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Thermal imaging techniques to map ground disturbances in a former Nottinghamshire coal mining area

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BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/02/007

Thermal imaging techniques to map ground disturbances in a former Nottinghamshire coal mining area

G J Ager, A D Gibson, D A Gunn, M G Raines, S H Marsh, A R Farrant, D J Lowe, A Forster, and M Culshaw

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British Geological Survey offices

Keyworth, Nottingham NG12 5GG
☎ 0115–936 3100 Fax 0115–936 3200
e-mail: sales @bgs.ac.uk
www.bgs.ac.uk
Online shop: www.geologyshop.com

Murchison House, West Mains Road, Edinburgh EH9 3LA
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Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU
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Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF
☎ 028–9038 8462 Fax 028–9038 8461

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491–838800 Fax 01491–692345

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff, CF15 7NE
☎ 029–2052 1962 Fax 029–2052 1963

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793–411500 Fax 01793–411501

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Executive summary

A multidisciplinary team conducted a study at Chilwell Dam in Nottinghamshire in order to develop the British Geological Survey's (BGS) capability to detect abandoned mineshafts. To this aim an airborne thermal survey of the site was commissioned. The thermal data was analysed in conjunction with site visits, geophysical surveys, soil stripping of the top layer of soil from the site and analysis of aerial photography, geological field slips and mine plans. The BGS had previously applied the technique with success in an area where mineshafts had obvious surface expression. This report presents the results of the study at Chilwell Dam, where the mineshafts did not have a clear surface expression.

1 Introduction

1.1 Overview

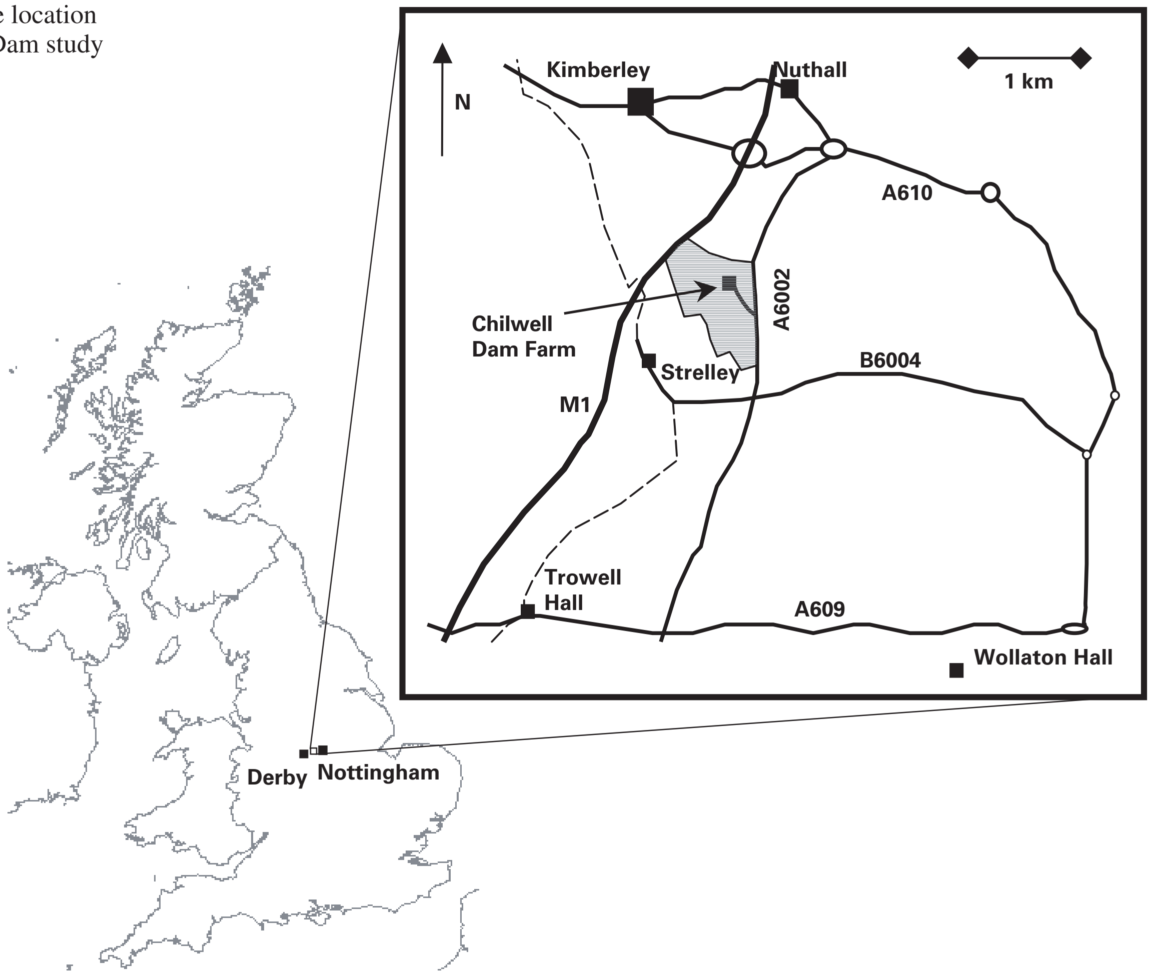
Planned construction of the Nottingham Business Park by Wilson Bowden Ltd at a former mining site in west Nottingham highlighted the need for the abandoned mineshafts that underlay the site to be accurately located. Appropriate sealing of the shafts prior to site development could then take place. A multidisciplinary team at the British Geological Survey (BGS) have been developing a technique to remotely detect abandoned mineshafts. The team extended the development of the technique through research conducted at the former mining site, Chilwell Dam Farm. This report presents the results of research undertaken at Chilwell Dam Farm, to detect the mineshafts and to further develop BGS mineshaft detection capability.

1.2 Background

Mining activity within the British Isles has left a legacy of abandoned mineshafts, adits, bellpits, wells, soughs and culverts. Mineshafts and related features represent a significant environmental hazard. They are prone to collapse and can leak noxious gases and acid mine waters. However, the location of abandoned mineshafts and related features are largely unrecorded or inaccurately recorded on mine abandonment plans. In former mining areas it is critical to locate abandoned mineshafts prior to development of a site. Traditional methods of mineshaft detection can be time consuming, unreliable and expensive. Remote sensing provides the potential for a rapid, cheap and non-intrusive technique for mineshaft detection.

A previous study was conducted at Baildon Moor in West Yorkshire (Gunn et. al., 2002a). The study was focussed on shaft detection from thermal imagery, acquired both pre-dawn and late morning. The study demonstrated that mineshafts with obvious surface expression can be detected from thermal imagery and indicated that there is potential for shafts with little or no surface expression to be detected. Typically, shafts on the Moor had an obvious surface expression, being circular depressions a few metres deep at surface and up to 15 m in diameter. In contrast to Baildon

Figure 1.1 The location of the Chilwell Dam study site.



