the River Ely. Periodic monitoring and hydrochemical analysis at known outfall locations along the River Ely provides an indication of any leachate escaping from the original peripheral drain, which is understood to have been connected into the modern system.

Observation well monitoring indicated elevated leachate and possibly perched conditions within the waste-mass. This was attributed to a failure to fully implement the leachate pumping system installed in 1999. In response, a reconnaissance-scale geophysical survey was commissioned in March 2002 to gain further visualization of the distribution of leachate within the waste-mass (Section 3.1.8). As described in George (2002) this geophysical survey, utilising the Electrical Resistivity Tomography technique, indicated widespread saturation within the waste-mass and frequent localized perched conditions. Therefore, leachate drainage was perceived to be ineffective at that time and it was recommended that pumping and disposal to sewer should resume. A review of the 2002 reconnaissance-scale geophysical investigation is provided in Section 3.1.8 of this chapter.

A multi-method geophysical investigation was commissioned in 2003 to assess the integrity and sub-surface characteristics of the lined disposal cell as there are no conventional means for monitoring of the cell. The multi-method geophysical survey forms a component of this research project (Section 4).

### 3.1.8. A Geophysical Survey at Ferry Road, March 2002

In response to persistent elevated leachate measurements and possible identification of perched conditions in the main waste-mass following site restoration, a reconnaissance geophysical survey was commissioned in 2002 to assess the spatial and vertical distribution of leachates. Cardiff Council, the site proprietors, opted to consult a geophysical contractor who was appointed to design and undertake a non-invasive geophysical survey across the Ferry Road landfill. An Electrical Resistivity Tomography (ERT) survey was recommended on the basis that landfill leachate could be detected due to its high conductivity (low resistivity) compared to the bulk background higher resistivity. Various other waste characteristics could be identified by ERT, including the distribution of dry and damp wastes, landfill basal and spatial margins, and rainwater ingress.

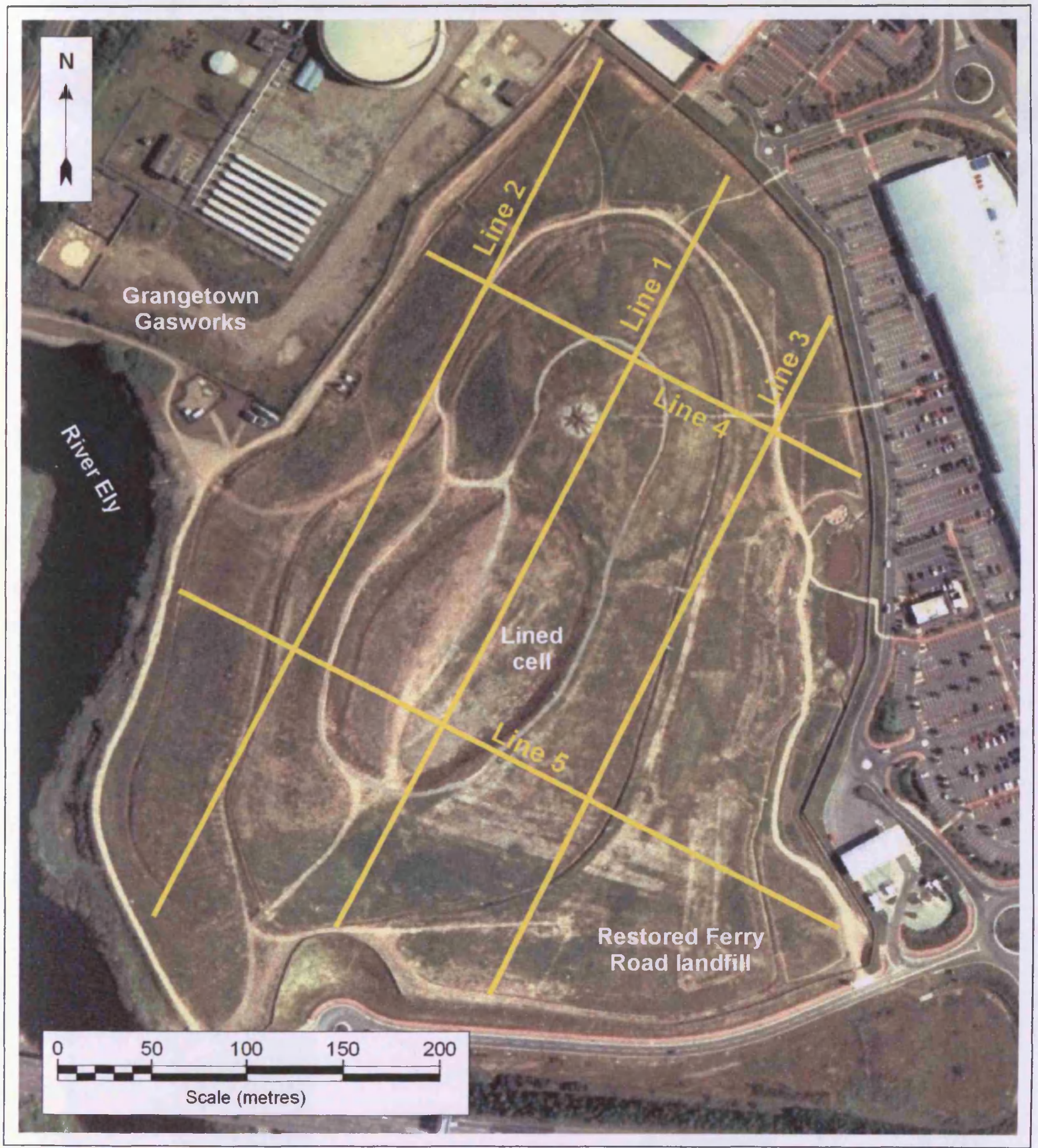
Figure 3.12 illustrates the layout and position of two-dimensional ERT survey profiles utilized during the Ferry Road survey in 2002. Figure 3.13 illustrates two of the five ERT profiles from the March 2002 survey.

Five individual profiles were deployed, with an inter-electrode spacing of 5 metres and it can be observed that two of the electrode arrays were intended to intersect the lined disposal cell. An IRIS Syscal 72-switch resistivity meter was used for data acquisition, whereby the Wenner-Schlumberger electrode address configuration was utilized. Raw data from the survey was processed using the inversion software RES2DINV®, the procedure for which is discussed in Section 2 of the thesis.

Within the waste-mass, widespread low to intermediate resistivity values are indicative of saturated waste and perched leachates – features that are identified in Figure 3.13. The near-surface of the landfill is characterised by intermediate to high resistivity values indicating dry conditions, however zones of elevated conductivity (low to intermediate resistivity) are characteristic of rainwater ingress (Figure 3.13).

Certain constraints are however evident with ERT surveying on such a large scale. Using a large electrode spacing of 5 metres over long array distances produces an increased depth extent of data recovery, but at the compromise of resolution, which is greater at reduced electrode spacings. Results from the Ferry Road survey of March 2002 indicate depth extent of data to between 30 – 40 metres below Ordinary Datum, however the data lacks resolution. As a result, it was not possible to accurately define the individual geological units and also not possible identify the gravel aquifer to assess its electrical conductivity.

In response to the findings of the reconnaissance geophysical investigation in 2002, leachate pumping from the waste-mass was resumed and it was recommended that the lined disposal cell should be characterised in greater detail involving non-invasive methods deployed on a smaller scale.




Aerial photograph source: Getmapping (2000)

Figure 3.12: *An annotated aerial photograph showing the layout of five ERT survey profiles deployed during the Ferry Road reconnaissance geophysical survey of March 2002.*

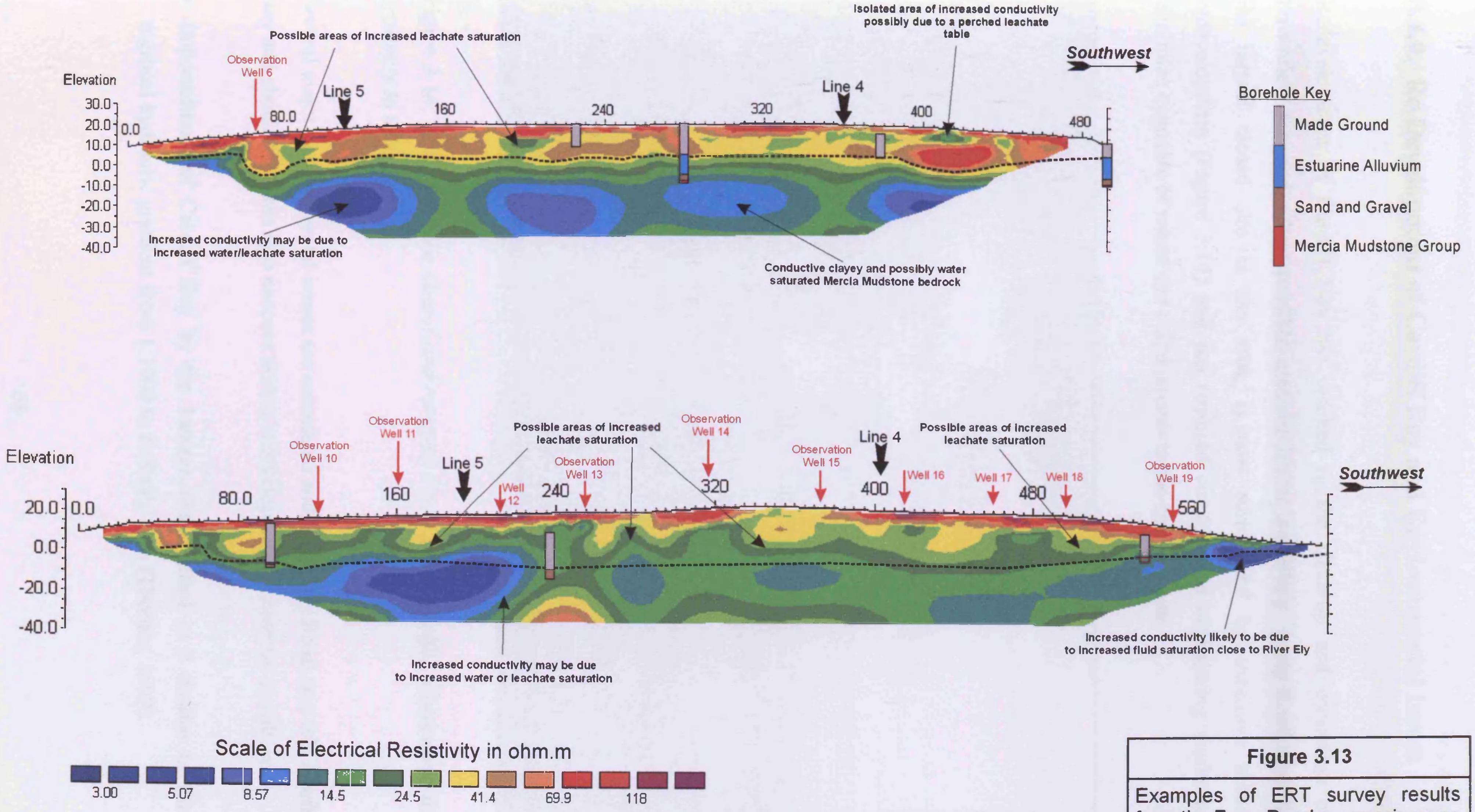



**Figure 3.13**

Examples of ERT survey results from the Ferry Road reconnaissance geophysical survey of March 2002
*Reproduced by permission of Cardiff City Council*

### 3.1.9. Re-Development of Cardiff Bay and Environmental Issues

Redevelopment of Cardiff Bay has resulted in the clean-up and utilization of brownfield sites and, where possible, areas of former landfilling. Ferry Road landfill, the largest closed site in the area, is now surrounded by extensive urban redevelopment (Figure 3.14) and has required considerable engineering works to minimize exposure of waste and contaminants to the environment.

Figure 3.14: *A view of the closed and restored Ferry Road landfill, illustrating its proximity to urban areas.*

Several major environmental issues are associated with the Ferry Road area of Cardiff Bay and should be taken into account during redevelopment. These are as follows:

- Impoundment of Cardiff Bay by the barrage has resulted in a decline of the regional hydraulic gradient from 1:1000 to virtually zero (Thomas, 1997).

- It is possible that a rise in groundwater level may have occurred since impoundment of the bay, resulting in elevated perched groundwater tables in potentially contaminated Made Ground (Thomas, 1997).

- Landfilling occurred initially within the drained River Ely channel where alluvial clays were absent and the gravel aquifer was exposed (Ove Arup and Partners, 1995).

- Migration of landfill leachate into the underlying gravel aquifer and the surrounding Made Ground perched groundwater will have occurred (Cherrill and Phillips, 2005).

- The fate of hydrocarbon contaminants and associated leachates in the engineered lined disposal cell constructed on the landfill between 1996 to 1999 is unclear (George, 2002).

It is therefore very important for landowners and redevelopers to understand the risks posed to environmental and human receptors from closed landfills and derelict land, and even with extensive engineering works to contain such sites the importance of regular monitoring and risk appraisal should be emphasized.

# 3.2. Lamby Way Active Landfill, Cardiff

## 3.2.1. Site Location and Description

Lamby Way landfill site is located approximately 4 km to the east of Cardiff City Centre at National Grid Reference ST 220 780 (Figure 3.15). The landfill site is situated on flat lying ground, known as the Wentloog Levels, which characterises much of the land on the northern shore of the Severn Estuary between Cardiff and Newport (Figure 3.15).

Lamby Way waste disposal site was initially developed in the 1970's and is now being extended eastwards. It comprises the closed 'Southern Site' together with waste disposal cells 1 and 2, which are currently active and may be observed on the aerial photograph reproduced in Figure 3.16. The site is bounded to the north by the Lamby Way road; to the west by the mouth of the River Rhymney; to the south by the tidal mudflats of the Severn Estuary and to the east by the Ystradyfodwg and Pontypridd Sewer.

In previous years, the oldest part of the landfill (Southern Site) received hazardous wastes; however the active parts of the present site now receive only non-hazardous domestic and commercial refuse. The Southern Site was developed according to the 'dilute and disperse' principle, whereas the more recent extensions of Cell 1 and Cell 2 have been developed using containment techniques.

At present, much of the domestic and commercial waste produced by Cardiff is deposited in the most recent extension of the landfill, known as Cell 2, as illustrated in Figures 3.16 and 3.17.


(Taken from the OS 1:50 000 Landranger Series, Sheet 171)

Figure 3.15: *An OS map extract of Cardiff illustrating the Lamby Way landfill location.*


Figure 3.16: *An aerial photograph illustrating the position of Cells 1 and 2 at Lamby Way, along with the older 'Southern Site' (Cardiff Council).*

### 3.2.2. Geological Setting and Hydrogeology

Solid and superficial deposits underlying the Lamby Way landfill site are similar to those described in Section 3.1 of the thesis and include the following:

- Triassic Mercia Mudstone Group bedrock
- Fluvioglacial Sands and Gravels
- Estuarine Alluvium
- Made Ground

A confined aquifer exists within the Fluvioglacial Sands and Gravels unit and perched groundwater conditions are encountered within the Made Ground deposit. Analysis of the Estuarine Alluvium deposit undertaken by various contractors (Hydrotechnica, 1991), (Exploration Associates, 1990., 1991) have indicated a very low vertical hydraulic conductivity of 1 x $10^{-10}$ m/sec. The underlying Triassic bedrock may be subjected to some limited movement of groundwater within its stratum, but for practical purposes its weathered top can be taken as an impermeable base to the groundwater system throughout the area.

### 3.2.3. Development of the Lamby Way Waste Disposal Site

Historical development of the Lamby Way site can be reviewed with respect to four chronological periods, which are described in Bathurst (2002) and include the following:

- **Pre 1978.** Prior to refuse disposal at the Lamby Way site the area was characterized by low-lying wetlands and farm pasture, which was crossed by several drainage ditches. The site was approved for use as a landfill in 1972 and waste disposal commenced in 1978.

- **1978-1995.** Waste disposal began on the southern site with a tipping area of 38 Ha. The original capacity was estimated at just under 2 million cubic metres and the waste was to be built to an elevation of +12 metres OD.

- **1995-2002.** Closure of the Ferry Road landfill to the west of Cardiff resulted in planning permission requirements to extend the Lamby Way site. Permission to extend was granted in 1995 resulting in the construction of Disposal Cell 1. Disposal Cell 1 was commissioned in 1998 and reached capacity in 2002.

- **2002-Present.** Construction of Disposal Cell 2 has allowed eastward extension of the landfill. Restoration of the Southern Site is nearing completion and includes installation of gas recovery wells and a suitable capping medium.

### 3.2.4. Control of Landfill Gas and Leachate

Lamby Way landfill was initially developed on the *dilute and disperse* principal, with leachate being discharged from the Southern Site waste-mass directly into the Bristol Channel and Rhymney River through outfalls. Subsequent extensions to the original landfill were developed to include control of leachate and disposal to the sewer system following pre-treatment to remove dissolved methane. Disposal cells 1 and 2 include a gravel drainage blanket laid onto the natural clay liner, which is engineered with a fall towards the leachate collection drain situated along the northern margin of both cells.

Landfill gas is recovered from the waste-mass comprising the Southern Site and Cell 1 through gas wells, which supply a system of electricity generators.

### 3.2.5. Conventional Site Monitoring

Monitoring of leachate levels within the landfill is undertaken by utilizing inspection chambers and boreholes emplaced within the waste-mass. Samples of leachate are recovered periodically for chemical analysis. Groundwater samples are recovered around the perimeter of the landfill by utilizing observation wells emplaced in the aquifer confined within the Fluvioglacial Sands and Gravels.

Monitoring of landfill gas characteristics is not undertaken by the landfill operator, however airborne particulate monitoring is performed on an annual basis.

### 3.2.6. Design and Construction of the Eastern Extension (Cell 2)

Construction of Disposal Cell 2 in 2002 has been discussed in Bathurst (2002) and involved preparation of the cell base together with construction of a clay retainment bund. A diagrammatic cross-section illustrating constructional attributes of Cell 2 is shown in Figure 3.17.

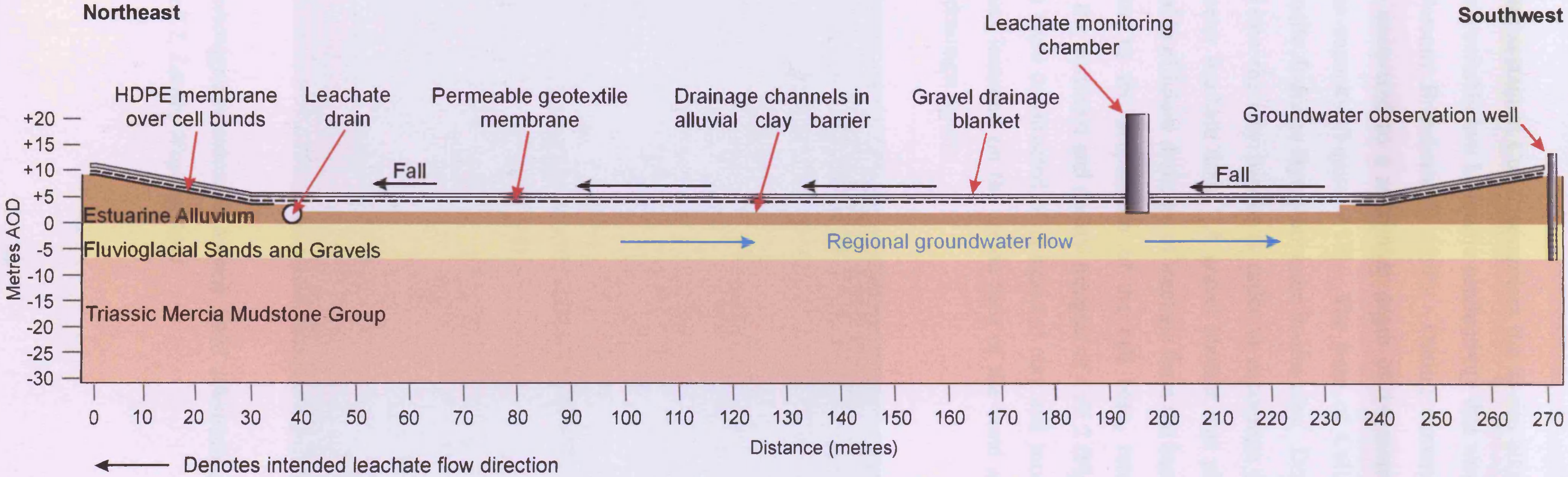



**Figure 3.17**

A diagrammatic cross-section illustrating the constructional attributes of Cell 2, Lamby Way.

An engineered liner system at Cell 2 comprises the in-situ alluvial clay, which was considered to have a suitably low hydraulic conductivity that would permit its use as a natural barrier (Parsons Brinckerhoff, 1999). During construction of Cell 2 the alluvial clay was excavated to a maximum depth of +4 metres AOD in order to increase the waste capacity (Figure 3.17). The base of Cell 2 was prepared by installing a geo-textile drainage layer above the in-situ clay. Drainage channels were also incorporated into the clay barrier in order to encourage movement of liquids towards the perimeter leachate drain. A gravel blanket was placed above the geo-textile layer to enable efficient drainage of leachate from the base of the cell (Figures 3.17). In addition to the preparation of the cell base, retainment bunds were constructed along the northeast and coastal margins of Cell 2 (Figures 3.17 and 3.18). Retainment bunds were constructed of compacted clay and incorporate HDPE liner material, which was installed on the inside face of the bund and overlain by geo-textile and gravel drainage layers.

Figure 3.18: *A photograph taken in March 2003 illustrating the start of refuse emplacement at Cell 2, Lamby Way (author).*

During construction of Cell 2, observation well chambers were installed in the cell base for the purpose of leachate monitoring (Figure 3.17). These plastic chambers will be gradually extended vertically as waste emplacement progresses.

At present, deposition of refuse is occurring in *raises* that are developed progressively eastwards across the base of the cell.

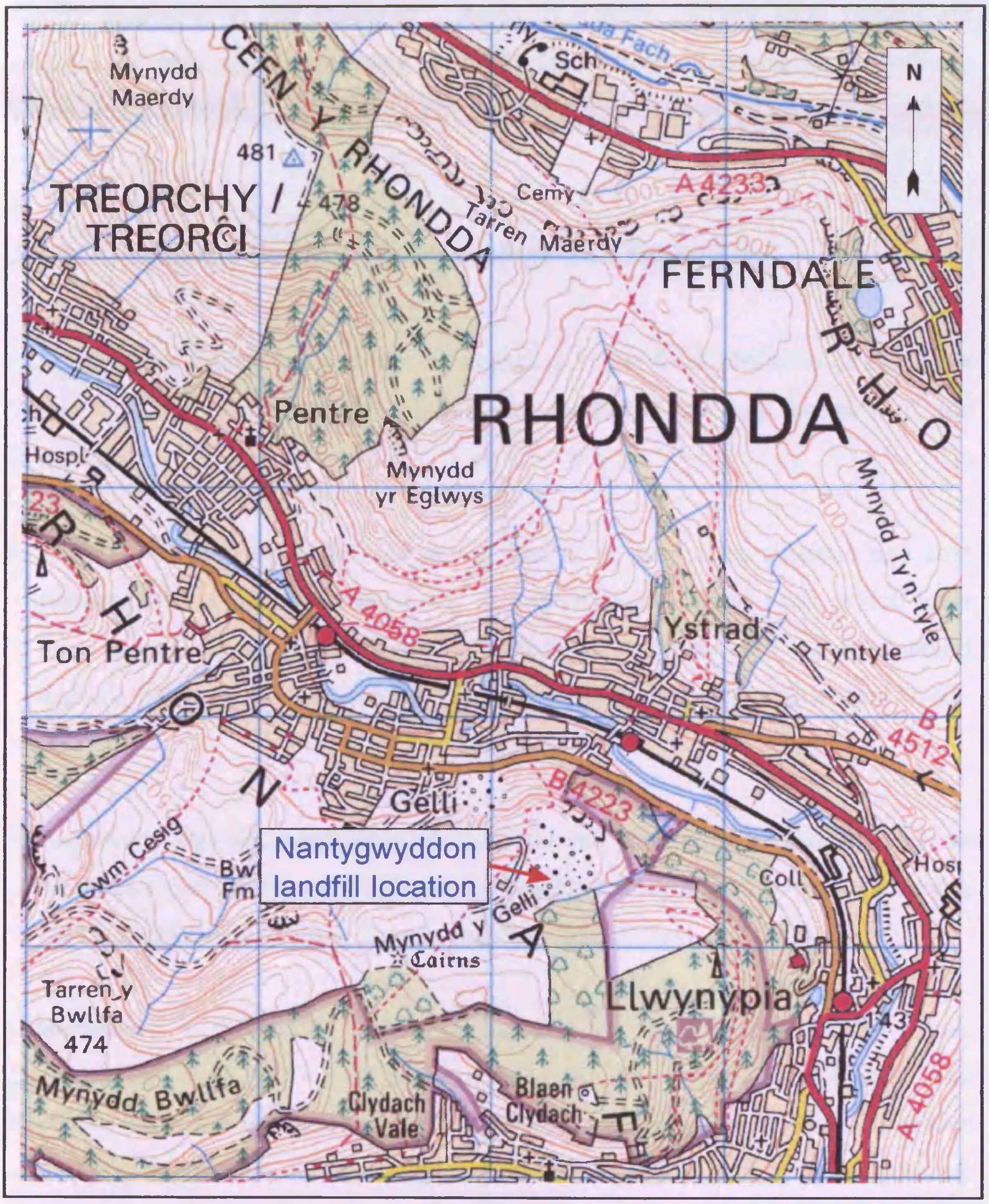
# 3.3. Nantygwyddon Landfill, Rhondda Valley

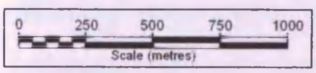
## 3.3.1. Site Location and Description

Nantygwyddon landfill is situated at an elevated position on Mynydd y Gelli plateau and Llwynypia Mountain on the west flank of the Rhondda Fawr valley (Figures 3.19 and 3.20). The site is centred on National Grid Reference SS 980 940 and lies approximately 1.7km to the northwest of Tonypandy (Figure 3.20). Access to the landfill is along a private road at Gelli, which is reached from the B4223.

Figure 3.19: *An oblique aerial photograph looking north taken in 2003 illustrating the setting of the Nantygwyddon landfill site (Amgen Rhondda Ltd).*

A natural depression at the head of the Nantygwyddon stream was utilised for landfilling, whereby the base of the containment cell is perceived to be at an elevation of 320 mAOD, with the current land surface at an approximate height of 353 mAOD.




(Taken from the OS 1:50 000 Landranger Series, Sheet 161)

Figure 3.20: *An OS map extract of the Rhondda Valley illustrating the location of the Nantygwyddon landfill site.*

Vegetation around the landfill is predominantly scrub land and marsh with a large conifer plantation to the southwest. Areas of historic colliery spoil tipping are evident, the most significant being the Gelli Tips derived from the Gelli Colliery, which closed in 1965.

### 3.3.2. Geological Setting, Hydrogeology and Hydrology

Nantygwyddon landfill is situated on Westphalian Upper Coal Measures of the South Wales Carboniferous Coalfield. Solid and superficial geology consists of the following:

- Bedrock, comprising cyclic deposits of mudstone, sandstone, siltstone and coal measures, the most significant being the *Rhondda* and *Llynfi* beds, which have been extensively mined in the region. A regional strata dip of 7° SE is observed and bedrock is locally dissected by the *Dinas* and *Cymer* faults, which trend NNE–SSW.

- Superficial deposits, comprising glacial sand and gravel are known to occur on Mynydd y Gelli, but do not underlie the landfill itself (Encia, 2004). Overburden removed prior to landfilling consists mainly of peat (Klinck and Trick, 2001).

Hydrogeology is influenced by the cyclothemic deposition nature of the Upper Carboniferous strata. Two main groundwater aquifers underlie the landfill: the *Rhondda Rider Aquifer* and the *High Aquifer* (C.L. Associates, 1998b). Pennant sandstones are known to have a significant permeability and fracture porosity allowing percolation of surface waters into the ground (Parish, 1992). Vertical hydraulic continuity is disrupted by less permeable coal and shale beds, which results in lateral groundwater flow and spring-lines along valley sides.

A number of small adit mines on slopes around the Rhondda Fawr valley could potentially increase drainage within the bedrock. A high annual rainfall is experienced at Nantygwyddon, with a long-term average of 1900mm being noted

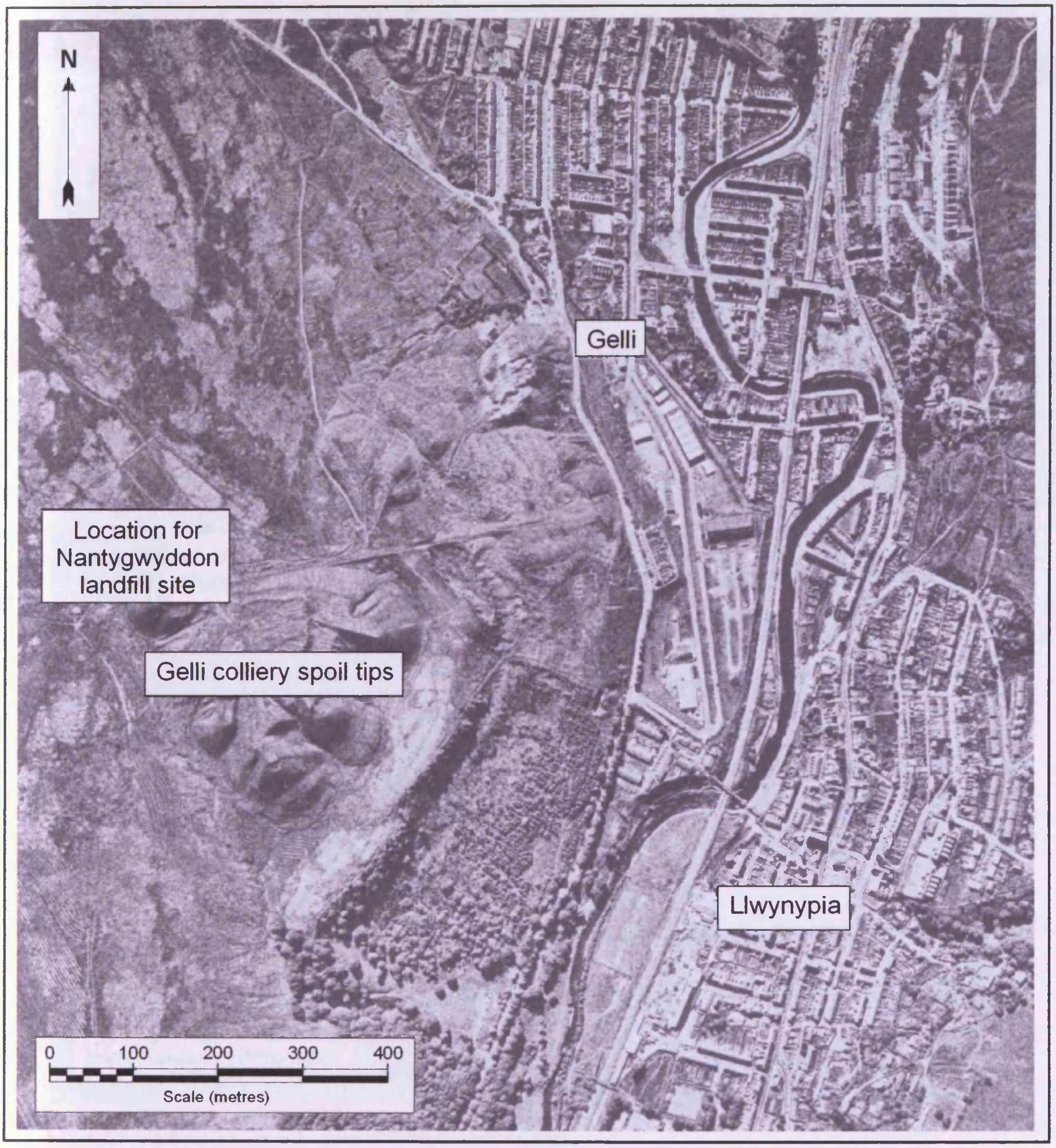
(Encia, 2004). Surface water is drained from the hillside via small streams, including the *Nantygwyddon* and *Cae Dafydd*, and run-off is rapid due to minimal vegetation cover. A number of springs, or *issues*, are noted around the Nantygwyddon site and occur at the outcrop of sandstones. Surface water tributaries feed the *Afon Rhondda Fawr* and environment agency records indicate that the river meets quality standards both up- and down-stream of the landfill (Ling, 2005).

### 3.3.3. Historical Development of the Nantygwyddon Landfill

Prior to landfilling on Mynydd y Gelli, the area was predominantly utilised for rough grazing, minor stone extraction and more significantly the disposal of mine spoil from the Gelli Colliery (Figure 3.21). Landfilling operations commenced in September 1988 following preparation of the site and associated engineering works (Figure 3.22).

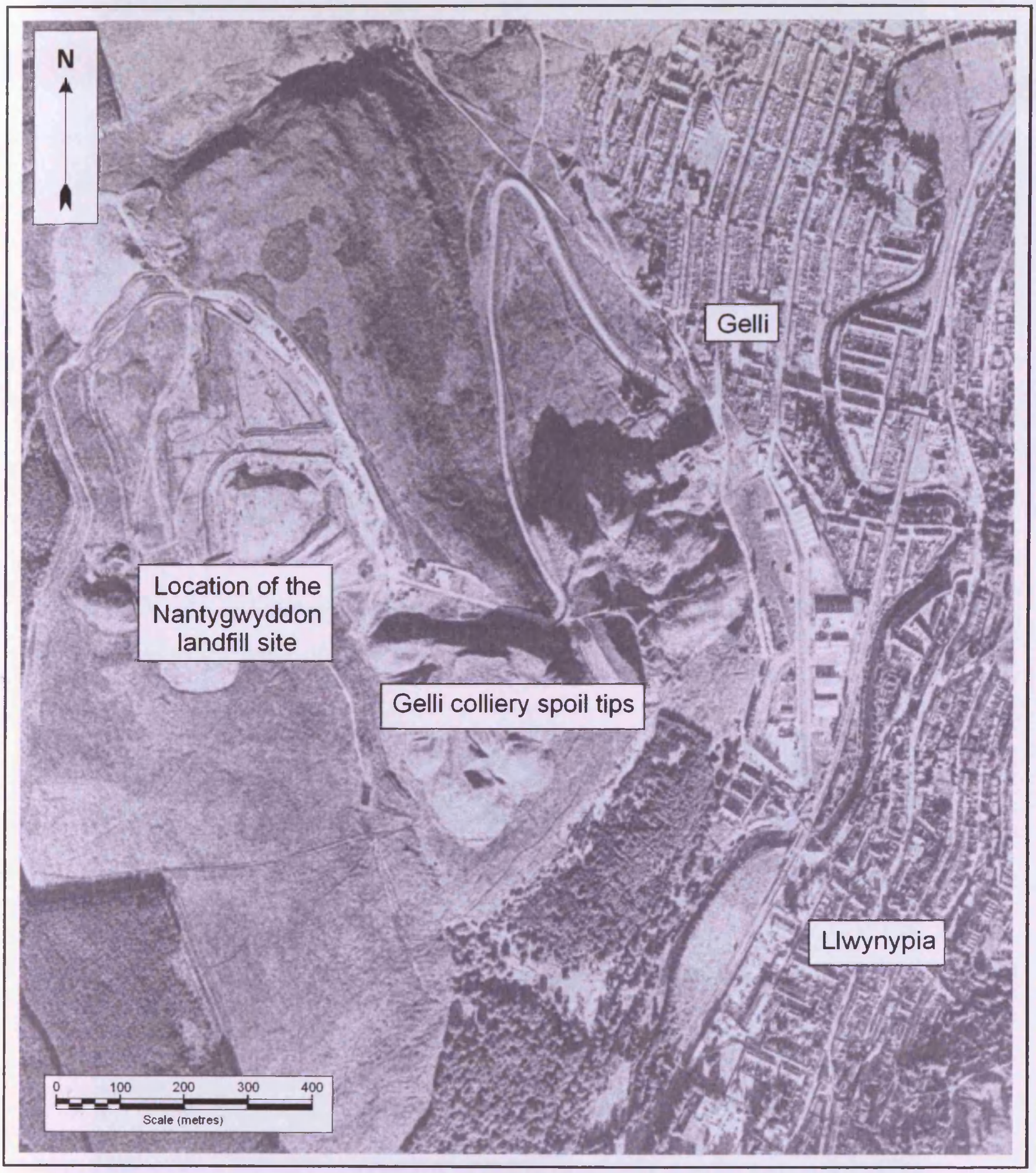
Nantygwyddon landfill was the main waste disposal facility for Rhondda Cynon Taff and is now superseded by Bryn Pica landfill near Aberdare. The site operated until March 2002, whereby closure occurred due to increasing public pressure towards a perceived threat to the local populus and environment.

Areas of deposited waste within Phase I were subsequently capped with a temporary colliery spoil cover (Figures 3.23 and 3.24). Restoration of the landfill commenced in mid-2005 involving the covering of Phase I with an engineered capping system and additional measures for the control of gas, leachate and surface water.




Aerial photograph source: Central Register of Air Photography for Wales

Figure 3.21: *An aerial photograph of the Rhondda Fawr area taken in 1983 illustrating the Nantygwyddon site prior to landfilling.*




Aerial photograph source: Central Register of Air Photography for Wales

Figure 3.22: *An aerial photograph of the Rhondda Fawr area taken in 1988 illustrating the commencement of landfilling operations at Nantygwyddon.*

Figure 3.23: *An oblique aerial view towards the south taken in 2003 illustrating the Nantygwyddon site after closure (Amgen Rhondda Ltd).*

Figure 3.24: *A photograph taken after closure of Phase I at Nantygwyddon, which received waste between 1988 and 2002 (author).*

### 3.3.4. Nature of Wastes Deposited

Phase I at Nantygwyddon received approximately 1.4 million cubic metres of waste between September 1988 and March 2002 (Encia, 2004). Refuse deposited included a mixture of municipal, domestic, commercial and industrial wastes. Disposal of *special*, *difficult*, or *hazardous* waste was prohibited; however between May 1995 and January 1997 a quantity of calcium sulphate (29,664 tonnes) in the form of industrial filter cake was deposited (Encia, 2004). As a result of calcium sulphate waste being accepted, large volumes of hydrogen sulphide gas were generated and caused public concern in the surrounding communities.

Waste arisings from gas well emplacement in 2004 consisted of paper, textiles, rubber, plastics, electrical cable and components, metal fragments, timber, glass, demolition rubble, and soils.

### 3.3.5. Management of Landfill Gas and Leachate

Landfill gas generated in the waste-mass at Phase I is controlled by burning through a High Temperature Enclosed Flare, which exerts a negative pressure (suction) on the gas field. Gas is extracted directly from the waste-mass through a series of wells connected to three main manifolds supplying the flare. Extraction wells are usually emplaced at 50 metre centres and extend through up to 80% of the waste-mass depth. They typically consist of 160mm slotted HDPE pipe with a gravel packing and bentonite seal around the collar (Amgen, 2002a).

On the principal of total containment, the Phase I disposal cell was engineered to include leachate drainage and disposal. As described in Amgen (2002b), leachate is collected from three systems, including: the leachate drainage system installed beneath the waste-mass prior to waste disposal; a secondary leachate collection system installed within an inert bund on the northeast of Phase I; and from a natural low point under the landfill where leachate collects under gravity.

These three systems are connected to the sub-liner drainage installed to reduce hydrostatic pressures under the landfill. Leachate removed from Phase I is fed into a series of holding and settlement lagoons within the site margins, from where it is discharged to foul sewer.

### 3.3.6. Conventional Site Monitoring

Since acquiring the Nantygwyddon landfill in 1999, the current site proprietor Amgen Rhondda Ltd has implemented an environmental monitoring regime based on published EA guidance on best practice. This regime is under continual review and improvement in response to the on-going analysis of data collected (Encia, 2004).

Amgen Rhondda Ltd undertakes regular monitoring of in-situ gas generation, flare-stack emissions and ambient air quality; leachate levels and quality; groundwater levels and quality; and surface water quality on- and off-site.

A discrepancy appears to exist regarding the practice of leachate level measurement from various apparatus. Leachate levels are recorded from three observation sources, including: standpipe piezometers installed within the waste-mass, gas well installations, and man-hole (MH) chambers above the leachate drainage system.

Levels recorded from gas wells suggest leachate heads ranging from 6.0 to 22.7 metres above the basal liner, whereas MH installations suggest a much lower overall head ranging between 0 to 3.0 metres above the basal liner (Encia, 2004). Monitoring of ten standpipe piezometers installed within the waste-mass in 2003 suggested the presence of perched leachate ranging between 18.0 to 25.0 metres above the basal liner and a series of lower leachate bodies ranging between 8.0 to 17.0 metres above the liner. It has been observed that generally the lower leachate bodies do not exhibit hydraulic continuity with the perched tables above (Encia, 2004).

### 3.3.7. A Conventional Geophysical Survey at Nantygwyddon, February 2004.

A conventional Electrical Resistivity Tomography (ERT) survey was undertaken during February 2004. Information derived from the ERT survey is utilised as part of the site desk study presented in this section of the thesis and does not form part of the author's own work. The survey involved deployment of two survey traverses along the ground surface, the location of which are illustrated on Figure 3.25 of the thesis.

A geophysical contractor was instructed to undertake the reconnaissance geophysics during February 2004. Results were submitted to Amgen Rhondda Ltd in interpreted format and were provided to Cardiff University in raw data format. A report based on the investigation methods and survey results was submitted by the contractor to Amgen Rhondda Ltd and is dated March 2004.

Results and findings from the reconnaissance geophysical survey provided some useful information, but were not totally satisfactory. Significant improvement in the geophysical approach to monitoring at Nantygwyddon and other similar sites were therefore sought as part of the present research project.

As described in Section 2 of this thesis, the ERT method is well suited to near-surface investigations on landfill sites where variations in resistivity of the sub-surface may indicate internal structure, level of saturation and distribution of leachates. During the reconnaissance survey, two individual traverses were deployed, the locations of which are illustrated on Figure 3.25. ERT Survey Line 1 had an overall length of 360 metres and extended in a southwest – northeast orientation. ERT Survey Line 2 extended in a southeast – northwest orientation with an overall length of 350 metres.

An IRIS SYSCAL 72-switch® resistivity meter (Figure 3.26) was used to perform data acquisition along both traverses, whereby the Wenner-Schlumberger array-type was utilised.