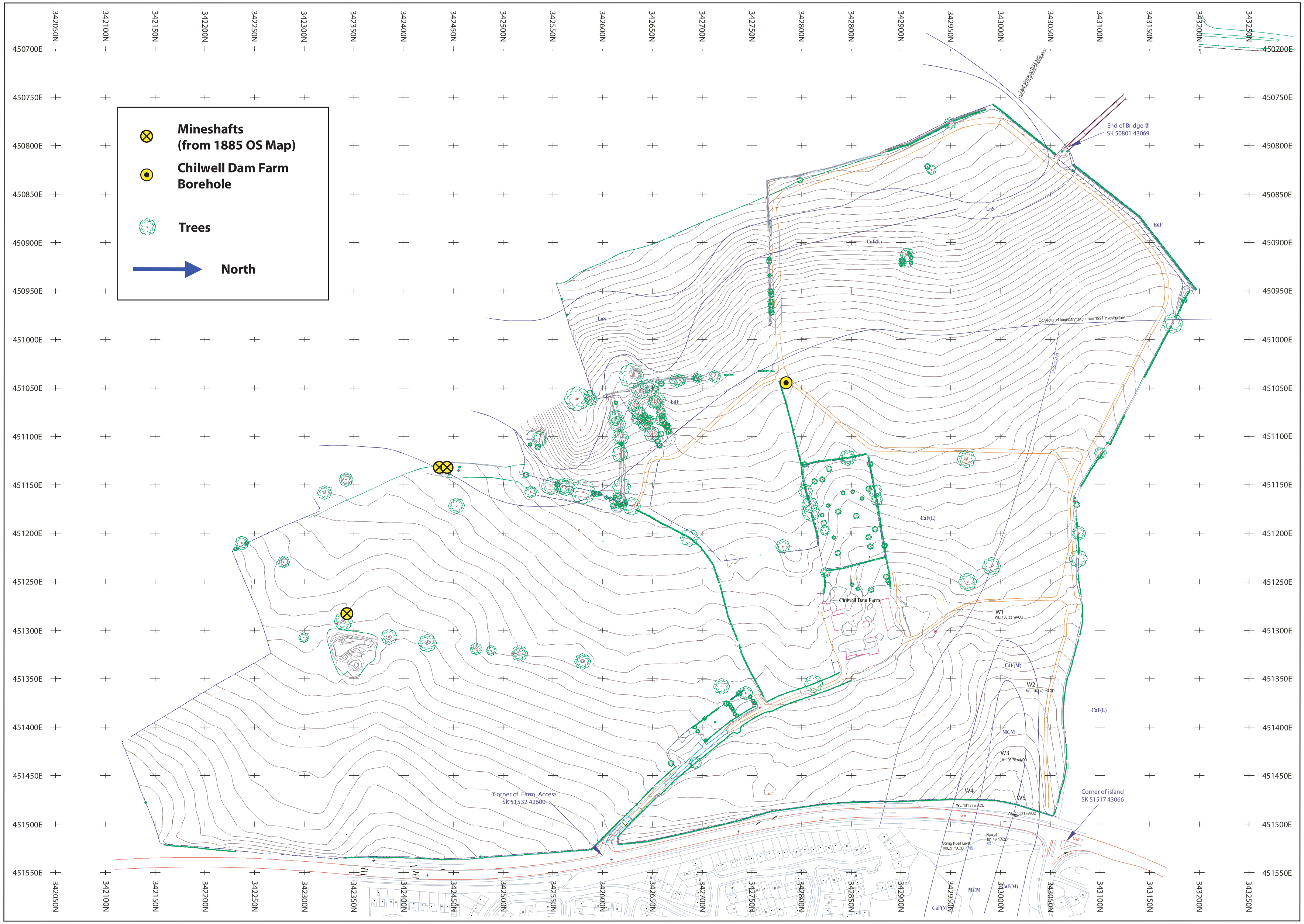


Figure 1.2 Chilwell Dam study site.

Moor, the Chilwell Dam site had been farmed until recently and there was no obvious surface expression of abandoned mineshafts. The site was selected for this reason and because thermal imagery of the site could be acquired in conjunction with a previously planned flight over the city of Nottingham. The site was to be stripped of its surface layer prior to construction of the Business Park, enabling verification of mineshaft location. In addition, an opportunity was provided to compare thermal data flown by a commercial 8-bit sensor over this site with the 16-bit thermal data flown by the NERC aircraft over Baildon Moor.

1.3 Research objectives

The aim of the research was to develop BGS capability to rapidly detect abandoned mineshafts. This would be achieved by application of the airborne thermal surveying technique at a site where mineshafts did not have an obvious surface expression. The specific objectives were to:

- detect thermal anomalies over known mineshafts without obvious surface expression
- detect unknown mineshafts
- determine whether known mineshafts are missed by the technique
- investigate the physical basis of any anomalies recorded by use of geophysics
- verify the existence of unknown mineshafts by field observation post-soil stripping and by geophysical investigation.

1.4 Research methodology

- *Desk study*. Thermal imagery, aerial photography and geological field slips of the site were analysed to locate known mineshafts at the site and to identify thermal anomalies with potential to be mineshafts.
- *Pre-soil strip site survey*. An initial site visit was conducted to observe the field appearance at the locations of known and potential mineshafts.
- *Geophysical survey*. A geophysical survey was conducted at selected locations to detect disturbed ground associated with mineshafts.
- *Post- soil strip site survey*. This site visit took place to verify the existence of mineshafts following removal of the surface vegetative and soil layer.

1.5 Study area

Chilwell Dam Farm is situated on the west side of Nottingham, within the city limits, as shown in Figure 1.1. It is approximately 800 m at its widest and 1.8 km at its longest. It comprises a roughly triangular area of farmland with its eastern boundary along the A6002, its northwestern boundary along the M1 motorway and other boundaries formed by hedgerows. Access to the site is via a slip road that runs off the A6002. Until recently, wheat was cultivated in the fields and fruit trees grew in the orchard next to the farm buildings. The 1885 edition Ordnance Survey map shows the site as a series of orchards and plantations surrounded by pasturelands. The site is within an area of former coal mine workings, and this map also shows old coal pits [shafts] on the west boundary and within the southwest of the study area. Their exact position is shown on the site map in Figure 1.2. This also shows the routes of several tracks in the northern half of the site, which, apart from the access track off the A6002, comprise ground compacted by passing vehicles. Also shown are the positions of the derelict farm buildings with an orchard immediately to the west. Within the site are two small copses that surround hollows, which may have mining or quarrying related origin.

1.6 Development at Nottingham Business Park

The design of the substructure for the development at Nottingham Business Park (Chilwell Dam Farm) has taken due account of the mineshafts encountered.

2 Effect of mining related ground disturbances on thermal properties

2.1 Temperature contrast between mineshafts and their surroundings

Mineshafts are air-filled voids which are commonly capped to some degree following disuse. They may also be partially or wholly backfilled at a lower density than the insitu ground. Air and solid rock have different heat capacities and hence a temperature difference can be expected to occur between the two. Mineshafts are cooler than their surroundings for much of the year, but tend to be warmer than the enclosing ground in winter, particularly during freezing conditions. Dependant on the effectiveness of the mineshaft capping a thermal anomaly may be produced at the earth's surface. Anomalously high temperatures have been observed to cause melting of frost over capped mineshafts and measurements indicate that anomalies can average 2–3°C under ideal conditions (Donnelly, 1995). Gases are associated with some mineshafts and can exert an influence on the strength of the thermal anomalies through possible exothermic reaction as they reach the surface. There is a tendency for gases to build up during a period of high pressure and to be released during low atmospheric pressure.

2.2 Effect of ground disturbances on thermal properties

Causes of thermal anomalies include the ground disturbances due either to the excavation of a shaft or related actives of hauling, crushing, bagging and sorting, and transportation. Building and water pumping works would also disturb the ground and provide potentially anomalous surface areas. These ground disturbances have very localised effects on the physical, chemical, drainage and moisture properties of the surface geological materials. All of these properties have a direct and significant control on the diurnal heating and cooling cycles of the ground and on its ability to radiate heat energy. Soil density changes are caused by shaft excavations, compaction by heavy trafficking about the shaft, mixing of surface soils with deeper derived rock spoil and looser shaft infilling materials. Shafts and associated ground fractures can either drain surface waters or provide spring sources for rising mine-waters. Thus, localised disturbances to water flow, drainage and material density will create secondary moisture content changes in the vicinity of a mineshaft. Changes in soil chemistry are caused by the mixing of surface soils with the mining spoils, and also by shaft infilling with materials, sometimes borrowed from sources outside of the local area. Soil chemistry, density, drainage and moisture content changes affect the localised distribution of the flora, and thus the heat radiation pattern about mineshafts, and could potentially be identified as anomalies on thermal infrared images.

2.2.1 Effect of density changes

Soil density changes caused by soil mixing have a very significant effect on the soil's thermal inertia. Thermal inertia is the resistance of a material to temperature change, indicated by the time dependent variations in temperature during a full heating/cooling cycle (a 24-hour day for Earth). It is defined as:

$$P = (K.c.\rho)^{1/2} = c.\rho\,(k)^{1/2} \qquad 2.1$$

Where
K = thermal conductivity ($W.m^{-1}.K^{-1}$)
c = thermal (or specific heat) capacity ($J.kg^{-1}.K^{-1}$)
ρ = bulk density ($Mg.m^{-3}$)
k = thermal diffusivity ($m^2.s^{-1}$)

The thermal diffusivity governs the rate of temperature change within a material; it is a measure of a substance's ability to transfer heat in and out of that portion that received solar heating during the day and cooling at night. The thermal capacity is a measure of a material's capacity to store heat energy. It governs the amount of heat energy that must be exchanged to cause a temperature change in the material. As components of thermal inertia, thermal capacity and diffusivity control the heat transfer rate across a boundary between two materials. e.g., air/soil. Because materials with high thermal inertia possess a strong inertial resistance to temperature fluctuations at a surface boundary, they show less temperature variation per heating/cooling cycle than those with lower thermal inertia, as shown in Figure 2.1.

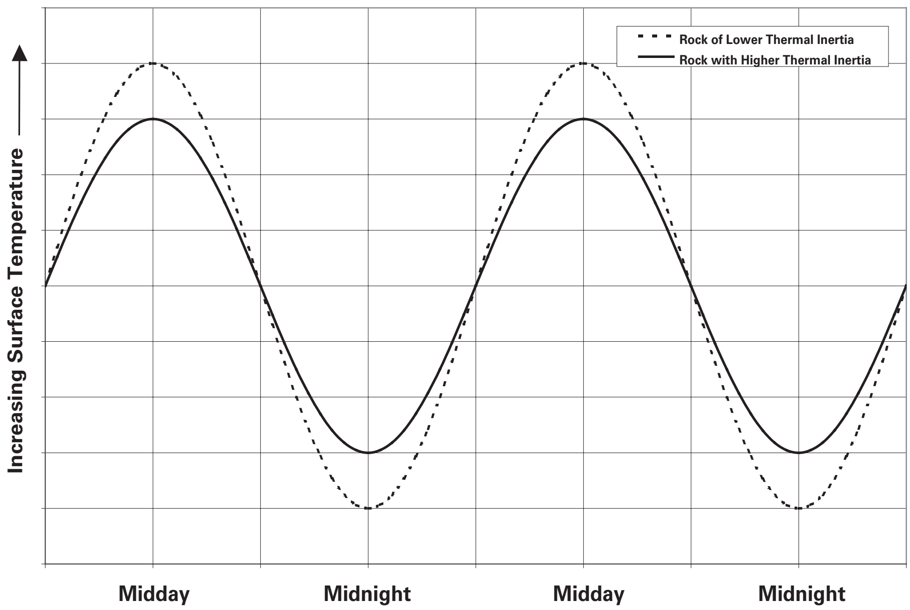
Density controls the mass of material present per unit area of the boundary, and thus the amount of heat energy that will be exchanged during heating and cooling. So significant is the control of density, that Sabins (1978) showed that a generalised relationship could be established to predict thermal inertia as its dependent variable, as shown in Figure 2.2. In the dry state, soils have lower densities than rocks and thus lower thermal inertia, and low-density, high-porosity rocks will have lower thermal inertias than high-density, low-porosity rocks.

The Chilwell Dam Borehole was drilled in 1959 by the National Coal Board, at NGR 451051, 342775 as shown in Figure 1.2. The Cinderhill Main Coal Seam was proved at a depth of 22 m. The seam was described as being approximately 1 m thick consisting of bands of bright and dull coal, whose specific gravities varied from 1.34 to 1.48 (National Coal Board, 1959a). This is very low-density material when compared with the basic components of the local soils, sand and clay, which have a mean specific gravity of around 2.5. Figure 2.3 shows an example of the coal/soil mixing found during a soil survey at the Chilwell Dam Farm site, (located at NGR 451225, 342275; close to mineshaft no.34 in Appendix A). Table 2.1 shows the estimated percentage change on the thermal inertia of a medium porosity soil with coal mixing. Being dependent upon a specific activity, the degree of soil mixing at the site is very variable, but coal proportions of up to 30% were estimated in places, which leads to 30% thermal inertia changes due to density effects alone.