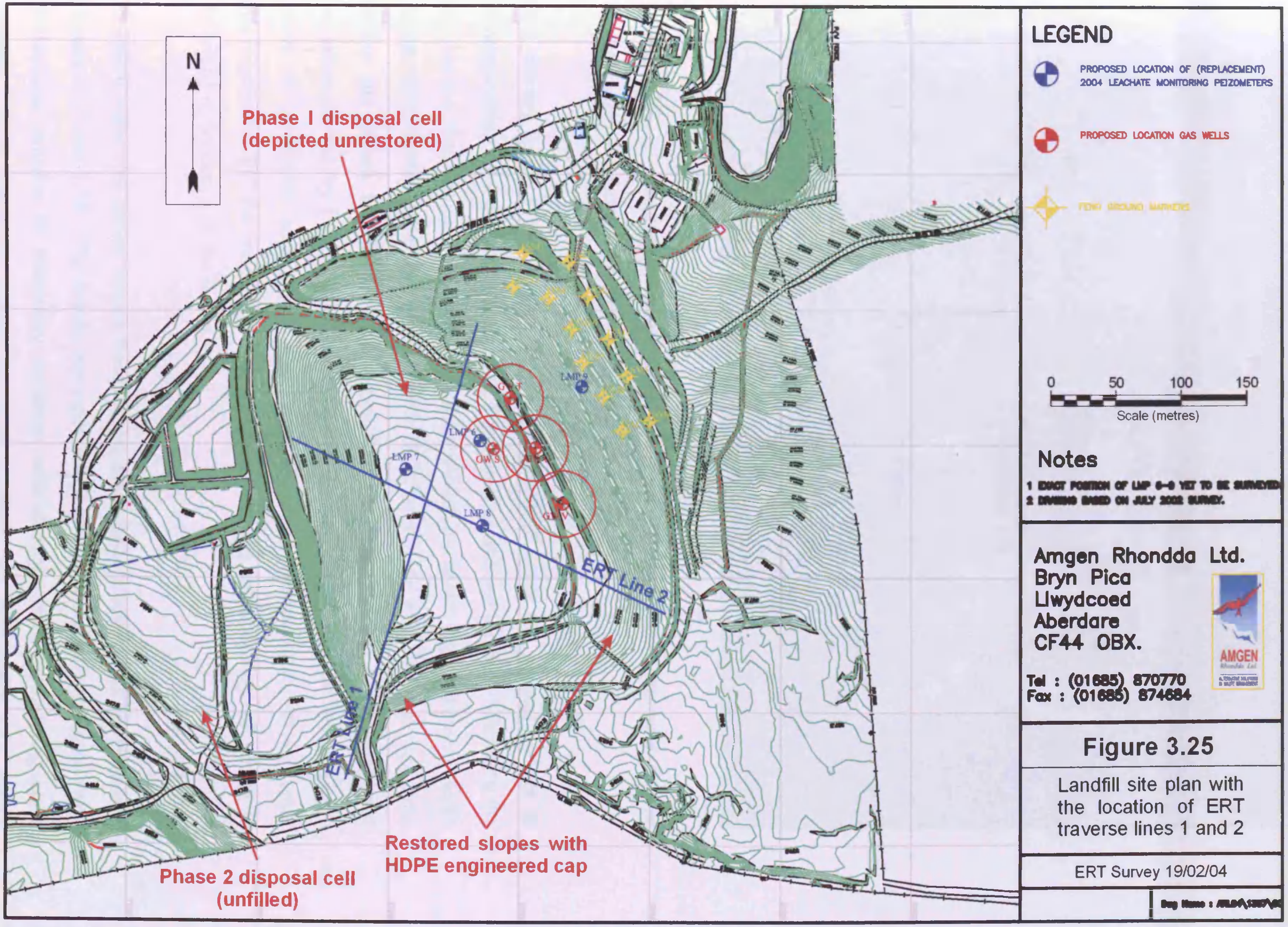



Figure 3.25
Landfill site plan with the location of ERT traverse lines 1 and 2

*Source of Autocad base map: Amgen Rhondda Ltd*

Figure 3.26: *A photograph illustrating the ERT measurement equipment in use during the reconnaissance survey in February 2004 (author).*

ERT Survey Lines 1 and 2 were deployed separately along the ground surface at Nantygwyddon. An electrode spacing of 5 metres was utilised for both lines with the anticipation that resolution would be compromised by achieving maximum depth extent. Both survey lines were positioned in order to provide some overlap onto parts of the site where HDPE capping materials exist (Figure 3.25). Topographical variations for Survey Lines 1 and 2 were recorded with a differential GPS giving high levels of positional accuracy. Raw data from the geophysical survey were downloaded to PC for modeling and interpretation, the methodology of which is described in Section 2 of the thesis.

Electrical resistivity survey results from the reconnaissance investigation are shown in Figures 3.27 and 3.28. The results are represented as colour-scaled, contoured two-dimensional profiles of resistivity variation with distance and depth along each traverse. Each resistivity profile has been adjusted for topography and actual elevation / depth is shown in metres AOD. A scale of resistivity values in ohm.meter is provided with each profile, whereby the range in resistivity is given from minimum to maximum.

The most striking feature evident across ERT Survey Lines 1 and 2 is the widespread zone of very low resistivity, which is laterally continuous and appears to extend from very near to the ground surface in places, to some depth. Very low resistivity values indicate widespread saturation of the waste-mass by leachate, whereas low to intermediate values near to the surface indicate rainwater ingress, which undoubtedly sustains the leachate saturation. It is not possible to accurately define a single leachate head or table; instead it is reasonable to infer that the whole waste-mass is saturated to varying degrees of leachate concentration. Furthermore, by observation of the ERT images, it is not possible to define perched leachate conditions, probably due to the low resolution of the survey data and distortions within the near-surface. Zones of low resistivity in the sub-surface, which are in continuity with leachate bodies, but which extend to the surface down-gradient indicate leachate surface spillage, or 'break-out'.

Both ERT survey lines were deployed in a manner as to provide some overlap with HDPE-capped areas of the landfill, as indicated on Figure 3.25. By observation of the ERT images, these HDPE-capped areas are indicated by very high resistivity shadows extending vertically from the ground surface to depth. These shadows are caused by the electrically-insulating properties of liner plastic where current flow into the ground is not possible. In close proximity to the capped areas, intermediate to high resistivity zones at the ground surface indicate damp to dry conditions with no leachate saturation.

No obvious feature is present on either ERT image to indicate the location at depth of the landfill base, its bedrock geology, and its basal liner. This indicates a fundamental problem with the surface ERT method employed on landfills.

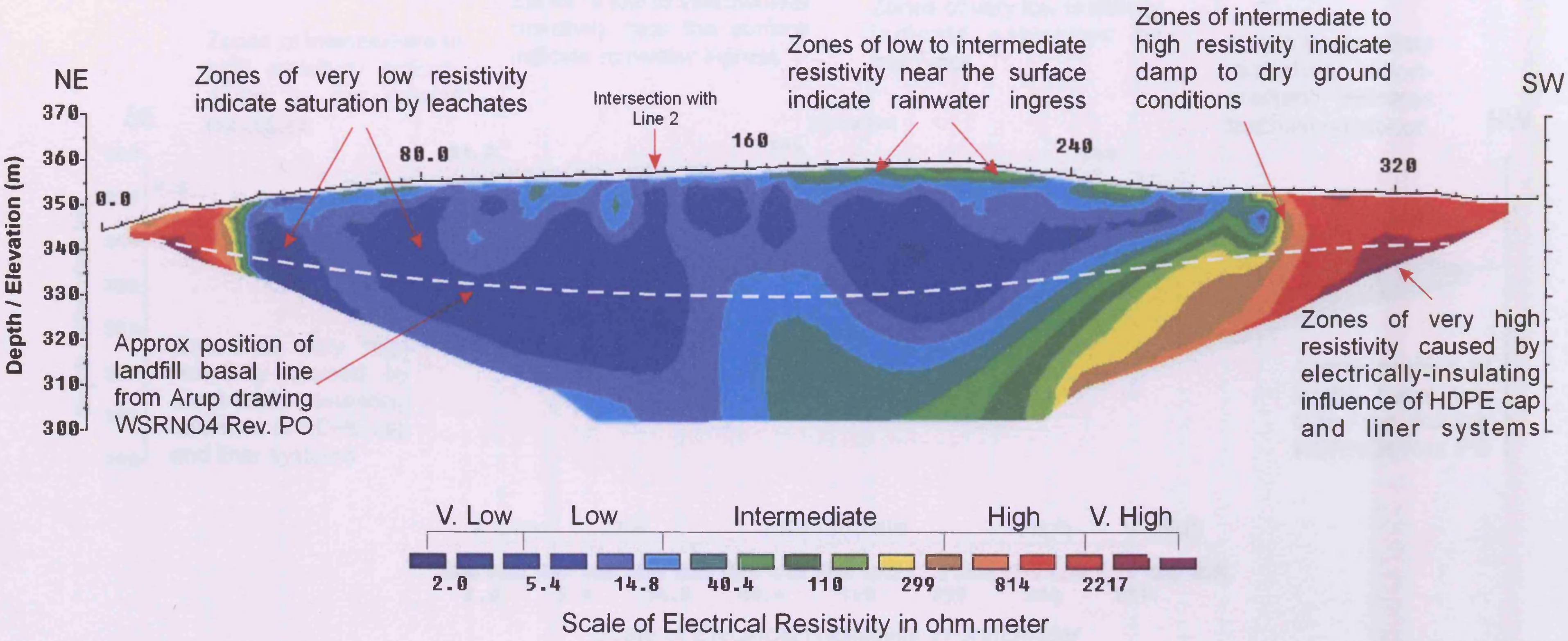



**Figure 3.27**

**ERT Survey Line 1 of the conventional ground surface investigation, February 2004**

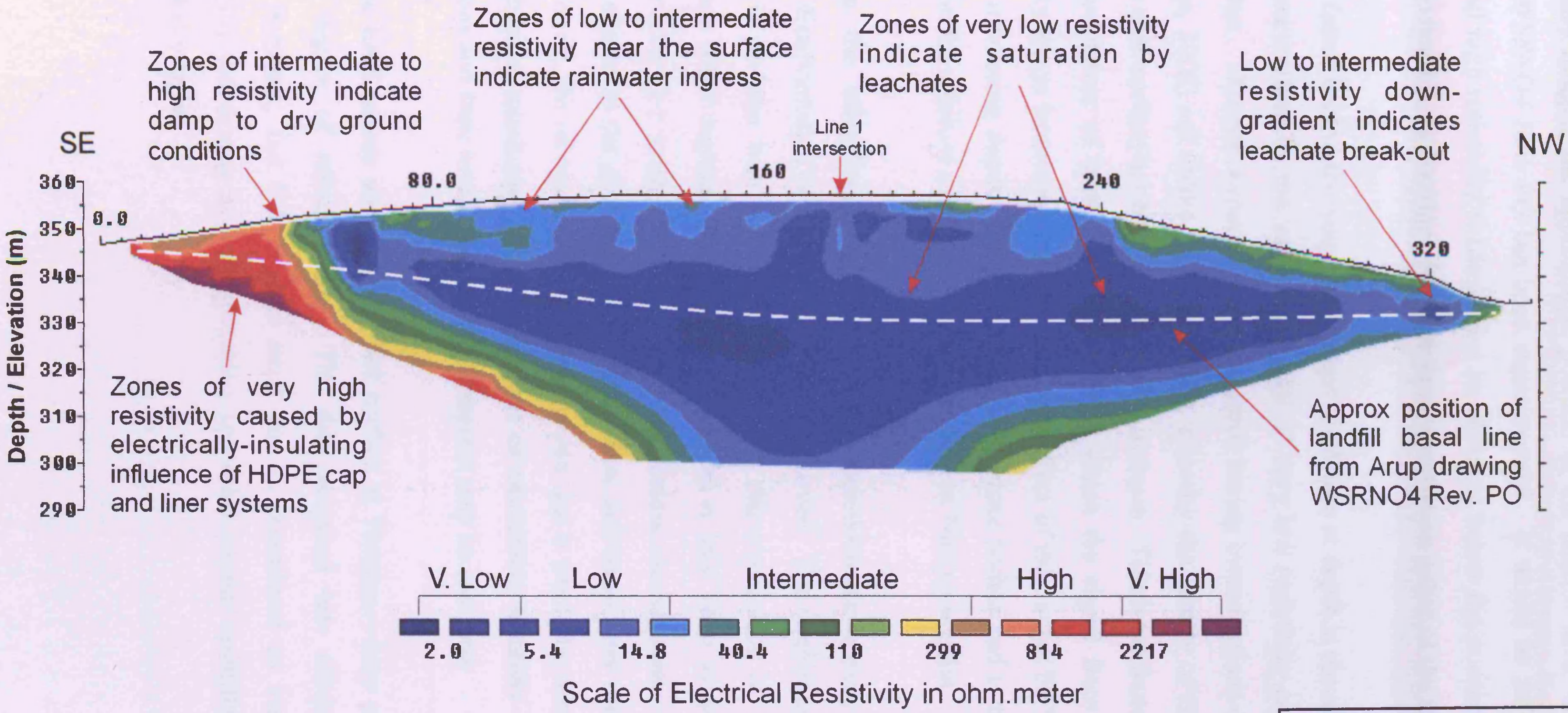



**Figure 3.28**

**ERT Survey Line 2 of the conventional ground surface investigation, February 2004**

On both resistivity images, the approximate position of the landfill basal line from *Arup Drawing WSRNO4 Rev. PO* has been superimposed. It would be anticipated that a widespread high resistivity shadow must be observed below the position of the basal liner and indicating its position. No such feature exists on either of the images.

The underlying factor behind the very poor image resolution at depth is the distortion of data in the near-surface by the widespread zone of very low resistivity caused by leachate saturation. This phenomenon has been noted during investigations on other landfills (George, 2002) not unlike Nantygwyddon, whereby the quality of ERT data is reliable in the near-surface but becomes unreliable at depth. This is attributed to the highly-conductive nature of landfill leachate within which the signal from ground surface resistivity arrays becomes distorted. A major effect of this is that ERT data is unreliable with increasing depth through and below leachate bodies and is the most likely explanation for a failure to identify the landfill base at Nantygwyddon.

When assessing the effectiveness of the initial reconnaissance survey, major advantages and disadvantages of the method can be observed. The usefulness of the data generated is perhaps best evaluated in terms of characterisation of leachate saturation and rain water ingress, whereby the survey has at least been successful in near-surface horizons (0-5 metres depth). Within and below the leachates, the data has become unreliable to the extent that the landfill base and basal liner can not be identified. Above all, the reconnaissance survey showed that it would be desirable to undertake geophysical monitoring to greater levels of resolution, whereby perched leachate conditions and their interaction with rain ingress may be assessed.

To conclude, the ERT survey along the ground surface at Nantygwyddon provided only a limited degree of reliable data. The data acquired was adequate for reconnaissance purposes, but this method must not be considered as viable for temporal / monthly monitoring at Nantygwyddon and other similar landfills, where high quality data is sought.

### 3.2.8. Landfill Restoration Strategy

Closure of the Nantygwyddon site in 2002 required a regime of on-going monitoring and a strategy for landfill restoration. Physical restoration and capping commenced in mid-2005 and was completed by October 2005. A fully engineered cap was installed, including Low Density Polyethylene (LDPE) to prevent rainwater ingress and also utilizing sub-cap gas and leachate control pipe work. Restoration soils were placed on top of the capping medium to a minimum depth of 1000mm and consisting of screened colliery spoil later hydro seeded to promote vegetation growth. Surface water drainage channels and anti-erosion matting are included to prevent damage to the cap during periods of heavy rainfall.

# (4)

# A Multi-Method Geoelectrical Investigation Strategy for the Characterisation of a Lined Hydrocarbon Disposal Cell at a Restored Landfill

## 4.1. Background and Objectives of the Investigation

Desk study research undertaken for the restored Ferry Road landfill site in Cardiff Bay (Section 3) identified a complex history of waste disposal including initial closure and reactivation of the site in the mid 1990's with subsequent capping and landscaping by 1999.

The main waste-mass at Ferry Road comprises mixed domestic, commercial and industrial wastes and is subject to environmental monitoring and gas/leachate management by the site proprietors. During site reactivation between 1996 to 1999, a lined disposal cell was incorporated into the pre-existing landfill in order to receive hydrocarbon-contaminated soils removed from an adjacent redevelopment site.

During initial site selection for geophysical survey applications, the lined disposal cell provided a focus for interest as the cell had not been subject to specific environmental monitoring and its present content and integrity remained un-investigated. In 2002 the lined disposal cell was selected as a field test site for the application of a combined multi-method geophysical approach to landfill investigation. It was considered necessary by the site proprietors to perform a range of complimentary geophysical investigations to characterise sub-surface conditions within the lined cell, whilst utilising non-invasive methods to preserve the landfill cap integrity and reduce the risk of exposure to its contents. The procedure for a multi-method geophysical investigation is detailed including descriptions of the survey methods and interpretation of the results obtained. The overall purpose of the research is to undertake an appraisal of existing applicable geophysical survey capabilities; to provide best practice guidance for monitoring of landfill sites and to identify the scope for effective monitoring of new sites of a similar nature.

A multi-method investigation strategy was planned for the lined disposal cell with reference to a conceptual site model and with the following objectives:

- Utilising non-invasive electrical resistivity tomography (ERT), provide a characterisation of waste material above the liner with particular regard to identifying zones where possible hydrocarbon biodegradation and inert material occur; locating rainwater ingress from the ground surface; locating the extent of the HDPE liner; detecting any possible subsidence of the liner and subsequent leachate overspill.

- Undertake self-potential (SP) mapping across the aerial extent of the lined disposal cell and its immediate margins with the surrounding older landfill to identify any anomalous signatures in the natural potential fields, which may be analogous to fluid flow/migration and rainwater ingress.

- Investigate the landfill capping integrity with regard to the distribution of electrical conductivity variance corresponding to zones of clay-rich and clay-deficient near-surface material by utilising shallow electromagnetic (EM38) surveying.

- Delineate, with electromagnetic (EM31) surveying, the spatial distribution of electrically-conductive fill material at depth, which may correspond to zones of advanced hydrocarbon degradation and leachate accumulation.

- Utilise DGPS instrumentation to provide a high degree of positional accuracy during deployment of field equipment and data recovery and to construct a three-dimensional ground surface model to enhance the presentation of geoelectrical data.

- Compare the results of ERT, SP, EM38 and EM31 surveying in combination to provide an optimal interpretation of near-surface geoelectrical characteristics.

## 4.2. Conceptual Site Model

A conceptual site model (CSM) has been produced based on the lined disposal cell design specifications and functional attributes, and represents the cell as a total containment feature (Figure 4.1). A clay landfill cap was emplaced to prevent major rainwater ingress, whereby surface water run-off is collected in a perimeter drain installed beneath the encircling drainage ditch. Uncontaminated surface water run-off is channelled away from the cell and disposed of via outfalls into the River Ely.

Slight, but unquantified, rainwater ingress was expected. Resulting leachate is collected by a gravel drainage blanket laid above the HDPE liner, with an engineered fall from the centre of the cell towards a perimeter leachate bund at which the liner is terminated. Leachate is collected by a perimeter drain, which was initially connected to a storage tank on-site for subsequent disposal. Following completion of the cell, it was understood that the perimeter drain was connected to the main landfill leachate drainage system for appropriate disposal (George, 2002).

Gas migration from the mature domestic, industrial and commercial wastes beneath the lined cell is collected in a sub-liner gravel drainage blanket and disposed of through the main landfill gas system.

A full conceptual site model for any landfill or contaminated land project demonstrates the possible links between *source-pathway-receptor* relationships. For the lined cell model, the *source* of pollutants is the hydrocarbon-contaminated soil and gasworks waste emplaced within the containment cell. The cell is represented as it was intended to function; therefore potential pathways and receptors are not shown. These relationships would become established if the cell ceased to function as intended. For example; a blockage or failure of the perimeter leachate collection drain could result in overspill of leachate and migration away from the cell through the surface water drain. Leachate escape may also occur if subsidence of the liner, due to degradation and compaction of the underlying mature waste, enabled leachate overspill at the cell margins.

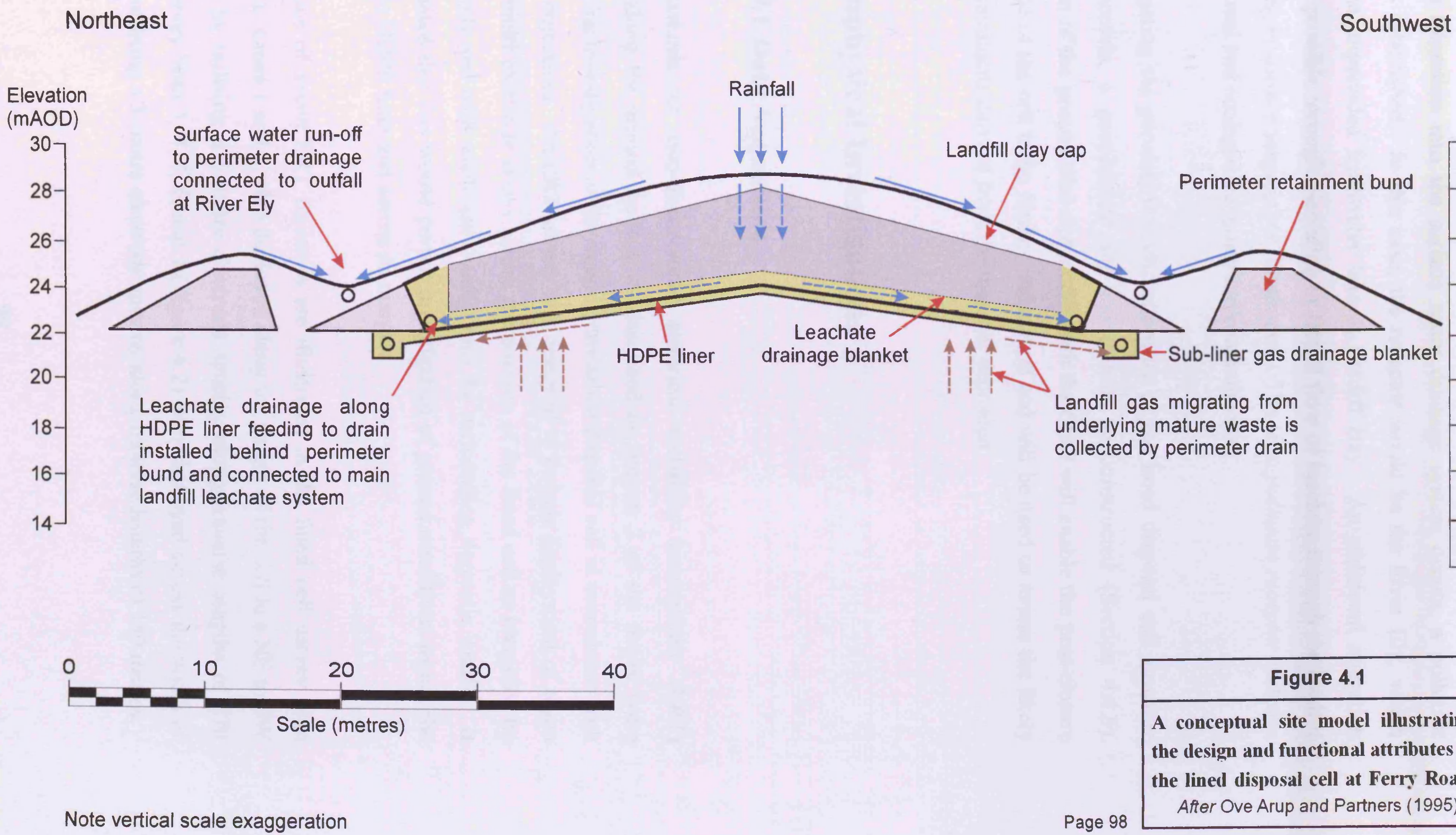



**Figure 4.1**

**A conceptual site model illustrating the design and functional attributes of the lined disposal cell at Ferry Road.**
*After* Ove Arup and Partners (1995)

If leachate migration into the surface water drainage system occurs, a pollutant *pathway* is established. In this case, the *receptor* would be the River Ely, which supplies the impounded freshwater lake at Cardiff Bay. An additional migration pathway is possible through ascending or lateral flow of leachate through the landfill cap resulting in surface seepage, or 'break-out'. The term *pollutant receptor* includes human, animal and ecological exposure to contaminants.

By investigating the geoelectrical characteristics of the lined disposal cell structure and its contents, a geophysical site model will be constructed (Section 4.4.5). Comparison of the geophysical site model with the CSM will enable the post-closure performance of the cell to be further understood and will be used to assess the likely fate of contaminants derived from the material deposited.

# 4.3. Geophysical Investigations

## 4.3.1. ERT Data Acquisition

Field procedures for two-dimensional electrical resistivity tomography (ERT) surveying along the ground surface, as described in Section 2 of the thesis, were applied during investigation of the lined hydrocarbon disposal cell in accordance with the survey objectives. An ERT survey was designed to include deployment of seven individual multi-electrode arrays across the position of the lined cell as identified by the desk study and with sufficient overlap into the surrounding domestic landfill. It was anticipated that this would permit investigation of ground conditions within the extent of the HDPE liner and across its margins.

The locations of seven ERT traverses are illustrated in the lined cell survey plan (Figure 4.2). Lines 1 and 2 were deployed along the length of the cell in a NE to SW orientation by utilising a 5-metre electrode spacing along traverse lengths of 270 metres. Survey lines 3, 4, 5, 6, and 7 (Figure 4.2) were deployed across the width of the cell by utilising a 5-metre electrode spacing along traverse lengths of 180 metres.

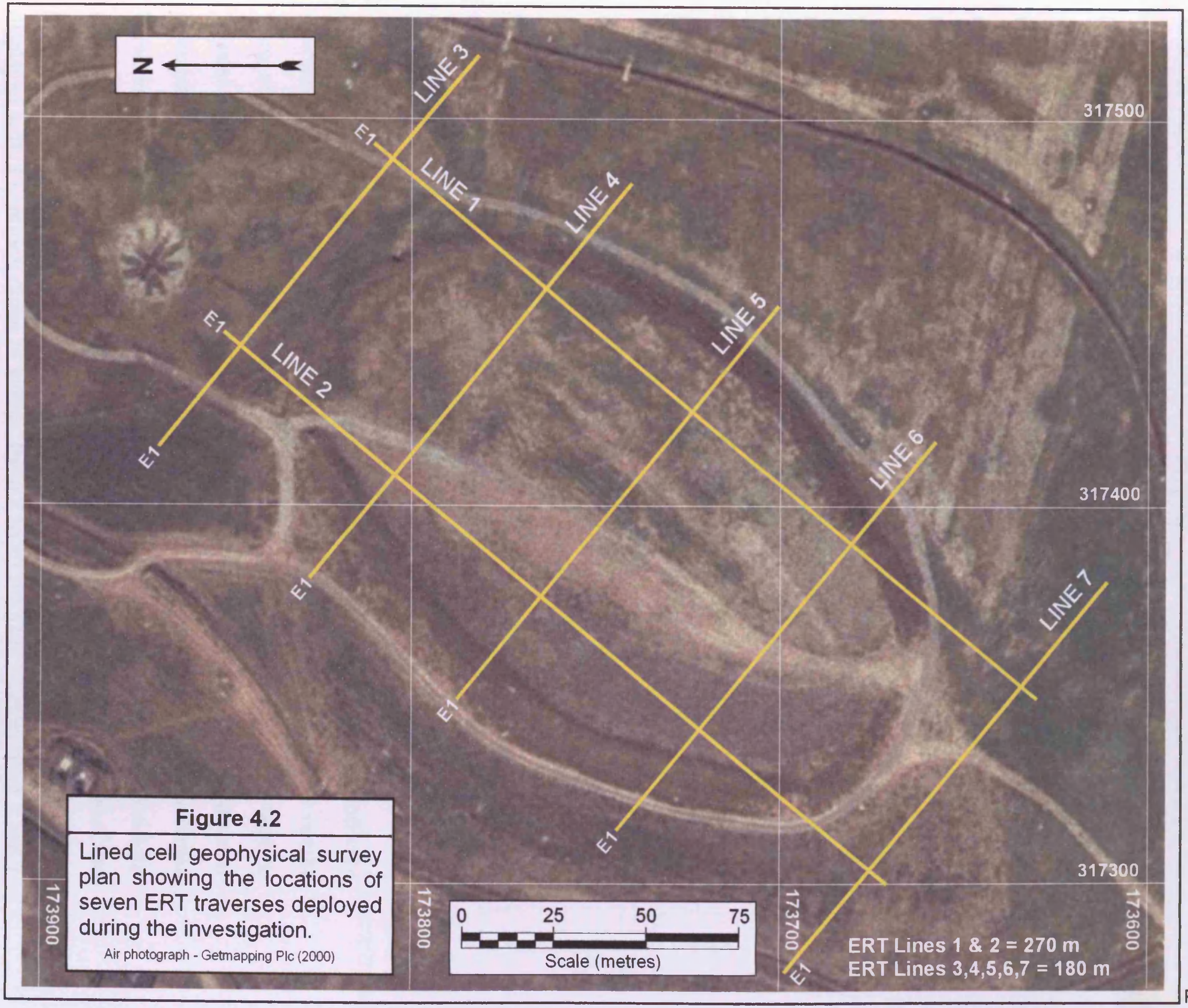



**Figure 4.2**

Lined cell geophysical survey plan showing the locations of seven ERT traverses deployed during the investigation.

Air photograph - Getmapping Plc (2000)

In order to provide a comparison with ground conditions outside the margins of the disposal cell, lines 3 and 7 were positioned beyond the perceived extent of the HDPE liner, as documented in Figure 3.8 of the desk study.

ERT Survey Lines 1 to 7 were deployed across the lined disposal cell during June 2005 under warm and dry weather conditions. An IRIS SYSCAL 72-channel resistivity meter (IRIS Instruments®), as illustrated in Figures 2.3 and 2.4, was utilised during data acquisition whereby readings of apparent resistivity ($\rho a$) were recorded using the Wenner-Schlumberger array configuration.

During the ERT survey it was necessary to respond to frequent high contact resistance readings (>4kΩ) with application of saline water to the corresponding electrodes. High contact resistances were attributed to dry and stony conditions along the ground surface and were subsequently reduced after addition of a small amount of water to the base of each electrode.

Checking of raw data was performed using PROSYS® (IRIS Instruments®) interface software supplied with the resistivity instrument, which enables the user to check data quality and remove erroneous readings prior to processing. Analysis of raw data showed a standard deviation of 3% or less for all datasets indicating lack of noise interference during the surveys and negating the need to remove bad measurements.

Inversion of apparent resistivity datasets was performed using RES2DINV software (Geotomo Software®). During inversion, it was found that significantly better results were obtained by adjusting the default parameters, such as the damping factors, vertical to horizontal flatness filter ratio, and by using a model with the half the unit electrode spacing, thereby producing model resistivity results with realistic variance between the expected very low resistivity signature of leachate and high resistivity response of HDPE. Inversion results for survey lines intersecting the position of the lined cell (lines 1, 2, 4, 5, and 6) showed similar extremes of resistivity and are displayed with a common range in values, from 2 to >3368 Ωm. Survey lines 3 and 7 are displayed with the same range in values for continuity of interpretation. Inversion statistics from processing of the resistivity data are reproduced in Appendix I.

## 4.3.2. SP Data Acquisition

Field procedures for Self-Potential data acquisition, as described in Section 2 of the thesis, were applied during the lined cell investigation in accordance with the objectives. An SP survey grid was designed with reference to the lined cell position and perceived liner extent and included ground coverage from outside the margins of the cell, as illustrated on the lined cell survey plan (Figure 4.3).

Natural voltage potential measurements were recorded by the fixed base principle at 5-metre stations along traverses deployed at 5-metre intervals, (Figure 4.3). The SP survey was performed during June 2005 under warm and dry conditions, although a prolonged rainfall had occurred on the day previous to the start of fieldwork. SP survey equipment comprised a pair of non-polarising electrodes connected to a high impedance voltmeter with a reel of single core electrical cable. The positive voltmeter input was connected to the mobile electrode, whilst the negative input was connected to the base, or reference electrode located outside of the survey area. Removal of several centimetres of soil and turf at each measurement station was necessary to improve ground contact with the roving electrode and each voltage measurement was noted after reaching a stable voltmeter reading.

Processing of raw data involved contouring the voltage readings with reference to survey grid coordinates by using SURFER® software. The univariate contouring statistics are reproduced in Appendix II. In addition, the two-dimensional surface contour map of SP values in millivolts was overlain on a three-dimensional surface topography model recorded with DGPS instrumentation and the dipolar range in millivolt values is displayed with a colour scale.

## 4.3.3. EM Data Acquisition

In accordance with the investigation objectives, an electromagnetic (EM) survey was devised by utilising shallow EM38 (~1/~1.5 metre) and deeper EM31 (~5 metre) methods. The extent and coverage of the survey is illustrated in Figure 4.3.

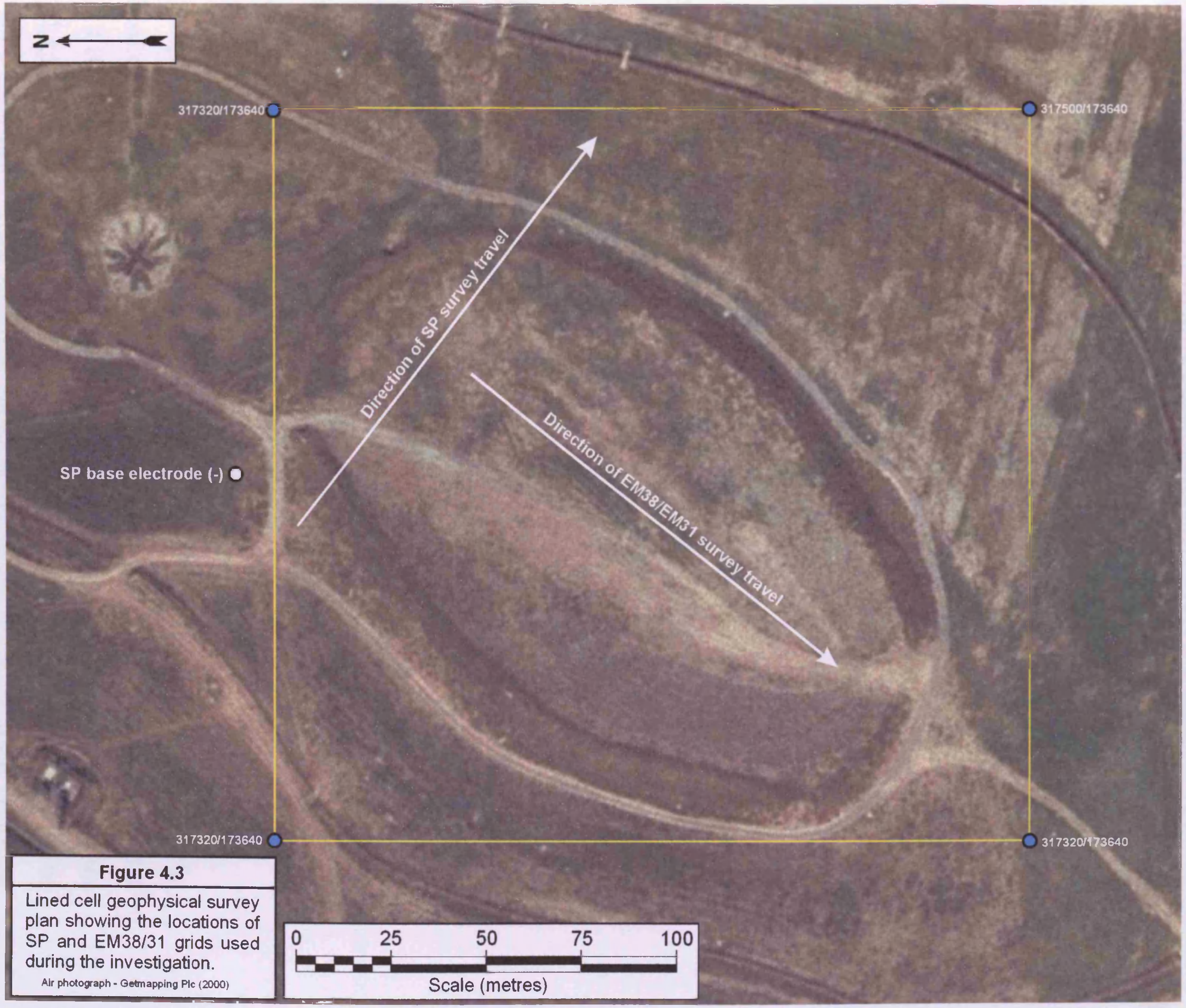



**Figure 4.3**

Lined cell geophysical survey plan showing the locations of SP and EM38/31 grids used during the investigation.

Air photograph - Getmapping Plc (2000)

The EM surveys were performed on a single day during June 2005 under warm and dry conditions, although a prolonged rainfall had occurred on the day previous to the start of fieldwork. Shallow EM mapping of the ground surface was performed using a Geonics® EM38 conductivity meter mounted on a mobile platform and towed by quad-bike across the survey area (Figure 4.3), the extent of which was pre-determined with reference to the cell construction details as reproduced in the desk study. The EM38 instrument was used on a continuous measurement setting in the vertical loop mode and a Trimble® DGPS station was used to record measurement positions within the survey grid. Mapping of ground conductivity to a greater depth (~5 metres) was performed using a Geonics® EM31 conductivity meter. This instrument was moved within the survey area by hand and was also used on a continuous measurement setting in the vertical loop mode with positions recorded by Trimble® DGPS.

Processing of raw data from the two individual surveys involved contouring the conductivity readings with reference to survey grid coordinates using SURFER® software. Univariate contouring statistics are reproduced in Appendix II. The two-dimensional surface contour map derived from shallow EM38 mapping was overlain on a three-dimensional surface topography model recorded with DGPS instrumentation. A colour scale indicates the range in conductivity for each EM plot.

## 4.4. Interpretation of Geoelectrical Site Characteristics

### 4.4.1. ERT Two-Dimensional Profiling

Interpreted results of two-dimensional non-invasive ERT profiles deployed across the lined cell ground surface, as described in Section 4.3.1 are reproduced in Figures 4.4 to 4.10. ERT lines deployed across the inferred extent of the lined cell (survey lines 1,2,4,5 and 6) show a strong contrast in resistivity values, from very low (2 Ωm) to high (>3368 Ωm). High resistivity values are attributed to the electrical insulating effects of the HDPE liner, in which case the liner acts as an electrical barrier preventing current flow below it. This geoelectrical property may be used to define the spatial extent of the liner and its position with depth.

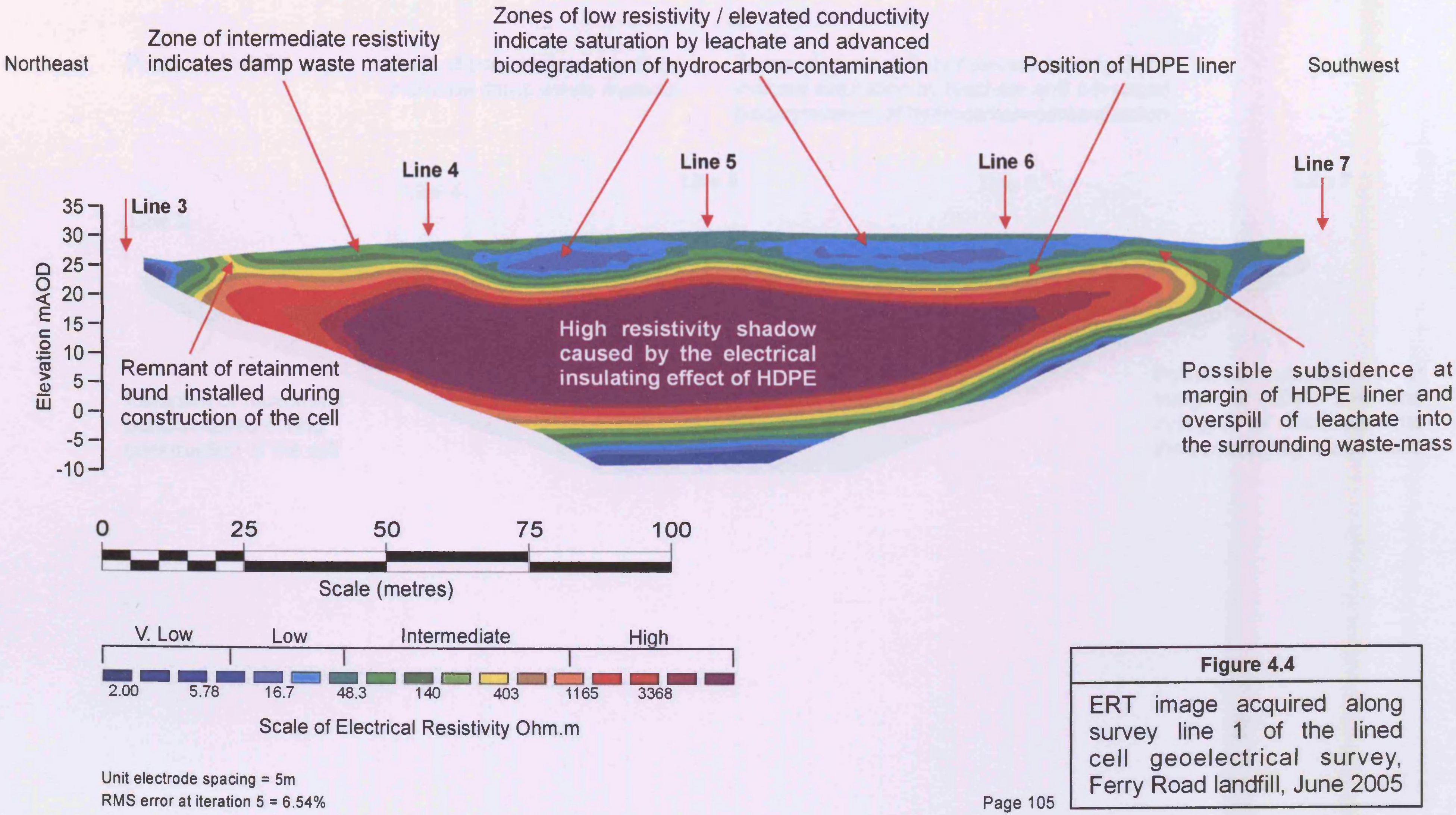



**Figure 4.4**

ERT image acquired along survey line 1 of the lined cell geoelectrical survey, Ferry Road landfill, June 2005

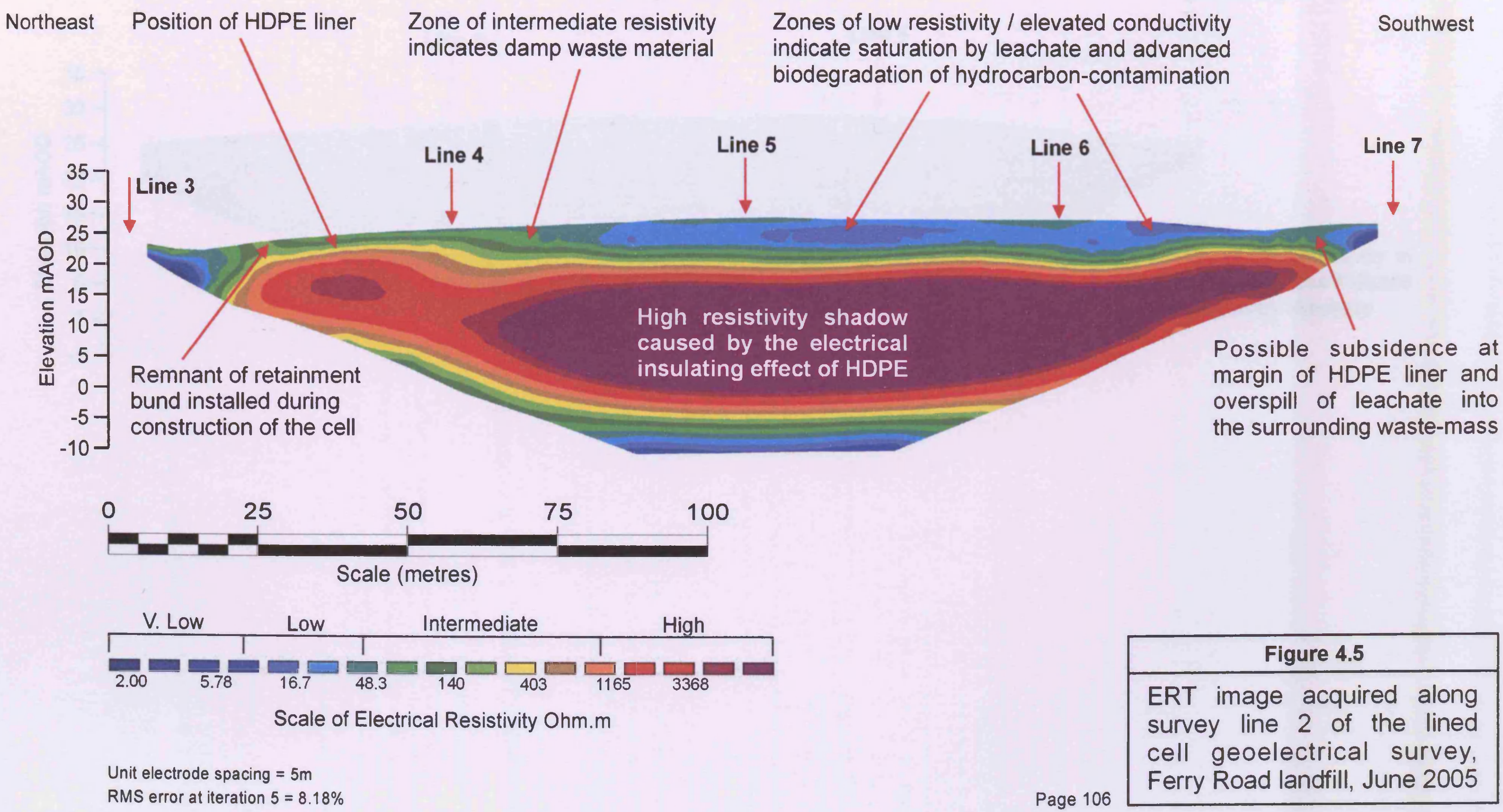
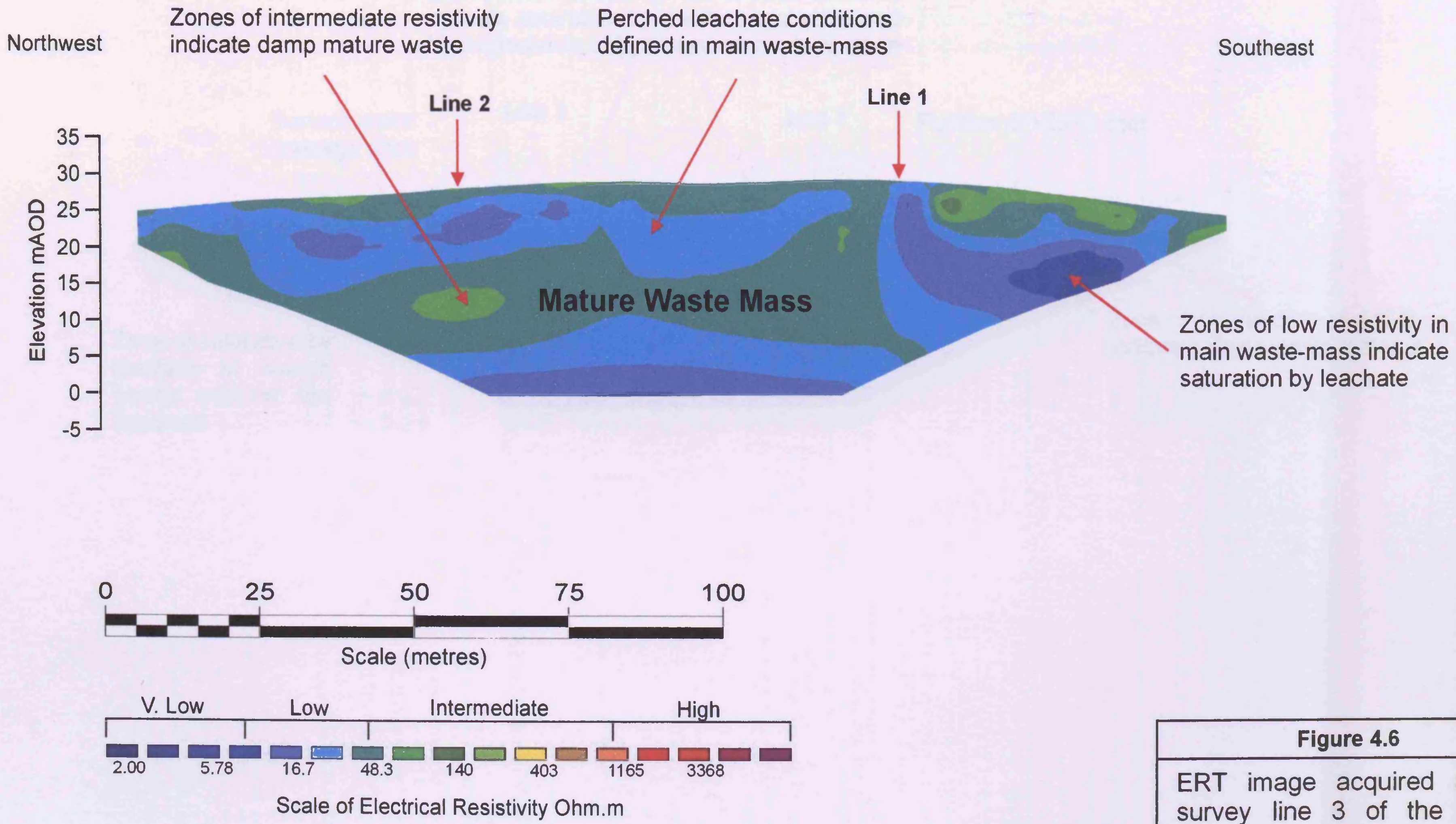





**Figure 4.5**

ERT image acquired along survey line 2 of the lined cell geoelectrical survey, Ferry Road landfill, June 2005




Unit electrode spacing = 5m
RMS error at iteration 5 = 5.14%

**Figure 4.6**

ERT image acquired along survey line 3 of the lined cell geoelectrical survey, Ferry Road landfill, June 2005

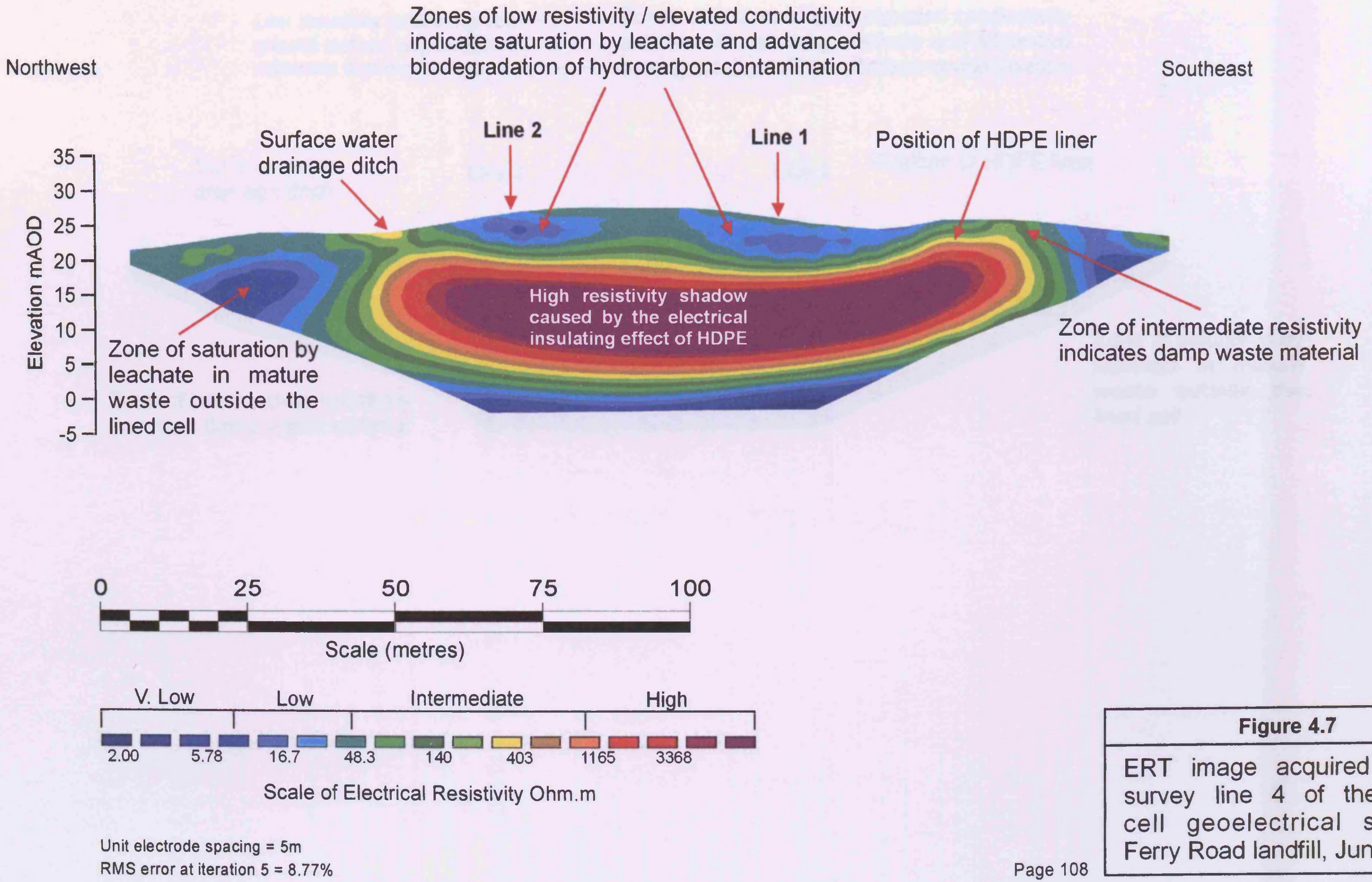



**Figure 4.7**

ERT image acquired along survey line 4 of the lined cell geoelectrical survey, Ferry Road landfill, June 2005

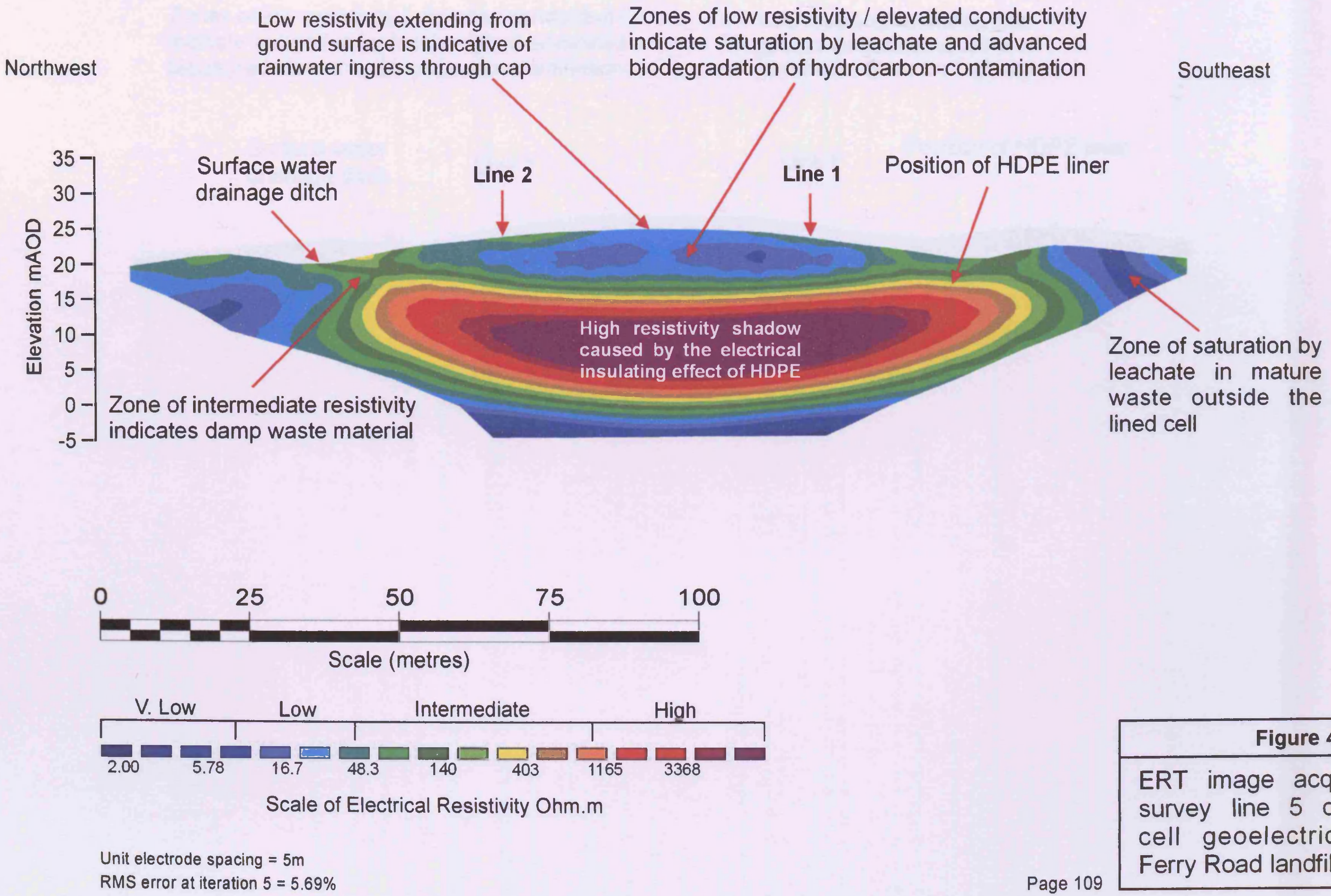



**Figure 4.8**

ERT image acquired along survey line 5 of the lined cell geoelectrical survey, Ferry Road landfill, June 2005

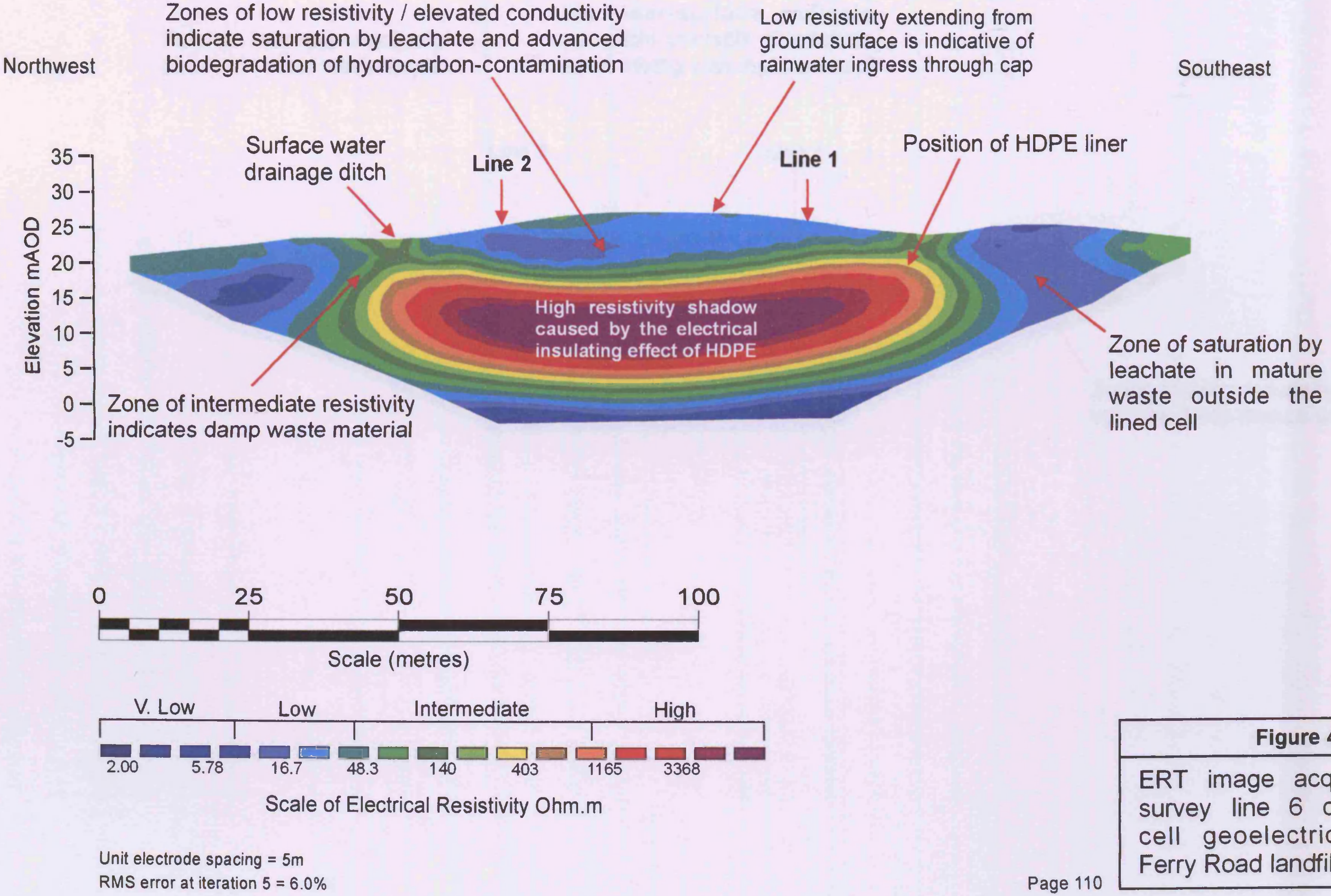
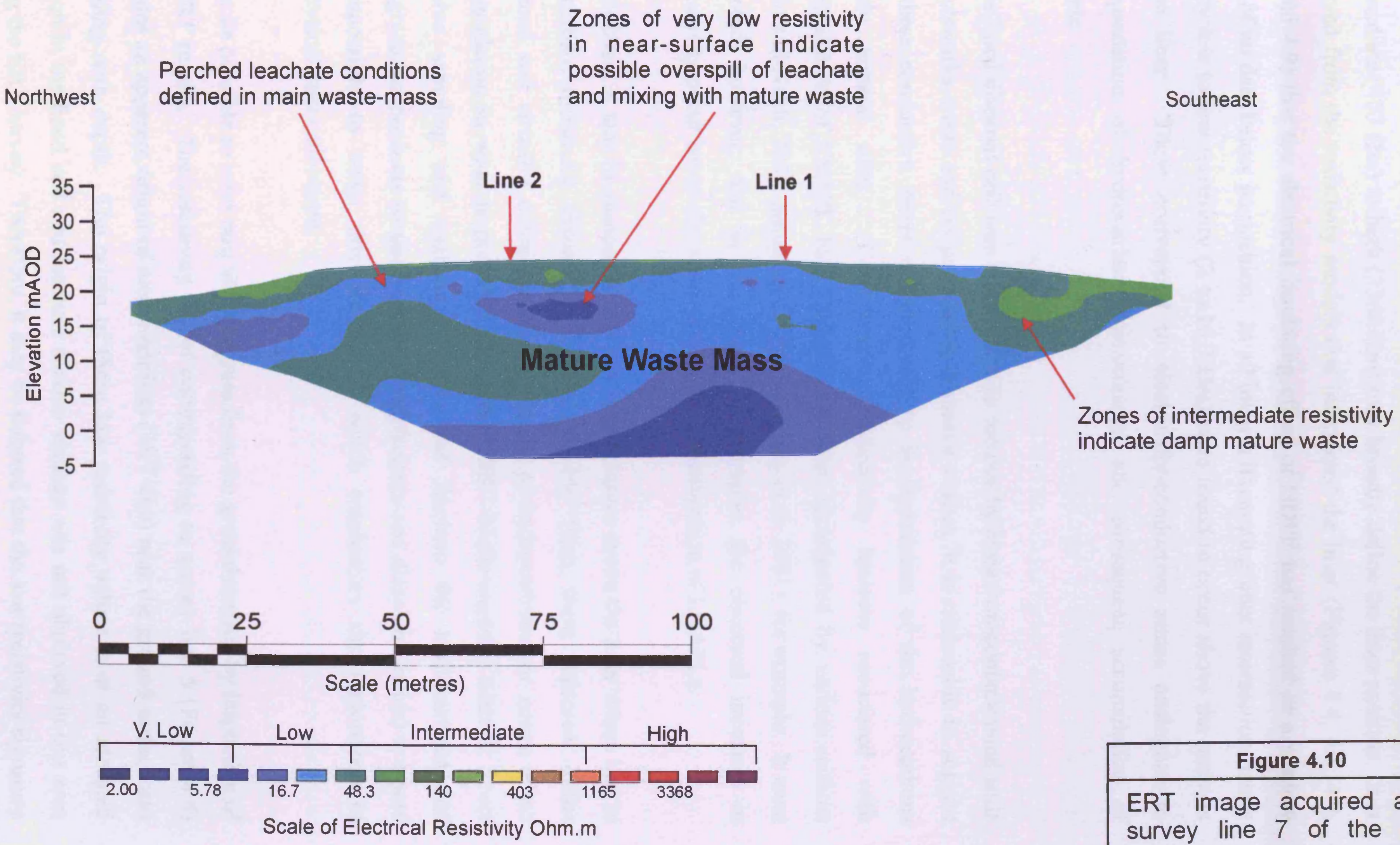



**Figure 4.9**

ERT image acquired along survey line 6 of the lined cell geoelectrical survey, Ferry Road landfill, June 2005




Unit electrode spacing = 5m
RMS error at iteration 5 = 1.66%

**Figure 4.10**

ERT image acquired along survey line 7 of the lined cell geoelectrical survey, Ferry Road landfill, June 2005

However, it may be inferred that a broad range in contoured resistivity values from intermediate (403 Ωm) to high (3368 Ωm) may broadly define the liner position. It is observed from the resistivity models that intersected the liner (Figures 4.4, 4.5, 4.7, 4.8 and 4.9) that the electrical insulating effect of HDPE has resulted in a shadow zone of no data below its position. In all images illustrating liner intersection, zones of very low to low resistivity (2 to 16.7 Ωm) were found to occur above the position of the liner. These correspond to electrically-conductive zones analogous to biodegradation of hydrocarbon contaminants and subsequent accumulation of leachate.

As the lined disposal cell was constructed to receive hydrocarbon-contaminated soils and gasworks waste and no putrescible domestic wastes, it is reasonable to suggest that these conductive zones are attributed to biodegradation of the hydrocarbons (mainly mineral oils). Considerable conductivity increase associated with biodegradation of LNAPL hydrocarbons has been documented by various authors (Godio and Naldi, 2003; Sauck et al. 1998; Cassidy et al. 2001), for example. It must be noted, however, that in the published examples the observed increases in conductivity occur below the water table with emulsification of LNAPLs.

On this basis, it may be reasonable to infer that the areas above the liner where low to intermediate resistivity values occur (48.3 to 140 Ωm), these represent either advanced and virtually complete biodegradation of hydrocarbons, or zones of no biodegradation in what is probably damp inert fill. Unfortunately, without direct intrusive sampling and analysis of soils and leachate for hydrocarbons and biodegradation products (organic acids, biosurfactants and dissolved solids) it would be impossible to make this distinction, which emphasises the importance of geophysical data calibration.

It may be possible to infer rain water ingress from the ground surface by inspection of the ERT results. The resistivity model corresponding to survey line 5 (Figure 4.8) indicates an apparent origin of wet conditions (16.7 Ωm) near the ground surface and spreading with depth. The origin of these low resistivity values is at an elevated position in the lined cell and leachate surface spillage was not observed in this area during the ERT survey. Therefore, it may be inferred that the low resistivity signature is attributed to rain water ingress, which may be contributing to effective biodegradation of hydrocarbons and subsequent accumulation of leachate.

ERT survey lines 3 and 7 (Figures 4.6 and 4.10) were deployed outside the inferred extent of the lined disposal cell in order to provide a comparison with ground conditions away from the influence of the HDPE liner. The resistivity models from these two survey lines are similar in nature and indicate the generally conductive signature of the mature domestic landfill waste-mass on which the lined cell was built. In these models, very low resistivity values (2 Ωm) may be attributed to landfill leachate, as discussed in George (2002). Models corresponding to survey lines 4, 5 and 6 also exhibit very low resistivity anomalies outside the margins of the lined cell. Without intrusive sampling and analysis for the hydro-geochemical signature of these very low resistivity zones, it is impossible to associate them to a source inside the lined cell extent. Therefore, it must be assumed that the very low resistivities observed outside the cell margins are attributed to domestic landfill leachate, especially as the ERT images show no continuity in these anomalous values across the liner edge. However, models corresponding to survey lines 1 and 2 (Figures 4.4 and 4.5) do show a continuity of very low resistivity values across the southwest margins of the cell liner, which may be analogous to leachate overspill.

Resistivity models intersecting the disposal cell apparently indicate the approximate liner surface to be slumped with localised depressions where leachates appear to have accumulated. This may indicate subsidence of the liner, so that the engineered fall on either side of a northeast – southwest axis (Figures 3.8 and 3.9) is no longer effective. An alternative explanation is that the apparent 'depressions' in the liner may be a product of the resistivity inversion, whereby zones of conductive material above the liner cause a decrease in accuracy directly below. As it is not recommended to physically probe the position of the HDPE liner for subsidence and depression zones, this ambiguity requires that the resistivity models should be compared to another geophysical method, for example EM31 conductivity mapping, which could indicate localised 'low spots' in the liner as being positions where conductive leachates accumulate.

### 4.4.2. Mapping of Natural Voltage Variance by SP Techniques

Interpreted results of Self-Potential mapping across the lined cell and its margins are reproduced in Figure 4.11. Generally, the area within the lined cell extent is characterised by a marked positive potential field. Strong positive to negative dipolar anomalies appear to the west and southwest of the cell (-45 to +65 mV) and to a lesser magnitude across the cell margins.

Without calibration by physical sampling and analysis of surface and sub-surface materials the origin of natural voltage variance is unclear. However, it is possible that positive anomalies are attributed to rainwater ingress and descending flow, whereas negative trends may indicate ascending flow within the extent of the contained material, for example at the liner margins. The general northeast to southwest variance from positive to negative potentials may indicate a preferential drainage, or flow of leachate towards the southwest of the cell. As no calibration of SP values was undertaken during this reconnaissance survey, it would be desirable to compare the variance in natural voltages with shallow (EM38) conductivity values, as this may indicate areas of clay-deficiency within the cap permitting rainwater ingress.

### 4.4.3. Conductivity Mapping by EM38 Techniques

Interpreted results of shallow EM38 conductivity mapping across the extent of the lined cell and its margins are reproduced in Figure 4.12. Across the survey area, localised variance in electrical conductivity was observed in the range of 14 to >50 mS/m. Values from the low end of the conductivity scale observed may correspond to areas of clay deficiency in the landfill cap and could be regarded as potential zones of rainwater ingress. High conductivities may correspond to clay-rich capping materials, however caution must be expressed as these zones may alternatively indicate fluid saturation or ascending rain water migration to the near-surface (i.e. -1 to -1.5 metres).

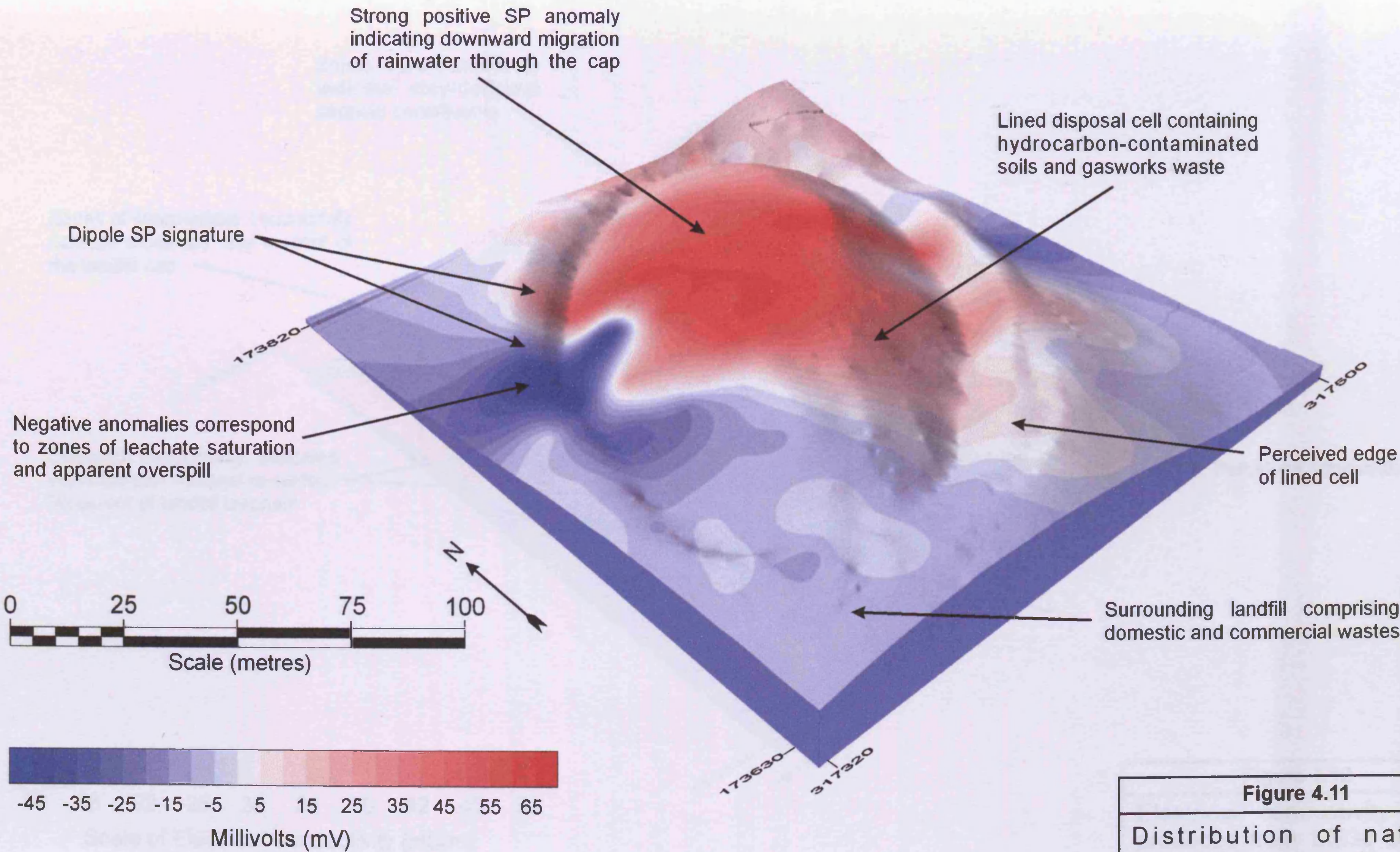



**Figure 4.11**

Distribution of natural potentials across the lined hydrocarbon disposal cell, Ferry Road landfill, June 2005.

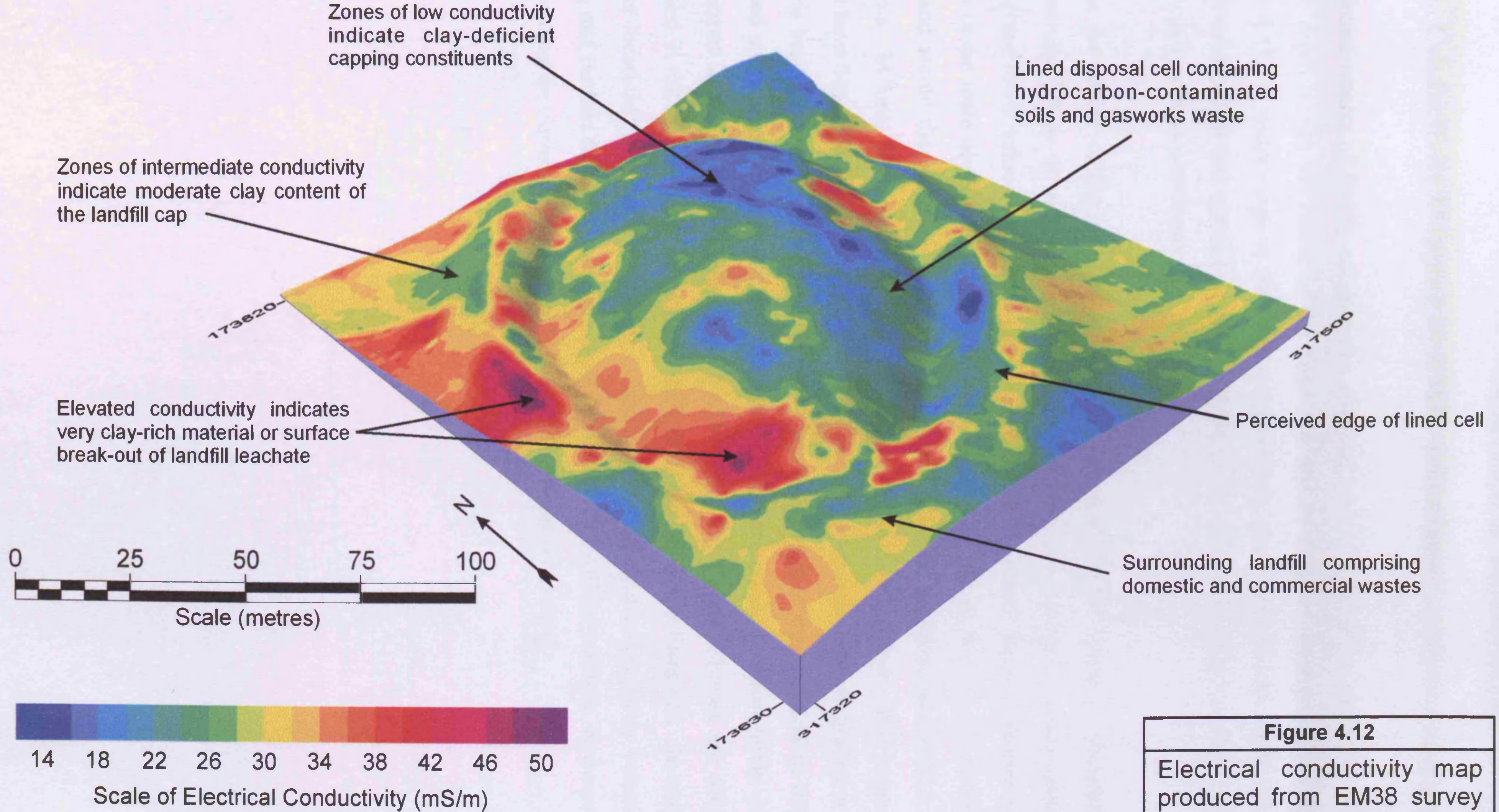



**Figure 4.12**

Electrical conductivity map produced from EM38 survey across the lined disposal cell ground surface at Ferry Road, June 2005.

## 4.4.4. Conductivity Mapping by EM31 Techniques

Interpreted results of EM31 conductivity mapping with a penetration extent of ~5 metres depth across the extent of the lined cell and its margins are reproduced in Figure 4.13. A wider range in electrical conductivities was observed with depth (38 to >98 mS/m) than that noted by shallow EM38 surveying and localised variance in conductivity values was observed.

Within the extent of the lined cell the fill is characterised by localised elevated conductivity (78 to 98 mS/m), particularly towards the liner periphery, with more widespread lower values away from the margins (38 to 66 mS/m). Low conductivity values in the scale observed (38 to 46 mS/m) could correspond to 'high spots' in the liner and would therefore be free draining towards slumped positions in the liner. This may, in turn, have benefited decomposition of hydrocarbons from these areas, which have become effectively flushed of the conductive products of biodegradation. On this basis, zones of elevated conductivity towards the liner margins and in the slumped areas inferred from the ERT models would correspond to accumulation of conductive leachates derived from biodegrading fill. High conductivities are also observed in the mature domestic waste outside the margins of the lined cell. In two distinct locations there appears to be continuity in the elevated conductivity values within and outside the cell extent, which may indicate overspill of leachate, however caution must be expressed as this may be a product of data contouring.

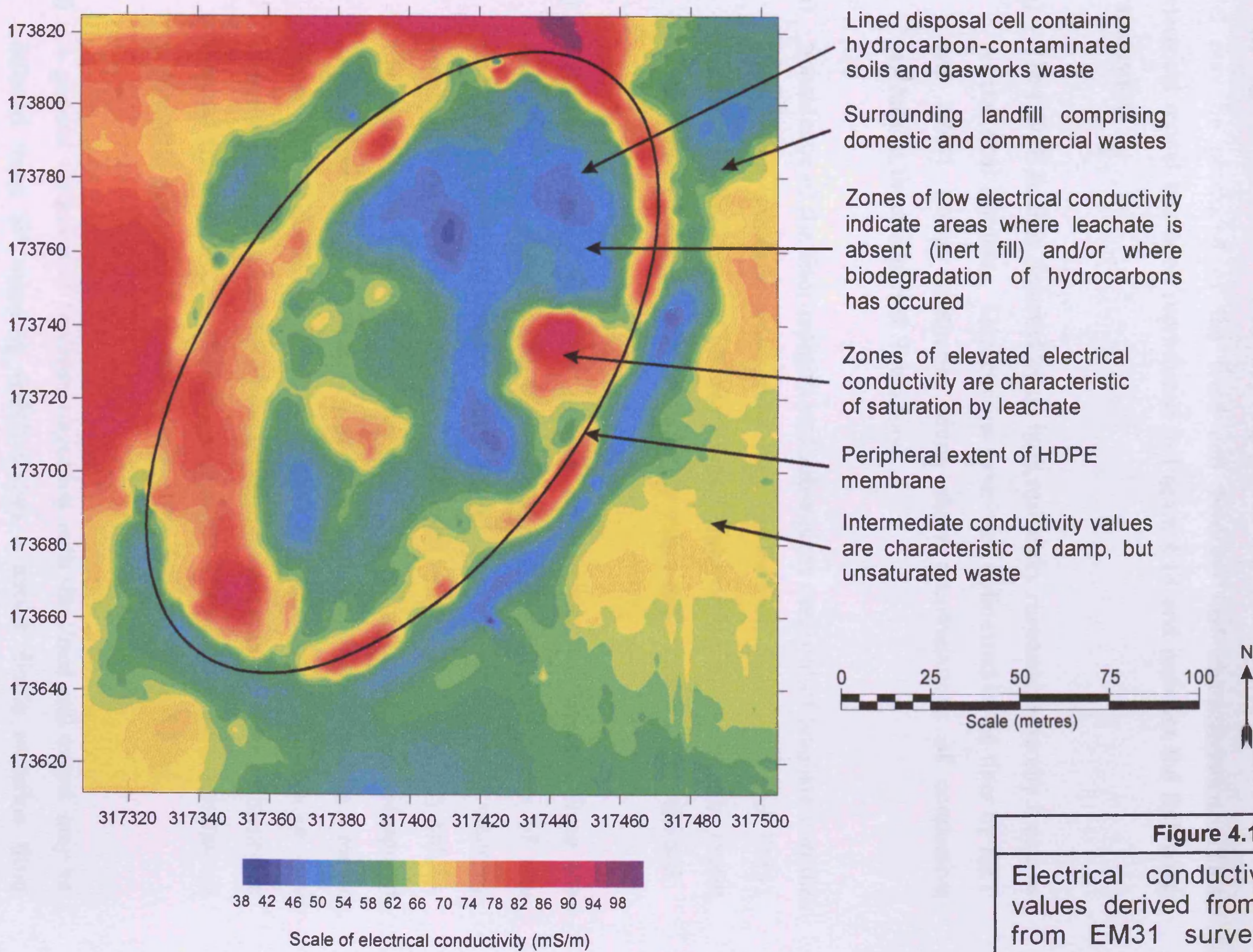



**Figure 4.13**

Electrical conductivity map of values derived from ~5m depth from EM31 surveying across the lined disposal cell ground surface at Ferry Road, June 2005.

### 4.4.5. Interpretation of Combined Geoelectric Response

By observing the combined sub-surface response to the geoelectrical methods used, a model may be produced of the lined cell function and characteristics. This geoelectrical model has been reproduced in Figure 4.14 and includes the following characteristics:

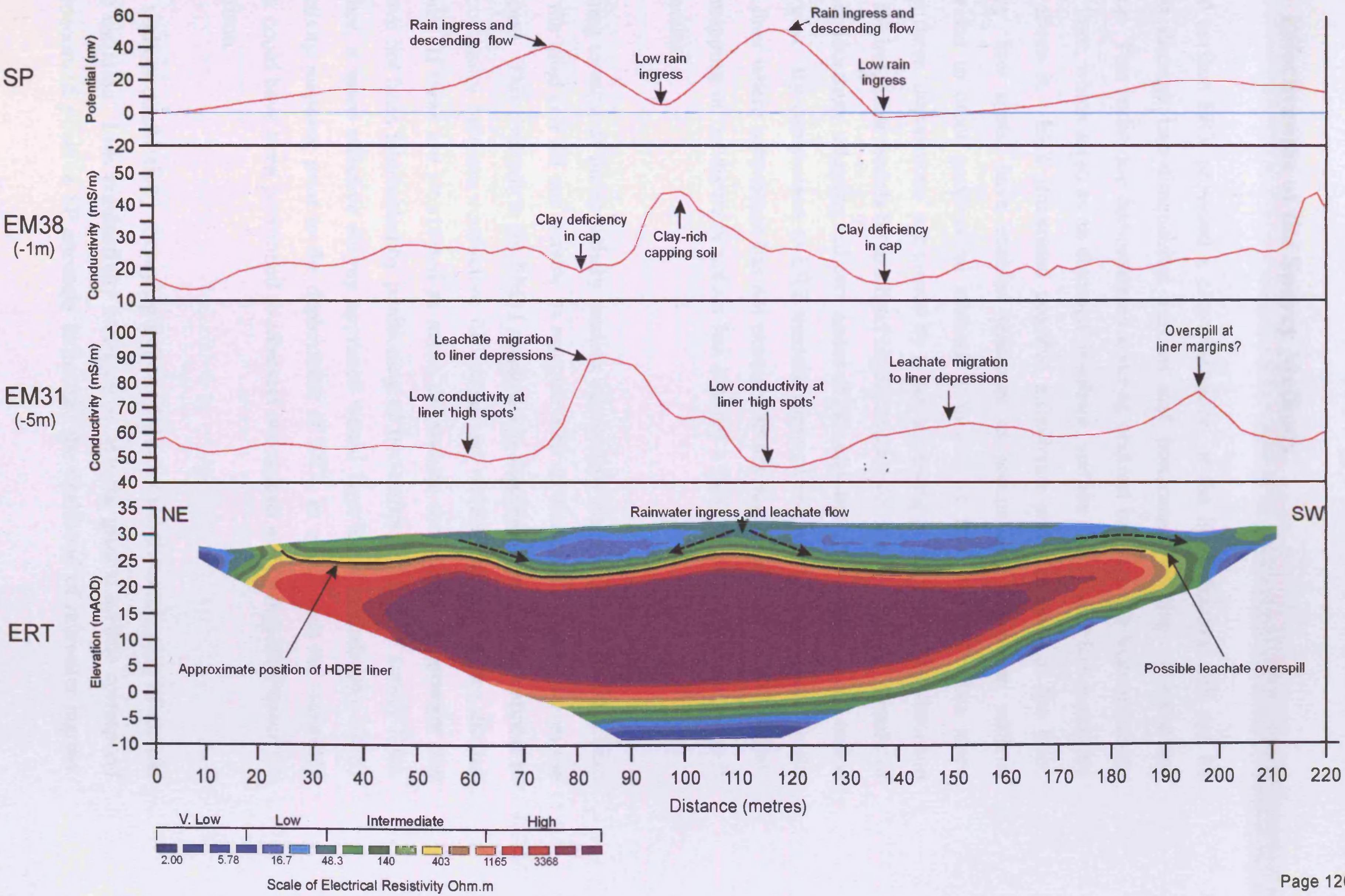
**a)** The HDPE liner is detected by its high resistivity response, whereby it acts as an electrical insulator. Depressions have been delineated in the liner by ERT and EM31 survey methods, which show accumulations of conductive leachate in these apparent 'low spots'.

**b)** Subsidence of the liner margins and subsequent overspill of leachate into the surrounding domestic waste-mass may be inferred from ERT and EM31 results, whereby zones of low resistivity / high conductivity within the extent of the lined cell appear to be in continuity with similar zones outside the cell.

**c)** Rainwater ingress from the ground surface may be inferred from the combined ERT, EM38 and SP response. ERT indicates zones of low resistivity spreading from the ground surface to depth, whereby accumulations of leachate occur, as indicated by very low resistivity values. Elsewhere above the liner, the waste is characterised by widespread intermediate resistivity indicating damp conditions, which would be a major factor in the sustained biodegradation of hydrocarbons. Zones of low resistivity near the ground surface correspond with areas of clay deficiency as inferred from EM38 conductivity mapping. These zones also correlate to pronounced positive SP anomalies indicating descending fluid flow.

**d)** A general direction of leachate migration with the lined cell extent may be inferred from SP mapping which shows a strong dipole variation from positive to negative towards the west and southwest. EM31 conductivity mapping indicates leachate accumulation towards the cell margins and more significantly towards the west and southwest.

Figure 4.14: *Model of the combined geoelectrical response across part of the lined disposal cell, June 2005.*



# 4.5. Discussion of Survey Methodology and Results

## 4.5.1. Effectiveness of the Survey Methods

Ground surface ERT provided a characterisation of the lined disposal cell and its margins through two-dimensional vertical and horizontal profiling of resistivity variance. This technique demonstrated a strong contrast between the high resistivity HDPE liner, which acted as an electrical insulator, and the low to very low resistivity zones above it. ERT illustrated possible subsidence and slumping of the liner, whereby 'low spots' have enabled leachates to accumulate. However, without comparison to other geophysical methods it is unclear from the ERT data alone whether these 'depressions' are caused by actual slumping of the liner or by distortion within the inversion models by localised highly conductive material above. Results of EM31 conductivity mapping indicate zones of low conductivity within the cell and at its margins. By comparison to ERT models, these correspond to 'high spots' in the HDPE liner where subsidence has not occurred to any significant extent. Therefore, depth mapping of conductivity values has enabled a more effective interpretation of ERT results.

According to most of the resistivity models, conductive material was delineated both within the lined cell fill and outside its margins with no obvious continuity across the liner edges. This contradicts the EM31 conductivity mapping results, which appear to show continuity between conductive fill inside and outside the cell at two distinct locations. If these are interpreted as zones of leachate overspill, it is apparent that they have not been intersected by positioning of two-dimensional ERT survey lines. Therefore, a more effective survey approach would have been to undertake EM31 conductivity mapping prior to the deployment of ERT, in which case the resistivity profiles could have been positioned to intersect anomalous and background zones for comparison.