2.2.2 Effect of soil moisture changes

The thermal inertia of water is similar to that of rocks and soils, (Figure 2.2), but water bodies appear cooler on

Figure 2.1 Effect of thermal inertia on the diurnal temperature cycle of rocks, (after Sabins, 1978).



pre-dusk images and warmer on pre-dawn images. This is because convection currents maintain a relatively uniform temperature at the surface of a water body (Sabins, 1978). Convection does not occur in rocks and soils, thus heat from solar flux is concentrated near their surfaces, causing a higher surface temperature during the daytime. At night the heat from rocks and soils is radiated to the atmosphere and is not replenished by convection currents, causing a lower surface temperature. Thus, water bodies have very different diurnal temperature cycles to rocks and soils, as shown in Figure 2.4. Damp ground is cooler than dry ground on both pre-dawn and pre-dusk images, due to the cooling effect as absorbed water is evaporated. Damp areas adjacent to water bodies, areas where the natural water table is just below the surface and rain-damp areas are all relatively cool on pre-dawn and pre-dusk images.

Abandoned mineshafts can have a significant effect on the localised surface and groundwater pathways. Gunn et al. (2002a,) observed open and backfilled shafts with water at the surface on Baildon Moor that were at altitudes 10 m to 20 m below the summits of local sandstone hills. Rising mine waters escaped from the open shaft, providing a spring line that flooded the surrounding ground. This area of ground had a mottled appearance on the thermal image that was caused by patchy areas of damp ground and surface water. The backfilled shafts had up to 6 m diameter pools of standing water over their central areas that caused relatively warm anomalies on pre-dawn thermal images.

2.2.3 Effect of soil chemistry and vegetation

Mixing with mining spoils will add additional minerals to the topsoil and change its overall chemistry. Coal Measures sequences are often very rich in carbonaceous materials like coal and black shales, and suphide-rich minerals like iron pyrites, (Waters *et al.* 1996). The by-products of methane oxidisation, carbon dioxide and the positive hydrogen cation are both readily soluble in water (Mellor, 1935). Often rising mine waters are acidic due to these dissolved compounds, again affecting the chemistry of the topsoils it saturates.

Soil chemistry, density and moisture variations associated with mining related ground disturbances can

Figure 2.2 General relationship between thermal inertia and rocks and water, (after Sabins, 1978).

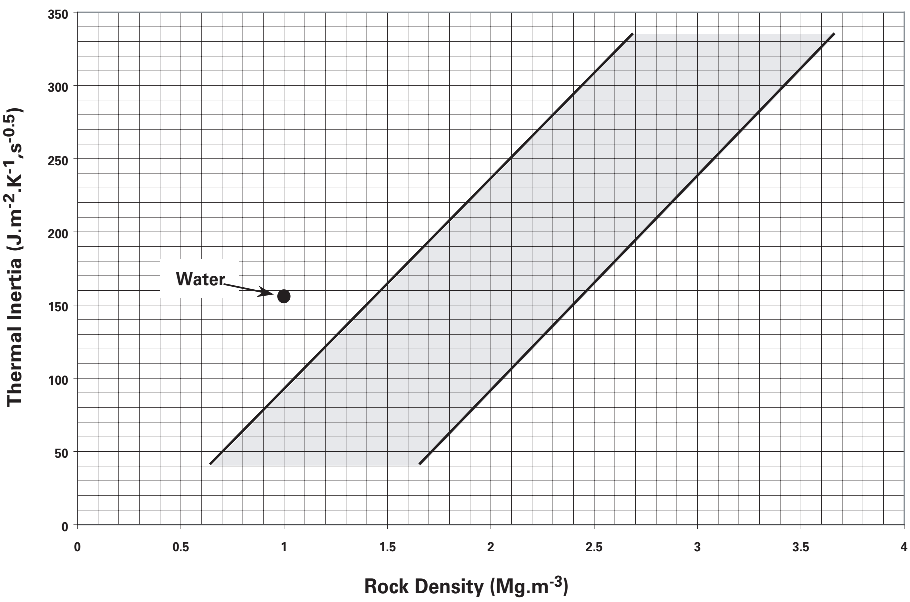


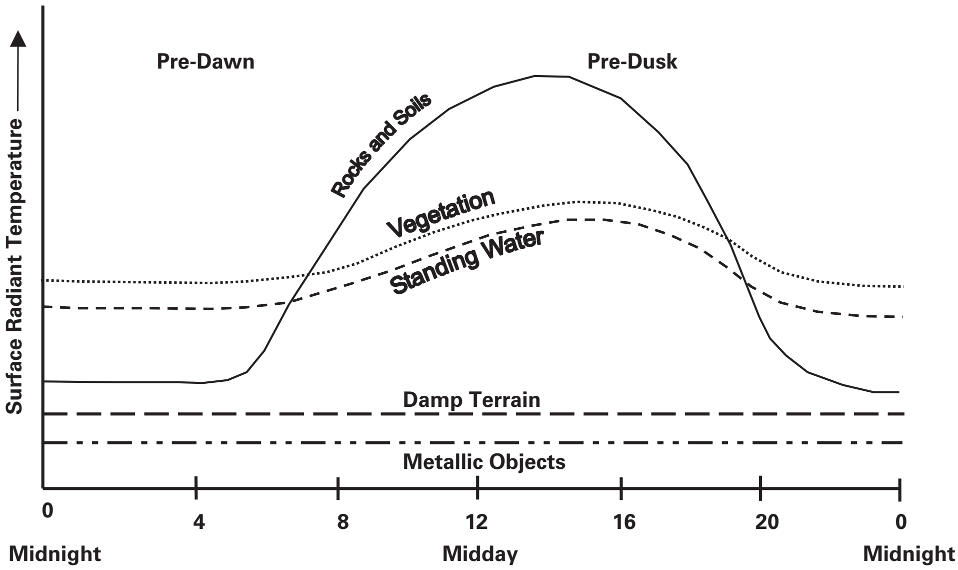
Table 2.1 Estimated percentage change in soil thermal inertia due to mixing with low density coal from the Cinderhill Main Seam.