EM38 shallow conductivity surveying indicated similar trends to mapping of natural voltage variation. Low conductivity zones on or near the ground surface correspond to a pronounced positive SP anomaly indicating the likelihood of rainwater ingress.

Natural voltage variation appears to show a general flow or migration of fluids towards the west and southwest of the cell. This would correlate with the EM31 map, which indicates accumulation of conductive leachates towards these areas of the cell.

ERT, EM and SP techniques were utilised in a non-invasive manner permitting relatively fast ground coverage and minimal site disturbance. The survey was designed as an initial reconnaissance investigation to characterise surface and sub-surface conditions according to the geoelectrical response. Results of the survey may be used to plan detailed follow-up investigations, including intrusive hydro-geochemical sampling, and for possible site restoration design. The four techniques were utilised in accordance with specific objectives, however the data interpretation was optimised by multi-method comparison. Perhaps the greatest uncertainty exists with the cause of shallow conductivity and natural voltage anomalies and it would be necessary to test for vertical moisture variation and clay content of the capping medium for calibration.

## 4.5.2. Capabilities for Routine Monitoring

Following the initial reconnaissance geophysical investigation, routine monitoring of the lined disposal cell would be advisable to investigate further subsidence of the HDPE liner; leachate generation, accumulation and migration; and variation in conductivity of the fill, which may analogous to biodegradation of hydrocarbons.
It would be recommended that routine monitoring, i.e. repeated ERT, SP and EM surveying, should ideally be undertaken with calibration through intrusive sampling and analysis of soils and leachate.

Electromagnetic methods were deployed with rapid data acquisition requiring no physical contact of instrumentation with the ground surface; therefore repeated EM surveying may be regarded as cost-effective. Self-Potential surveying required contact of the non-polarising electrodes with the ground and was not as rapid; however information was gained in support of EM data whereby the process of rain water ingress and leachate flow could be inferred.

ERT surveying was labour intensive, requiring the deployment of multi-electrode arrays and topographic surveying. Furthermore, the two dimensional profiling method had not identified important anomalies detected by EM31 conductivity mapping. Therefore, with successive routine monitoring it would be advisable to deploy EM31 surveying initially and utilise ERT to intersect any conductivity anomalies and confirm background zones located in the earlier EM31 mapping.

It is proposed that cost-effective routine geoelectrical surveying of the lined disposal cell should continue at 12-month intervals if a strategy of monitored natural attenuation were to be considered. However, if in-situ restoration was undertaken, repeated geoelectrical surveying would provide a valuable monitoring tool during leachate extraction, remediation of hydrocarbons, and clay capping.

# (5)

# Geoelectrical Monitoring of the Waste-Mass Characteristics within an Active Landfill Setting

## 5.1. Background and Objectives of the Monitoring Strategy

The potential of geophysical surveys in landfill management is now increasingly apparent for waste-mass characterisation within active disposal sites (McDowell et al; 2002). Through the deployment of geophysics, in particular the geoelectrical methods, landfill operators are able to assess problems such as the occurrence of leachate and rainwater ingress, and can apply suitable treatment techniques. Conventionally, leachate saturation and migration in landfill waste is monitored through dip level measurement in observation wells. A drawback with this monitoring technique is that information is provided at point locations and correlation can only be inferred. By applying geoelectrical monitoring and calibrating the information with observation well measurements, leachate-saturated and drier wastes may be delineated in two- or even three-dimensions resulting in a more effective site characterisation.

A frequently utilised technique for waste-mass characterisation is ERT, which responds well to near-surface variations in electrical signature of dry, damp and saturated fill. Through ERT surveying, it is generally possible to distinguish leachate of a very low resistivity (2 to 10 Ωm), from damp (10 to 200 Ωm) and dry (>200 Ωm) wastes. A constraint with ground surface ERT is that resolution and accuracy of the resistivity model decreases with increasing depth of measurement. Adjacent anomalous zones with similar resistivity values, for example perched leachates, may not be distinguished and would appear as a larger anomaly through the problem of *equivalence*, as discussed in Section 2.8. These constraints have major implications for the delineation of basal leachates acting upon an engineered liner system and the differentiation between overlying perched leachate tables. It is certainly due to these constraints that ERT is only reliably used to investigate the *vadose zone*, i.e. the depth to leachate, and to broadly define landfill waste from background natural geology.

A review of the capabilities and restrictions of ERT surveying (Section 2) indicated that the technique must be adapted for use in an active landfill setting, requiring an alternative approach to the application of electrical current and measurement of voltage potential. For the accurate delineation of basal leachates in particular, the resolution and accuracy of a resistivity model must be consistent through the entire waste-mass.

A strategy for the advancement of ERT monitoring of waste-mass characteristics in an active landfill setting was planned with the following objectives:

- Modify the methodology for electrical resistivity measurement to provide consistent accuracy and resolution through landfill waste. An effective method should enable basal and perched leachates to be defined and differentiated.

- Assessment of the modified methodology by field testing in a new landfill cell through performing electrical resistivity data acquisition during progressive waste infilling.

- Identify and apply a suitable approach to resistivity data processing, interpretation and calibration.

- Perform a comparison of the adapted ERT technique against conventional ground surface resistivity measurement.

- On the basis of results obtained, outline the capabilities for repeated routine monitoring at active landfills and provide recommendations for geophysical best practice.

In December 2002, an extension of the Lamby Way active landfill site in Cardiff was approved for waste disposal. Licensing permits for Cell 2 specified a maximum leachate head of 2 metres above the basal engineered clay barrier. This provided a focus for interest as conventionally leachate head is monitored at Lamby Way by dip level measurement from observation well chambers constructed through the waste-mass. This strategy was adopted by the landfill operator for monitoring within the Cell 2 extension and meets the requirements established by the Environment Agency. Accordingly, the new landfill cell at Lamby Way was selected as a test site for the application of ERT monitoring with the overall aim of providing a reliable technique for lateral and vertical extensive identification of leachate, in particular directly above the basal liner system.

## 5.2. Conceptual Site Model

A conceptual site model (CSM) has been produced for the active disposal cell at Lamby Way landfill (Figure 5.1). The CSM is based on the design and functional attributes of Cell 2 and represents the cell as a total containment feature, following temporary capping with a clay cover.

Slight rainwater ingress through the clay cap is anticipated, resulting in leachate generation and migration through the waste profile. Lateral leachate flow at the base of the cell is assisted by a gravel drainage blanket laid over the clay barrier during construction of the landfill. An engineered fall, or gradient, across the cell base from southwest to northeast enables lateral leachate flow towards a collection drain installed close to the northeast margin of the waste-mass. Cell 2 was designed and constructed to permit a maximum leachate head of 2 metres above the clay barrier. Leachate head is monitored through observation chambers constructed through the waste profile. Groundwater quality in the underlying confined gravel aquifer is monitored with observation wells installed beyond the waste limits, both up- and down-gradient of the cell. Site restoration is scheduled to involve retro-fitting of gas extraction wells and coverage with LDPE capping materials at the anaerobic degradation stage.

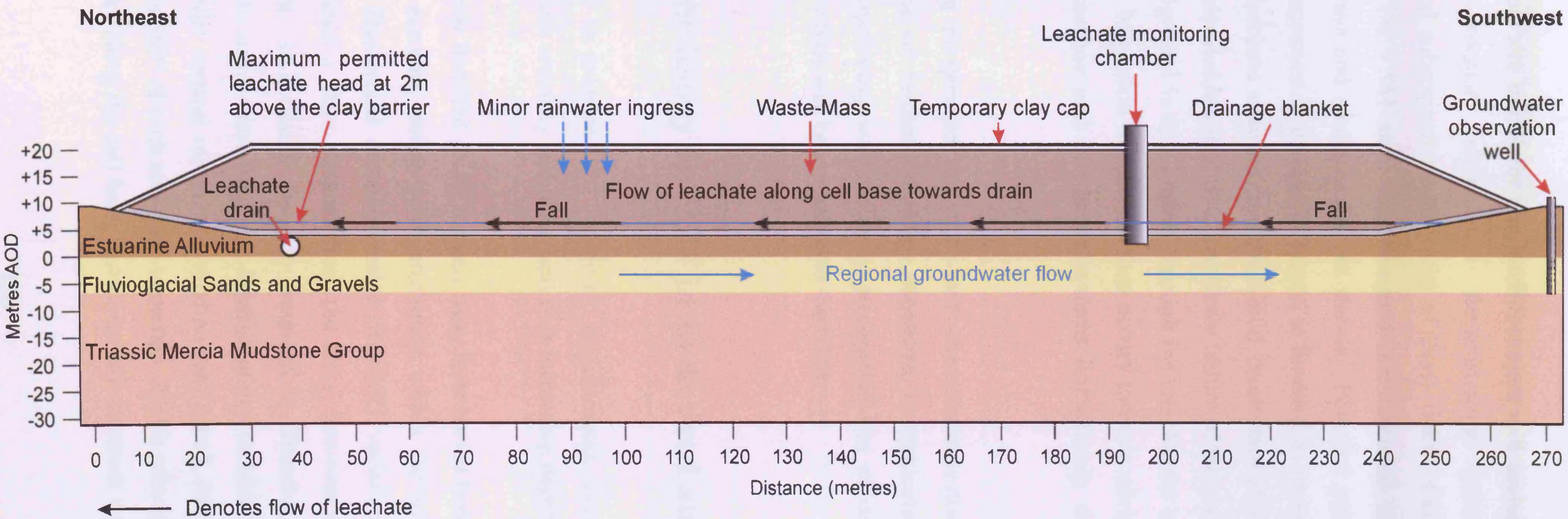



**Figure 5.1**

**A Conceptual Site Model (CSM) of the active Lamby Way landfill illustrating the leachate control measures.**

A full conceptual site model for any landfill project will include the links between *source-pathway-receptor* relationships demonstrating potential risk to the environment and subsequent management of those risks. Cell 2, Lamby Way, is represented in the CSM as it was designed and intended to function, therefore potential pathways and receptors are not shown. Pollutant pathways and receptors would become apparent if the landfill ceased to function as intended. For example; a failure of the leachate drainage system would cause saturation in the waste-mass resulting in an elevated leachate head and likely failure of the clay barrier. A *pathway* for pollutant migration is thus created through the clay barrier and into the confined gravel aquifer. Migration of leachate then occurs towards environmental *receptors*, such as the coastline and marine ecosystems immediately down-gradient of the landfill.

By investigating the geoelectrical waste-mass characteristics during filling of Cell 2, the performance of leachate drainage measures in particular will be assessed. Geoelectrical monitoring will enable a geophysical site model to be constructed (Section 5.7.4), which will be compared to the CSM.

## 5.3. A Methodology for ERT in an Active Landfill Setting

A methodology is proposed for resistivity measurement through the waste-mass enabling consistent accuracy and resolution with increasing depth.

An electrode array installed along the cell base, later buried beneath the waste-mass, would provide accurate resistivity measurement within the zone of basal leachate accumulation. This would certainly enable resistivity variation to be distinguished laterally and within a short distance from the array, however directional indication would be absent. In a similar situation presented by Tsourlos et al. (2003), single vertical electrode arrays were used in a landfill setting to identify zones of leachate saturation. Whilst vertical resistivity variation was noted, the directional origin of anomalies within 360° of each array was uncertain. If this principal was applied using a horizontal array along the cell base, resistivity measurement would occur within the waste-mass and underlying superficial deposits. This would be ineffective for basal leachate delineation as the measurements would need to be constrained to the waste-mass only. Directional indication from the basal array would be ensured by utilising the buried electrodes in conjunction with an overlying ground surface array (Figure 5.2). On this basis, it would be possible to devise two electrode address configurations combined in one protocol. Resistivity measurement would be performed along the ground surface array initially, but to a depth level (*n*) equivalent to the cell base position for each survey event. On completion of the surface-only electrode address sequence, resistivity measurement would then be performed by utilising the buried and surface electrodes, whereby electrical current is applied and voltage potentials are measured across the two arrays.

This adapted ERT method for an active landfill setting would require permanent installation of a horizontal electrode array along the cell base within the drainage medium. Construction attributes of the array should consider the effects of physical loading and compaction of overlying waste and chemical attack from leachates. In addition, the basal wiring should be routed to a remote access location at the cell boundary for connection to the resistivity meter.

It would be anticipated that the ground surface electrode array must be deployed and removed during each monitoring event and that the acquisition geometrical parameters should be adjusted to account for increasing waste thickness and the separation between the two arrays. Raw data would be processed by least-squares inversion and each resistivity model would ideally be adjusted for the effects of ground surface topography.

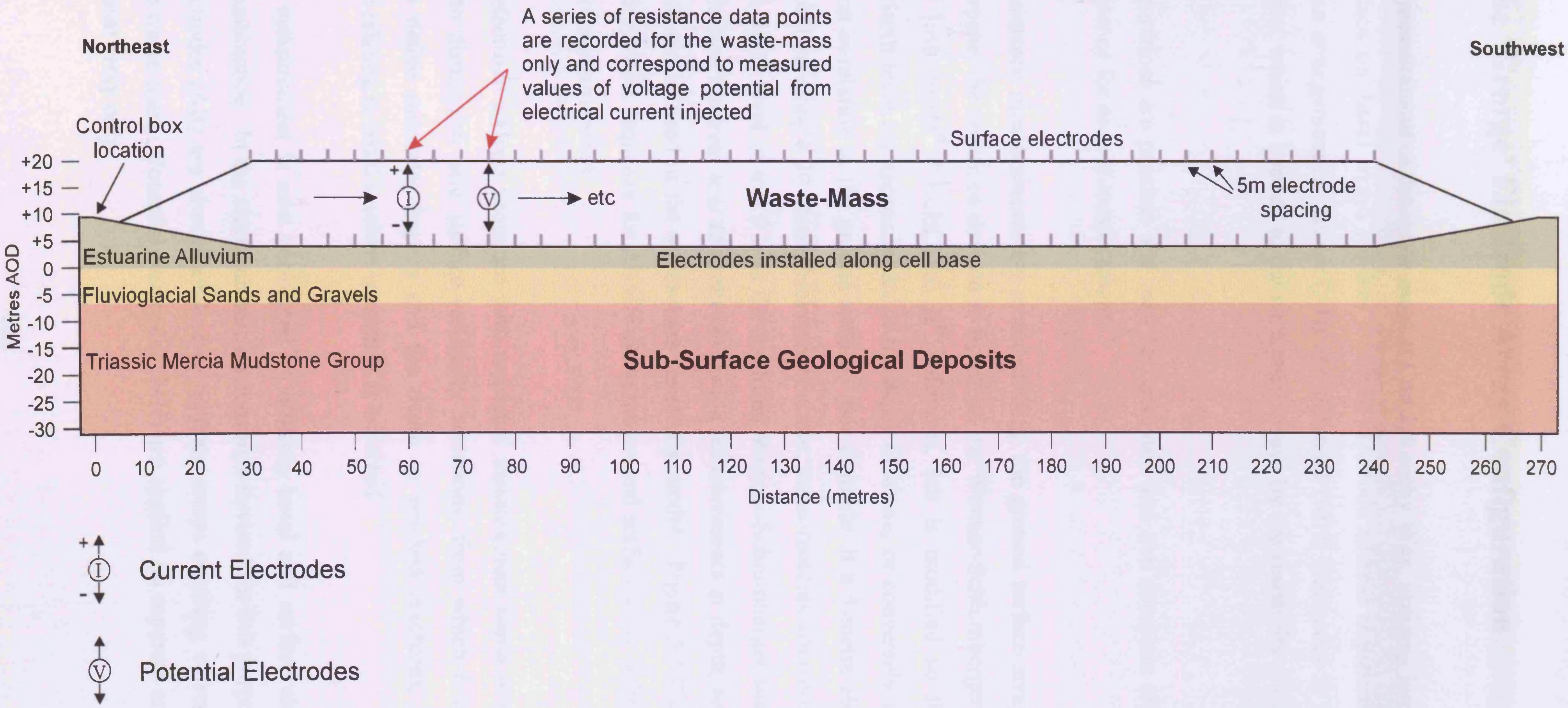



**Figure 5.2**

**An adapted methodology for resistivity measurement in an active landfill setting at Cell 2, Lamby Way.**

## 5.4. The 'George' Electrode Array Configuration

Resistivity measurement of the waste-mass at Cell 2, Lamby Way, utilising horizontal ground surface and basal arrays requires a unique electrode address sequence. This comprises an arrangement of current (AB) and potential (MN) electrodes in various configurations, which is applied to the horizontal arrays by the resistivity acquisition instrument.

Two configurations are possible and may be combined into one complete electrode address sequence for ease of measurement.

Initially, resistance measurements are recorded using the ground surface array only. For this purpose, the sequence devised is based on the Wenner-Schlumberger array-type (IRIS Instruments® / ELECTRE II® software), but is modified so that the maximum depth level (*n*) approximates to the depth of waste, or conversely the cell base position in relation to the ground surface. For example: if a 5-metre electrode spacing is utilised along a 20-metre thickness of waste, measurements are recorded to a maximum depth level of $n = 6$ with the modified Wenner-Schlumberger sequence. This modification removes low accuracy/resolution measurements at depth, which in this case will not be used in the waste-mass resistivity model. Figure 5.3 illustrates the electrode address sequence for ABMN along the ground surface array indicating a sample set of measurements.

A surface electrode address sequence with restricted measurement depth is used in this study to distinguish near surface resistivity variations, from which it may be possible to define rainwater ingress and the depth to perched leachates, but no information relating to basal leachate saturation is expected.

Resistivity measurement is next performed by utilising basal and surface electrode arrays in combination. In the electrode address sequence devised for this purpose, the current electrodes (AB) are always applied to separate arrays ensuring current flow through the waste-mass. Potential electrodes (MN) are applied on separate arrays or along the basal array only.

The electrode configurations used are MA-NB, AM-BN, and MNA-B, (where A is always applied to the basal array and B is constant to the surface array).

The arrangement of current (AB) electrodes in the basal to surface sequence is an important consideration. It may be perceived that a landfill waste-mass consists of localised vertical and horizontal variation, i.e. lenses of different waste-types, which may be saturated or dry. It must be anticipated that highly resistive layers comprising dry compacted wastes confine electrically conductive bodies consisting of leachate-saturated waste. Delineation of such horizontal and vertical resistivity variations would require a suitable approach to the application of current flow lines through the waste-mass in a manner that produces measurable distortion of equipotentials.

The application of current (AB) electrodes influencing the angle of current flow lines with respect to the perceived orientation of anomalous resistivity has been discussed in Goes and Meekes (2004). In an applied case study the authors used vertical electrode arrays to detect thin horizontal resistive layers in the sub-surface. With a vertical electrode address a large current flow line angle was required to provide appreciable distortions and a large variation in the equipotential flow lines. Conversely, by using basal and surface horizontal arrays, the direct line between the current (AB) electrodes should have a small angle compared to the perceived horizontal orientation of layers within the waste-mass. The current electrodes should be applied successively along the two arrays by maintaining a small, or vertical angle, which would allow horizontal variations to be delineated. Figure 5.4 illustrates the arrangement of current (AB) and potential (MN) electrodes across the basal and surface arrays, whereby a sample set of measurements is shown.

The surface-only and basal-to-surface electrode address sequences are combined into one protocol (the *George array*) that is uploaded and stored on the resistivity acquisition instrument. Raw data acquired is processed ensuring all measurements are confined to the two-dimensional plane between the basal and surface arrays.

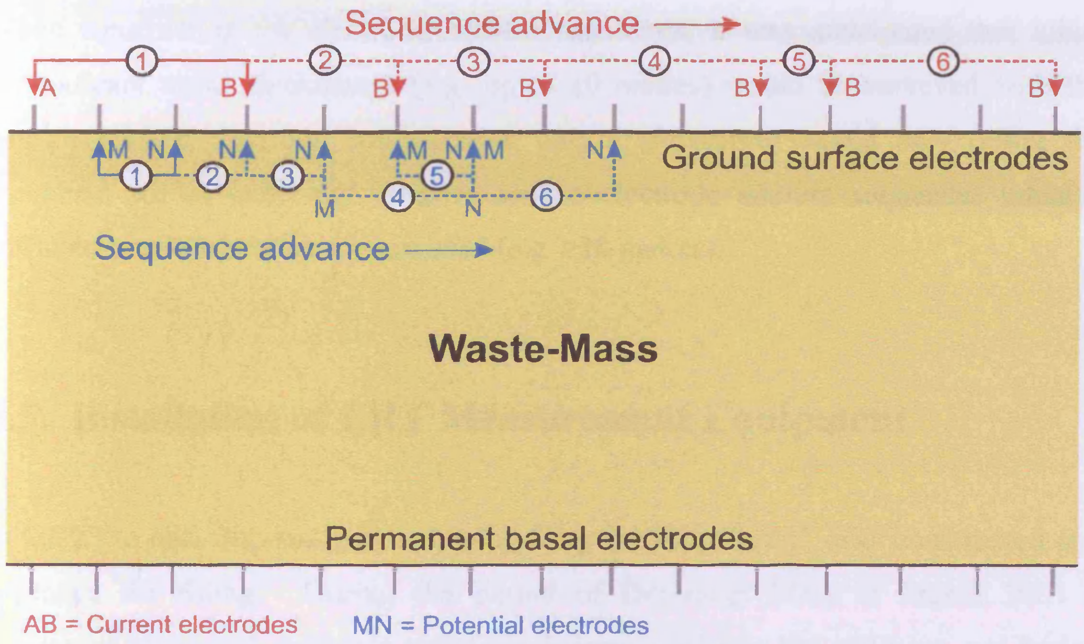



Figure 5.3: *Electrode address sequence for ABMN along the ground surface array only, showing a sample set of measurements.*

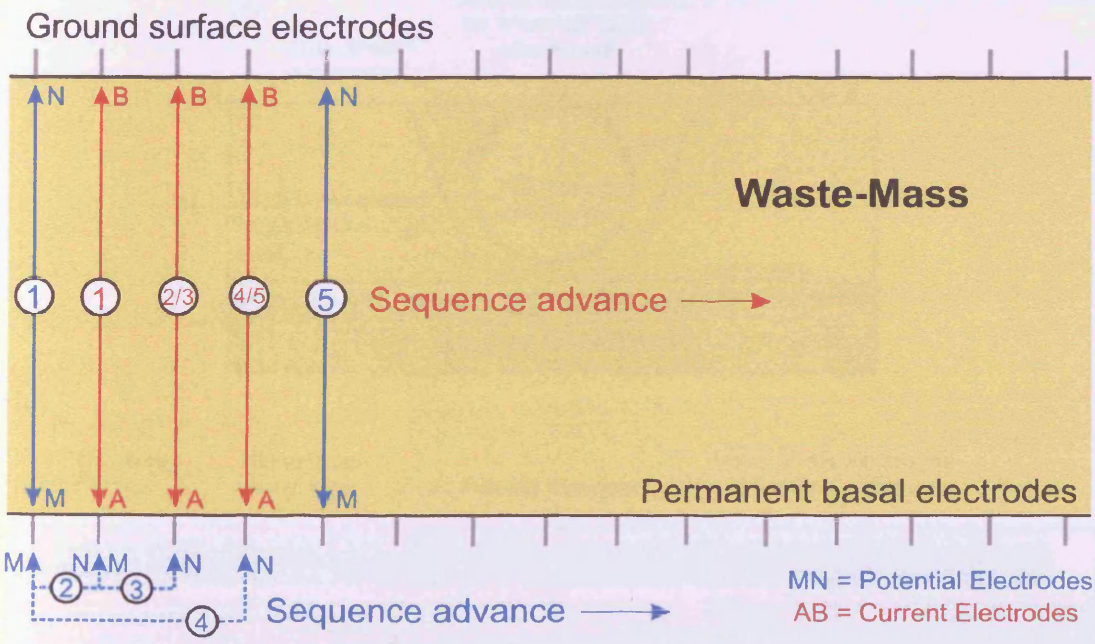



Figure 5.4: *Electrode address sequence for MA-NB; AM-BN; MNA-B, applied to the basal and ground surface horizontal arrays, showing a sample set of measurements.*

When constructing the electrode address sequences, it was anticipated that initial insignificant waste thicknesses (e.g. up to 10 metres) would be surveyed with the basal-to-surface electrode configuration only. Monitoring would only utilise the combined surface-only and basal-to-surface electrode address sequences when a sufficient waste-mass has accumulated (e.g. >10 metres).

## 5.5. Installation of ERT Measurement Equipment

In 2002 the new disposal cell at Lamby Way landfill, Cardiff, was constructed and approved for filling. During the period of December 2002 to March 2003 a permanent horizontal electrode array was incorporated into the cell base and buried with refuse. Figures 5.5 (a) and 5.5 (b) illustrate the design of the permanent basal electrode array installation.

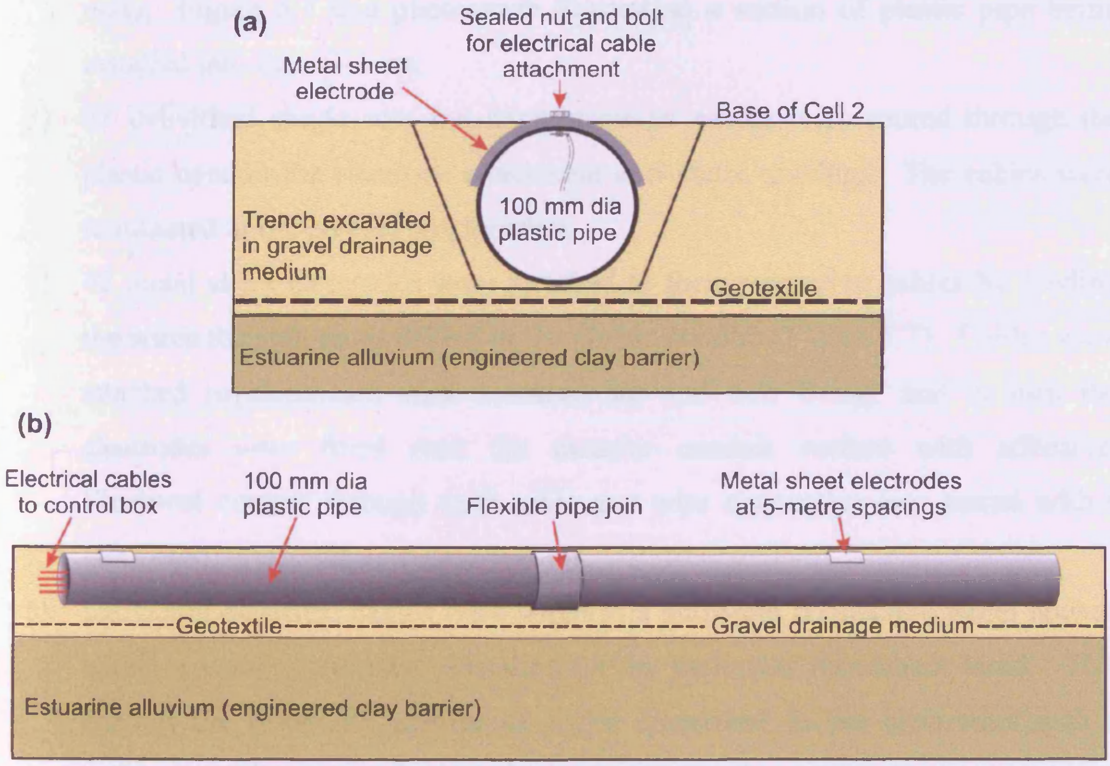



Figure 5.5: *Design of a permanent resistivity basal electrode array at Cell 2.*

The design incorporates a 210-metre long plastic conduit through which electrical cables are routed to individual metal sheet electrodes mounted on the exterior surface of the pipe. The plastic conduit and electrodes are concealed within a trench excavated in the basal gravel drainage medium.

This design was implemented by adopting the following installation procedure:

1) A narrow trench was excavated through the gravel drainage medium to incorporate a 210-metre length of plastic conduit equivalent to the length of the basal electrode array. A 30-metre extension of the trench was dug from the cell base to the edge of a clay retainment bund where a cable access box would be located. Figure 5.6 shows a plan of Cell 2 indicating the basal electrode array position and control box location.
2) Sections of plastic tubing were laid in the trench to provide a suitable conduit for electrical cables. 3-metre lengths of HDPE pipe were joined with flexible connections to allow for settlement and compaction of the overlying waste-mass. Figure 5.7 is a photograph illustrating a section of plastic pipe being installed into the cell base.
3) 42 individual single-core insulated electrical cables were routed through the plastic conduit for electrode attachment at 5-metre spacings. The cables were terminated at the control box location.
4) 42 metal sheet electrodes were attached to their respective cables by feeding the wires through holes drilled in the plastic conduit (Figure 5.7). Cables were attached to electrodes with a sealed nut and bolt fixing, and in turn the electrodes were fixed onto the exterior conduit surface with adhesive. Electrical contact through each cable and wire connection was tested with a voltmeter.
5) Individual electrical cables were wired to a multi-pin connection panel housed within a weatherproof box installed on the perimeter retainment bund. This enables the resistivity instrument to be connected to the electrodes with a multi-pin cable adapter fed into the connector panel.
6) Along the cell base and retainment bund the trench excavation was backfilled to conceal and protect the electrode array during waste infilling.

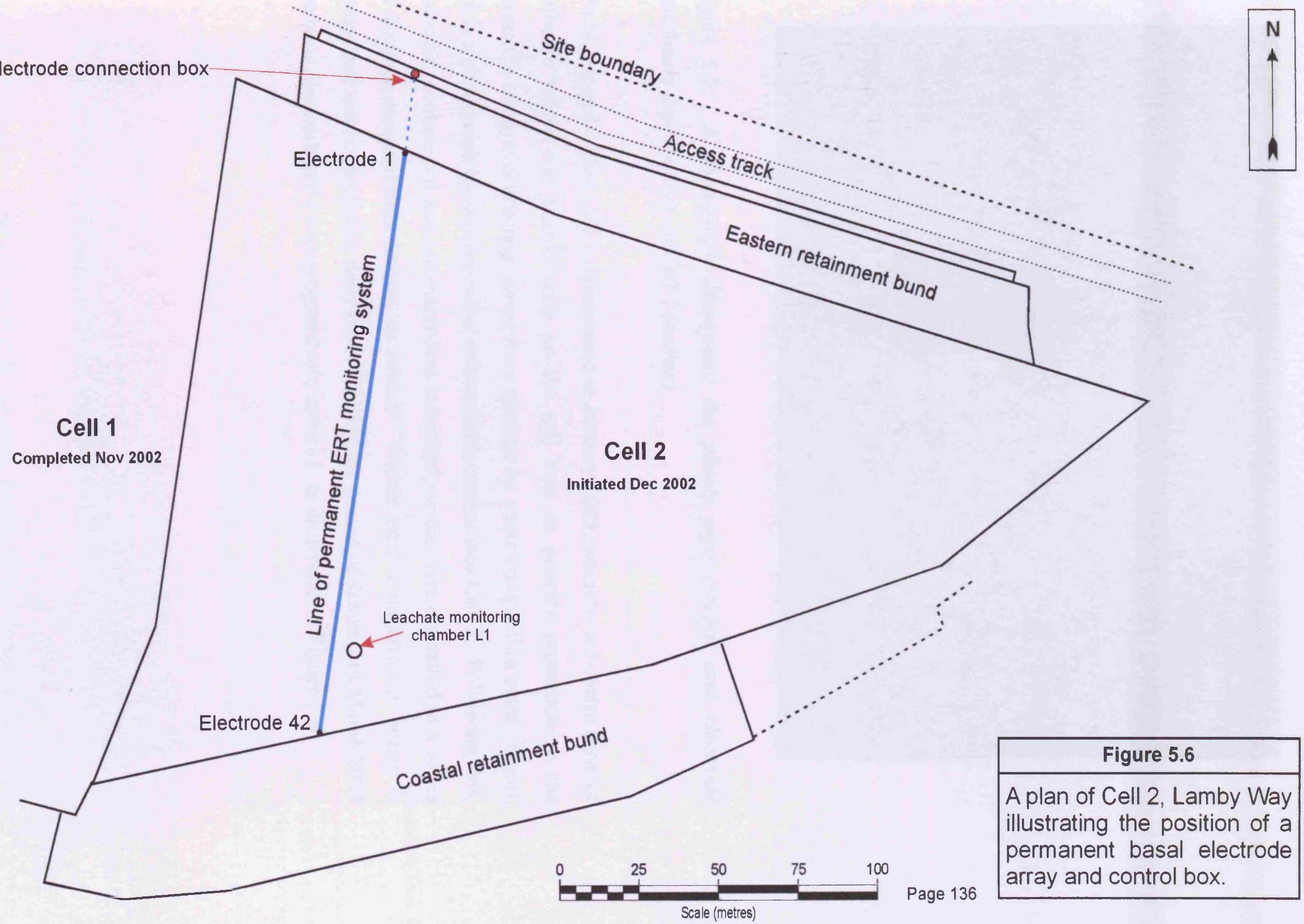



**Figure 5.6**

A plan of Cell 2, Lamby Way illustrating the position of a permanent basal electrode array and control box.

Figure 5.7: *A photograph illustrating the plastic pipe conduit and electrode attachment deployed across Cell 2 (author).*

Waste disposal within Cell 2 commenced in January 2003, whereby a 3-metre layer of domestic refuse was laid directly on the cell base to provide protection to the geotextile and gravel drainage layers from damage by waste compaction plant. Figure 5.8 is a photograph illustrating initial refuse emplacement into Cell 2. Following this, domestic, commercial and non-hazardous industrial wastes were deposited in a series of bunded compartments known as *raises*. Within each compartment, waste is compacted and covered on a daily basis. During the period of January to March 2003 the basal electrode array was progressively covered, as illustrated in Figure 5.9.

Figure 5.8: *A photograph illustrating domestic refuse disposal across Cell 2 in January 2003 (Dr. T. Jones, Cardiff University).*

Figure 5.9: *A photograph illustrating progressive burial of the electrode array by a series of refuse raises (author).*

## 5.6. ERT Monitoring Procedure

### 5.6.1. Setting-up the Instrumentation

During an ERT monitoring event at Cell2, a temporary electrode array is deployed along the waste-mass ground surface directly above the concealed basal array and by utilising a 5-metre electrode separation. To compensate for the effects of ground surface topography, the temporary array will include a greater number of electrodes than the basal array; therefore the electrode address sequence utilised by the resistivity meter should be adjusted accordingly. The temporary surface and concealed basal arrays are connected to the resistivity meter at the control box location (Figure 5.10). Ground surface electrodes are surveyed for elevation to enable the necessary topographical adjustments to be performed on the inverted data.

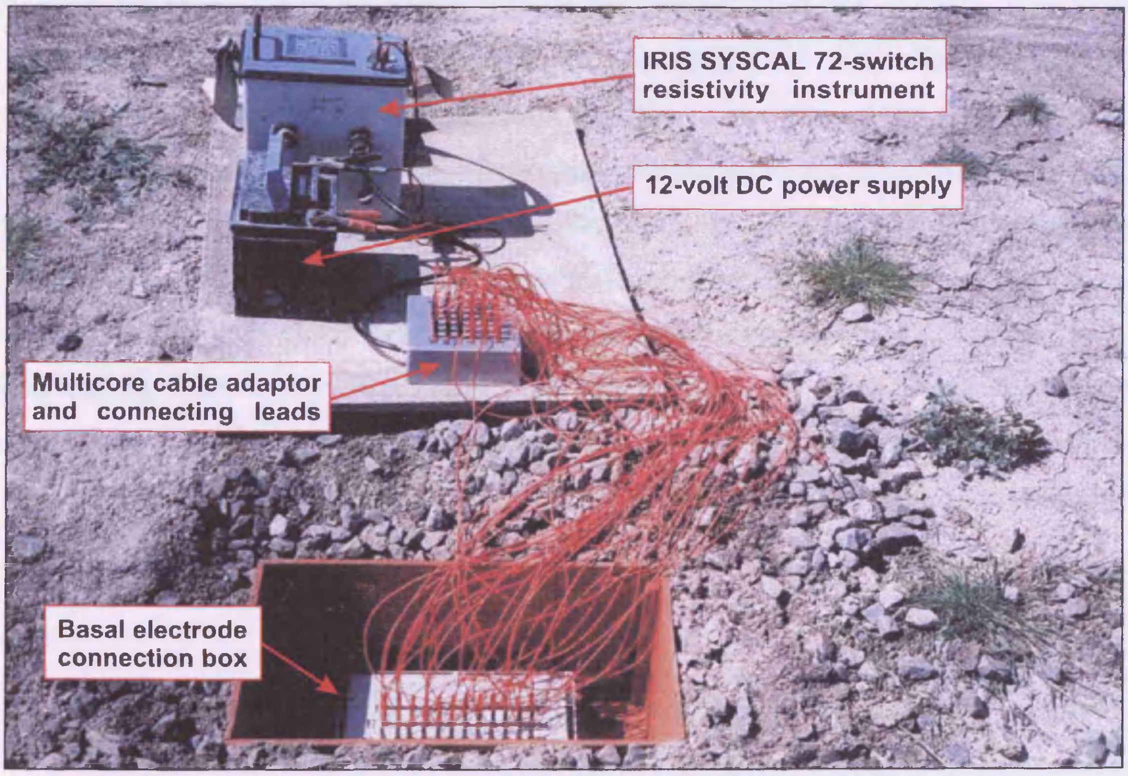



Figure 5.10: *A photograph illustrating connection of the concealed basal electrodes to the resistivity acquisition instrument at the control box location (author).*

Monitoring at Cell 2 required the use of a modern automated resistivity meter and accordingly an IRIS Instruments® SYSCAL 72-switch® was selected. This resistivity meter incorporates two multi-pin sockets for conventional multi-core cable connection. This presented a problem for connection of the individual basal electrodes, therefore a multi-pin cable adaptor was fabricated (Figure 5.10). In the conventional manner a 12-volt DC car battery power source is used during data acquisition.

### 5.6.2. System Testing and Data Acquisition

Following connection of the temporary ground surface array and basal electrodes to the resistivity meter, a system test is performed. The resistivity meter provides a measurement of contact resistance between electrode pairs along the buried and surface arrays. For optimal data quality and reduction of electrical noise the ideal contact resistances between adjacent electrodes should be 4 kΩ or less. Any high resistances between ground surface electrodes are rectified by improving the electrode contact with the ground or by the addition of saline water around the electrode base. High contact resistances along the concealed electrode array are impossible to rectify; however, by performing the system test any readings from problematic electrodes may be identified and subsequently removed during data processing. During research at Cell 2, no high contact resistances were measured along the basal electrode array and readings were consistently in the range of 0.1 to 2.0 kΩ. Upon completion of the contact resistance test, the resistivity meter will acquire measurements by application of the electrode address sequence designed for the system. Raw data is downloaded to laptop PC for processing off-site.

### 5.6.3. Processing of Raw Data

Raw data must be initially checked for errors prior to processing by least-squares inversion. A data editing programme (PROSYS®) supplied with the IRIS SYSCAL® resistivity meter enables the user to remove erroneous measurement points and export the data in a format suitable for inversion. At this stage, the standard deviation and geometrical factor (*k*) are important considerations. Measurements are only included in the pre-inversion dataset with a standard deviation of 3% or less and any zero or negative apparent resistivities are removed. Negative *Rho* values may arise where the geometrical factor (*k*) does not agree exactly with the positions of electrodes in the field (Goes and Meekes, 2004).

Edited raw data is processed by least-squares inversion (*after* Loke and Barker, 1996a). Measurements recorded along the temporary ground surface array may be inverted separately from the basal-to-surface array data; however, this may only be necessary for comparison of the two datasets. It was perceived during design of the monitoring system that ground surface and basal-to-surface measurements should be processed in one inversion model for the reasons discussed in Section 5.3. A rectangular finite element grid with uniform node distribution is used for data inversion. During resistivity inversion in general, a finite element grid is used with block dimensions equivalent to the electrode spacings. However, a model with finer descretisation, whereby the block dimensions were half the spacing of the electrodes, provided improved results for the Cell 2 data. Inversion results are compensated for the ground surface topographical effects by performing a highly-damped distortion of the finite element grid node positions. A highly-damped distortion method would be ideally suited to the resistivity model produced for Cell 2 because the ground surface topographical variation is insignificant and the distortion factor of sub-surface model blocks is decreased rapidly with depth. This produces a model where the blocks are only significantly affected by topography near to the surface and that the blocks at depth are largely undisturbed corresponding to the horizontal position of the basal electrode array. Inversion statistics for the resistivity raw data are reproduced in Appendix III of the thesis.

Inversion results are saved in *x y z* format for contouring of data points with a suitable programme; in this case SURFER® software. The final image represents a two-dimensional plane of contoured and colour-scaled resistivity variation with distance and depth through the waste-mass. A colour-scaled range in model resistivity values (ohm.meter) is provided for interpretation.

### 5.6.4. ERT Survey Results during Progressive Waste Emplacement

Resistivity data acquisition utilising the methodology previously described was performed during progressive waste emplacement into Cell 2. It was assumed that the waste-mass physical characteristics would not change appreciably until a significant thickness had accumulated and subsequent rainwater ingress had occurred. On this basis, it was not deemed necessary to perform regular, i.e. monthly, monitoring of the waste. Instead, ERT surveying was performed upon appreciable changes in the emplacement of waste, i.e. large increases in thickness. In April 2004 it was observed that the 3-metre layer of domestic refuse placed directly on the cell base had entirely concealed the basal electrodes and was further covered by up to 5 metres of mixed domestic, industrial and commercial wastes; therefore ERT monitoring was initiated. ERT surveys were further performed in February 2005 at a waste thickness of 15 metres and in June 2005 when the disposal cell was close to capacity with 23 metres of refuse. Interpreted results of progressive ERT surveying during these monitoring events are reproduced in Figures 5.11, 5.12 and 5.13.

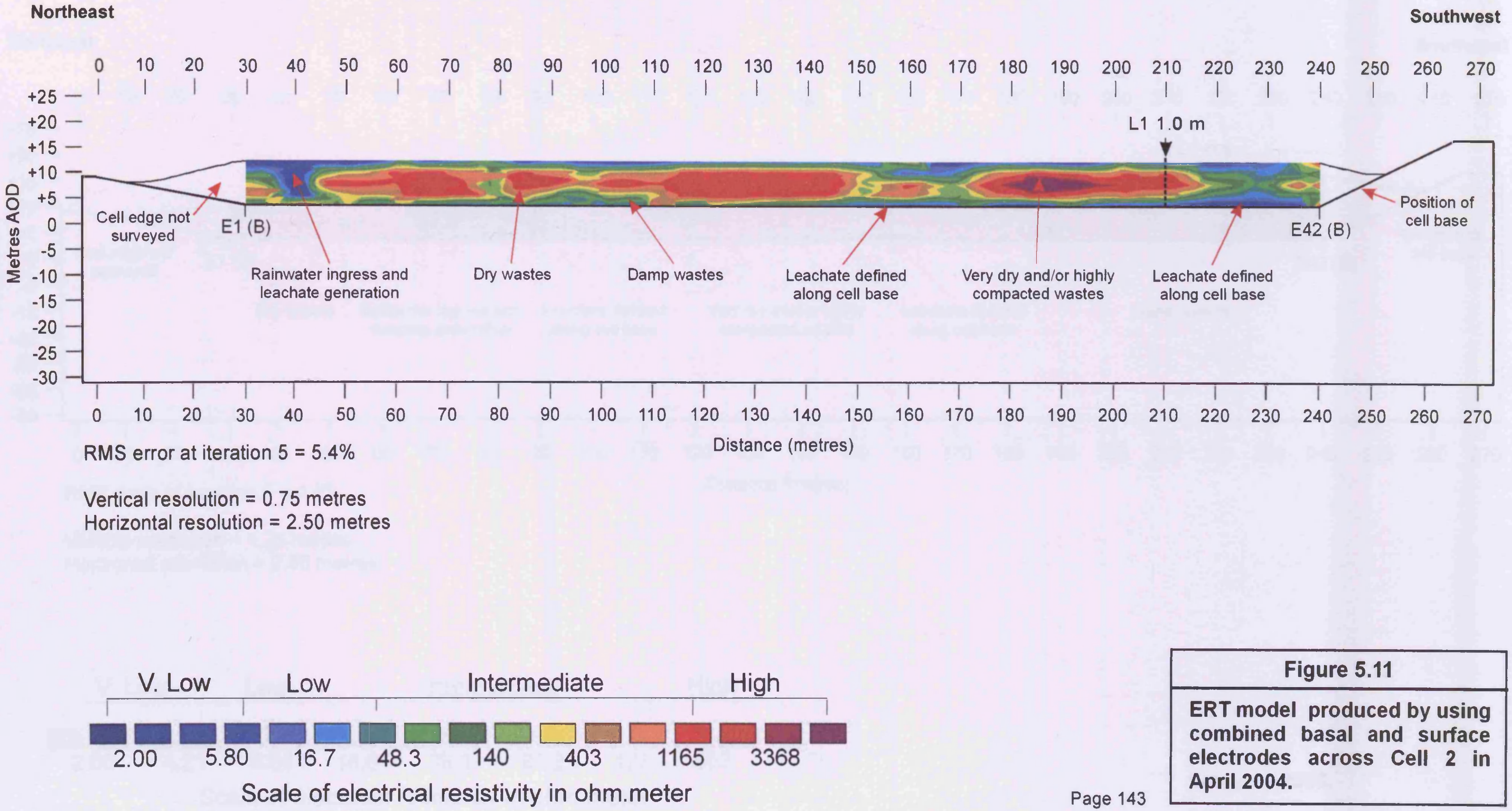



**Figure 5.11**

**ERT model produced by using combined basal and surface electrodes across Cell 2 in April 2004.**

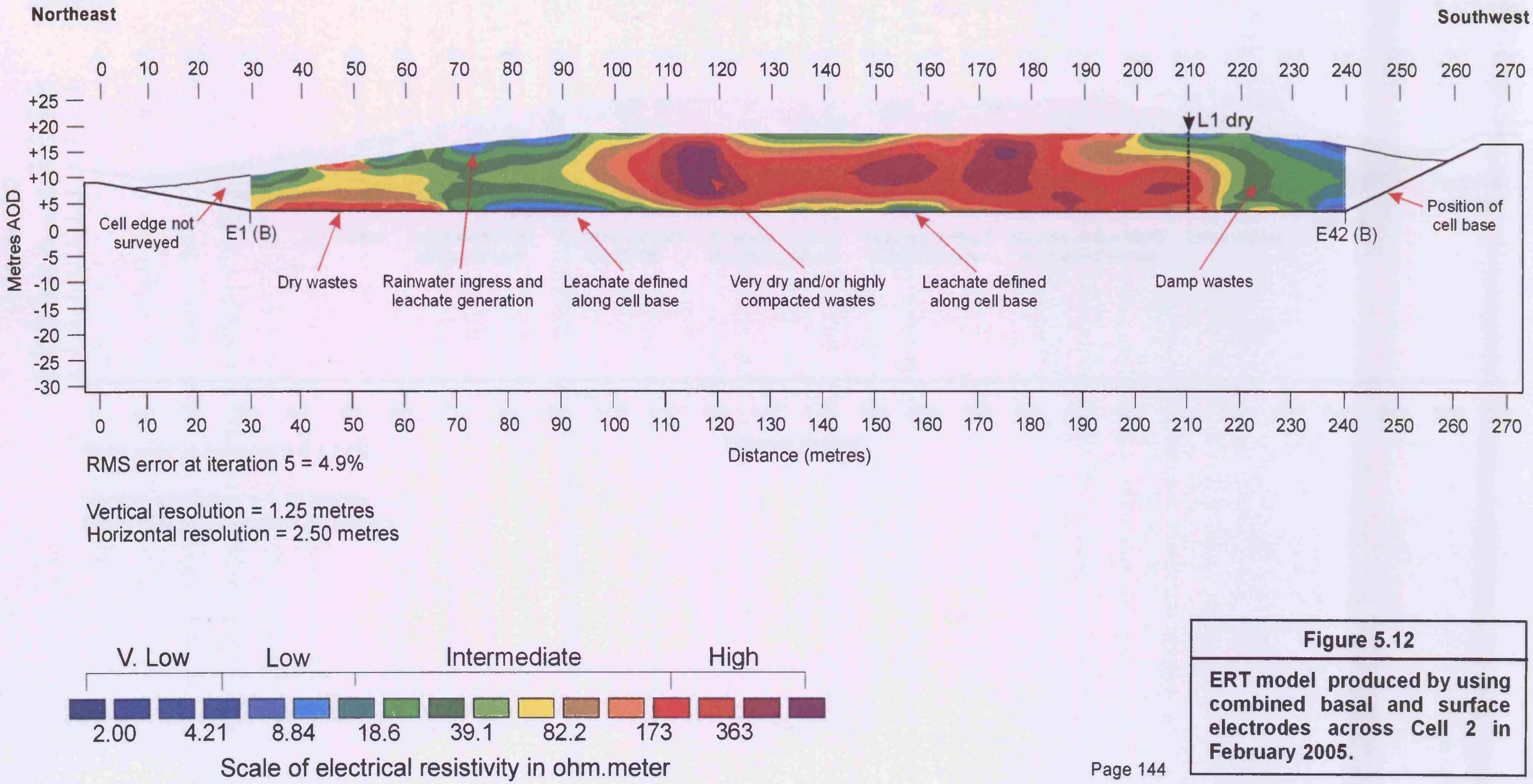
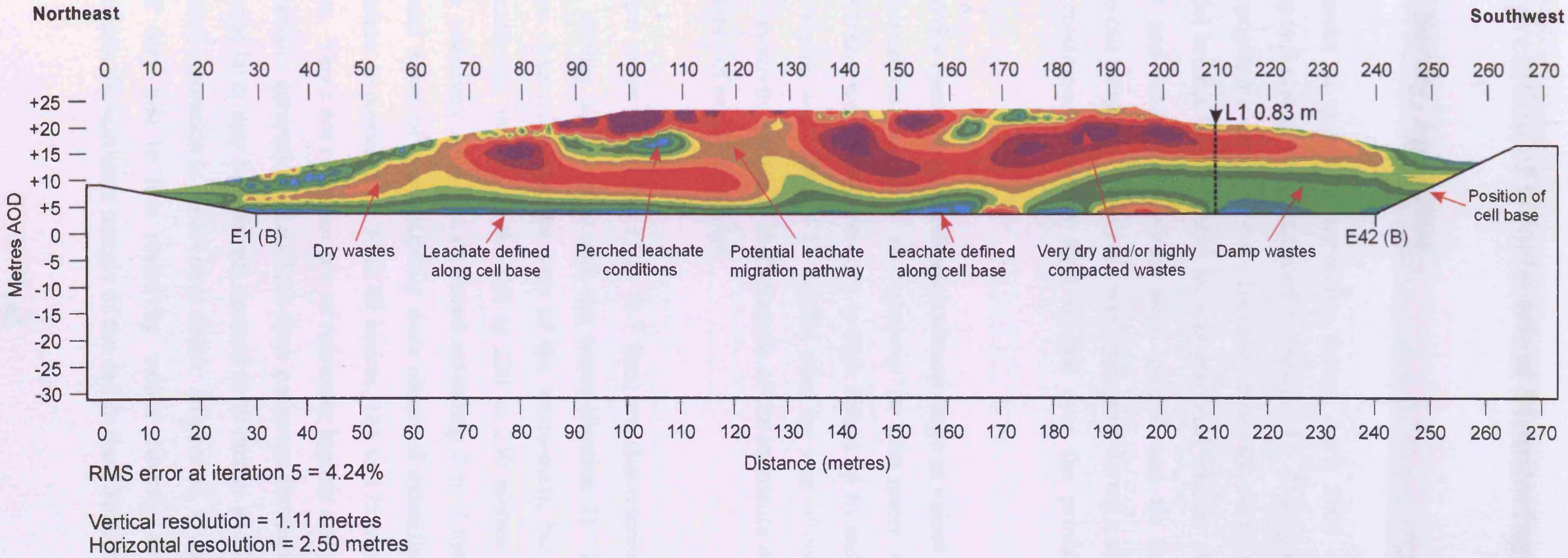



**Figure 5.12**

**ERT model produced by using combined basal and surface electrodes across Cell 2 in February 2005.**



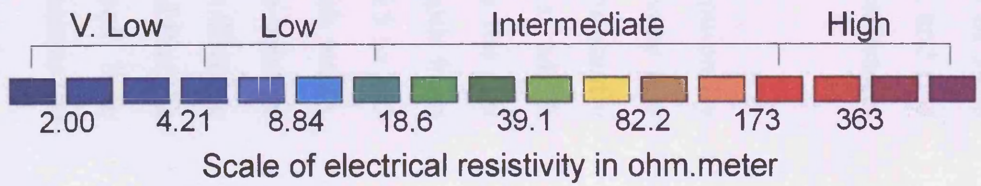




**Figure 5.13**

**ERT model produced by using combined basal and surface electrodes across Cell 2 in June 2005.**

# 5.7. Interpretation of Geoelectrical Monitoring Data

## 5.7.1. ERT Survey, April 2004

Interpreted results of resistivity surveying during April 2004 with a waste-mass thickness of up to 8 metres are reproduced in Figure 5.11. During the ERT survey, no appreciable topographic variation was observed across the waste-mass, therefore the inversion model has not been adjusted for topographical effects. An equal number of parallel basal and surface electrodes were utilised and no measurements were acquired at the cell margins. The survey was performed during a single day and under dry weather conditions, although light rainfall over the previous two days had occurred.

Initially, resistivity measurement indicated a broad range in values through the waste-mass, as indicated on the scale of resistivity in ohm.meter (Ωm). Very low resistivities of 2 Ωm were noted, through to high values up to and in excess of 3368 Ωm. ERT surveying was initiated 15 months after the start of cell infilling and this wide range of resistivity values is characteristic of the immature nature of the waste-mass and the types of refuse emplaced.

Very low to low resistivity values (2 to 16.7 Ωm) are characteristic of saturation by leachates and mixing of rainwater with the waste (Section 2). Zones of very low resistivity were observed along the base of the waste-mass, but only significantly towards the southwest margin of the cell at 220 to 230 metres distance, at which location a low resistivity zone was observed extending 2 to 3 metres above the cell base. Additional zones of low resistivity were observed extending with depth from the ground surface, in particular at 30 to 60 metres, 165 to 175 metres and 215 to 235 metres distance. These are characteristic of rainwater ingress and mixing with waste, resulting in leachate generation. Leachate flow pathways through the waste-mass to the basal drainage layer may be inferred, centred at 40 metres and 230 metres distance where widespread saturation is observed at depth. In general, it was observed that the occurrence of very low to low resistivity values directly above the cell base diminished towards the northeast margin of the cell in the direction of flow across the basal gravel drainage medium. From this it may be inferred that the basal drainage was effective; however, the determination of actual flow in progress is not possible from resistivity measurement alone.

The model indicates anomalous high resistivity values up to and in excess of 3368 Ωm, which were extensive through the waste-mass and elongated horizontally. The exact cause of such high resistivity is unclear without intrusive investigation. Such values are usually attributed to dry, granular and well-drained material, but if this was the case rainwater infiltration would be expected and subsequently lower resistivity values observed. High values in this setting are therefore likely to characterise waste constituents such as plastic, rubber, wood, and demolition rubble with a high degree of compaction occurring, thus preventing fluid ingress. Elsewhere within the resistivity model a broad range of intermediate values, from 48.3 to 1165 Ωm is characteristic of damp to dry variation.

A leachate dip level observation of 1.0 metre above the cell base was recorded at monitoring point L1 at the time of the ERT survey. This corresponds directly with the zone of very low resistivity observed above the cell base at the intersection point of L1, which is not vertically extensive.

Based on the results of ERT surveying in April 2004, recommendations were provided to the landfill operator that inferred zones of rainwater ingress and leachate generation could be controlled and reduced by temporary capping with clay soil at 30 to 60 metres, 165 to 175 metres and 215 to 235 metres distance. It was also inferred that leachate was not accumulating in significant quantity above the cell base and that the basal drainage medium was effective.

## 5.7.2. ERT Survey, February 2005

Interpreted results of ERT surveying during February 2005 with a waste-mass thickness of up to 15 metres are illustrated in Figure 5.12. During the ERT survey, variation in the ground surface topography was observed and the inversion model has been adjusted for topographical effects as described in Section 5.6.3. The survey was performed during a single day and under dry weather conditions, although rainfall had occurred over the previous week. A reduced range in resistivity values was recorded in February 2005 in contrast to the previous survey. Very low to low resistivity values (2 to 8.84 Ωm) were noted in February 2005 and the high range in the scale of values observed reached 525 Ωm.

Very low to low resistivity values were observed above the cell base in two localised positions: at 75 to 95 metres and 235 to 240 metres distance. This is characteristic of leachate accumulation, although the vertical extent of saturation is insignificant, being limited to approximately 2 metres height above the cell base. Similar values were observed along the ground surface and extending slightly with depth. Very low to low resistivities observed at 70 to 90 metres, 205 to 215 metres and 225 to 240 metres distance are characteristic of significant rainwater ingress and mixing with wastes resulting in leachate generation. Within two distinct zones of the waste-mass, there appeared to be a relationship between very low to low resistivity at the ground surface and similar values at depth, notably at 70 to 90 metres and 215 to 240 metres distance. This is analogous to rainwater ingress and leachate generation from the ground surface in continuity with basal leachates, therefore preferential fluid flow paths may be inferred.

A notable zone of apparent surface to basal fluid continuity at 70 to 90 metres distance was less developed in the previous survey of April 2004, being centred at 80 metres. Conversely, zones of inferred rainwater ingress and fluid migration through the waste-mass noted in April 2004 at 30 to 60 metres, 165 to 175 metres and 215 to 235 metres distance had largely diminished by the February 2005 survey indicating the effectiveness of temporary clay capping in reducing leachate generation.

Localised basal and surface low resistivity zones were separated by intermediate values (18.6, 39.1 Ωm) indicating damp, but unsaturated conditions. Intermediate resistivity values were observed along the ground surface and extending slightly with depth, notably at 30 to 40 metres, 50 to 60 metres and 125 to 155 metres distance. These are characteristic of rain water ingress, however appreciable leachate generation and migration appeared to have been constrained by more-resistive material below, particularly at 125 to 155 metres distance, possibly indicating reduced permeability.

The range in resistivity values observed in February 2005 was considerably less than that noted in the previous survey. It may be inferred that the high range resistivity (around 363 Ωm) is characteristic of the resistive nature of certain wastes, such as those described in Section 5.6.1, rather than being indicative of dry, well-drained conditions. However, the reduction in high range resistivity by a factor of 10 indicates that the resistive wastes have become wetter with time, suggesting fluid percolation and refuse degradation.

At the time of the ERT survey, monitoring point L1 was found to be dry, which corresponds directly with the zone of high resistivity observed above the cell base at the intersection point of L1.

Recommendations for temporary capping after the April 2004 survey were followed with the result of leachate reduction within the waste-mass; however, it was observed that flow paths may have developed where no clay capping was emplaced. On the basis of ERT results obtained in February 2005, recommendations were made for temporary clay capping at 65 to 95 metres and 210 to 240 metres distance to prevent further rainwater ingress and leachate generation where there appeared to be a particular continuity through the waste-mass to basal leachates. It was also demonstrated, although inferred, that basal leachate accumulation was insignificant and confined to 1 to 2 metres height in localised areas of saturation.

## 5.7.3. ERT Survey, June 2005

Interpreted results of ERT surveying during June 2005, when Cell 2 was close to filling capacity with a waste thickness of up to 23 metres, are reproduced in Figure 5.13. The survey was performed during a single day and under dry weather conditions with no rainfall noted over the previous two weeks. A variation in ground surface topography was observed during the ERT survey, therefore, the resistivity model has been adjusted for the effects of topography. The range in model resistivities observed in the June 2005 inversion was similar to those values derived from the previous data; therefore, the two consecutive resistivity models were produced with the same scale of resistivity, in contrast to the April 2004 survey. Due to the effects of topography, a greater number of electrodes were utilised in the temporary ground surface array, which was further extended to recover measurements from the cell edges, a practice not undertaken for the previous two surveys.

Very low to low resistivity values (2 to 8.84 Ωm) were noted directly above the cell base, but not extending significantly into the overlying waste-mass, being constrained to a maximum localised leachate head of 2 metres. Similar values were also observed isolated within the waste-mass at 100 to 110 metres distance and 16 to 18 metres above the cell base, set within a broader zone of low to intermediate (18.6, 39.1 Ωm) resistivities. This isolated anomaly is characteristic of saturation by perched leachates and appears to be driven by rainwater ingress from the ground surface at 75 to 85 metres distance, as indicated by the low to intermediate values observed. A similar zone of rainwater ingress and potential perched leachate formation was observed at 160 to 180 metres distance and 17 to 23 metres above the cell base. These inferred zones of isolated and perched fluid saturation within the waste-mass appear to be constrained at depth by higher resistivity below, indicating a change in waste characteristics and reduction in permeability. Shallow rainwater ingress was also noted at 10 to 60 metres distance leading to minor leachate saturation, as inferred from the intermediate to low resistivity values.

Intermediate resistivity values (18.6, 39.1 Ωm) extending above the cell base are characteristic of damp, but unsaturated conditions. These damp zones diminish in vertical extent towards the northeast margin of the cell in the direction of the engineered basal flow, indicating effective drainage from the waste-mass. By comparison to the February 2005 survey, damp wastes appeared to have been more extensively developed, particularly above the cell base at 30 to 70 metres and 110 to 215 metres distance.

Zones of rainwater ingress and leachate generation inferred from the February 2005 model at 70 to 90 metres and 205 to 240 metres distance, appeared to have diminished and were no longer in continuity with basal leachates in the June 2005 model. This indicates the effectiveness of temporary clay capping at the intervals suggested. However, the June 2005 model indicated a potential fluid migration pathway developing from the isolated perched leachate table and extending through the waste-mass at 110 to 130 metres distance and 10 to 17 metres above the cell base. This is inferred from the zone of intermediate values (around 82.2 Ωm) extending through the higher-resistivity waste between the perched and basal low resistivity zones. Anomalous zones of high range resistivity (up to and in excess of 363 Ωm) are laterally and vertically extensive and are characteristic of compacted impermeable wastes.

A leachate dip level observation of 0.8 metres above the cell base was recorded at monitoring point L1 at the time of the ERT survey. This corresponds directly with the zone of intermediate resistivity observed above the cell base at the intersection point of L1, which is characteristic of damp but unsaturated conditions.

On the basis of the ERT survey results obtained in June 2005 it was inferred that leachate accumulation at depth was insignificant and basal drainage was effective. The establishment of perched leachates within the waste-mass was also demonstrated, indicating areas to avoid when emplacing gas well installations due to potential problems of well flooding.

### 5.7.4. Geophysical Site Model

A geophysical site model representing a two-dimensional profile through the waste-mass at Cell 2 (Figure 5.14) has been produced based on the result of the June 2005 ERT survey. For ease of interpretation, the four significant ranges in model resistivity are represented by a colour scheme. A maximum leachate head of 2 metres above the basal clay barrier is represented in the model. It is observed that the zones of very low to low resistivity analogous to leachate saturation are within the permitted vertical limit and decrease towards the northeast margin of the cell and position of the drain, which indicates effective leachate drainage.

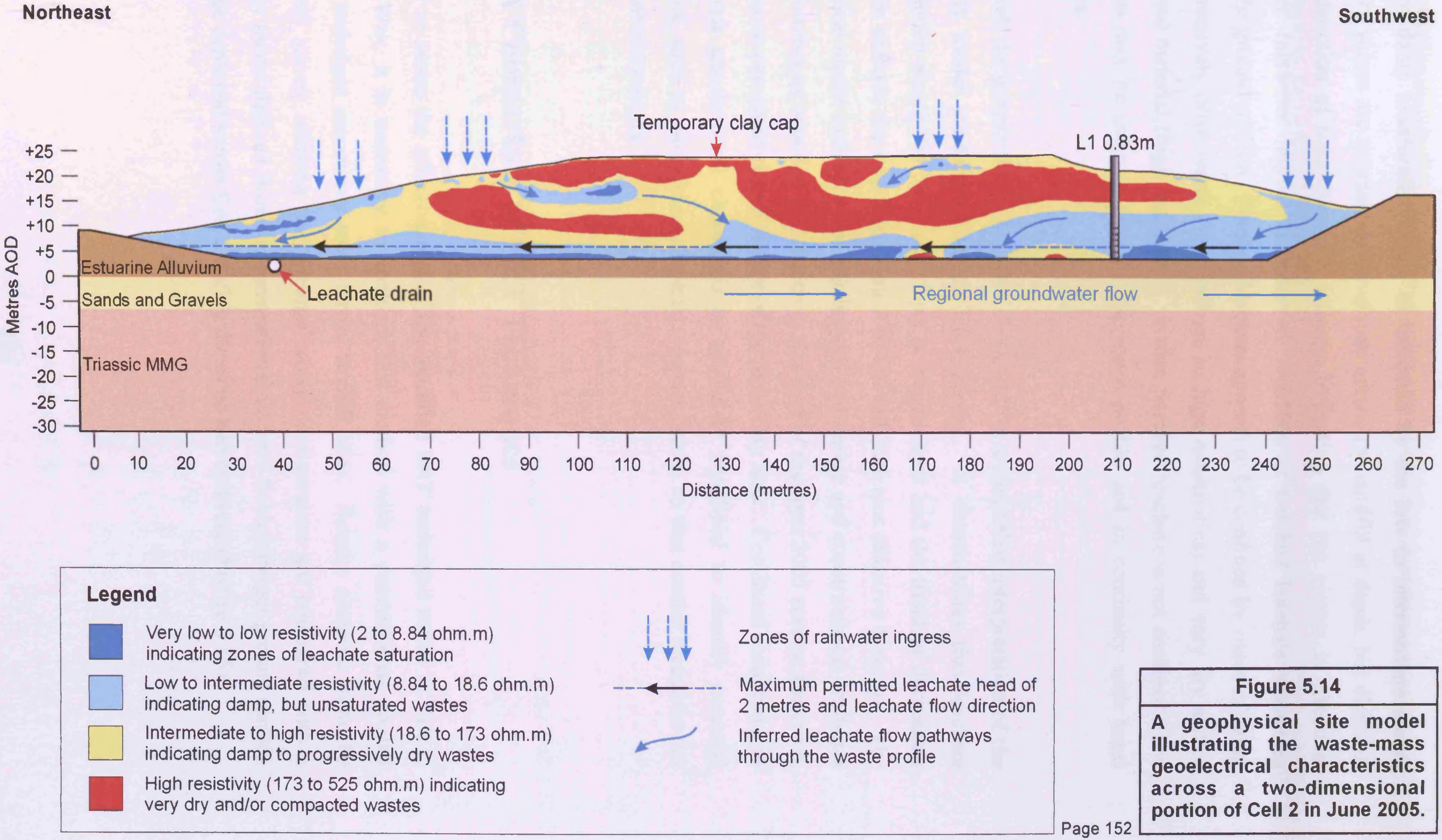





**Figure 5.14**

**A geophysical site model illustrating the waste-mass geoelectrical characteristics across a two-dimensional portion of Cell 2 in June 2005.**

Zones of damp unsaturated waste, as indicated by the low to intermediate model resistivity values are extensively developed across the landfill at depth, but diminish in the direction of basal leachate drainage indicating that the system is effective. Localised rainwater ingress is observed, resulting in perched leachate saturation below the ground surface. Perched leachate appears to be confined by zones of damp to progressively drier waste (intermediate to high resistivities) and very dry and/or compacted material (high resistivity). Where perched leachate is not confined, flow pathways may be inferred through the waste profile and in continuity with basal leachates.

In general, the geophysical site model for Cell 2 is a simplified interpretation of the resistivity model produced from an ERT survey. It demonstrates that leachate accumulation above the basal clay liner is insignificant and the trend of decreasing saturation towards the northeast margin of the cell indicates effective drainage. The geophysical model indicates that the disposal cell design and constructional attributes are performing as intended to function at the time of the June 2005 survey; therefore, there was no perceived risk of failure of the basal clay liner. Continued monitoring of waste-mass geoelectrical characteristics would be beneficial to identify potential future risk, such as widespread elevated leachate levels, so that control measures can be applied accordingly.

## 5.8. A Comparison of ERT Techniques

In order to assess the effectiveness of the modified ERT technique tested at Cell 2, Lamby Way, it is necessary to compare this method with a conventional ground surface technique commonly used across landfill sites. Results obtained from the June 2005 survey utilising the 'George' array configuration are compared with a resistivity model derived from the conventional Wenner-Schlumberger ground surface array-type deployed across Cell 2 during the same survey event (Figure 5.15).

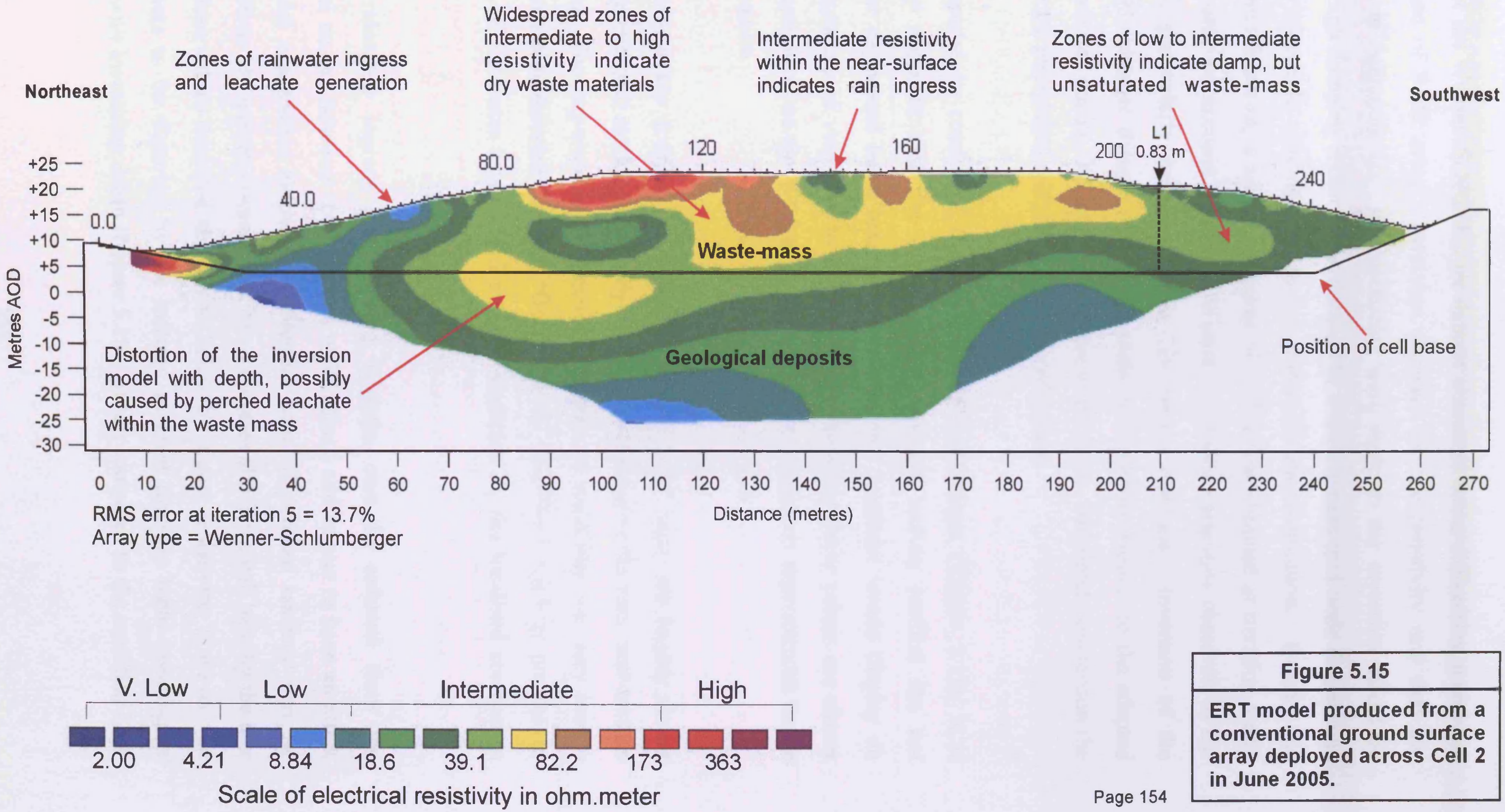



**Figure 5.15**

**ERT model produced from a conventional ground surface array deployed across Cell 2 in June 2005.**

Inversion of the Wenner-Schlumberger dataset presented some difficulties, mainly in the reduction of RMS error. Inversion statistics for the resistivity raw data are reproduced in Appendix III. Improvements were made to the inversion model by utilising a high damping factor and reducing the finite element grid node dimensions to half the electrode spacing, i.e. to 2.5 metres in the *x*-direction. Despite the inversion modifications, a high RMS error of 13.7% was obtained at iteration 5 and this is probably on account of the significant resistivity variations observed in the near-surface particularly between 60 to 120 metres distance. Inversion of the Wenner-Schlumberger dataset provided a scale of resistivity similar to the adapted ERT method used during the same survey event; therefore, for direct comparison the two models are interpreted with the same scale of values.

When compared to results of the modified ERT technique (Figure 5.13), it is immediately apparent that the conventional resistivity survey method has not identified or delineated basal leachate accumulation. Leachate would display an expected signature of very low to low resistivity, however these values are absent from the depth level of the Wenner-Schlumberger model which approximates to the cell base position.

Resistive sub-surface conditions detected by the 'George' array are largely absent from the conventional model, being only comparably defined in the very near-surface depth levels. The importance of detecting extremes of resistivity, i.e. very low to high, has been demonstrated using the 'George' array, whereby it has been possible to infer zones of rainwater ingress and perched leachates by the localised contrast in resistivities.

Zones of rainwater ingress and perched leachate may be inferred from the conventional model, however they are less well defined and appear to have an effect on the model resistivities below. A potential zone of perched leachate may be inferred at 90 to 110 metres distance and 7 to 13 metres above the cell base by the low to intermediate values bounded above and below by higher resistivity; however, the model appears to be distorted by the inferred perched leachate table resulting in inaccuracy with increasing depth (Figure 5.15). When compared to the modified ERT

technique, these results indicate that perched leachates may be more accurately defined using the 'George' array, whereby very little or no distortion is evident.
As discussed in Section 5.7, intermediate resistivity values (18.6, 39.1 Ωm), are characteristic of damp, but unsaturated waste. Such zones are identified by the Wenner-Schlumberger array technique, however they are less clearly defined with increasing depth; therefore, it is difficult if not impossible to provide information in support of effective basal drainage across the cell. The model derived from the 'George' array indicates clearly defined intermediate values directly above the cell base and diminishing in the direction of engineered basal drainage.

By comparing the two ERT techniques it may be concluded that conventional ground surface resistivity surveying contributed little information of value to the landfill operator and regulatory body, particularly in the delineation of basal and perched leachates, the identification of potential flow pathways, and the effects of rainwater ingress with depth.

# 5.9. Discussion of ERT Methodologies and Outcomes

## 5.9.1. Effectiveness of the Survey Methods

ERT surveying along the ground surface is anticipated to show a decrease in resolution and accuracy with increasing depth. An important aspect of geoelectrical surveying at Cell 2, Lamby Way, was the requirement for delineation of leachate saturation within the waste-mass, particularly in the distinction between perched and basal leachates. A modified ERT technique was developed and tested at various stages of cell infilling to provide consistent accuracy and resolution through the waste-mass. Results indicated basal leachate accumulation occurring in localised saturated zones with damp, unsaturated conditions developing above and diminishing in the direction of engineered basal drainage. Perched leachates were defined and distinguished from basal fluids without any apparent distortion of the inversion model. Furthermore, rainwater ingress and its effect on leachate generation were identified and potential fluid migration pathways defined.

The effectiveness of the modified ERT technique lies with the arrangement of resistivity measurement electrodes and configurations for application of electrical current and measurement of voltage potential. For this purpose it was necessary to permanently install electrodes within the landfill structure across the cell base prior to waste emplacement. Therefore, the modified technique is not regarded as retrospective, i.e. it can not be applied to the investigation and monitoring of closed landfills. Instead the method provides capability for ongoing monitoring of new landfill cells with potential for continuation of surveying after closure. Installation of measurement electrodes was undertaken in a cost effective manner using components designed to withstand physical loading and settlement of the above waste-mass. Pre-survey testing of concealed electrodes by the automated resistivity instrument demonstrated that no damage had occurred during waste emplacement and that the components had withstood inevitable settlement and distortion.

To justify the effectiveness of the modified ERT technique and associated electrode address configuration, a conventional resistivity method was deployed and the results compared. The Wenner-Schlumberger array-type is conventionally used during ERT surveys across active and closed landfills to investigate sub-surface geoelectrical characteristics of the waste-mass. Ground surface ERT surveying would normally be prescribed to determine leachate saturation within the waste to assist the landfill operator in maintaining legislative compliance with respect to leachate extraction/treatment strategies and site restoration. It became apparent through a comparison of the ERT techniques that conventional ground surface resistivity surveying provides little information of value to the landfill operator. Basal leachate saturation and relationships with perched tables and rainwater ingress were not satisfactorily defined. An inversion of conventional ERT survey data indicated distortion of the resistivity model and inaccuracy with depth.

Demonstration of a modified ERT technique has involved the use of a single electrode array position, therefore data interpretation was only possible across a portion of the landfill and in two-dimensions. Interpretation of waste-mass characteristics would be enhanced significantly with the use of several concealed electrode arrays across the base of a landfill cell, enabling three-dimensional analysis.

Calibration of the resistivity data obtained at Cell 2, Lamby Way, was quite limited and possible only by comparison with leachate dip level observations made at one monitoring well location. Enhanced calibration of further monitoring results may only be possible with the installation of piezometers into the waste-mass during site restoration. These would be used to confirm basal leachate variation and persistent accumulations of perched leachate, furthermore to prove the distinction between dry, damp and saturated wastes.

### 5.9.2. Capabilities for Routine Monitoring

Once installed, the permanent concealed basal electrodes may be used at any stage during the development of a landfill cell, however they must be utilised in conjunction with temporary ground surface electrodes. This electrode configuration may present difficulties upon closure of a site and subsequent capping with HDPE/LDPE plastic membranes. To overcome this problem it may be suggested that upon closure of a site, permanent electrode arrays are installed along the waste surface below the cap to enable continuation of monitoring. Post-closure routine monitoring would assist in the appraisal of landfill capping and leachate extraction strategies and would enable the site operators to achieve legislative compliance.

# (6)
# Geophysical Monitoring during Restoration of a Closed Landfill

## 6.1. Background and Objectives of the Landfill Study

Closed landfill sites in the UK are now subject to stringent monitoring of waste-mass and groundwater characteristics in accordance with environmental legislation aimed at ensuring sites are suitably contained, or identifying and rectifying occurrences of contaminant migration. Geophysical survey methods are often integrated with conventional post-closure landfill monitoring strategies, whereby the information is utilised in support of data from leachate and groundwater observation wells. By utilising techniques such as non-invasive ERT and EM surveying, it may be possible to distinguish variation in sub-surface geoelectrical characteristics relating in particular to accumulation and off-site migration of leachate.

The effectiveness of geophysical surveying across a closed landfill lies with the ability to obtain accurate and reliable data with depth through the waste-mass, especially regarding legislative requirement for identification of basal leachates above impermeable liner systems and their continuity with overlying perched tables and rainwater ingress. As discussed in Section 2, there are constraints to using non-invasive geoelectrical methods across closed landfills, in particular the expected decrease in accuracy and resolution with increasing depth of investigation. In accordance with these constraints, there is requirement for development of a geophysical methodology to obtain accurate and reliable data at closed landfills, whereby information can be directly compared with conventional monitoring results providing a correlation between sampling locations.

The potential for improved geophysical characterisation of closed landfills provided a focus for interest during the research project and accordingly a methodology is proposed, which has been applied to a typical test site.

Nantygwyddon landfill in South Wales was active from 1998 to 2002 and received domestic, commercial and industrial wastes, as described in Section 3.3. Following closure, a site management strategy involved temporary soil capping, progressive leachate and groundwater monitoring, and gas extraction. Further to this, a restoration strategy was devised including capping with plastic membranes and leachate extraction from the waste-mass. Following site closure, leachate occurrence within the waste-mass was monitored by conventional means including dip level measurement from gas wells, piezometer installations and monitoring boreholes. Monitoring data indicated variance in the techniques used for identifying leachate heads within the landfill. It was inferred from piezometer readings that leachate saturation occurred relatively high up in the waste profile, ranging between 18 to 25 metres above the basal liner. In addition, a series of lower bodies were inferred, ranging between 8 to 17 metres above the landfill base and not being in direct hydraulic continuity with those above. By contrast, observations from gas wells suggested leachate heads ranging from between 6 to 22.7 metres within the landfill, whilst measurement from monitoring boreholes suggested a much lower overall leachate height of 0 to 3 metres.

Based on the lack of correlation of the results provided by various leachate monitoring techniques used, there existed opportunity to implement geophysical sub-surface characterisation. However, an adapted methodology was sought enabling data recovery with consistent accuracy and resolution through the waste-mass. This opportunity was further emphasised during a period of intrusive drilling and gas well emplacement, during which there was potential to install measurement equipment at depth within the landfill. Installation of arrays mounted on the gas well casings allowed permanent ERT measurement electrodes to be utilised to characterise sub-surface geoelectrical variation to assist with the delineation of leachate saturation and the appraisal of site restoration work including capping and leachate extraction. In accordance, a strategy for geophysical monitoring of waste-mass characteristics at Nantygwyddon landfill was planned with the following objectives:

- Identify a methodology for the permanent installation of ERT measurement electrodes with depth through the waste-mass and capabilities for data acquisition, processing, interpretation and calibration.

- Acquire baseline information relating to the occurrence of leachate saturation through the waste profile prior to restorative work.

- Perform ERT sub-surface characterisation following site capping with plastic membranes to identify geoelectrical variation resulting from exclusion of rainwater.

- Utilise the adapted ERT methodology to identify geoelectrical variation arising from leachate extraction from the waste-mass.

- On the basis of results obtained, outline the capabilities for further geoelectrical monitoring and provide recommendations for geophysical best practice at closed landfills and during site restoration.

## 6.2. Conceptual Site Model

A conceptual site model (CSM) has been produced for the closed Nantygwyddon landfill site and background geology (Figure 6.1). The CSM illustrates the elevated landfill position and represents the site as a total containment feature following temporary soil capping and prior to restoration. Rainwater ingress was anticipated through the temporary soil cover emplaced after closure of the landfill. Percolating rainwater and mixing with wastes will result in leachate saturation, both perched within the more porous layers of refuse and accumulating at depth above the basal HDPE liner. Various measures have been put in place to reduce ingress and leachate accumulation, mainly through drainage of leachate from the waste-mass and removal of surface water.

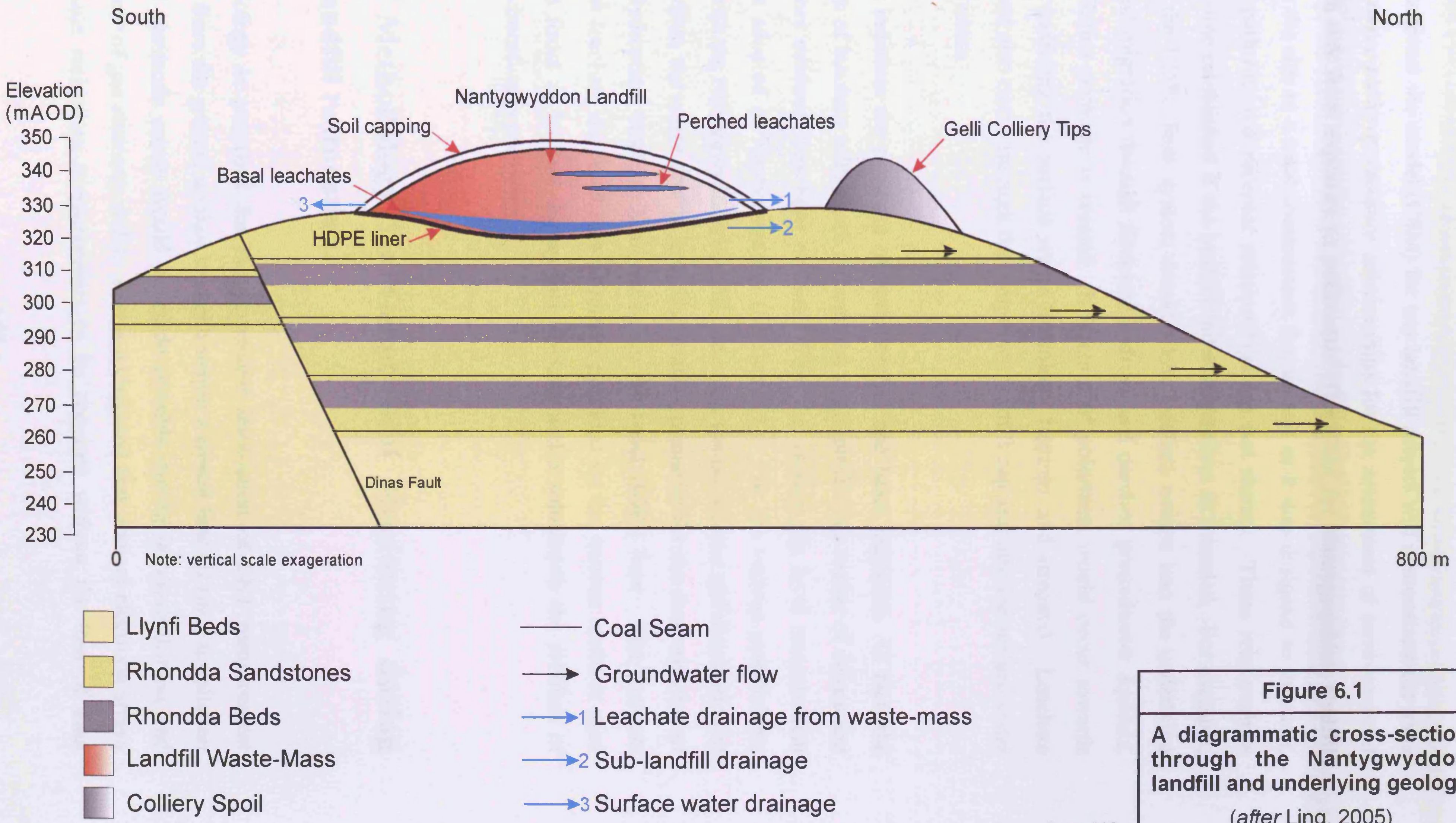



**Figure 6.1**

**A diagrammatic cross-section through the Nantygwyddon landfill and underlying geology**

(*after* Ling, 2005)

A full conceptual site model (CSM) for any landfill project will demonstrate the links between *source-pathway-receptor* relationships for the assessment of environmental and human risk from exposure to pollutants. The CSM for Nantygwyddon landfill represents the site as a total containment feature and as it was designed to function; therefore, pathway and receptor relationships are not shown. These relationships would become established if the landfill failed to perform as intended. For example; failure of the HDPE liner system would allow leachate escape into the underlying geology and migration through fractured bedrock and perched groundwater aquifers, thus a pollutant *pathway* is created. Migration of pollutants would occur towards receptors, including the surface water hydrology (springs and streams). Leachate escape could also occur through the temporary landfill cap and into the surface water drainage system.

The CSM indicates the presence of both perched and basal leachates. In fact, the distribution of leachate with depth through the waste profile is a matter of debate and contradictory evidence has been obtained from the various dip level measurement procedures adopted at Nantygwyddon (Section 6.1). For the various stakeholders involved with the Nantygwyddon landfill, assessing the occurrence and distribution of leachate within the waste profile is of importance, primarily for the determination of effective hydrostatic leachate head acting on the basal HDPE liner. The apparent variation in leachate dip level measurements provided by the various methods used provided a focus of interest during this research and a solution to the problem of leachate delineation is presented.

## 6.3. A Methodology for Geophysical Monitoring during Landfill restoration.

A methodology is proposed for the permanent installation of ERT measurement electrodes from the ground surface to depth within a closed landfill site. Installation of vertical electrode arrays would be made possible during intrusive drilling and emplacement of gas recovery wells. It was anticipated that vertical electrode arrays would enable resistance measurements to be acquired without the loss of data accuracy and resolution with increasing depth, which is normally attributed to ground surface ERT surveying.