Proportion of Coal %	Density of Soil of 35% Porosity $Mg.m^{-3}$	Estimated Thermal Inertia of Soil $J.m^{-2}.K^{-1}.s^{-0.5}$	% Change in Thermal Inertia due to Coal/Soil Mixing %
0	1.63	110.59	0%
20	1.47	88.70	20%
40	1.32	66.82	40%
60	1.17	44.93	59%

often be accompanied by vegetation changes. Green deciduous vegetation is relatively warm on pre-dawn images. Transpiration of water vapour lowers leaf temperature and causes a relatively cool appearance on pre-dusk images (Sabins, 1978). However, the relatively high pre-dawn and the relatively low pre-dusk temperatures of conifers are due to the composite emissivity of the needle clusters approaching that of a black body. Dry vegetation, such as crop stubble in agricultural areas, is relatively warm on pre-dawn images, in contrast to bare soil, which is relatively cool, as shown in Figure 2.4. Dry vegetation insulates the ground that retains heat and causes the relatively warm pre-dawn image. Thus, the varied vegetation distribution about mining disturbed ground is likely to cause a localised thermal anomaly. The photographs shown in Figures 2.5a and 2.5b are of abrupt vegetation changes that are close to the recorded location by the Coal Authority of abandoned mineshafts within the study site. Figure 2.5a is located at NGR 451470, 342770 and shows a localised patch of clover and nettles confined to an area of less than 3 m in diameter. This was a site of thermally anomalous ground, located on a mound south of mineshafts nos. 15 and 16 in Appendix A and was later stripped. Figure 2.5b is located at NGR 450885, 342955 and shows a dense patch of nettles in an area about 4 m across. This was also a site of thermally anomalous ground, located close to mineshaft no.5 in Appendix A.

Figure 2.3 Example of the coal/soil mixing at Chilwell Dam Farm, (NGR 451225, 342275).

Figure 2.4 Comparison of the diurnal radiant temperature cycle of surface materials, (after Sabins 1978).



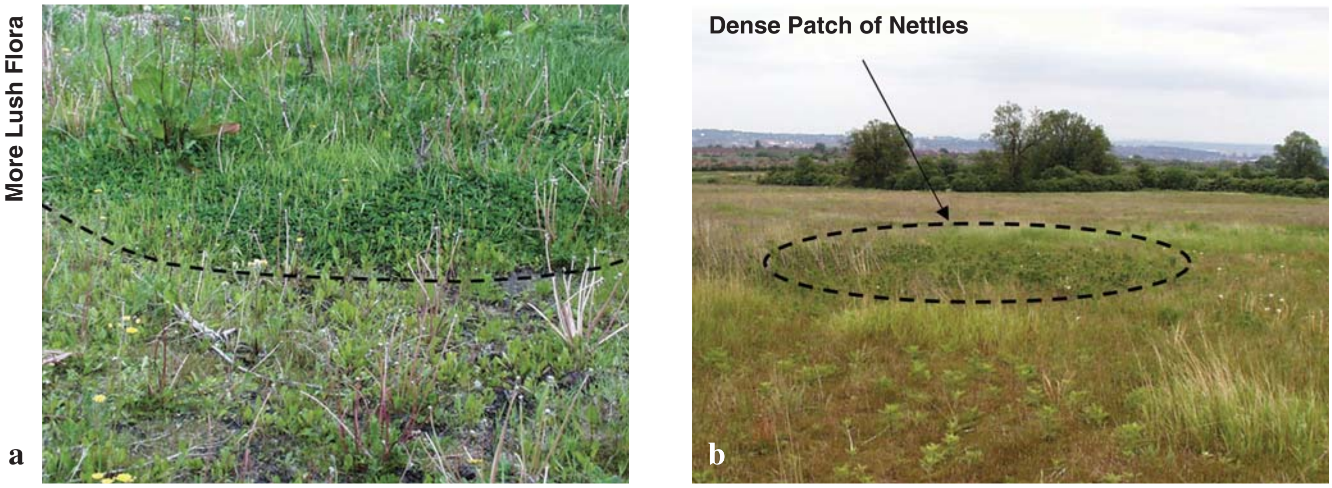


Figure 2.5 Vegatation changes over abandoned mineshafts at Chilwell Dam Farm.

a Clover and nettles over a former mineshaft, (NGR 451455, 342790). Shaft 16, Appendix A
b Dense patch of nettles over a mapped abandoned mineshaft, (NGR 450880, 342950). Shaft 5, Appendix A

3 Geology and mining at Chilwell Dam Farm

3.1 Geological description of Chilwell Dam Farm

The upper carbonate facies of the Cadeby Formation outcrops over most of the site (Figure 3.1). Dip is 10 degrees with a prevailing easterly direction. A normal fault striking ESE–WNW with a down throw side to the north cuts through the site. On the west side of the site the Lenton Sandstone Formation overlies the Edlington Formation, which overlies the Cadeby Formation 'carbonate facies'. At the NE corner of the site the Cadeby 'carbonate facies' is underlain by the lower 'mudstone facies' of the Cadeby Formation, which rests unconformably on Middle Coal Measures. A cover of Glacial Till is found on the small hill formed by the Lenton Sandstone on the west side of the site.

Figure 3.2 summarises the stratigraphical relationships between the solid geological rock formations. The Middle Coal Measures were deposited during the Upper Carboniferous (Silesian) Period, while all the other rocks were deposited during the Permian Period. The Middle Coal Measures were deposited, within sedimentation cycles that usually began with the deposition of marine or near-marine shales, which pass up through mudstones into deltaic siltstones and sandstones. At the top of each cycle are the products of the compaction and alteration of peats, namely coals and seatearths. The Cadeby Formation is sub-divided with a lower 'mudstone facies' and an upper 'carbonate facies'. At Chilwell Dam the 'mudstone facies' comprises a marl about 3 to 5 m thick. The Cadeby 'carbonate facies' comprises dolomites. The rock has the texture of a sandstone or coarse siltstone, and is composed of dolomite rhombs, with minor quartz grains. The Edlington Formation comprises an approximately 10 m thick red, purple-brown or yellow silty mudstone with green layers and thin beds of dolomitic sandstone or sandy dolomite. The Lenton Sandstone Formation is up to 15 m thick consisting of bright red-brown sandstone with yellow mottling. It is fine to medium grained and commonly friable or soft.

The Glacial Till is up to 5 m thick and generally comprises red-brown or grey silty or sandy clays with gravel and cobbles of locally derived or exotic rocks.

3.2 Mining at Chilwell Dam Farm

3.2.1 Mining history in the region

Coal has been mined west of Nottingham since at least the Middle Ages and probably considerably earlier, (Charsley *et al.* 1990). Much of the wealth of the Willoughby family, who constructed Wollaton Hall in the 16th century, and other Nottingham landowners was founded on coal mining in the area of exposed and shallowly concealed coalfield west of Wollaton Hall, (Figure 1.1). By 1604 Huntington Beaumont constructed a wooden wagonway from bell pits at Strelley down to Wollaton Lane, for carriage to the Nottingham market, (Healey 2001). During the 19th century mines were generally leased from landowners by partnerships of mining entrepreneurs who raised the necessary capital for development. Villages like Hucknall and Bulwell in the Leen Valley grew to accommodate the workforce. Improved steam pumping could drain deeper shafts, and one of the first deep shafts was sunk in 1841 at

Figure 3.1 Geology of the Chilwell Dam Farm study site.