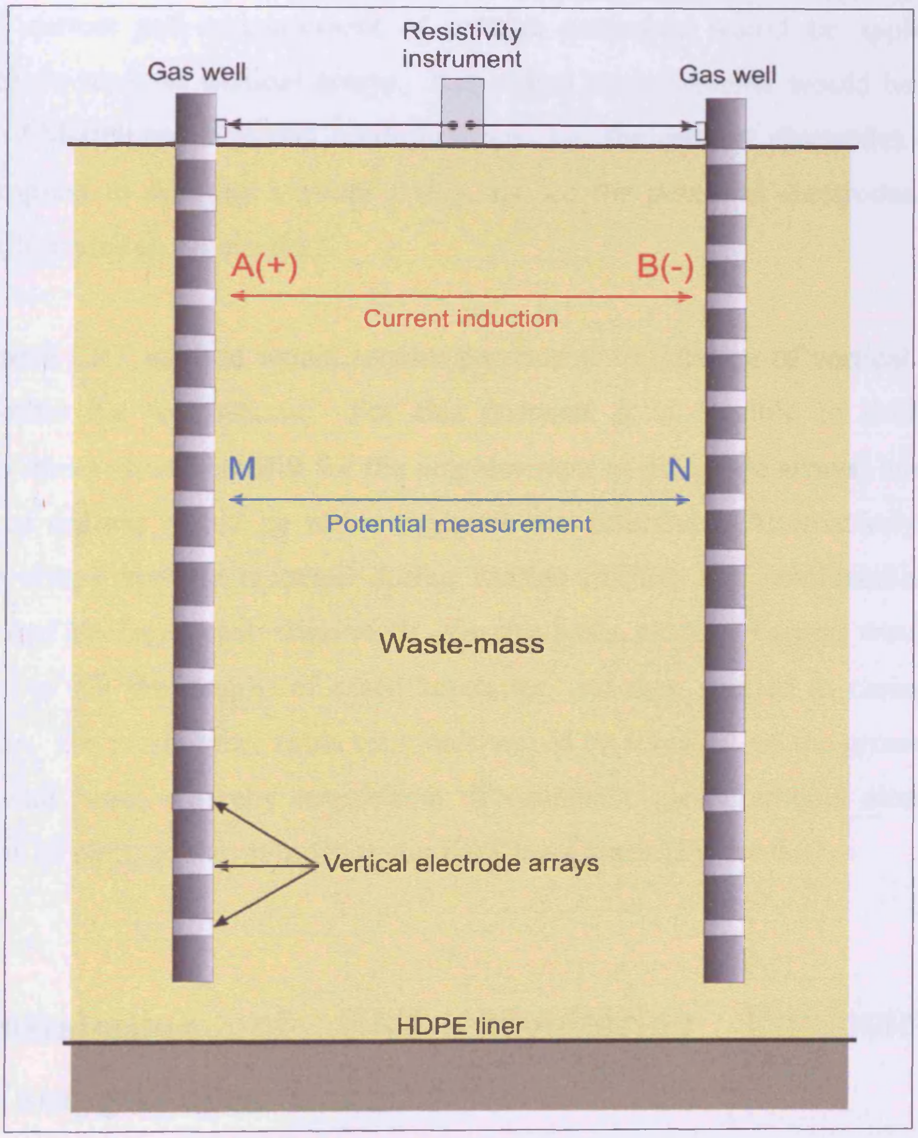



Figure 6.2: *A diagram illustrating the use of vertical electrode arrays mounted on gas well casings for measurement of resistance within a closed landfill waste-mass.*

The use of single vertical electrode arrays to monitor leachate accumulation and migration on closed landfills has been demonstrated by Tsourlos et al. (2003). In this published example resistivity variation was noted in the vertical direction along the array length without spatial directional indication within 360° of the electrode array. This technique could not be applied to investigate the possible hydraulic continuity between zones of rainwater ingress with perched and basal leachates.

Field methods described by Tsourlos et al. (2003) could be further adapted to provide spatial directional indication of anomalous resistivity zones by utilising vertical electrode array pairs in relatively close proximity. On this basis the induction of electrical current and measurement of voltage potentials would be applied using electrodes on separate vertical arrays. Resistance measurements would be recorded with the AM-BN and AN-BM configurations, i.e. the current electrodes (AB) are always applied to separate vertical arrays, as are the potential electrodes (MN), a concept illustrated in Figure 6.2.

This adapted ERT method would require permanent installation of vertical electrode arrays within the waste-mass. For this purpose, it is feasible to drill uncased boreholes into a closed landfill for the emplacement of electrode arrays, however the expense of drilling would be not considered cost-effective. Alternatively, vertical electrode arrays may be installed during routine drilling and emplacement of gas recovery and leachate observation wells. On this basis, electrode arrays would be pre-fabricated to suit the lengths of cased boreholes, and then applied to casings during installation. Electrode array cable terminals would be accessed on the ground surface at each well head, whereby acquisition of resistance measurements must involve connection of electrode array pairs to the ERT instrument (Figure 6.2).

## 6.4. Installation of ERT Monitoring Equipment at Nantygwyddon Landfill

An adapted ERT methodology was implemented at the Nantygwyddon landfill during emplacement of gas recovery wells after site closure, but prior to restoration enabling baseline sub-surface conditions to be identified and compared with geoelectrical variation during site capping and leachate extraction. As part of an ongoing strategy for treatment of landfill gas, three recovery wells were emplaced within a portion of the landfill after closure, the locations of which are illustrated in Figure 6.3.

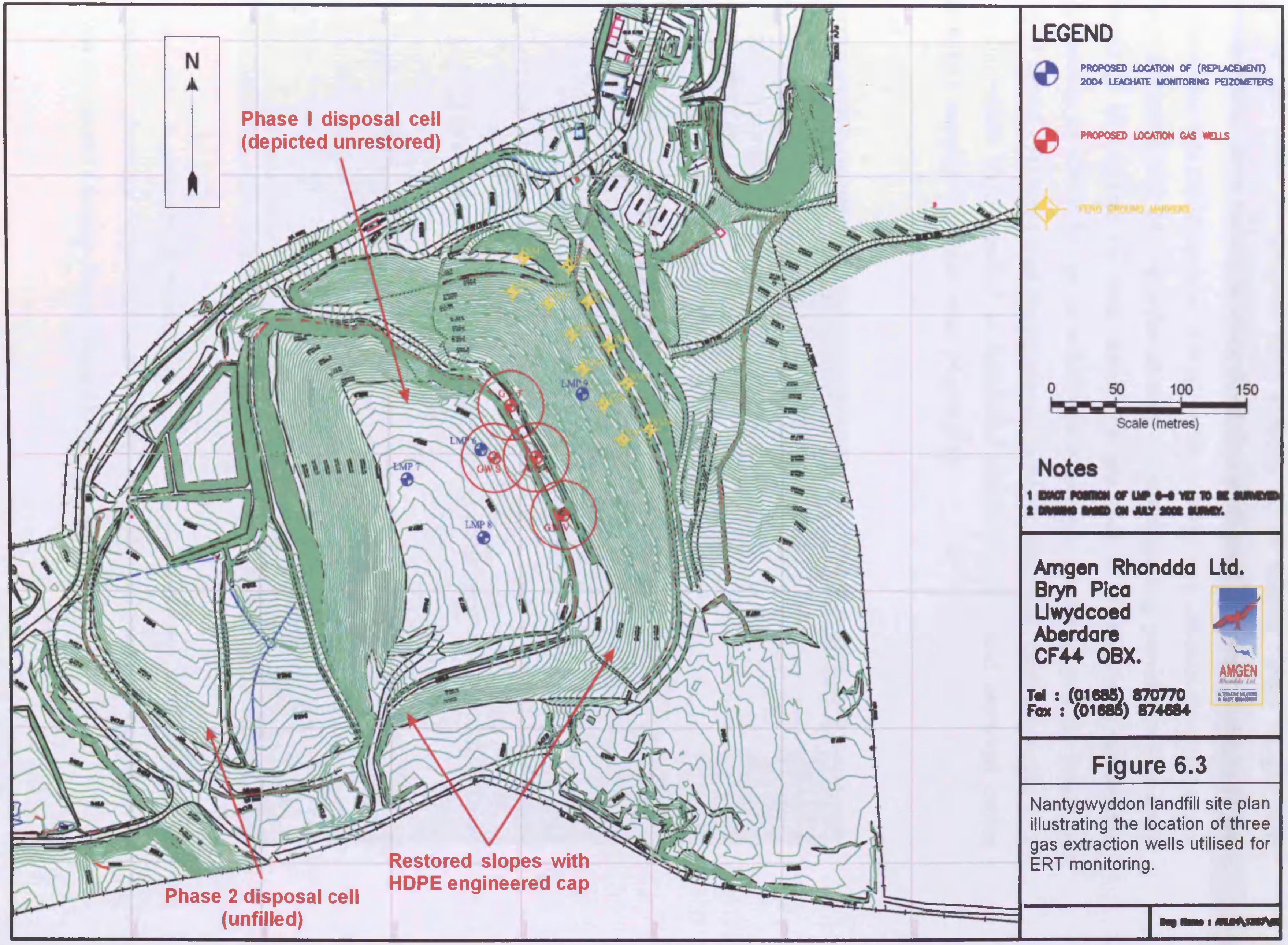



**Figure 6.3**

Nantygwyddon landfill site plan illustrating the location of three gas extraction wells utilised for ERT monitoring.

*Source of Autocad base map: Amgen Rhondda Ltd*

Gas wells 'S' and 'U' were designed with a depth of 20 metres through the waste profile and well 'T' designed with a depth of 15 metres. Prior to gas well emplacement, three individual electrode arrays were pre-fabricated off-site to fit the planned gas well casing lengths. For gas wells S and U, two identical electrode arrays were fabricated with 18 electrodes set on a 1.1-metre spacing, providing a total array length of 19.8 metres for each well. For gas well T, an array was constructed comprising 18 electrodes set to a 0.83-metre spacing, providing an array length of 14.94 metres. Stainless steel sheets were utilised for electrodes, each measuring 10 x 15 cm, which were attached to individual single-core insulated electrical cables forming a complete electrode array (Figure 6.4).

Figure 6.4: *A photograph illustrating a pre-fabricated electrode array comprising single-core electrical cables and stainless steel sheet electrodes prior to emplacement within the landfill (Jeremy Jones, Encia Consulting Ltd).*

Gas well emplacement involved the use of a rotary barrel auger rig to drill 300 mm diameter open boreholes into which the sections of slotted HDPE casing were installed to the prescribed well depth. During installation of the 3-metre casing sections into each borehole, a pre-fabricated electrode array was attached onto the casing exterior surface using self-adhesive tape (Figure 6.5). Following emplacement of gas well casings and electrode arrays a gravel pack and bentonite seal was applied to each borehole in the conventional manner.

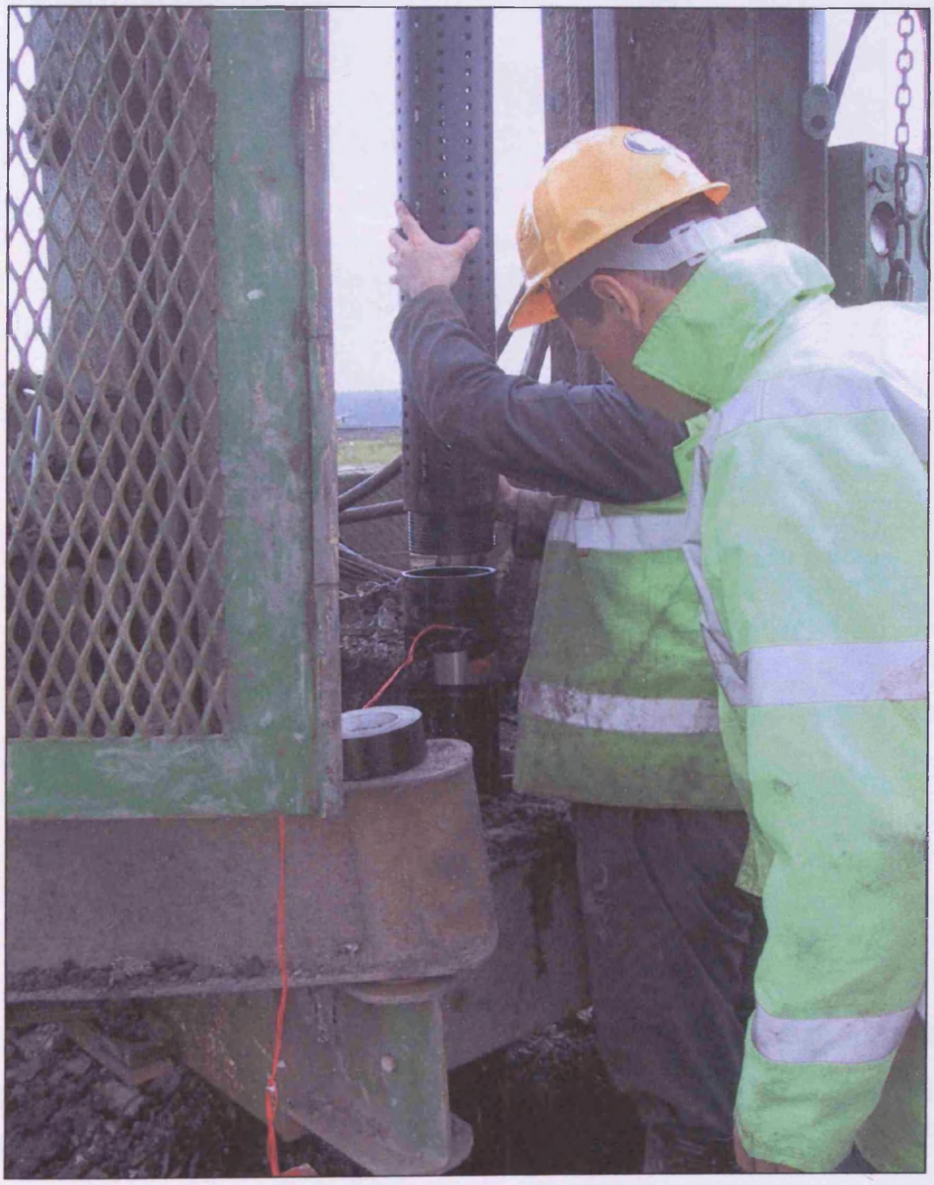


Figure 6.5: *A photograph illustrating attachment of an electrode array onto the exterior casing surface during emplacement of a gas recovery well at Nantygwyddon (Jeremy Jones, Encia Consulting Ltd).*

Electrode cables were terminated at each gas well head above ground by routing the wires into a plastic weatherproof junction box with removable cover (Figure 6.6). Panel-mounted sockets enable connection of electrode array pairs to the ERT instrument with use of a multi-core cable adapter.

Figure 6.6: *A photograph illustrating the electrode array connection box mounted at each gas well head for connection to the ERT instrument (Dr. P. Brabham, Cardiff University).*

Installation of the vertical electrode arrays was achieved without incurring significant delay to the drilling process and by utilising inexpensive materials, therefore the technique was considered highly cost-effective.

# 6.5. Operation of the Monitoring System

## 6.5.1. Application of an Electrode Address Configuration

For resistance measurement of the plane of ground between two vertical electrode arrays, an electrode address configuration is applied using the automated resistivity meter. This configuration comprises an arrangement of current (AB) and potential (MN) electrodes with respect to the number and positioning of electrodes in the field.

When designing an electrode address configuration for the vertical electrode arrays installed at Nantygwyddon, a number of important considerations were taken into account. As discussed by Goes and Meekes (2004), electrode configurations designed for cross-borehole ERT surveys commonly use arrangements where the current (AB) and potential (MN) dipoles are on separate arrays, i.e. AB-MN configurations. This may only be effective for closely-spaced vertical arrays as the signal to noise ratio would be much lower with borehole electrode arrays that are wide apart. AB-MN configurations therefore require the distance between borehole arrays to be less than the array lengths, i.e. the ratio of $y/x$ should be 1.5 or more. Furthermore, when the current (AB) dipole is applied to single arrays, electrical 'shorting' may occur in saturated ground resulting in restricted current flow into the surrounding medium and measurement of very low voltage potential, which may be obscured by noise.

Considering the distances between gas wells 'S', 'T','U' and the likely saturated ground conditions, an electrode address configuration including AM-BN arrangements would be more effective. On this basis, the current and potential dipoles are applied across both vertical electrode arrays with a number of advantages, as discussed in Goes and Meekes (2004). The potential dipole is measured across two vertical arrays and near the current dipole so that the potential differences will be fairly large and less susceptible to obscurement by background noise. Also, the current dipole is always applied across the two arrays forcing current flow through the ground between them. Therefore, a configuration was designed for the Nantygwyddon ERT system including AM-BN and AM-NB arrangements (Figure 6.7) on the basis that approximately horizontal perched and basal leachates may be defined by enhanced current flow through them, between vertical electrode array pairs.

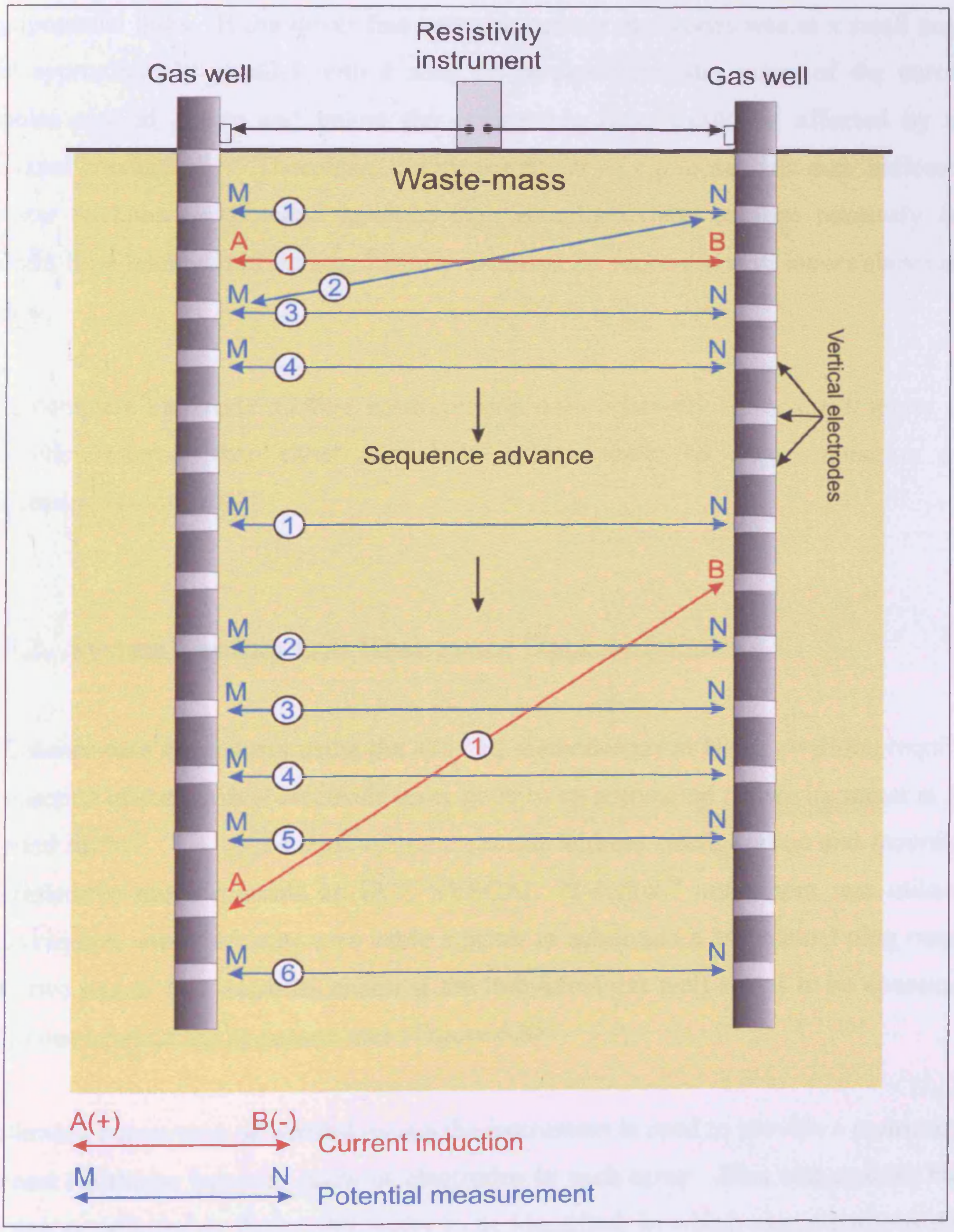



Figure 6.7: *Examples of AM-BN, AM-NB and MA-NB dipole-dipole arrangements considered to be effective for the Nantygwyddon ERT monitoring system.*

It was perceived that perched leachates may be highly localised and interspersed with more resistive layers of lower permeability. Therefore, to accurately define near horizontal localised conductive and resistive variations the arrangement of current dipoles must include some large angles resulting in a more significant change in equipotential lines. If the direct line between current electrodes was at a small angle and approximately parallel with a zone of perched leachate, many of the current dipoles applied above and below the conductive zone would be affected by the elevated conductivity. Therefore, the measurement of equipotentials may indicate a greater thickness of perched leachate than actually exists, because relatively few current flow lines would be significantly distorted by more-resistive layers above and below.

The complete electrode address configuration uses relatively fewer quadrapoles (4-elecrode patterns) than other cross-hole arrangements, so data acquisition and processing is more rapid.

### 6.5.2. System Testing and Resistance Data Acquisition

Resistance data acquisition using the adapted methodology at Nantygwyddon requires connection of the vertical electrode array pairs to an automated resistivity meter at the ground surface. For application of the electrode address configuration and recording of resistance measurements an IRIS SYSCAL 72-switch® instrument was utilised. This requires use of a multi-core cable adapter to subdivide a 36-channel plug output into two sets of 18 electrodes enabling the individual gas well arrays to be connected from one location in the survey area (Figure 6.8).

Following connection of vertical arrays the instrument is used to provide a measure of contact resistance between pairs of electrodes in each array. This test enables high contact resistances or faulty electrodes to be identified, in which case erroneous data points may be anticipated and subsequently removed from the dataset. Resistance measurements are recorded in the gas well sequence of S to T, S to U and U to T, and are processed to represent two-dimensional planes with distance and depth between the wells. Raw data is downloaded to laptop PC for processing on- or off-site.

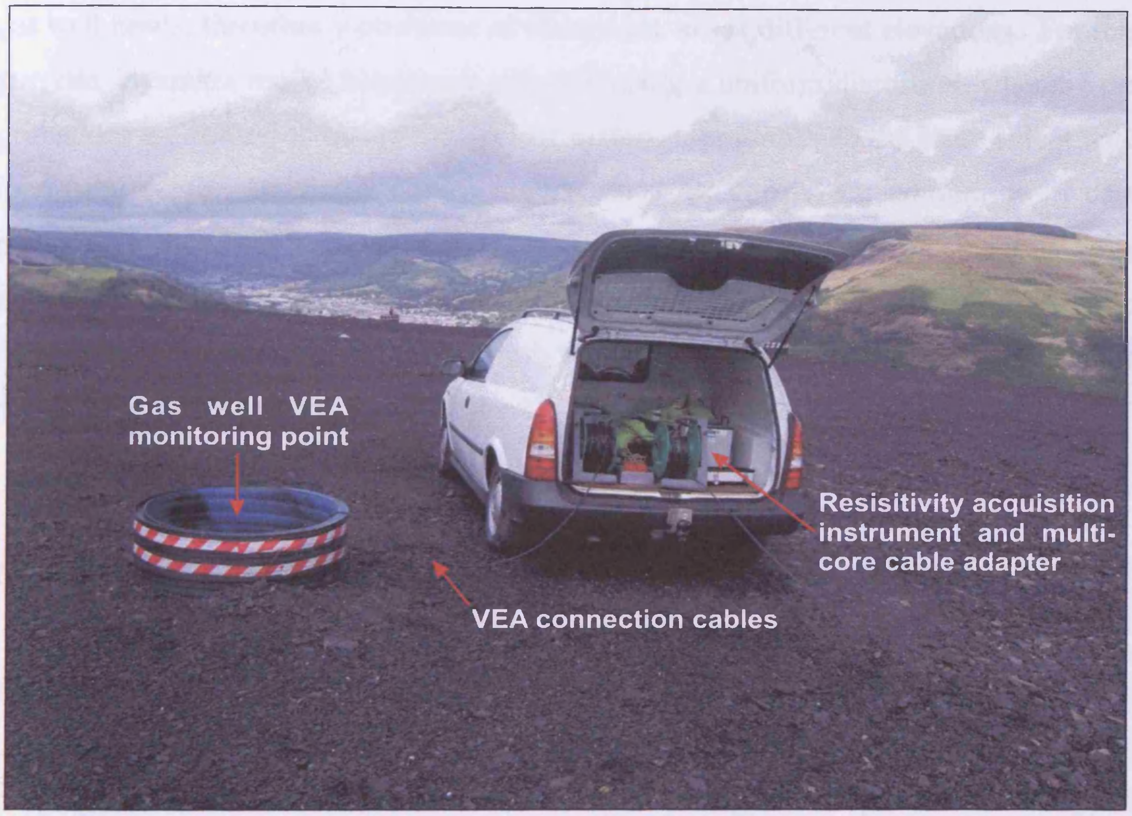



Figure 6.8: *A photograph illustrating the resistivity acquisition equipment in use at the closed Nantygwyddon landfill (author).*

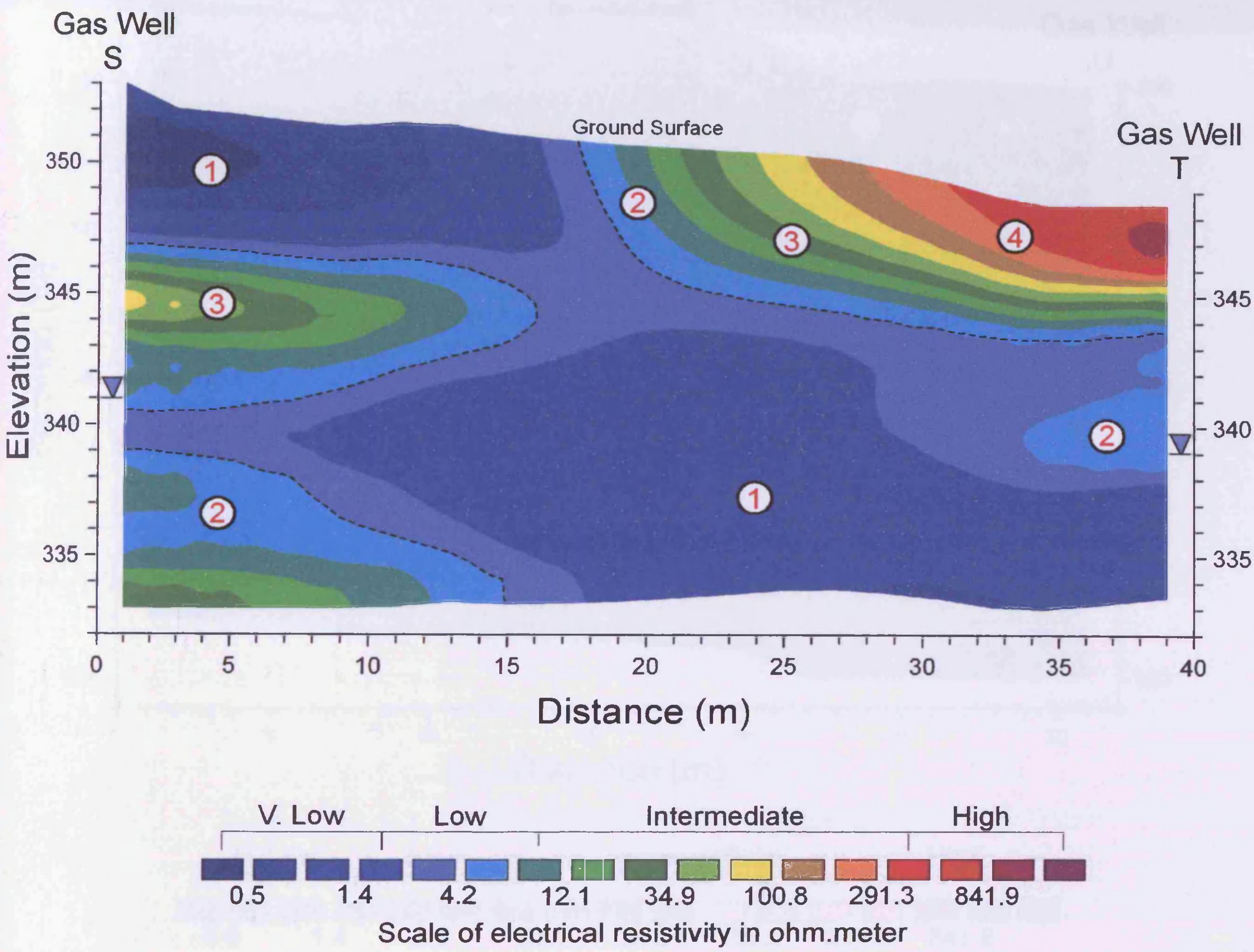
### 6.5.3. Data Processing

Processing of raw data follows a similar routine to that described in Section 5.6.3. Data is initially checked for errors using an editing programme (PROSYS®) supplied with the resistivity instrument. For optional modelling input, measurements are only included with a standard deviation of 3% or less and negative or zero apparent resistivity values are removed. Edited raw data is processed by least-squares inversion using a rectangular finite element grid with node dimensions corresponding to the electrode spacings (*after* Loke and Barker, 1996a). The inversion statistics for resistivity data acquired at Nantygwyddon are reproduced in Appendix IV. To obtain a reasonably uniform grid the distances between vertical electrode arrays (in the *x*-direction) must be subdivided to match the electrode separations in the *y*-direction. Inversion results are adjusted for the effects of ground surface topography because the gas well heads, therefore *y*-positions of electrodes, are at different elevations. For this purpose, inversion model blocks are adjusted using a uniform distortion, whereby the grid nodes are shifted to match the ground surface topography to the same extent with increasing depth. Inversion results are saved in *xyz* format for contouring of data points with SURFER® software. The final output for each vertical electrode array pair comprises a two-dimensional plot of contoured model resistivity values with distance between the gas wells and depth through the waste profile. A colour-scaled range in model resistivity is provided with each image for interpretation.

### 6.5.4. Baseline ERT Results Recorded Prior to Landfill Restoration

Prior to the installation of landfill capping, baseline conditions were recorded to enable a subsequent comparison of geoelectrical variations resulting from landfill capping and leachate extraction. ERT surveying using the adapted methodology at Nantygwyddon was performed on a single day during September 2005 immediately prior to commencement of restoration works. The baseline survey was performed under dry weather conditions, although prolonged rainfall had occurred during the previous week. Interpreted baseline survey results from the gas well configurations S to T, S to U and U to T are reproduced in Figures 6.9, 6.10 and 6.11 respectively.

Survey results are interpreted on the basis of variation in model resistivities. In general, during resistivity surveying across closed landfills very low to low resistivity values of around 2 to 10 ohm.meter are characteristic of saturation by leachate. Low to intermediate values of around 10 to 200 ohm.meter are usually indicative of damp wastes and rainwater ingress through to progressively drier ground conditions. High values up to and in excess of 500 ohm.meter are generally characteristic of dry conditions and presence of non-conducting materials. Leachate dip levels recorded from gas wells are indicated; this does not represent a calibration method, but enables the practice of gas well dip measurement to be scrutinised.




**Descriptive Annotations**

① Zones of very low resistivity indicate saturation by leachates

② Zones of low resistivity indicate wet ground conditions and dilute leachates

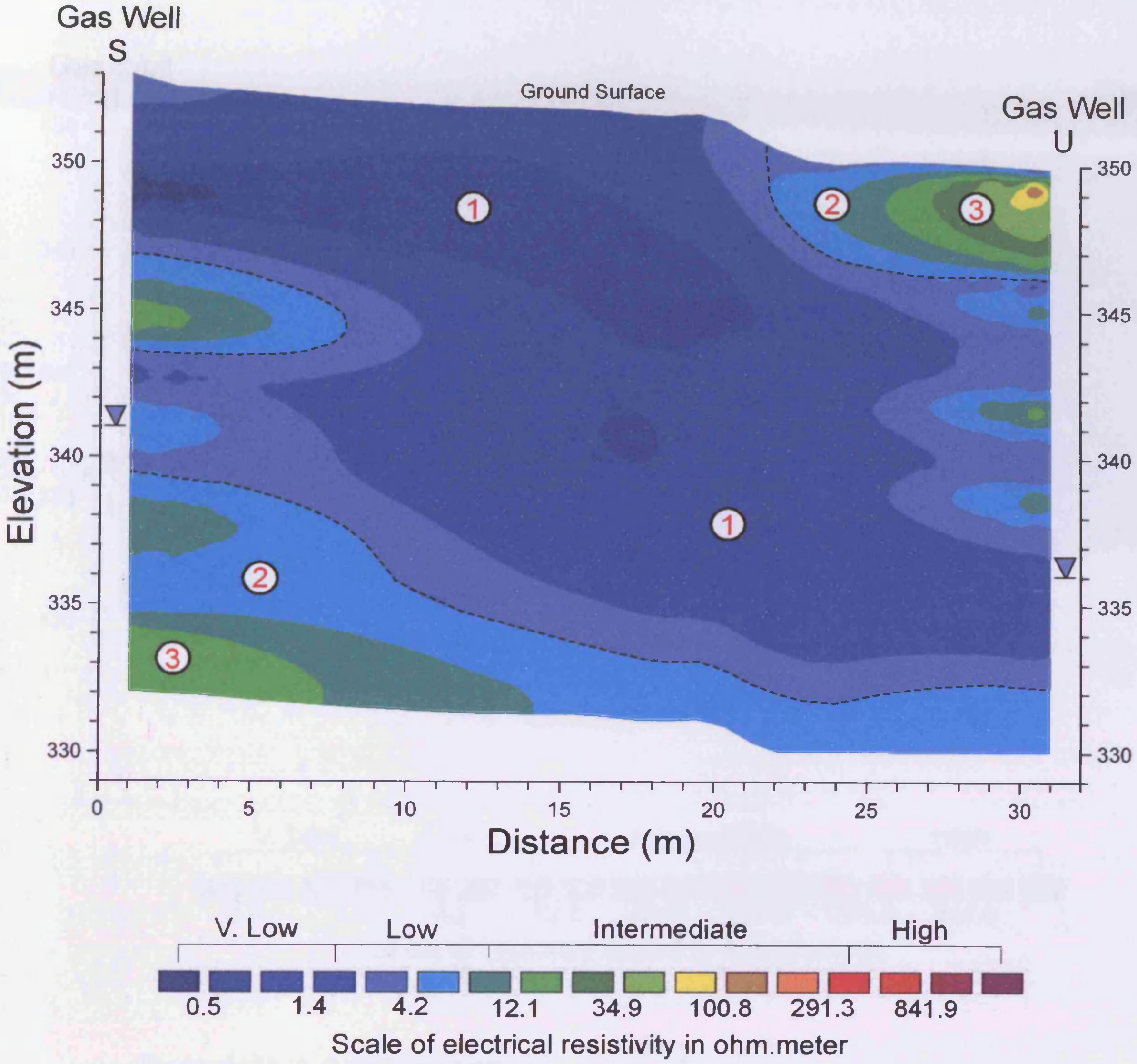
③ Zones of low to intermediate resistivity indicate damp, unsaturated waste

④ Zones of Intermediate to high resistivity suggest dry conditions

--------- Denotes inferred leachate table in waste-mass

▽ Denotes leachate dip level in gas well

Figure 6.9: *Baseline ERT results recorded between gas wells S to T during September 2005.*




**Descriptive Annotations**

(1) Zones of very low resistivity indicate saturation by leachates

(2) Zones of low resistivity indicate wet ground conditions and dilute leachates

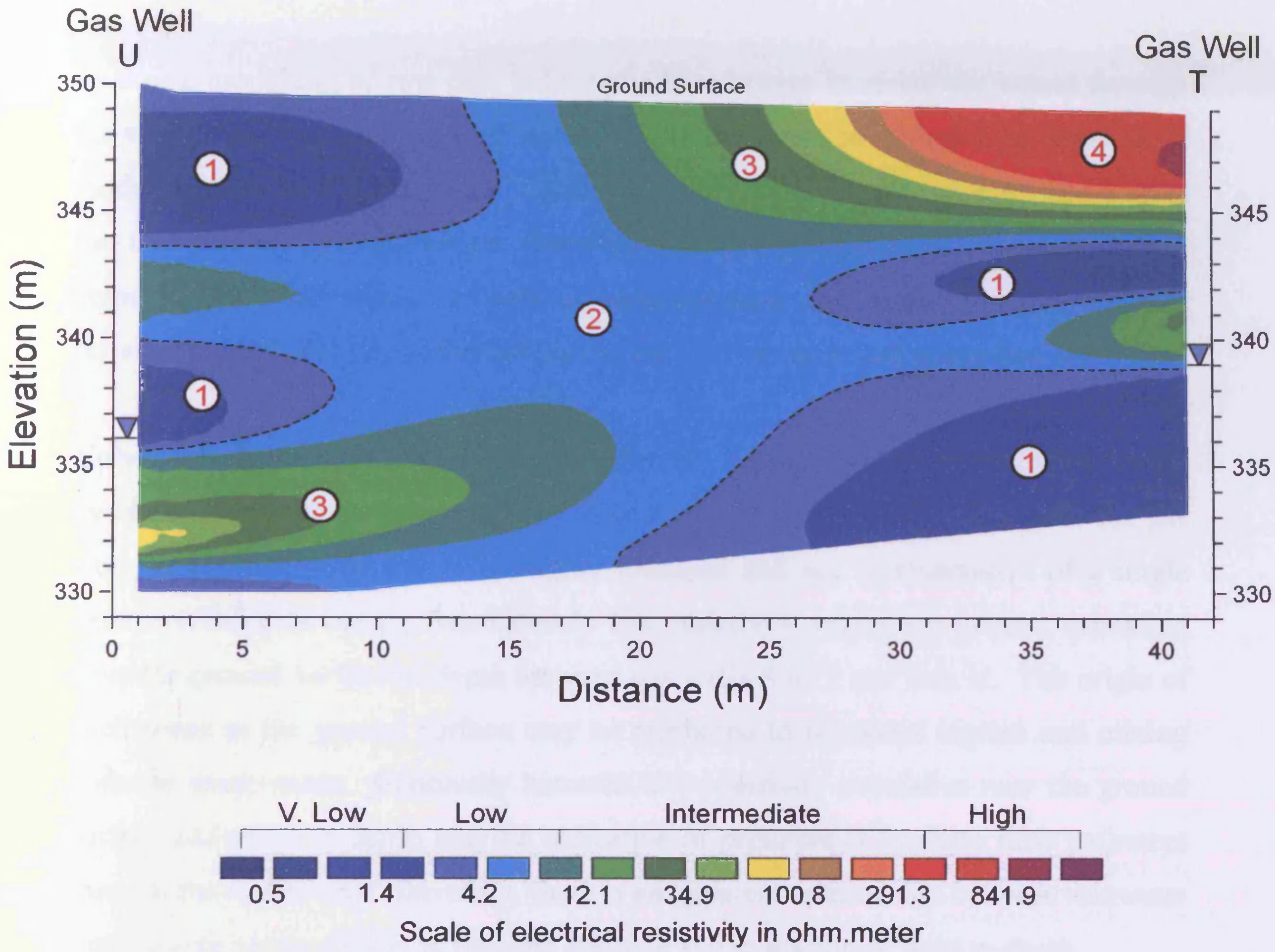
(3) Zones of low to intermediate resistivity indicate damp, unsaturated waste

(4) Zones of Intermediate to high resistivity suggest dry conditions

--------- Denotes inferred leachate table in waste-mass

▼ Denotes leachate dip level in gas well

Figure 6.10: *Baseline ERT results recorded between gas wells S to U during September 2005.*




**Descriptive Annotations**

① Zones of very low resistivity indicate saturation by leachates

② Zones of low resistivity indicate wet ground conditions and dilute leachates

③ Zones of low to intermediate resistivity indicate damp, unsaturated waste

④ Zones of Intermediate to high resistivity suggest dry conditions

---------- Denotes inferred leachate table in waste-mass

▼ Denotes leachate dip level in gas well

Figure 6.11: *Baseline ERT results recorded between gas wells U to T during September 2005.*

## 6.6. Interpretation of Baseline ERT Surveys

Inversion modelling of raw data indicated a broad range in resistivity values through the waste-mass between gas well vertical electrode arrays, as indicated by the scale of model resistivities in ohm.meter. Similar ranges in model resistivity were noted from the three survey configurations; therefore the ERT images were produced with a common scale in values for ease of interpretation and comparison. Very low resistivity of 0.5 Ωm was noted through to high values up to and exceeding 841.9 Ωm.

Very low to low resistivities (0.5 to 12.1 Ωm) are generally characteristic of saturation by electrically-conductive leachates. Zones of very low resistivity between the gas well configurations appear to be highly localised and not representative of a single extensive leachate body. Anomalously low resistivity values are evident extending from the ground surface to depth between gas wells S to T and S to U. The origin of such zones at the ground surface may be attributed to rainwater ingress and mixing with the waste-mass. Continuity between low resistivity anomalies near the ground surface and those at depth may be indicative of preferential leachate flow pathways through the waste-mass; therefore, there is an apparent relationship between rainwater ingress with accumulation of perched leachate and migration of fluid to depth.

A broad range in intermediate resistivities (12.1 to 291.3 Ωm) is characteristic of wet through to dry ground conditions. Between the gas well configurations, intermediate values appear to separate saturated horizons, possibly indicating that leachate bodies are perched over zones where a greater degree of waste compaction has resulted in lower permeability.

High resistivities in the model scale were noted near to the ground surface in proximity to gas well T, which are indicative of dry and/or highly compacted ground conditions.

A baseline ERT survey has indicated extensive, but localised leachate saturation within the waste-mass, which is directly affected by rainwater ingress through the temporary landfill cap. The localised nature of leachate saturation may explain the apparent discrepancies over various methods used to measure leachate dip levels. It may be inferred that gas well dip measurements are representative of leachate accumulation at depth, whereas perched leachates are unidentified. Results of ERT surveying correlate more closely with dip levels recorded from piezometer installations through the waste-mass at Nantygwyddon, which indicate leachate bodies ranging between 8 to 17 metres and 18 to 25 metres above the basal liner. However, it was determined from piezometer levels that basal leachates were not in continuity with perched water tables above, whereas ERT surveying appeared to indicate the opposite at the time of the baseline survey.

## 6.7 Geoelectrical Sub-Surface Characteristics Following Site Restoration

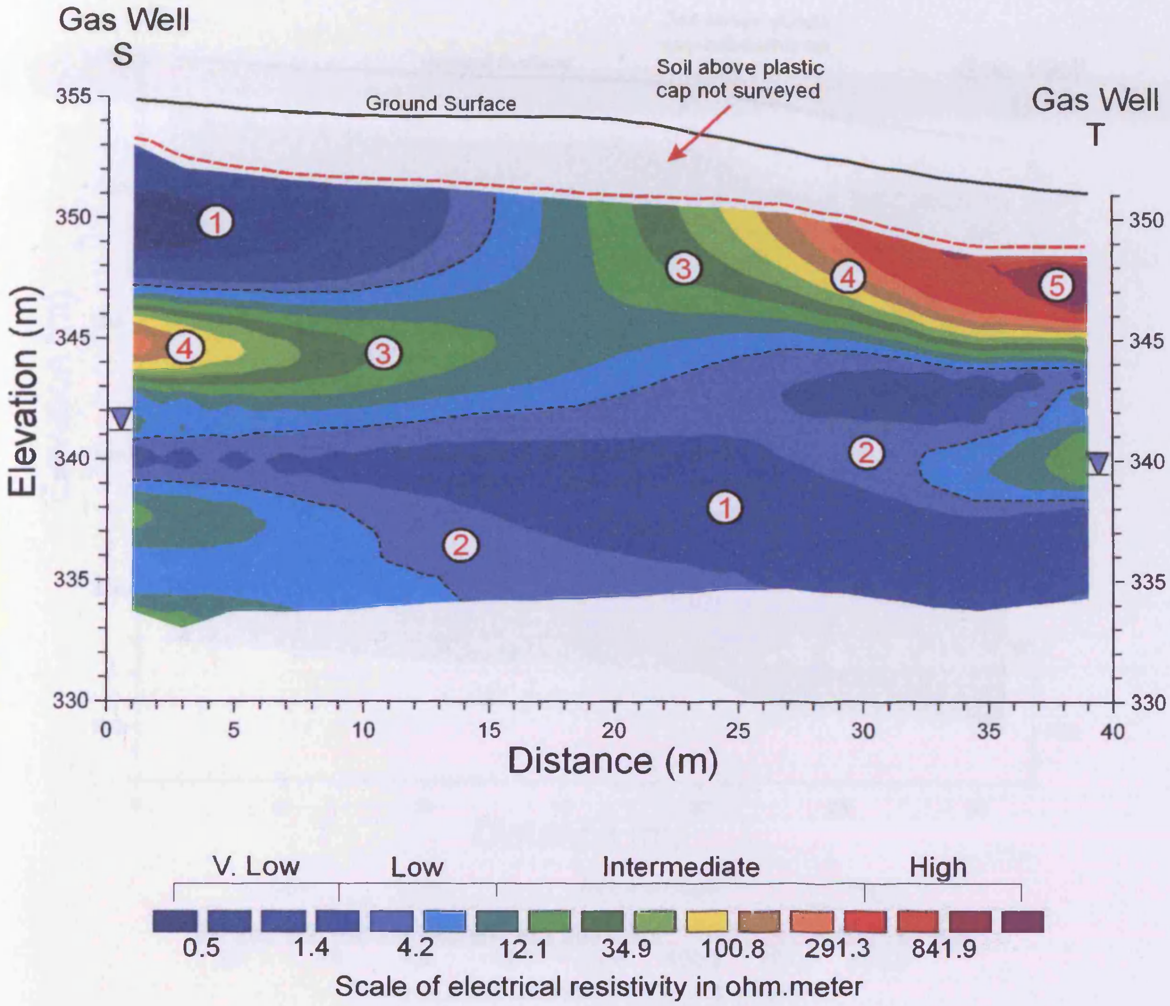
### 6.7.1. Restorative Works and Continuation of ERT Monitoring

Following closure of the Nantygwyddon landfill, a temporary soil cap was used to cover the Phase I waste-mass. Subsequent restoration between September 2005 and January 2006 involved the emplacement of an engineered capping system comprising a welded LDPE (low density polyethylene) impermeable membrane with a soil cover of up to 2 metres thickness. In addition, leachate extraction is undertaken using pumps installed in gas wells on a trial basis.