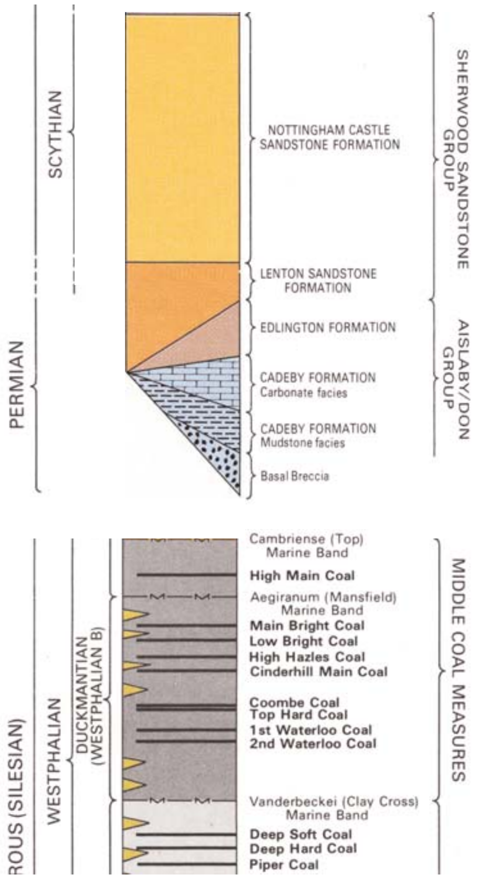


Figure 3.2 Geological sequence showing the stratigraphical relationships between the rocks at Chilwell Dam Farm, (after Charsley et al., 1990).

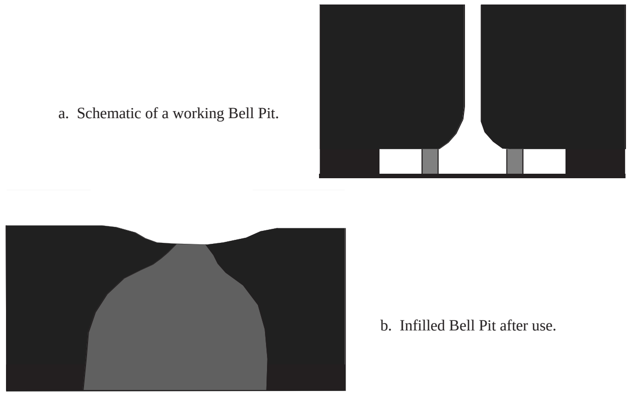


Figure 3.3 Section through the ground at a Bell Pit, (Whittaker and Reddish 1989).

Cinderhill, and another in 1851 at Hucknall. Before the First World War, coal production from Britain's 3 024 mines was at its peak, (Healey 2001). Nottinghamshire coalmines stretched the length of the county and in Eastwood alone 40% of the workforce were employed down the coal pits. After many pit closures in the 1980s, most of the sites have been completely cleared. Many spoil heaps have been reshaped and re-planted while others have been reused as industrial estates.

3.2.2 Mining at Chilwell Dam Farm

Coal Authority records indicate in excess of thirty abandoned mineshafts over the Chilwell Dam Farm Site. The shallowest coal at the site is the Cinderhill Main Seam, which is a metre thick at a depth of 22 m (National Coal Board 1959a). The distribution of the abandoned mineshaft locations suggests an ad hoc approach to mining on the land where the landowner leased mining rights to several different co-operatives, (as was the practice at the time). If this is the case then mining may have been via the use of unusually large Bell Pits (Figure 3.3). Some shafts would have been lined either to provide stability from collapse or spalling of the rock, or possibly, to control the ingress of water into the mine workings. Commonly shafts have been commonly lined since the 17th century and many materials have been used. Littlejohn (1979) reported the use of wooden planks arranged vertically like a barrel, and Boulton (1907) reported that it was common for shafts less than 3.5 m in diameter to use moulded brick linings in the 19th century. Figure 3.4 shows a brick-lined shaft,

Figure 3.4 Brick-lined mineshaft on Chilwell Dam Farm, (NGR 51285, 42342), mineshaft No. 32 in Appendix A.

a Green algae on some brick suggests previously only partial light and possible recent collapse of the shaft cover.
b No capping material visible; infilling of soil, logs and metal objects.

Figure 3.5 Evidence of mineshafts in the stripped soil at Chilwell Dam Farm.

a Soil lightening by Coal Measures mudstones, (NGR 451114, 343017).
b Soil darkening by coal, (NGR 451231, 342752).

approximately 2 m in diameter, that was observed on the Chilwell Dam Farm site at NGR 51285, 42342 (mineshaft no.32 in Appendix A). The lining is of dry-stacked red-brick and its collar is within 1.5 m of the ground's surface (Figure 3.4a). The growth of algae is restricted on the bricks, which suggests that until very recently there was a fuller soil cover over the shaft (Figure 3.4b). A recent collapse of the cover may have been caused by a slump in the infill materials, which appear to be of soil, logs and metal objects. Other infill materials include the soft light grey Coal Measures mudstones and coal spoils. These were observed causing localised soil lightening or darkening in several areas after the topsoil was stripped away (Figure 3.5). However, topsoil stripping involved the removal of the upper 0.3 to 0.5 m of surface materials and it is possible that shaft linings could still be concealed beneath the surface.

4 Desk-based research

4.1 Desk study

Thermal imagery, geological field slips and aerial photography were interpreted prior to the field survey at the site to determine the location of known and potential mineshafts.

4.2 Thermal imagery interpretation

Thermal imagery was acquired at Chilwell Dam Farm on two dates as an extension to a building heat loss survey in Nottingham. Data was acquired pre-midnight on 15 February 2001 and pre-dawn on 12 March 2001. Pre-dawn is the preferred time of data acquisition for shaft detection (see Gunn et. al., 2002a), hence the pre-dawn dataset was the focus of the research at the Chilwell Dam site. Two flight lines provided full coverage of the site. The flight lines were georectified and mosaiced together prior to interpretation of the mosaiced image (Figure 4.1). Thermal anomalies most likely to relate to mineshafts were dark relative to the rest of the image and generally circular in shape. Such anomalies were marked on the thermal image for later investigation in the field (Figure 4.2). Several larger anomalously dark areas were also marked on the image.

4.3 Interpretation of geological field slips

A comparison was made between the location of known mineshafts, derived from geological field slips of the Chilwell Dam site, and the location of thermal anomalies. The thermal anomalies that corresponded with the location of known mineshafts were coloured red in Figure 4.3.

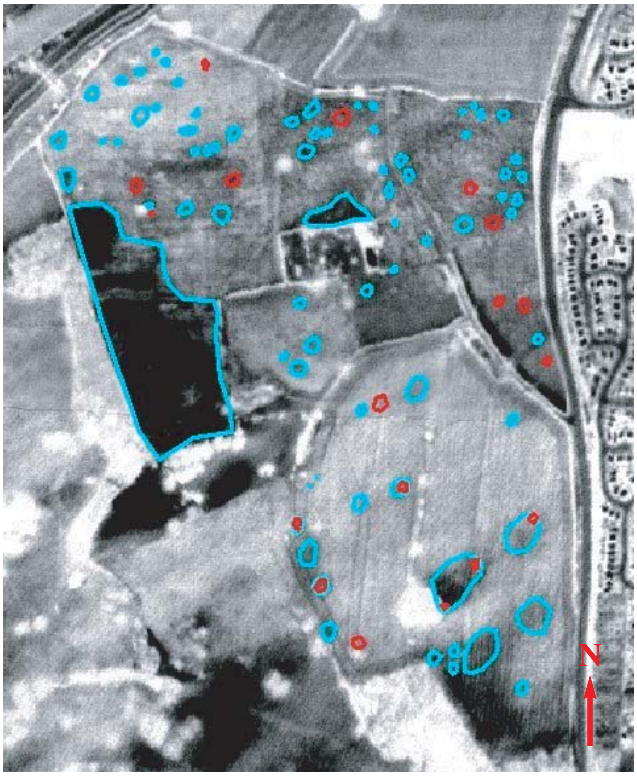
4.4 Analysis of aerial photography

A series of 1:25 000 scale aerial photographs were examined using a mirror stereoscope. These black and white images were taken on 25 May 1978 from an altitude of approximately 3690 m. It was anticipated that areas of mining-related disturbance would be indicated by isolated patches of tonal contrast or by the remains of pit workings (Culshaw & Waltham, 1987; Norman & Watson, 1975). Scanned images of the photographs were also examined with the aid of a number of visual enhancement techniques. Although this process did enhance the contrast between some features, no major improvements were made in the interpretation of the photographs.

A comparison of the aerial photographs with the map of ‘known’ mine shaft locations revealed that some shaft sites were easily identified as areas of lighter tone of near-circular shape, approximately 10 m in diameter (Figure 4.4), often with trees nearby. Using these criteria,

Figure 4.1 Thermal Image of the Chilwell Dam Farm Site.

Figure 4.2 Thermal anomalies identified at Chilwell Dam Farm.



Legend

- = thermal anomalies identified from the thermal image
- = thermal anomalies identified from the thermal image that correspond with the location of mapped shafts

Figure 4.3 Thermal anomalies that corresponded with the location of mapped shafts within the study site.

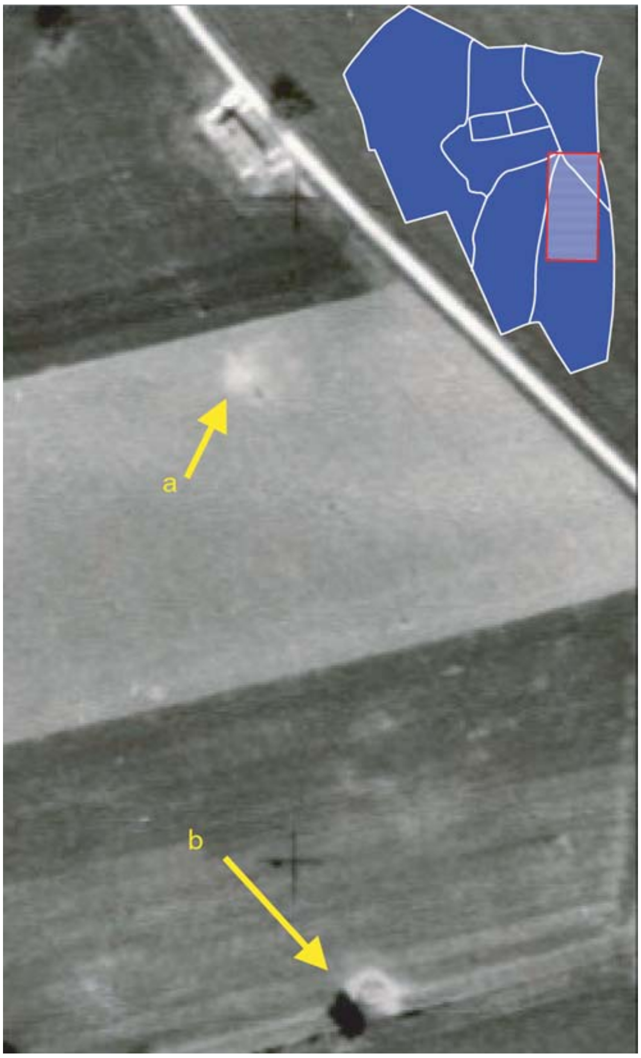


Figure 4.5 The features identified as shaft sites on the aerial photographs that were not in agreement with the locations of known shaft sites. The linear feature running diagonally from top right to bottom left, cutting through the feature (a) is thought to be an abandoned fence line.

the rest of the photograph coverage was examined for similar features. 17 potential shaft locations were identified, 15 of these were in agreement with known shaft locations, while two, situated ESE of the Chilwell Dam Farm site were not (Figure 4.5). It was noted that these features also lie upon relict field boundaries, indicating that they could be sites where trees have been removed, leaving behind a circular footprint.

4.4.1 Remains of workings/infrastructure

The remnants of several man-made structures, indicated by regular shaped areas of tonal difference, were identified from the photographs. The largest of these is the footprint of a disused tramway that ran close to the northern border of the site (Figure 4.6). A series of bright features forming a rectangle shape can also be seen in the centre of Figure 4.6. These correspond to man made features visible

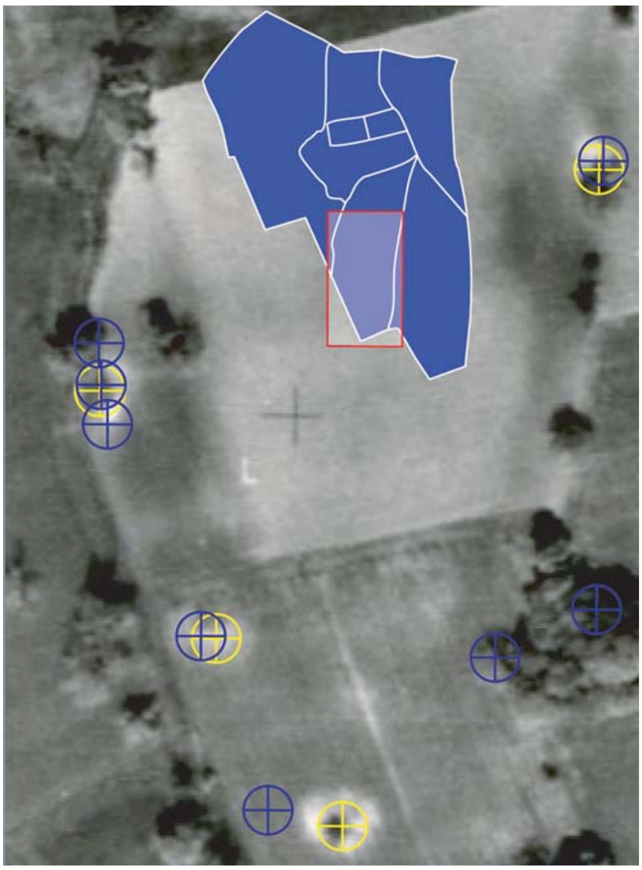


Figure 4.4 Locations of some 'known' shafts (blue symbol) appear as areas of lighter tone (yellow symbol) on aerial photographs.