An initial baseline ERT survey of sub-surface characteristics between gas wells S, T and U performed during September 2005 had identified leachate saturation and drier wastes on the basis of typical geoelectrical signatures. It was anticipated that the effects of restorative capping and leachate extraction may be observed through variation in geoelectrical characteristics with respect to the baseline ERT results. With exclusion of rainwater ingress, zones of very low resistivity originating at the ground surface may be expected to diminish indicating establishment of drier conditions, which would be inferred from an increase in resistivity. It was further expected that the exclusion of rainwater ingress would result in a break in continuity between perched and basal leachate-saturated zones. On the basis of these anticipated outcomes, a repeated ERT survey 1 month after landfill capping would be performed to assess the effects of rainwater exclusion with depth through the waste profile. Gas well S was retro-fitted with a trial leachate extraction pump 1 month after completion of site capping. It was anticipated that the effects of leachate pumping from gas well S would be visualised by performing a repeat ERT survey after 1 month of leachate extraction to assess the variation in geoelectrical signature in proximity to the well and by comparison with the previous survey results.

### 6.7.2. ERT Survey Results Following Site Restoration

A repeat ERT survey was undertaken 1 month after completion of site capping, by utilising the adapted methodology as performed for the baseline survey. The survey was performed on a single day during January 2006 and under dry weather conditions, although rainfall had occurred over the previous day. Interpreted ERT results from the gas well configurations S to T, S to U and U to T during January 2006 are reproduced in Figures 6.12, 6.13 and 6.14 respectively. Further to this, a second repeat survey was undertaken 1 month after installation of a leachate extraction pump in gas well S and corresponding to a period of 2 months after completion of landfill capping. The second repeat ERT survey was performed on a single day in February 2006 and under damp weather conditions, although the previous week had been dry. Interpreted ERT results during February 2006 are reproduced in Figures 6.15, 6.16 and 6.17 respectively. Repeated ERT surveying has recorded geoelectrical ground characteristics from below the position of the LDPE cap. Characteristics of the capping medium and overlying soil cover have not been surveyed due to the position of the topmost gas well electrodes being below the cap and the electrical insulating effects of LDPE plastic. Surface topography surveyed between the gas well configurations following completion of capping works has been included for reference of the ground surface position. As discussed in Section 6.5.4, leachate dip levels from the gas wells are indicated for comparison with the ERT results and enable the practice of gas well dip measurement to be scrutinised. Installation of a leachate extraction pump in gas well S prevented further dip levels to be obtained from the well.




**Descriptive Annotations**

① Zones of very low resistivity indicate saturation by leachates

② Zones of low resistivity indicate wet ground conditions and dilute leachates

③ Zones of low to intermediate resistivity indicate damp, unsaturated waste

④ Zones of Intermediate to high resistivity suggest dry conditions

⑤ Zones of high resistivity indicate the insulating effect of LLDPE

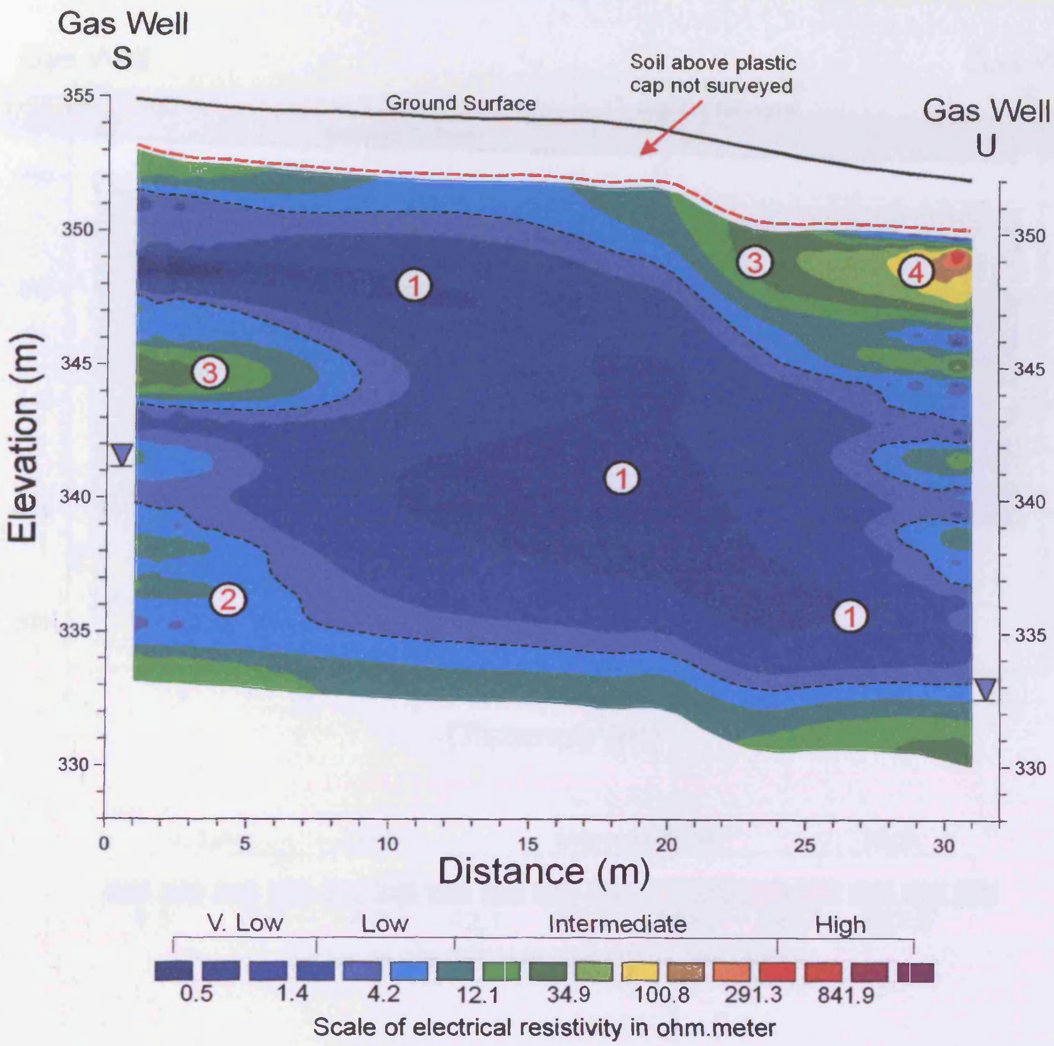
——— Post-capping topography

- - - - (red) Approximate position of LLDPE cap

- - - - - - - - - Denotes inferred leachate table in waste-mass

▼ Denotes leachate dip level in gas well

Figure 6.12: *ERT results between gas wells S to T recorded during January 2006, one month after completion of landfill capping.*




**Descriptive Annotations**

① Zones of very low resistivity indicate saturation by leachates

② Zones of low resistivity indicate wet ground conditions and dilute leachates

③ Zones of low to intermediate resistivity indicate damp, unsaturated waste

④ Zones of Intermediate to high resistivity suggest dry conditions

⑤ Zones of high resistivity indicate the insulating effect of LLDPE

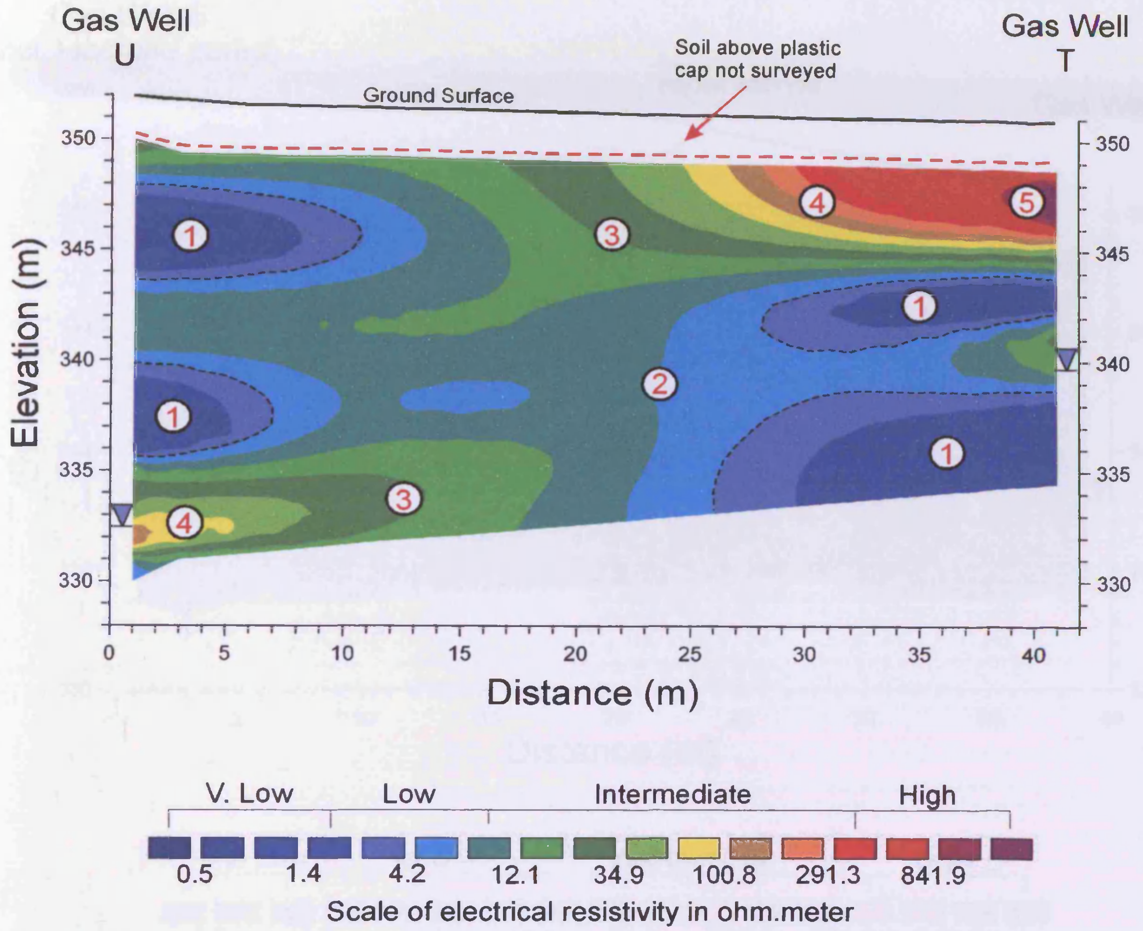
——— Post-capping topography

- - - - (red) Approximate position of LLDPE cap

- - - - Denotes inferred leachate table in waste-mass

▽ Denotes leachate dip level in gas well

Figure 6.13: *ERT results between gas wells S to U recorded during January 2006, one month after completion of landfill capping.*




**Descriptive Annotations**

① Zones of very low resistivity indicate saturation by leachates

② Zones of low resistivity indicate wet ground conditions and dilute leachates

③ Zones of low to intermediate resistivity indicate damp, unsaturated waste

④ Zones of Intermediate to high resistivity suggest dry conditions

⑤ Zones of high resistivity indicate the insulating effect of LLDPE

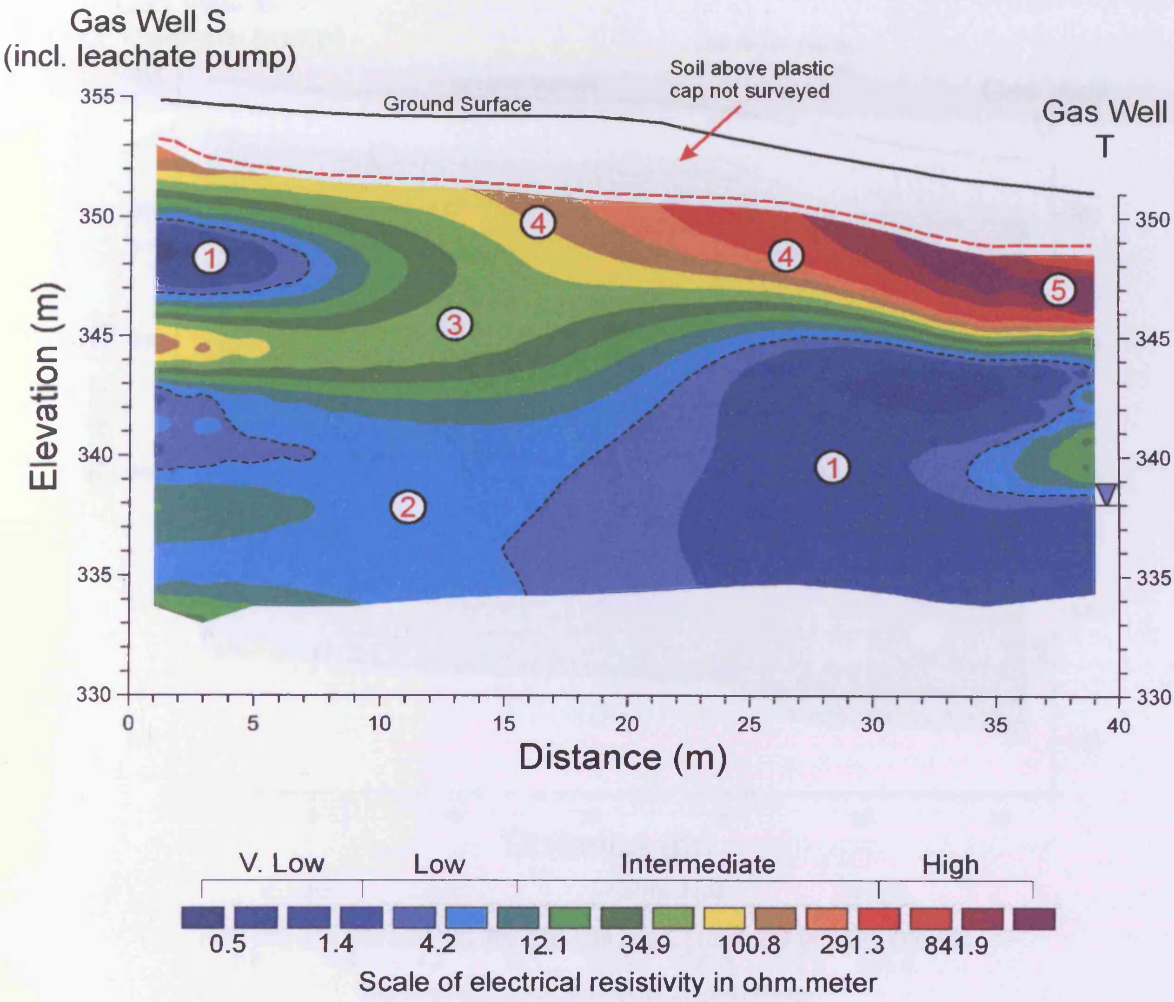
———— Post-capping topography

- - - - - - (red) Approximate position of LLDPE cap

- - - - - - Denotes inferred leachate table in waste-mass

▼ Denotes leachate dip level in gas well

Figure 6.14: *ERT results between gas wells U to T recorded during January 2006, one month after completion of landfill capping.*




**Descriptive Annotations**

(1) Zones of very low resistivity indicate saturation by leachates

(2) Zones of low resistivity indicate wet ground conditions and dilute leachates

(3) Zones of low to intermediate resistivity indicate damp, unsaturated waste

(4) Zones of Intermediate to high resistivity suggest dry conditions

(5) Zones of high resistivity indicate the insulating effect of LLDPE

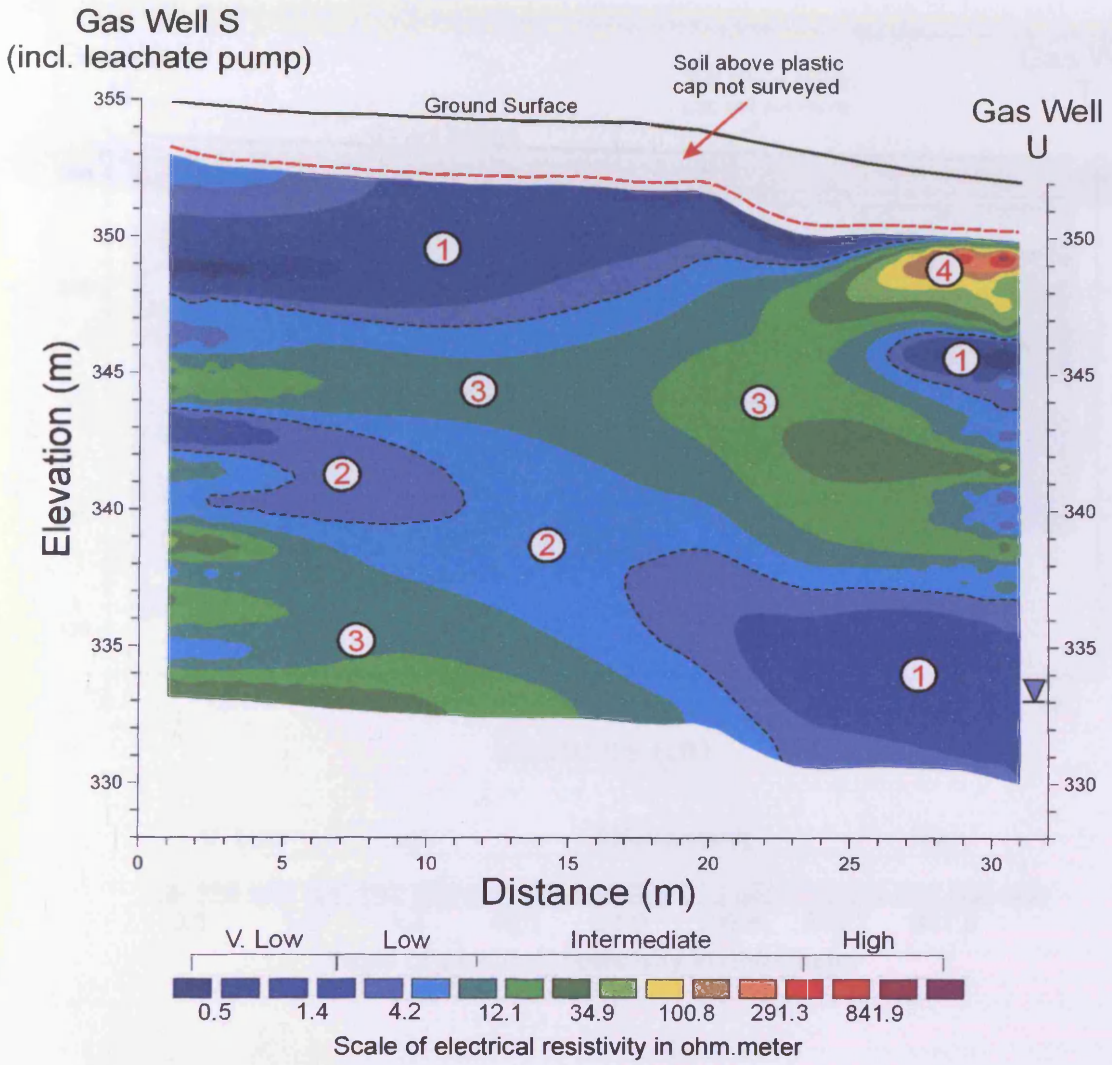
———— Post-capping topography

- - - - (red) Approximate position of LLDPE cap

- - - - Denotes inferred leachate table in waste-mass

▼ Denotes leachate dip level in gas well

Figure 6.15: *ERT results between gas wells S to T recorded during February 2006 after one month of leachate pumping.*




**Descriptive Annotations**

① Zones of very low resistivity indicate saturation by leachates

② Zones of low resistivity indicate wet ground conditions and dilute leachates

③ Zones of low to intermediate resistivity indicate damp, unsaturated waste

④ Zones of Intermediate to high resistivity suggest dry conditions

⑤ Zones of high resistivity indicate the insulating effect of LLDPE

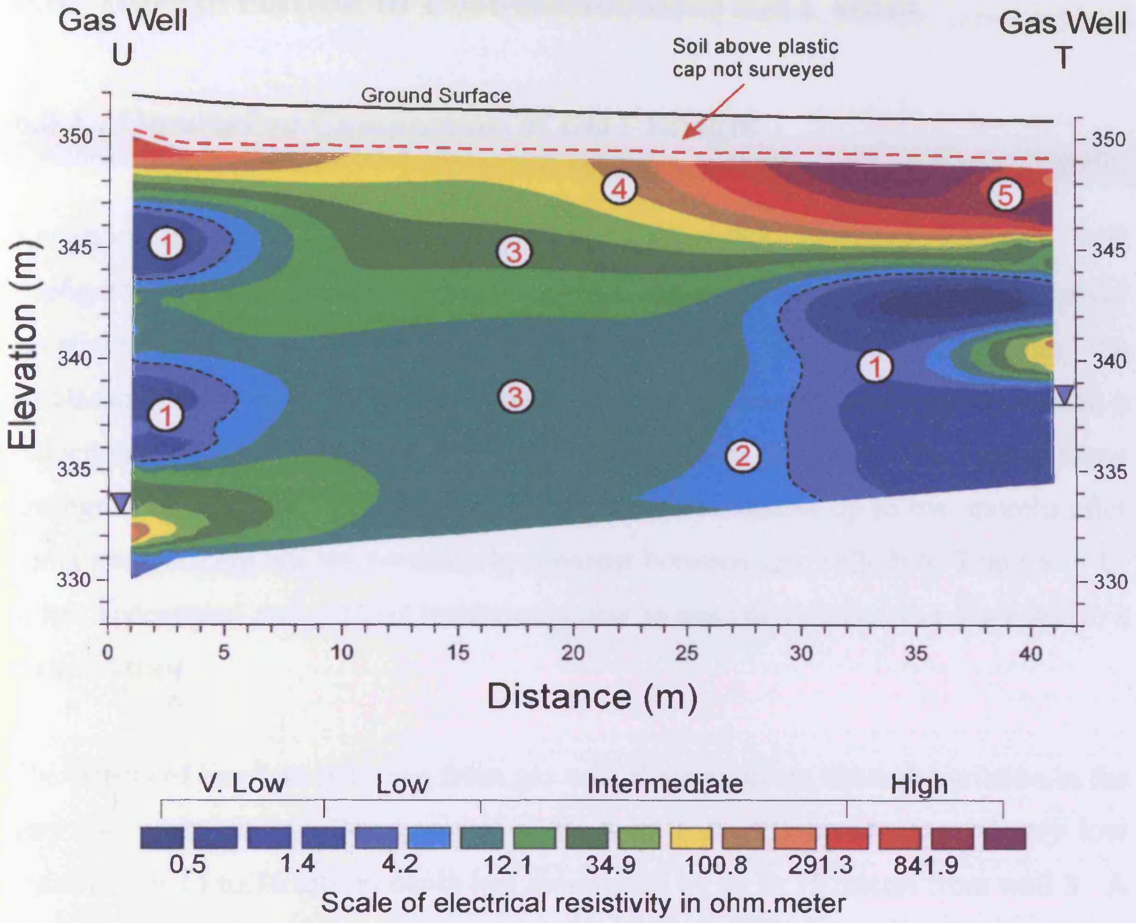
———— Post-capping topography

- - - - - (red) Approximate position of LLDPE cap

- - - - - Denotes inferred leachate table in waste-mass

▼ Denotes leachate dip level in gas well

Figure 6.16: *ERT results between gas wells S to U recorded during February 2006 after one month of leachate pumping.*




**Descriptive Annotations**

① Zones of very low resistivity indicate saturation by leachates

② Zones of low resistivity indicate wet ground conditions and dilute leachates

③ Zones of low to intermediate resistivity indicate damp, unsaturated waste

④ Zones of Intermediate to high resistivity suggest dry conditions

⑤ Zones of high resistivity indicate the insulating effect of LLDPE

——————— Post-capping topography

- - - - - - - - - (red) Approximate position of LLDPE cap

- - - - - - - - - Denotes inferred leachate table in waste-mass

▼ Denotes leachate dip level in gas well

Figure 6.17: *ERT results between gas wells U to T recorded during February 2006 after one month of leachate pumping.*

# 6.8. Interpretation of Post-Restorative ERT Data

## 6.8.1. Qualitative Comparison of ERT Images

Variation in sub-surface geoelectrical characteristics between the gas well configurations after landfill capping is apparent from visual inspection of the model resistivity images (Figures 6.9 to 6.17). Assuming zero rainwater ingress, the emplacement of a plastic capping membrane and exclusion of rainwater has caused a reduction in zones of very low to low resistivity (0.5 to 21.1 Ωm), these zones being analogous to saturation by leachates. Geoelectrical variations up to two months after completion of capping are particularly apparent between gas wells S to T and S to U, where widespread and perched leachates appear to have diminished and dispersed to a certain extent.

The effects of leachate pumping from gas well S are apparent through variation in the very low resistivities. Between gas wells S to T a widespread zone of very low resistivity at 14 to 16 metres depth had diminished by up to 15 metres from well S. A similar pattern of variation is observed between gas wells S to U, where very low resistivities had diminished below 15 metres depth and up to 15 metres away from well S.

Between gas wells U to T the scattered localised very low resistivity zones identified by the baseline survey were still apparent one month after completion of landfill capping; however the widespread low resistivity zone through which the localised perched leachates were in continuity was less significant.

After a period of two months from completion of landfill capping, zones of intermediate to high resistivity (>200 Ωm) were apparent directly below the plastic cap between gas well configurations S to T and U to T. An increase in resistivities in the near-surface corresponds to establishment of drier ground conditions with exclusion of rainwater ingress. However, between gas wells S to U, a zone of very low to low resistivity persisted in the near-surface directly below the plastic cap up to two months after capping. If zero rainwater ingress is assumed, the persistence of very low to low resistivity must be attributed to lateral migration of leachate from outside the survey area.

By visual comparison of the model resistivity plots, changes in sub-surface resistivity can only be attributed to desaturation resulting from capping and rainwater exclusion. However, geoelectrical variation may also be due to changes in fluid resistivity, i.e. leachates becoming dilute and less conductive, or concentrated and more conductive. The cause of resistivity variations may be further visualised by analysing percentage change in model resistivities up to two months after completion of capping in relation to the baseline data.

### 6.8.2. Analysis of Percentage Change in Resistivity

Percentage change in resistivity of the sub-surface between the gas wells was calculated for the inversion model grid node values in each configuration, whereby calculations were made for the intervals of one month and two months after completion of capping and in relation to the baseline data. Calculations indicate the percentage value by which the resistivity for each model grid node has increased or decreased in relation to the baseline survey resistivity values. Results of percentage change calculations are reproduced as images of contoured and colour-scaled resistivity increase/decrease in the sub-surface with distance and depth between the gas well configurations (Figures 6.18 to 6.23).

Large percentage increases and decreases in resistivity were observed, but must be treated with caution and compared to the model resistivity images. For example, a portion of the sub-surface may be marked by a 100% increase in resistivity, however if the initial resistivity was 2 Ωm and had increased to 4 Ωm the ground remains saturated, but the resistivity of the fluid has changed. Within zones of persistent leachate saturation (0.5 to 12.1 Ωm), it may be perceived that increases in resistivity are due to desaturation and dispersal, whereas decreases are attributed to increases in concentration of leachate, assuming zero rainwater input.

Between gas wells S to T, model resistivity variations indicate an apparent reduction in perched leachate and a break in continuity with deeper saturated zones up to two months after capping. In addition, intermediate to high resistivities (>200 Ωm) had developed directly below the cap indicating establishment of drier conditions. In this configuration, zones of persistent saturation are characterised by strong percentage increases in resistivity, which is analogous to desaturation if zero rainwater ingress is assumed. Saturated zones also show strong percentage decreases in resistivity, the most significant being evident two months after capping at 25 to 35 metres distance and 7 to 11 metres depth. Percentage change in resistivity may indicate the effects of leachate pumping from gas well S; however, percentage increase analogous to desaturation is only apparent within a localised zone at 16 to 19 metres depth and up to 8 metres from the well.

Between gas wells S to U, model resistivity images appeared to show little variation in the widespread very low to low resistivity zone characterising much of the sub-surface one month after capping. However, the plot of percentage change after one month showed a strong increase in near-surface resistivities directly below the cap and also within the zone of very low to low resistivities. These variations may be attributed to desaturation if zero rainwater input is assumed. Within the zone of inferred leachate saturation, strong decreases of up to -100% were observed, indicating concentration of leachate attributed to exclusion of rainwater.

Two months after capping, the model resistivity image between gas wells S to U indicates apparent dispersal within the widespread zone of very low to low resistivities and is reflected by a large zone of strong percentage resistivity increase indicating desaturation. The model resistivity image two months after capping appears to indicate leachate saturation persisting directly below the cap. Conversely, the corresponding plot of percentage change showed an increase in resistivity within this zone indicating desaturation, with exception of an area of up to -50% decrease corresponding to localised concentration of leachate. A zone of strong percentage decrease between 10 to 20 metres depth and up to 18 metres from well S had disappeared after one month of leachate pumping, being replaced by low to moderate increases in percentage change, which may be attributed to leachate extraction and desaturation.

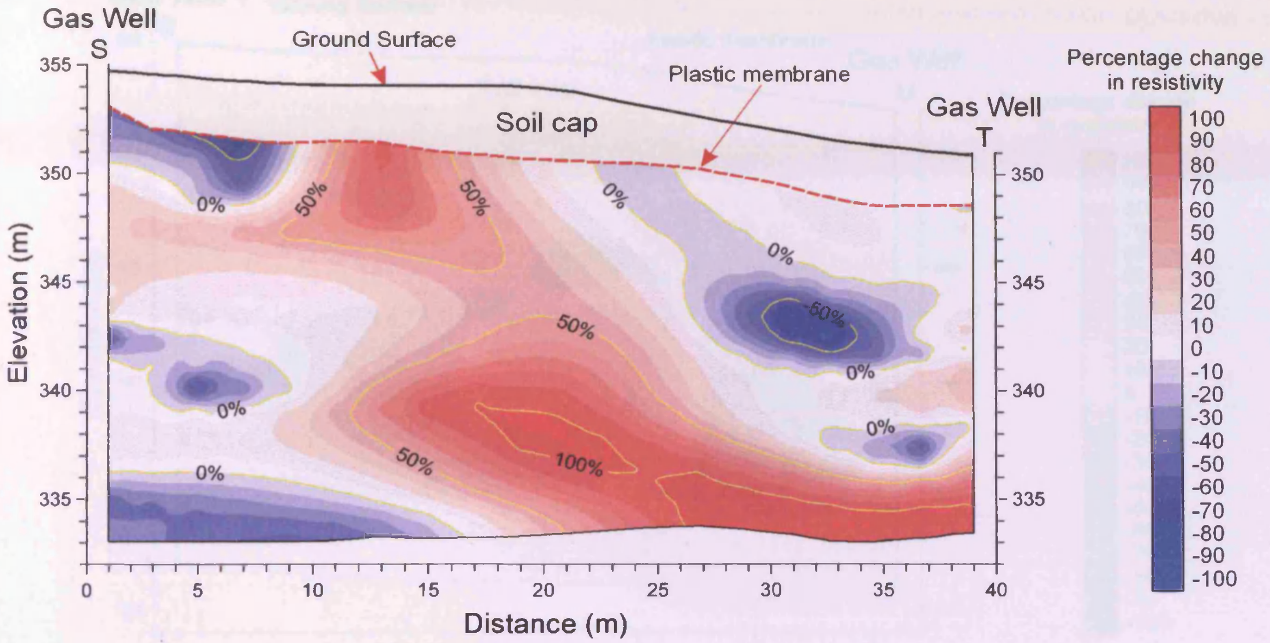



Figure 6.18: *Percentage change in resistivity of the sub-surface between gas wells S to T one month after completion of landfill capping.*

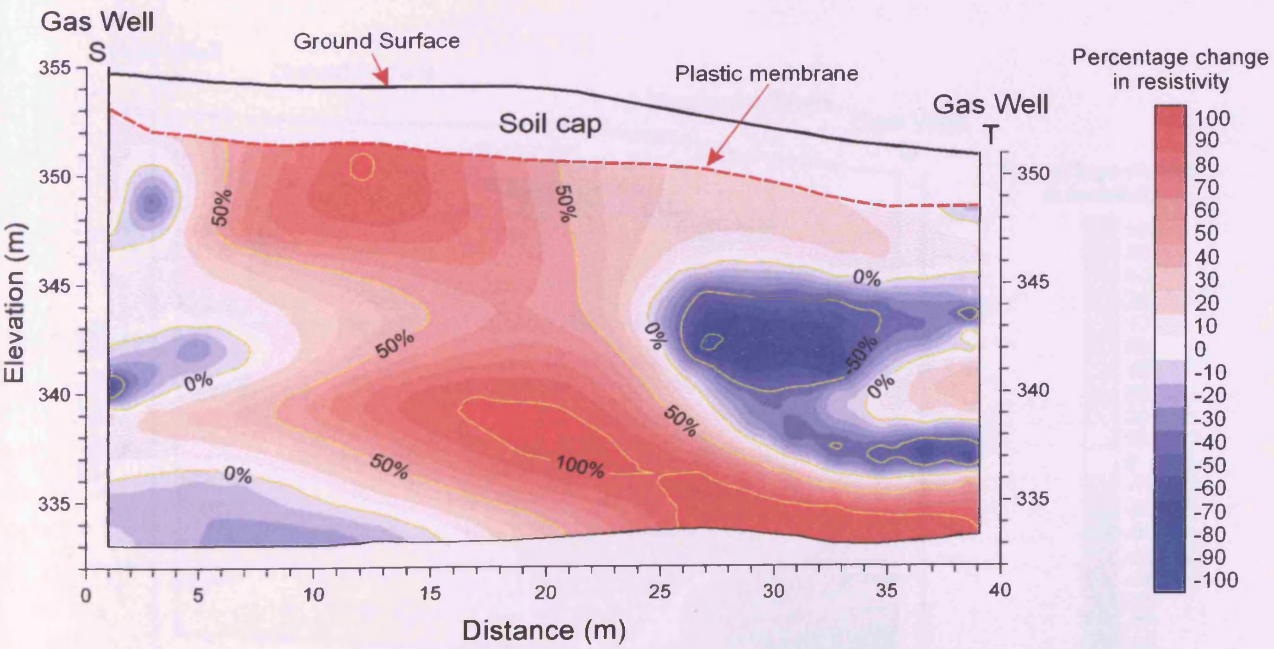



Figure 6.19: *Percentage change in resistivity of the sub-surface between gas wells S to T two months after completion of landfill capping and following one month of leachate extraction.*

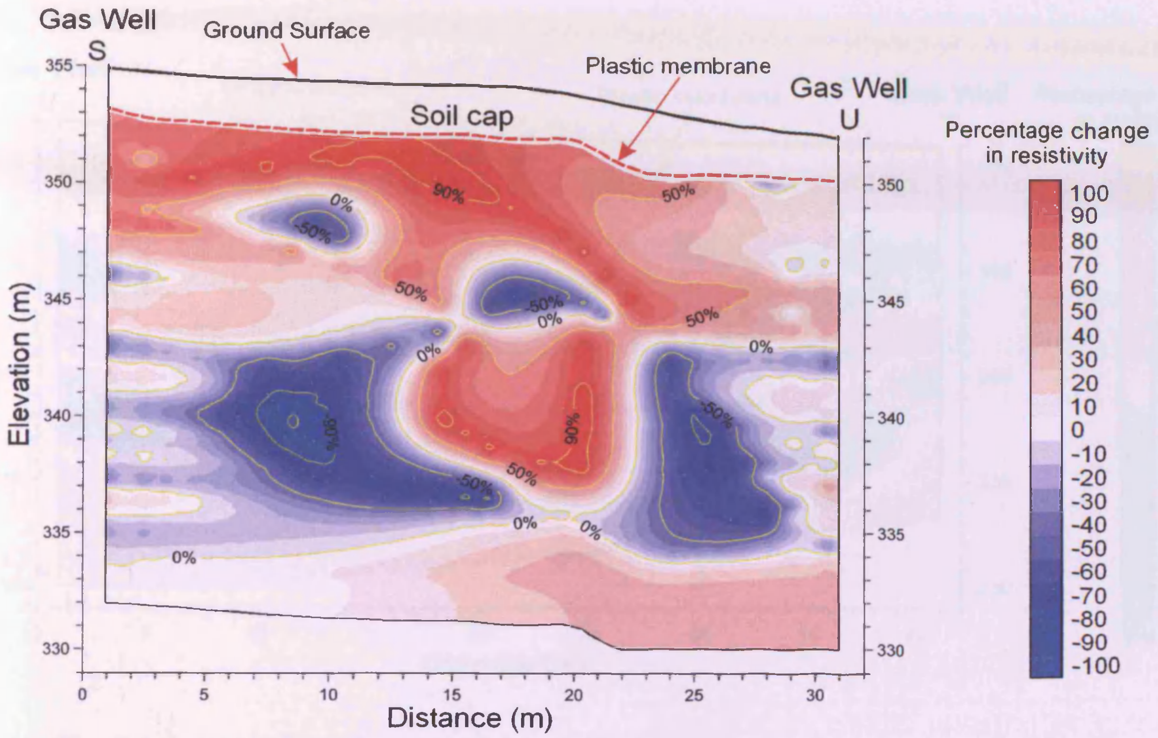



Figure 6.20: *Percentage change in resistivity of the sub-surface between gas wells S to U one month after completion of landfill capping.*

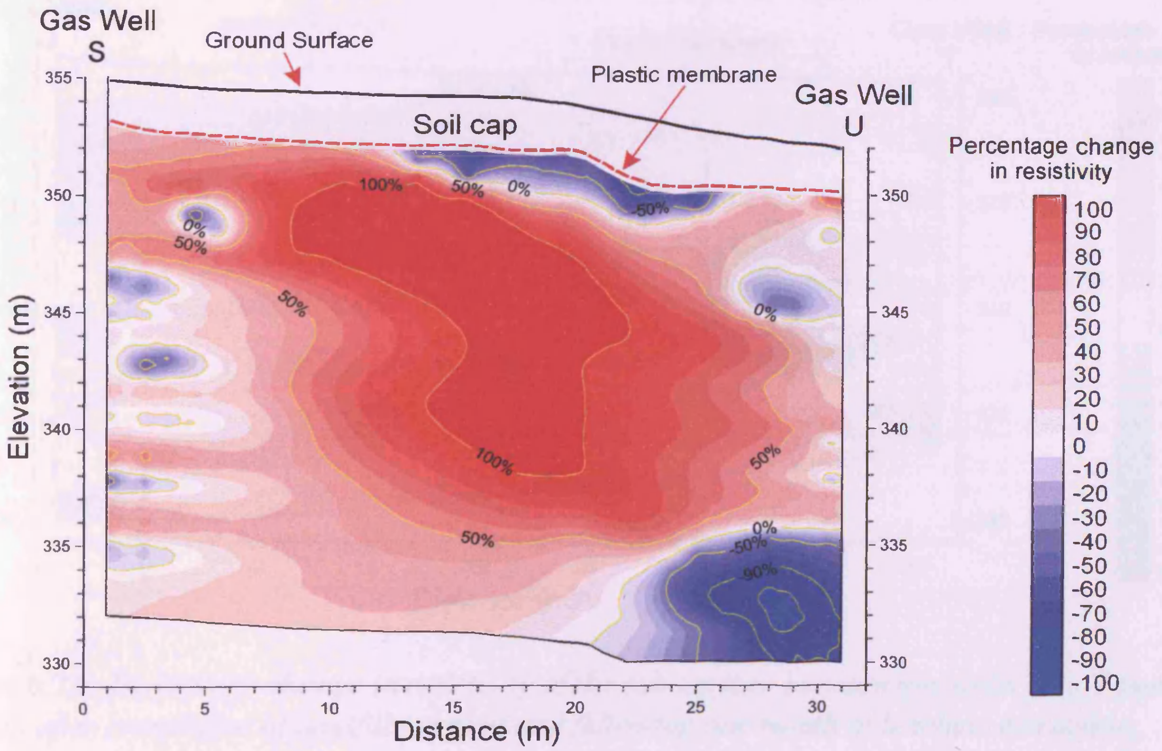



Figure 6.21: *Percentage change in resistivity of the sub-surface between gas wells S to U two months after completion of landfill capping and following one month of leachate extraction.*

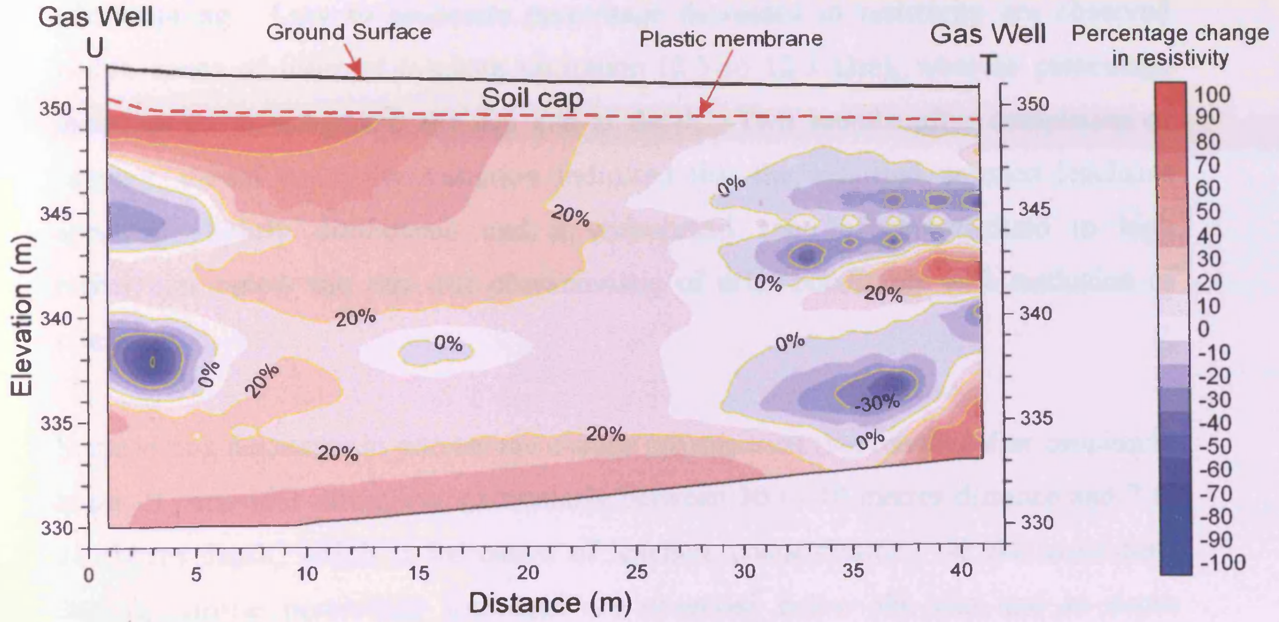



Figure 6.22: *Percentage change in resistivity of the sub-surface between gas wells U to T one month after completion of landfill capping.*

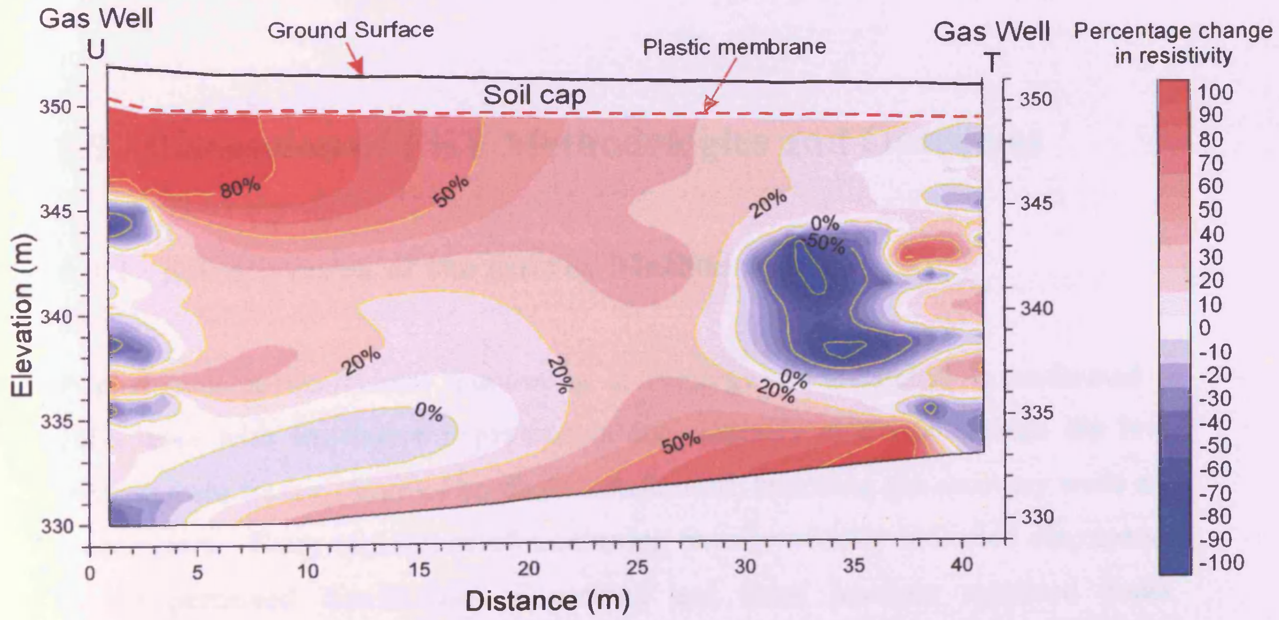



Figure 6.23: *Percentage change in resistivity of the sub-surface between gas wells U to T two months after completion of landfill capping and following one month of leachate extraction.*

Between gas wells U to T, little variation is observed in model resistivities one month after capping. Low to moderate percentage decreases in resistivity are observed within zones of inferred leachate saturation (0.5 to 12.1 Ωm), whereas percentage increases are noted below the cap and at depth. Two months after completion of capping, model resistivity variation indicated that the localised perched leachates appeared slightly diminished and a widespread zone of intermediate to high resistivities below the cap was characteristic of drier conditions with exclusion of rainwater.

Some strong decreases in percentage change are apparent two months after capping in zones of persistent saturation, particularly between 30 to 40 metres distance and 7 to 14 metres depth, which is indicative of leachate concentration. At the same time interval, strong percentage increases are observed below the cap and at depth indicating desaturation of the waste profile. Variation in model resistivities and percentage resistivity increase/decrease changes between gas wells U to T are attributed to the effects of capping and rainwater exclusion only as leachate extraction from well S appears to have only a localised effect in proximity to that well.

## 6.9. Discussion of ERT Methodologies and Outcomes

### 6.9.1. Effectiveness of the Survey Methods

Post closure environmental monitoring at Nantygwyddon landfill is performed in accordance with legislative requirements and routinely involves leachate dip level measurement from a range of borehole installations, including gas recovery wells and piezometers. These techniques of monitoring have previously indicated discrepancy in the perceived distribution of perched and basal leachate saturated zones. Accordingly an additional method for waste-mass characterisation was required including the potential for geophysical ground investigation, whereby ERT would be a particularly relevant technique. However, due to the constraints associated with conventional ERT surveying along the ground surface, the need for an adapted resistivity measurement methodology was identified.

A technique was required which could be utilised in a closed landfill setting to provide a greater degree of resolution and accuracy with depth through a waste profile enabling perched and basal leachates to be identified and differentiated. Furthermore, with planned landfill restoration at Nantygwyddon it was intended that the adapted ERT technique should be used to characterise geoelectrical variations attributed to capping, rainwater exclusion and leachate pumping.

An adapted ERT methodology for the closed landfill setting utilises pairs of vertical electrode arrays installed with increasing depth through the waste profile. For this purpose a unique electrode address configuration was required, which includes arrangements of current (AB) and potential (MN) electrodes. Measurements of resistance are acquired from the sub-surface with distance and depth between vertical arrays and are processed by least-squares inversion to produce an image of contoured and colour-scaled model resistivities within a two-dimensional plane.

The effectiveness of the adapted ERT monitoring technique lies with the arrangement of resistivity measurement electrodes and configurations for application of electrical current and measurement of voltage potentials. Installation of vertical electrode arrays was performed in a cost-effective manner utilising routine drilling and gas well emplacement. Vertical electrode arrays were mounted onto gas well casings and are permanently installed, therefore the modified technique can be regarded as retrospective, i.e. it can be applied after closure of a landfill.

Considering the distances between vertical arrays at Nantygwyddon and the likely saturated ground conditions, an electrode address configuration was devised including AM-BN, AM-NB and MA-NB arrangements. Current dipoles are always applied across a pair of arrays, forcing current flow through the ground between. Potential dipoles are always measured across the two arrays and near the current dipole so that the potential differences will be fairly large and less susceptible to background noise. Large current dipole angles were included to provide a more significant change in equipotentials enabling vertical variations to be more accurately defined.

ERT data recovery was performed prior to landfill capping and trial leachate pumping enabling baseline conditions to be identified. Baseline survey results indicated localised perched leachates and widespread zones of saturation across the three gas well electrode array configurations. A repeated ERT survey at intervals of one and two months after completion of capping indicated apparent reduction in leachate saturation. By calculating percentage change in resistivity it was apparent that large percentage increases were attributed to desaturation and decreases were due to increased ionic concentrations in leachates, if zero rainwater input is assumed.

Gas well dip measurements were indicated on the ERT images. If the ERT results are taken to be accurate, comparison indicated that gas well leachate measurements tend to be more representative of leachate saturation at depth, that they do not define an actual leachate head, and are not indicative of perched leachates.

The adapted ERT technique has a number of advantages making it attractive to landfill site stakeholders, mainly that the equipment is installed in a cost-effective manner, it enables rapid and repeated monitoring, and correlation between point observation locations. A disadvantage encountered with this technique is the limited provision for calibration, for which ideally piezometers should be utilised.

### 6.9.2. Further Capabilities for ERT Monitoring of Closed Landfills

After installation within a closed landfill, the vertical electrode arrays may be used for regular repeated ERT monitoring culminating in timelapse interpretation and analysis of percentage resistivity change. During capping of a closed site, gas wells and observation boreholes are extended vertically to account for increased ground surface elevation. Therefore, the adapted ERT technique provides a geophysical tool for monitoring closed landfills after capping with HDPE/LDPE materials, which would render conventional ground surface geoelectrical surveying impossible due to the electrical insulating effect of plastic membranes. Post-closure routine monitoring would assist with the appraisal of restorative measures including capping and leachate extraction and would enable site stakeholders to achieve legislative compliance.

# (7)
# Recommendations for Geophysical Best Practice

## 7.1. Geoelectrical Investigation and Monitoring of Closed Lined Disposal Cells

Lined landfill cells can be periodically examined following closure by utilising non-invasive geophysics, although it would be desirable after the initial reconnaissance survey to calibrate progressive survey results with intrusive sampling and hydro-geochemical analysis. During planning and procurement of non-invasive geophysical surveys over lined landfill cells of the nature described in this thesis, the relevant parties should consider the following recommendations for best-practice:

- No single geophysical method will provide adequate characterisation for leachate generation, accumulation and migration; liner subsidence; rainwater ingress; degradation of waste. Therefore, a multi-method investigation strategy must be utilised.

- Ground conductivity mapping techniques are available for various depth investigations. EM31 mapping should be undertaken prior to ERT profiling to optimise the positioning of resistivity electrode arrays so that anomalous high and low conductivity zones are intersected for comparison.

- Techniques such as ERT and EM, when used initially during an investigation, provide a characterisation of ground conditions from which it would not be possible to ascertain the occurrence of fluid flow, i.e. rainwater ingress and leachate migration. Self-Potential mapping is advisable as the mechanisms of fluid flow, i.e. electrofiltration potential, give rise to natural voltage variance.

- A geophysical site model can be derived from combined geoelectrical response indicating the key findings of the investigation and upon which a follow-up strategy is devised, including routine monitoring, intrusive sampling, and site restoration.

It is now widely accepted that landfill cells are capped with HDPE/LDPE materials upon completion of waste disposal in which case non-invasive geoelectrical methods are ineffective due to the electrical insulating effect of the plastic. Therefore, cell construction could be planned to include permanent ERT and SP monitoring systems installed within the waste-mass below the landfill cap. For example; prior to capping, closely-spaced permanent ERT electrode arrays can be installed along the waste surface and would permit repeated resistivity measurements to be recorded during the post-closure aftercare strategy. On this basis, the resistivity/conductivity of the fill material would be assessed over time, in accordance with methods described in Paris (2005), from which the extent of waste degradation and leachate generation can be inferred and correlated to monitoring well observations. In a similar manner, a network of permanent SP electrodes installed prior to capping would permit repeated measurement of natural voltage variation from which fluid flow migration patterns could be established within the waste.

## 7.2. Progressive Geoelectrical Monitoring of Waste-Mass Characteristics in an Active Landfill Setting

During planning and procurement of monitoring strategies for new landfill cell developments, the relevant parties (landfill operator, regulatory body and waste engineers) may consider the use of geophysical survey techniques. On this basis, the following recommendations are made for geophysical monitoring practice:

- New landfill cells can be instrumented with permanent basal electrode arrays installed within the cell structure with minimal disturbance. Basal electrode arrays must be constructed in a manner to withstand physical loading and settlement of the overlying waste-mass and to resist chemical attack from leachates.

- Basal electrodes enable a greater degree of accuracy and resolution at depth than is possible from conventional ERT surveying, but must be used in conjunction with temporary ground surface arrays to constrain measurements to the waste-mass.

- A suitable electrode address configuration should be utilised for acquisition of resistivity measurements and should include depth constrained surface-only and basal-to-surface sequences, such as those demonstrated by the 'George' array.

- A least-squares inversion technique may be deemed suitable for processing of raw data, whereby a rectangular finite element grid is used and highly damped distortion of grid nodes would enable adjustment for topographical effects.

- ERT survey results would ideally be calibrated by comparison to leachate dip level observations recorded from monitoring wells, and/or piezometer readings. Resistivity models may be used for correlation between single point leachate monitoring locations.

- Upon site closure and subsequent capping with plastic membranes, continuation of resistivity monitoring would only be possible by installation of permanent electrode arrays directly beneath the landfill cap.

## 7.3. Geoelectrical Monitoring during Restoration of Closed Landfills

Planning and procurement of landfill closure and aftercare strategies will involve a requirement for ongoing environmental monitoring. Information provided by monitoring strategies contributes towards demonstration of legislative compliance and ensuring that restorative strategies are effective and that landfills are suitably contained. Contaminated land / landfill site stakeholders (incl. site owners, local authority, regulatory body, etc) may consider the use of geophysical survey techniques. On the basis of research undertaken at Nantygwyddon landfill, the following recommendations are made for geophysical best practice:

- ERT provides a capability for routine sub-surface characterisation, especially in the delineation of leachate saturation and differentiation from zones of damp and dry waste; however for this purpose resistivity surveying along the ground surface only may be deemed inadequate.

- Closure and subsequent capping of landfill sites with plastic membranes will render conventional ground surface geoelectrical surveys impossible due to the electrical insulating effects of HDPE/LDPE materials; therefore, ERT measurement electrodes must be installed internally within a waste-mass.

- For accurate delineation of geoelectrical variations with depth through a waste profile, vertical electrode arrays should be installed and utilised in pairs. For this purpose, vertical electrode arrays may be cost-effectively installed during routine drilling and emplacement of gas recovery wells and /or observation boreholes.

- A least-squares inversion technique should be used to process raw data, whereby a rectangular finite element grid is utilised with uniform topographical distortion.

- Baseline geoelectrical data must be collected prior to restoration to assess subsequent variations attributed to landfill capping, exclusion of rainwater ingress and leachate extraction.

- Geoelectrical survey results would ideally be calibrated by comparison to reliable leachate dip level information obtained from piezometers installed within the waste profile.

# (8)
# Conclusions and Outlook

Geophysical ground investigation techniques are increasingly being utilised for reconnaissance-scale and detailed characterisation of waste disposal sites. Environmental legislation requires that old disused landfills are located and monitored to assess and reduce risk to environmental and human receptors arising from exposure to contaminants and migration of pollutants. Active disposal sites are now suitably contained with engineered liner and capping systems. Monitoring strategies are instigated to identify and reduce environmental risk and to assist with efficient waste management. Conventional monitoring at landfill sites is performed through leachate level assessment and groundwater quality analysis by utilising observation boreholes emplaced through the waste-mass and background geology. This provides information at single point locations and has in recent years benefited from the use of geophysical ground characterisation for correlation between observation wells and for spatial interpretations.

## 8.1. Geoelectrical Characterisation of Closed Landfills

Initial reconnaissance-scale geophysical investigations across closed landfills invariably require the use of non-invasive methods to ensure minimal site disturbance. Results may be used to plan further detailed investigations almost certainly requiring conventional intrusive drilling and hydro/geochemical analysis of any anomalous zones identified and the background medium. Non-invasive geophysical methods are only effective in the absence of plastic landfill capping structures due to the electrical insulating effects of HDPE.

A field test site comprising a closed and restored hydrocarbon disposal cell (with an HDPE basal liner and a compacted clay cap) at Ferry Road landfill, Cardiff Bay, was examined using a multi-method geophysical approach to obtain the best possible sub-surface characterisation and interpretation in the initial absence of intrusive calibration data. Electrical Resistivity Tomography (ERT) profiles were deployed along the ground surface and positioned to intersect the documented position of the disposal cell. ERT Survey results suggested the presence of leachate accumulating above a basal HDPE liner and driven by rainwater ingress. These interpretations were based on the documented typical landfill geoelectrical signatures whereby leachate generally exhibits very low resistivity (2-10 Ωm) and plastic membranes display a high resistivity response (>2000 Ωm). From the ERT information alone, migration of leachates away from the containment structure was not immediately clear. Electrical resistivity results were compared with measurements of conductivity provided by spatial Electromagnetic EM31 mapping performed within and beyond the margins of the disposal cell. Electromagnetic measurements were acquired at depths of around 5 metres and indicated zones of elevated conductivity (>80 mS/m) situated across and beyond the engineered containment structure. This suggested the migration of leachate from the disposal cell and into the surrounding ground. Rainwater ingress from the ground surface was suggested by ERT surveying and this interpretation was based on the documented typical resistivity signature of landfill run-off and ingress (10-50 Ωm).

The occurrence of rain ingress was further confirmed by shallow (~1m depth) electromagnetic spatial mapping with the EM38 method. From the EM38 results zones of clay-deficient capping, which would enable rainwater ingress, were interpreted where low conductivity measurements occur (10-20 mS/m). Mapping of natural voltage potentials by the fixed-base Self Potential method suggested rainwater ingress and a preferred direction of leachate flow due to the variance in natural voltage established by the fluid flow mechanisms. Strong positive natural potentials (~65 mV) were determined and are analogous to fluid ingress and descending flow, whereas the negative potentials detected (~ -45 mV) are characteristic of leachate overspill, particularly at the western cell margin. On the basis of survey results a model was produced showing combined geoelectrical response. This served two purposes; to enable a correlation between the various geoelectrical methods used and to plan further detailed investigations including conventional intrusive site examination.

## 8.2. Geoelectrical Monitoring in an Active Landfill Setting

Electrical Resistivity Tomography has emerged as a significant geophysical tool for characterisation of landfill waste. ERT is conventionally deployed along the ground surface in a non-invasive manner and is performed to explore contrasts in waste-mass electrical resistivity/conductivity for the detection of leachates. Constraints of poor resolution and accuracy with increasing depth of investigation have required adaptation and development of ERT for use in an active landfill setting.

The effectiveness of ERT in a landfill setting lies with the arrangement of measurement electrodes and application of electrode address configurations. In an active domestic landfill setting at Lamby Way, Cardiff, basal electrodes installed within the cell drainage medium prior to waste emplacement were used in conjunction with ground surface electrodes deployed above the waste-mass. This configuration of electrodes requires a unique electrode address configuration for the application of electrical current and measurement of voltage potentials. The electrode address sequence designed for the Lamby Way landfill study includes current (AB) and potential (MN) electrode applications in two configurations. Resistance measurements are recorded initially along the ground surface array only and to a depth level ($n$) equivalent to the position of the cell base. This eliminates the recovery of low accuracy and poor resolution measurements from depth which are characteristic of conventional non-invasive ERT surveys. Incorporated into the electrode address sequence, current (AB) and potential (MN) configurations are applied using the buried and ground surface arrays in conjunction. In this configuration the current (AB) electrodes are always applied across the two arrays ensuring current flow through the waste-mass. Similarly, potential electrodes are applied using the two arrays but also along the basal array only, which provides accurate and high resolution measurements at depth.

A domestic landfill waste-mass is anticipated to comprise vertical layering of different waste types, resulting in the establishment of perched leachate tables in porous material, confined by low porosity wastes above and below. It is important to characterise these waste-mass variations accurately for the determination of leachate occurrence, volumes and flow paths. Vertical variations through the landfill, which may be characterised by localised changes in electrical resistivity from low to high, are identified by application of current and potential electrode configurations along the ground surface array. In this case, a greater number of resistance measurements are recovered with depth through a two-dimensional plane. Accuracy and resolution is achieved at depth, above the basal drainage medium, with the application of potential (MN) electrodes along the concealed basal array. Horizontal resistivity variations through the waste mass may be attributed to the development and distribution of waste cells during filling. These variations may result in the development of leachate flow paths and equal importance is placed on the characterisation of horizontal resistivity changes. Horizontal resistivity variations are determined by the application of current (AB) and potential (MN) electrodes using the basal and ground surface arrays in conjunction. The current electrode dipoles are configured at a large oblique angle to the perceived horizontal changes. In this case the current flow paths are strongly affected by horizontal changes from high to low resistivity.

Measurement of electrical resistivity variation utilising the concealed and ground surface arrays enabled delineation of basal leachate accumulation and differentiation from perched tables within the waste profile. Interpretations were based on documented typical geoelectrical signatures of domestic landfill waste. Leachate is expected to display low resistivity (2-10 Ωm) and high values correspond to dry compacted waste (~500 Ωm), with the intermediate resistivities indicating damp to dry material and rainwater ingress. This monitoring procedure was performed at three stages during initial waste emplacement into the landfill cell and surveying was performed following significant increases in the waste thickness. A good correlation was shown between accumulation of basal low resistivity zones and observation well dip measurements. Geoelectrical monitoring at Lamby Way was particularly beneficial for the landfill operator and regulatory body. The procedure contributed towards delineation of leachate accumulation and basal drainage, in which case the disposal cell design and engineering attributes were indicated to be performing as intended. ERT characterisation was only attempted in a single two-dimensional plane, therefore the results can not be taken to represent and be characteristic of the entire waste-mass. Future development of the adapted ERT technique should focus on installation of multiple basal arrays and when used in conjunction with ground surface electrodes this would enable three-dimensional analysis of resistivity.

## 8.3. Geoelectrical Monitoring during Landfill Restoration

A closed landfill site at Nantygwyddon, Rhondda, was scheduled for restoration including capping with an engineered plastic membrane and trial leachate extraction from gas well installations. This site provided a focus of interest for this research for two reasons. The emplacement of a plastic capping membrane would render non-invasive geoelectrical surveying impossible due to the electrical insulating effects of HDPE/LDPE. Also, prior to landfill restoration leachate dip levels within the waste profile were measured from gas wells, piezometers and observation boreholes with conflicting results. Geophysical research was undertaken at Nantygwyddon to provide a technique for sub-surface geoelectrical characterisation for the identification of leachate and monitoring the subsequent effects of site restoration. Electrical resistivity tomography (ERT) was considered for the purpose of geoelectrical monitoring and interpretations enabling interpretations based on the typical resistivity signatures of landfill waste. It was perceived that leachate had accumulated within the waste-mass at Nantygwyddon in localised perched and basal zones to depths of ~20 metres. Therefore, the identification of leachate saturation by geoelectrical means requires consistent accuracy and resolution with increasing depth. It was unlikely that conventional ground surface ERT would provide accuracy and resolution through perched leachate zones due to the constraints of electrical 'shorting' and equivalence, whereby adjacent anomalous zones are not individually distinguished.

A system for ERT monitoring was established by permanently installing vertical electrode arrays during routine drilling and emplacement of gas extraction boreholes prior to site restoration. Electrode arrays were installed with increasing depth into the waste mass using three boreholes. Arrays were attached along the entire length of plastic borehole casings by utilising electrode spacings of between 0.83 and 1.1 metres. The ERT methodology demonstrated at Nantygwyddon involves connection of vertical electrode array pairs to a resistivity meter at the ground surface. On this basis an electrode address configuration is applied to the borehole electrodes whereby current (AB) and potential (MN) dipoles are advanced with increasing depth through the waste profile in an attempt to obtain consistent resolution and accuracy through perched and basal leachates. An electrode address configuration was designed with AM-BN, AM-NB and MA-NB arrangements exclusively. The current (AB) and potential (MN) dipoles are applied across vertical array pairs with a number of advantages over the documented AB-MN borehole configurations. The potential dipole is measured across two vertical arrays and near to the current dipole so that the potential differences will be fairly large and less susceptible to background noise. Also, the current dipole is always applied across the two arrays forcing current flow through the ground between them. At Nantygwyddon it was perceived that perched leachates may be highly localised and interspersed with more-resistive layers of lower permeability. Therefore, to accurately define near-horizontal localised conductive and resistive variations the arrangement of current dipoles includes some large angles resulting in a more significant change in equipotential flow lines.

Resistance measurements between borehole vertical electrode arrays were processed by least-squares inversion to represent resistivity variation within a two-dimensional plane of ground for each borehole-borehole configuration. Baseline survey results recorded prior to landfill restoration indicated localised leachate saturation based on the typical leachate signature of 2-10 Ωm. Damp wastes and rain water ingress were identified by the typical low to intermediate resistivity signature of 20-200 Ωm. Leachate characterisation by ERT surveying appears to correlate closely with dip levels recorded from piezometer installations, which indicate leachate bodies ranging between 8-17 metres and 18-25 metres above the basal liner. However, it was determined from piezometer levels that basal leachates were not in continuity with perched tables above, whereas ERT surveying appeared to indicate the opposite at the time of the baseline survey.

At Nantygwyddon landfill, borehole ERT surveys were repeated after site capping with LDPE and following trial leachate extraction from one of the gas wells used for the monitoring system. With trial leachate extraction and the exclusion of rainwater ingress an apparent reduction in leachate saturation was observed. This interpretation is based on the increases in electrical resistivity observed below the position of the cap and the reduction of anomalous low resistivity zones. By calculating percentage change in resistivity between baseline and post restorative data it was apparent that large percentage increases were attributed to desaturation and decreases were due to concentration of leachates, if zero rain water input is assumed. Geoelectrical monitoring at Nantygwyddon provided a number of benefits to the site stakeholders and regulatory body. ERT surveying was regarded as a complimentary monitoring tool, which was operated alongside conventional borehole and piezometer dip level procedures. Geoelectrical monitoring provided additional information in support of the site restoration appraisal and it was demonstrated that the practice of gas well leachate dip level measurement indicated saturation at depth but was not representative of perched tables.

## 8.4. Outlook

This research focused on identifying applicable geophysical methods and adapting those techniques to provide optimal interpretation of landfill waste characteristics. Further work should concentrate on obtaining a more complete spatial site interpretation than has been possible here. New landfill cells should be instrumented with multiple horizontal electrode arrays to enable three-dimensional interpretation. Greater use should be made of routine intrusive drilling programmes for installation of vertical electrode arrays into closed restored and unrestored landfills. Available inversion programmes must include a standard function for measurements from parallel horizontal arrays and timelapse processing of repeated cross-borehole data. The use of geophysical survey methods alone will not substitute conventional intrusive investigation and monitoring strategies. However, by concentrating on techniques for improving geophysical accuracy and resolution through a landfill waste-mass, interpretations can be optimised. This will assist site stakeholders to achieve a more effective management of leachate control systems, to assess the effectiveness of restorative strategies, and to demonstrate legislative compliance with a greater degree of certainty.

# *References*

Amgen, 2002a. Nantygwyddon Landfill Site Gas Extraction System, Quality Assurance Report, Amgen Rhondda Ltd, November 2002.

Amgen, 2002b. Nantygwyddon Landfill Site Leachate Management Remedial Works, Construction Quality Assurance Report, Amgen Rhondda Ltd, October 2002.

Bathurst, R. 2002. An Assessment of Settlement at Lamby Way Waste Disposal Site, Cardiff. Unpublished MSc thesis, Cardiff University.

Becker, A., and Telford, W.M., 1965: Spontaneous Polarisation studies. *Geophysical Prospecting*, **13(2)**, 51-62.

Bing, Z., and Greenhalgh, S.A., 2000: Cross-hole resistivity tomography using different electrode configurations. *Geophysical Prospecting*. **48**, 887-912.

Binley, A., Ramirez, A. and Daily, W., 1995: Regularized image reconstruction of noisy electrical resistance tomography data. In: Beck, M.S., Hoyle, B.S., Morris, M.A., Waterfall, R.C. and Williams, R.A. (Eds), Process Tomography – 1995, Proc. Of the 4$^{th}$ Workshop of the European Concerted Action on Process Tomography, Bergen, April 1995, pp. 401-410.

Brabham, P.J., George, A.G., Paris, E.C., Harris, C., and Ling, S., 2005. Geophysical Investigations and Monitoring at Landfill Sites in South Wales. *Urban Geology of Wales, Volume II.* National Museums and Galleries of Wales.

Butler, D.K., and Llopis, J.L., 1990: Assessment of anomalous seepage conditions, *in* Geotechnical and Environmental Geophysics, **2**, Environmental and Groundwater, Ward, S.H., Ed., Society of Exploration Geophysics, Tulsa, 127-145.

C. L. Associates, 1998b. Investigation and Interim Remediation of Site Drainage at Nantygwyddon Landfill Site, Gelli, Rhondda, South Wales. C. L. Associates Ltd.

Cassidy, D.P., Werkema, D.D., Sauck, W., Atekwana, E., Rossback, S., and Duris, J., 2001. The effects of LNAPL biodegradation products on electrical conductivity measurements. *Journal of Environmental and Engineering Geophysics*, **(6) 1**, 47-52.

Cherrill, H., and Phillips, A., 2005. Remediation of Landfill: A case review of environmental liability to development success, Cardiff Bay. Urban Geology in Wales, National Museums and Galleries of Wales Geological Series No23, p 170-174.

Christensen, T.H., Kjeldsen, P., Bjerg, P.L., Jensen, D.L., Christensen, J.B., Baun, A., Albrechtsen, H.J., and Heron, G., 2001. Biogeochemistry of landfill leachate plumes. *Applied Geochemistry*, **16**, 659-718.

Coleman, A.R., 1991: The use of the self-potential method in the delineation of a reclaimed landfill site, *in* Proceedings of the Conference on Planning and Engineering of Landfills, 10-11 July 1991, University of Birmingham, The Midlands Geotechnical Society.

Dey, A. and Morrison, H.F., 1979: Resistivity modelling for arbitrary shaped three-dimensional structures. *Geophysics*, **44**, 753-780.

Di Maio, R., and Patella, D., 1994: Self-potential anomaly in volcanic areas, the Mt. Etna case history, *Acta vulcanologica*, **4**, 119-124.

Exploration Associates, 1990. Capital Waterside, Cardiff Phase 1A and Stage 1. Factual Report on Ground Investigation. Report No. B0011.

Exploration Associates, 1991. Capital Waterside. Initial Building. Factual Report on Ground Investigation. Report No. B1131.

Encia, 2004. Regulation 15 – Initial Appraisal of Nantygwyddon Landfill Site, Gelli, Mid-Glamorgan, Wales. Encia Consulting Ltd.

George, A.G., 2002: Geophysical investigation of a closed landfill site at Ferry Road, Cardiff Bay. Unpublished MSc thesis, Dept. Earth Sciences, Cardiff University.

Geotomo Software, 2002: Rapid two-dimensional resistivity and induced polarisation inversion using the least-squares method. *RES2DINV manual.*

Godio, A., and Naldi, M., 2003: Two-dimensional electrical imaging for detection of hydrocarbon contaminants. *Near Surface Geophysics*, **1(3)**, 131-138.

Goes, B.J.M. and Meekes, J.A.C., 2004: An effective electrode configuration for the detection of DNAPLs with electrical resistivity tomography. *Journal of Environmental and Engineering Geophysics*, **9(3)**, 127-142.

deGroot-Hedlin, C. and Constable, S.C., 1990: Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophysics*, **55**, 1613-1624.

Hämmann, M., Maurer, H.R., Green, A.G., and Horstmeyer, H., 1997: Self-Potential image reconstruction: capabilities and limitations. *Journal of Environmental and Engineering Geophysics*, **2(1)**, 21-36.

Hauck, C., 2001: Geophysical methods for detecting permafrost in high mountains. PhD thesis, ETH Zurich 2001.

Hydrotechnica, 1991. Cardiff Bay Barrage, Final Report on Groundwater Modeling. Report No. 12057RR385.

Keary, P., and Brooks, M., 1991: An Introduction to Geophysical Exploration. Blackwell Science. Second Edition. 173-216.

Keller, G.V. and Frischknecht, F.C., 1966: Electrical Methods in Geophysical Prospecting. Pergammon Press, Inc.

Kemna, A., Vanderborght, J., Kulessa, B., and Vereecken, H., 2002: Imaging and characterisation of sub-surface solute transport using electrical resistivity tomography (ERT) and equivalent transport models. *Journal of Hydrology*, **267**, 125-146.

Kilty, K.T., 1984: On the origin and interpretation of self-potential anomalies. *Geophysical Prospecting*, **32(1)**, 51-62.

Klinck, B.A., and Trick, J., 2001. A Review of the Hydrogeological Investigations at Nantygwyddon Landfill Site, South Wales. British Geological Survey.

Lanz, E., Boerner, D.E., Maurer, H., and Green, A., 1998. Landfill delineation and characterisation using electrical, electromagnetic and magnetic methods. *Journal of Environmental and Engineering Geophysics*, **(3) 4**, 185-196.

Ling, S., 2005. Assessing the Effectiveness of Remediation and Restoration at a Closed Landfill Site: Nantygwyddon Landfill Site. Progress Report, Cardiff University.

Loke, M.H. and Barker, R.D., 1996: Rapid least-squares inversion of apparent resistivity pseudosections using a quasi-Newton method. *Geophysical Prospecting*, **44**, 131-152.

McDowell, P.W., Barker, R.D., Butcher, A.P., Culshaw, M.G., Jackson, P.D., McCann, D.M., Skipp, B.O., Mathews, S.L., Arthur, J.C.R., 2002. Geophysics in Engineering Investigations. Geol. Soc. Eng. Geol. Spec. Publ. **19** CIRIA C562.

Newmark, R.L., Daily, W.D., Kyle, K.R., and Ramirez, A.L., 1998: Monitoring of DNAPL pumping using integrated geophysical techniques. *Journal of Environmental and Engineering Geophysics*, **3(1)**, 7-13.

Nyquist, J.E., and Corry, C.E., 2002: Self-potential: the ugly duckling of environmental geophysics. *The Leading Edge*, **21(5)**, 446-451.

Ogilvy, A.A., Ayed, M.A., and Bogoslovsky, V.A., 1969: Geophysical studies of water leakages from reservoirs. *Geophysical Prospecting*, **17**, 36-72.

Ove Arup and Partners, 1995. Cardiff Bay Development Corporation. Ferry Road. Hydrogeology and Groundwater Impact. Report No. 49480/ISLK.

Paris, E.C., 2005. Hydro-Geochemical Modelling of an Unlined Landfill Site. Unpublished PhD thesis, Cardiff University.

Parish, C. S., 1992. *Spoil sandwich seals mountain top site*. Wastes Management 1992.

Parsons Brinckerhoff, 1999. Lamby Way Eastern Extension. Geotechnical Review and Stability Assessment.

Ramirez, A.L., Daily, W.D., and Newmark, R.L., 1995: Electrical resistance tomography for steam injection and process control. *Journal of Environmental and Engineering Geophysics*, **0(9)**, 39-51.

Reynolds, J.M., 1997. An Introduction to Applied and Environmental Geophysics. Wiley.

Sasaki, Y., 1992: Resolution of resistivity tomography inferred from numerical simulation. *Geophysical Prospecting*, **40**, 453-463.

Sato, M., and Mooney, H.M., 1960: The electrochemical mechanism of sulphide self-potentials. *Geophysics*, **25(1)**, 226-249.

Sauck, W.A., Estella, A., Atekwana, E.A., and Nash, M.S., 1998: High conductivities associated with an LNAPL plume imaged by integrated geophysical techniques. *Journal of Environmental and Engineering Geophysics,* **2(3)**, 203-212.

Sharma, P.V., 1997: Environmental and Engineering Geophysics. Cambridge University Press. 190-306.

Slater, L.D., Brown, D., and Binley, A., 1996: Determination of hydraulically conductive pathways in fractured limestone using cross-borehole electrical resistivity tomography. *European Journal of Environmental and Engineering Geophysics,* 1: 35-52.

Slater, L., Binley, A.M., Zaidman, M.D., and West, L.J., 1997: Investigation of vadose zone flow mechanisms in unsaturated chalk using cross-borehole ERT. Proceedings of the EEGS European Section 3rd Meeting, Aarhus, Denmark, 17-20.

Slater, L., Binley, A.M., Daily, W., and Johnson, R., 2000: Cross-hole electrical imaging of a controlled saline tracer injection. *Journal of Applied Geophysics,* **44**, 85-102.

Stanley, P. C., 1995. The Potential Environmental Risk to Development Adjacent to, and the Remediation of, the Former Ferry Road Municipal Waste Disposal Site. MSc thesis, Cardiff University.

Sullivan, E., and LaBreque, D.J., 1998: Optimisation of ERT surveys: *in* Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP) Proceedings 1998, 571-581.

Thomas, B. R., 1997. Possible effects of rising groundwater levels on a gasworks site: a case study from Cardiff Bay, UK. Quart. Journ. Engin. Geol, 30. Part 1. The Geological Society. 79-93.

Tsourlos, P., Ogilvy, R., Meldrum, P., and Williams, G., 2003: Time-lapse monitoring in single boreholes using electrical resistivity tomography. *Journal of Environmental and Engineering Geophysics*, **8(1)**, 1-14.

Waters, R.A., and Lawrence, D.J.D., 1987. Geology of the South Wales Coalfield, Part III, the country around Cardiff. Memoir for 1: 50 000 geological sheet 263 (England and Wales). Third Edition, 52-101.

Xu, B., and Noel, M., 1993: On the completeness of datasets with multi-electrode systems for electrical resistivity survey. *Geophysical Prospecting*. **41**, 791-801.

# Appendix I

**Inversion statistics for electrical resistivity raw data acquired from the lined disposal cell ERT survey at Ferry Road landfill.**

**Table A1.1:** ***Inversion statistics for electrical resistivity raw data acquired from the lined disposal cell ERT survey at Ferry Road landfill.***

| Survey Line | Electrode Spacing | Number of Electrodes | Number of Data Points | % RMS Error It.5 | Min Model Res. (Ωm) | Max Model Res. (Ωm) |
|---|---|---|---|---|---|---|
| Line 1 | 5 | 45 | 305 | 6.54 | 2.0 | 3658.38 |
| Line 2 | 5 | 47 | 339 | 8.18 | 2.0 | 3658.38 |
| Line 3 | 5 | 36 | 211 | 5.14 | 2.0 | 3658.38 |
| Line 4 | 5 | 36 | 212 | 8.27 | 2.0 | 3658.38 |
| Line 5 | 5 | 36 | 196 | 5.69 | 2.0 | 3658.38 |
| Line 6 | 5 | 36 | 205 | 6.00 | 2.0 | 3658.38 |
| Line 7 | 5 | 36 | 208 | 1.66 | 2.0 | 3658.38 |

# Appendix II

**Univariate statistics of raw data contouring using SURFER® software for SP, EM31 and EM38 spatial mapping and topographical surveys across the lined disposal cell at Ferry Road landfill.**

**Table A2.1:** ***Univariate statistics of raw data contouring using SURFER® software for SP spatial mapping across the lined disposal cell at Ferry Road landfill.***

| Variable | *X* | *Y* | *Z*(mV) |
|---|---|---|---|
| Minimum | 317316.714444 | 173625.606821 | -47.4 |
| 25% tile | 317361.442776 | 173679.992383 | -2.7 |
| Median | 317401.596607 | 173733.361393 | 10.4 |
| 75% tile | 317436.413513 | 173780.122796 | 32.4 |
| Maximum | 317490.544945 | 173822.818024 | 63.6 |
| Midrange | 317403.6296945 | 173724.2124225 | 8.1 |
| Range | 173.83050099999 | 197.21120300001 | 111 |
| Interquartile range | 74.970736999996 | 100.13041300001 | 35.1 |
| Median Abs. Dev. | 37.358302999986 | 50.319352999999 | 15.3 |
| Mean | 317399.44412252 | 173728.04374105 | 14.445454545455 |
| Trim Mean (10%) | 317399.27758507 | 173728.31039341 | 173728.31039341 |
| Std. Dev. | 44.97907649676 | 55.990313371115 | 55.990313371115 |
| Variance | 2023.1173225014 | 3134.9151913957 | 615.41747933884 |

| | |
|---|---|
| Coef. of Variation | 1.7173297818433 |
| Coef. of Skewness | 0.18964313608367 |

**Table A2.2:** ***Univariate statistics of raw data contouring using SURFER® software for EM31 spatial mapping across the lined disposal cell at Ferry Road landfill.***

| Variable | *X* | *Y* | *Z*(mS/m) |
|---|---|---|---|
| Minimum | 317316.714444 | 173625.606821 | 16.1 |
| 25% tile | 317361.442776 | 173679.992383 | 55.48 |
| Median | 317401.596607 | 173733.361393 | 61.3 |
| 75% tile | 317436.413513 | 173780.122796 | 68.43 |
| Maximum | 317490.544945 | 173822.818024 | 164.4 |
| Midrange | 317403.6296945 | 173724.2124225 | 90.25 |
| Range | 173.83050099999 | 197.21120300001 | 148.3 |
| Interquartile range | 74.970736999996 | 100.13041300001 | 12.95 |
| Median Abs. Dev. | 37.358302999986 | 50.319352999999 | 6.5 |
| Mean | 317399.44412252 | 173728.04374105 | 62.942450691453 |
| Trim Mean (10%) | 317399.27758507 | 173728.31039341 | 62.256623016872 |
| Std. Dev. | 44.97907649676 | 55.990313371115 | 11.190717884333 |
| Variance | 2023.1173225014 | 3134.9151913957 | 125.23216676673 |

| | |
|---|---|
| Coef. of Variation | 0.17779285301728 |
| Coef. of Skewness | 1.3172711763773 |

**Table A2.3:** ***Univariate statistics of raw data contouring using SURFER® software for EM38 spatial mapping across the lined disposal cell at Ferry Road landfill.***

| Variable | *X* | *Y* | *Z*(mS/m) |
|---|---|---|---|
| Minimum | 317316.714444 | 173625.606821 | -96.5 |
| 25% tile | 317361.442776 | 173679.992383 | 22.1 |
| Median | 317401.596607 | 173733.361393 | 26.6 |
| 75% tile | 317436.413513 | 173780.122796 | 31.7 |
| Maximum | 317490.544945 | 173822.818024 | 119.9 |
| Midrange | 317403.6296945 | 173724.2124225 | 11.7 |
| Range | 173.83050099999 | 197.21120300001 | 216.4 |
| Interquartile range | 74.970736999996 | 100.13041300001 | 9.6 |
| Median Abs. Dev. | 37.358302999986 | 50.319352999999 | 4.8 |
| Mean | 317399.44412252 | 173728.04374105 | 27.774037427404 |
| Trim Mean (10%) | 317399.27758507 | 173728.31039341 | 26.971983273596 |
| Std. Dev. | 44.97907649676 | 55.990313371115 | 11.120491031534 |
| Variance | 2023.1173225014 | 3134.9151913957 | 123.66532078242 |

| | |
|---|---|
| Coef. of Variation | 0.40039159090934 |
| Coef. of Skewness | 2.5927455555172 |

**Table A2.4:** ***Univariate statistics of raw data contouring using SURFER® software for spatial topographical surveying across the lined disposal cell at Ferry Road landfill.***

| Variable | *X* | *Y* | *Z*(m) |
|---|---|---|---|
| Minimum | 317316.714444 | 173625.606821 | 21.31 |
| 25% tile | 317361.442776 | 173679.992383 | 23.67 |
| Median | 317401.596607 | 173733.361393 | 25.11 |
| 75% tile | 317436.413513 | 173780.122796 | 26.659 |
| Maximum | 317490.544945 | 173822.818024 | 31.386 |
| Midrange | 317403.6296945 | 173724.2124225 | 26.348 |
| Range | 173.83050099999 | 197.21120300001 | 10.076 |
| Interquartile range | 74.970736999996 | 100.13041300001 | 2.989 |
| Median Abs. Dev. | 37.358302999986 | 50.319352999999 | 1.494 |
| Mean | 317399.44412252 | 173728.04374105 | 25.190372173913 |
| Trim Mean (10%) | 14.670833333333 | 317399.27758507 | 25.180688223938 |
| Std. Dev. | 24.807609303172 | 44.97907649676 | 1.9545778631781 |
| Variance | 2023.1173225014 | 3134.9151913957 | 3.8203746232257 |

| | |
|---|---|
| Coef. of Variation | 0.077592258251833 |
| Coef. of Skewness | 0.046901339626494 |

# Appendix III

**Inversion statistics for electrical resistivity raw data acquired from the Lamby Way active landfill study.**

**Table A3.1:** ***Inversion statistics for electrical resistivity raw data acquired from the Lamby Way active landfill study.***

| Survey Line | Electrode Spacing | Number of Electrodes | Number of Data Points | % RMS Error It.5 | Min Model Res. (Ωm) | Max Model Res. (Ωm) |
|---|---|---|---|---|---|---|
| April'04 | 5 | 84 | 594 | 5.40 | 2.0 | 5724.84 |
| Feb'05 | 5 | 84 | 575 | 4.90 | 2.0 | 526.68 |
| Jun'05 | 5 | 86 | 637 | 4.24 | 2.0 | 526.68 |
| Conv. W-S | 5 | 53 | 420 | 13.7 | 2.0 | 526.68 |

# Appendix IV

**Inversion statistics for electrical resistivity raw data acquired from the Nantygwyddon closed landfill study.**

**Table A4.1:** ***Inversion statistics for electrical resistivity raw data acquired from the Nantygwyddon closed landfill study.***

| Survey Line | Electrode Spacing | Number of Electrodes | Number of Data Points | %RMS Error It.5 | Min Model Res. (Ωm) | Max Model Res. (Ωm) |
|---|---|---|---|---|---|---|
| S-T (B) | 1.10/0.83 | 36 | 280 | 6.40 | 0.5 | 1431.21 |
| S-U (B) | 1.10/1.10 | 36 | 282 | 7.32 | 0.5 | 1431.21 |
| U-T (B) | 1.10/0.83 | 36 | 280 | 5.45 | 0.5 | 1431.21 |
| S-T (1) | 1.10/0.83 | 36 | 280 | 6.57 | 0.5 | 1431.21 |
| S-U (1) | 1.10/1.10 | 36 | 282 | 8.21 | 0.5 | 1431.21 |
| U-T (1) | 1.10/0.83 | 36 | 280 | 6.35 | 0.5 | 1431.21 |
| S-T (2) | 1.10/0.83 | 36 | 280 | 6.39 | 0.5 | 1431.21 |
| S-U (2) | 1.10/1.10 | 36 | 282 | 7.11 | 0.5 | 1431.21 |
| U-T (2) | 1.10/0.83 | 36 | 280 | 5.59 | 0.5 | 1431.21 |

Note: (B) = Baseline survey – September 2005

(1) = One month after capping – January 2006

(2) = Two months after capping and one month after leachate extraction – February 2006