Figure 4.6 Tonal contrast within a conventional black and white aerial photograph were useful indicators of disused workings. The track of the Kimberly Colliery Tramway is indicated between two arrows whilst the remnants of other man-made features are also visible.

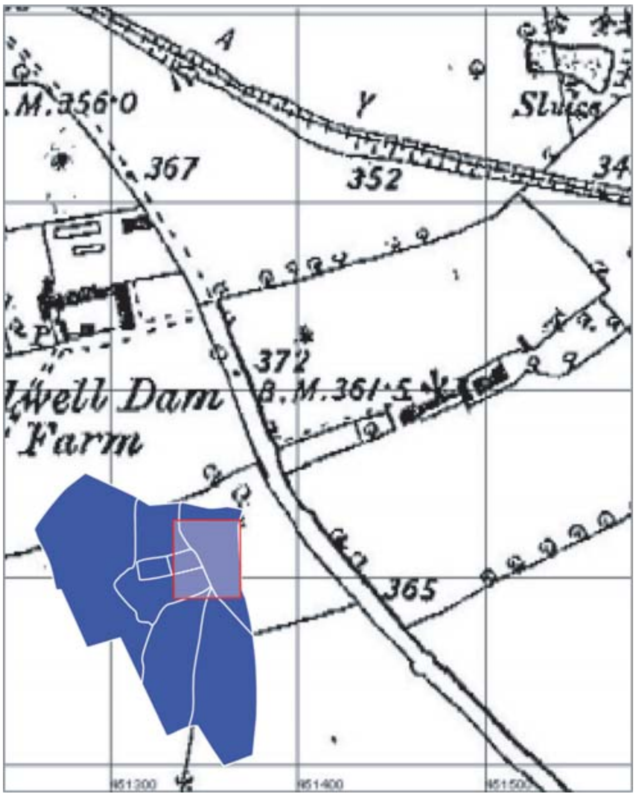


Figure 4.7 Location of man made features SSW of Chilwell Dam Farm, NGR 451475 342775 shown on the 1885 Ordnance Survey map of the area. Although the features are not labelled, the presence of an Ordnance Survey bench mark (elevation 361.5 ft) indicates that they were built structures. Also shown in the west of this image is the track of a tramway to the Kimberley Colliery which was disused by the time the Ordnance Survey Map of 1901 was published.

on pre- World War II maps (Figure 4.7). Interestingly, these features are visible on one of the two stereo-pair photographs used for this study (78/040/105), but not in the adjoining photograph (78/040/104), indicating that they are only visible under certain viewing conditions. It is also possible that the absence of these features from other frames of the flight line could indicate that the features are the result of damage to that frame. Supporting evidence from a personal account of a local resident (in conversation with D Gunn), and debris located during field survey, support the fact that these features are the remnants of either mining or agricultural buildings.

5 Pre-soil strip site visit

5.1 Overview

A field survey was carried out at the Chilwell Dam site on 1 June 2001 to identify any features at the ground surface that could indicate past mining activity and the presence of mineshafts. The weather during the visit was dry but overcast. Mineshafts were not obviously apparent at the site. Any features that could be attributed to mining disturbances and/or could affect the thermal imaging properties of the ground surface were noted. Vegetation cover varied across the site and generally reflected recent agricultural activity. The southern and easternmost parts of the site were those most recently tilled. Vegetation was lush, where present, but, when viewed it was apparent that much of the ground surface was bare soil and, for most of the area, still in crop furrows (Figure 5.1a). The north and northwest sections of the site, recently used as arable grazing, were covered in a lush growth of grasses and meadow plants (Figure 5.1b). In some areas immediately surrounding the farm site and in the far north-east of the site (Figure 5.1c), it appeared that no recent agricultural activity had taken place and, as a result, a dense vegetation cover was present. The features identified have been categorized as either topographical or compositional.

5.2 Topographic features

Despite reworking by agricultural processes for at least 100 years, a great deal of topographic evidence of mine workings was still visible across the site.

5.2.1 Remnants of shaft structure

As described in section 3.2.2, Figure 3.4, the brick lined collar of a disused mine shaft, Shaft 32, was located at NGR 451285 342342 (Table 5.1). Although the void formed at the surface is over 3 m wide at the surface it was not easily visible even from a short distance away (Figure 5.2). The tree that stands alongside the shaft visually obscures it by drawing attention away from the ground surface and by increasing the overall relief of the scene. It is also likely that the root system of the tree is providing support for ground in the area.

5.2.2 Water filled hollows

Although no other open shafts were located during the walkover survey, six locations were identified where one or more trees were found in association with a depression in the ground; in four cases the depression was filled with standing water. In one case (Figure 5.3a), the location of the shaft was obscured by the activities of shallow quarrying which had taken place to exploit the dolomitic limestone near to the surface. The largest pool of standing water was found at NGR 450911 342997 where a near-circular pond of 10 m diameter was found (Figure 5.3b, Table 5.1).

As indicated by the aerial photography interpretation and subsequent walkover surveys, it is clear that isolated trees may be good indicators of some mineshafts. It seems to be a reasonable proposition that trees may have been left at mineshaft locations as markers to prevent the loss of

Table 5.1 Examples of some features described in section 5.2 and the identifying factors that indicate the presence or otherwise of a mineshaft. Un-shaded rows are thought to be 'possible', blue rows 'probable' indicators and red shaded rows are definitive indicators of a shaft locality. All of the sites chosen as examples are known locations of mineshafts according to British Coal records. This table is not intended to be exhaustive but does include features identified during the walkover survey.

	Feature \ NGR	451475 342775 (mound)	451525 342775 (building remains)	451285 342342 (open shaft)	450911 342997 (depression)
At-surface	Coal fragments visible 5–10%	X	X		
	Coal fragments visible >10%	X			
	Coal Measures mudstone fragments visible 5–10%	X	X		
	Coal Measures mudstone fragments visible >10%				
	Brick Fragments visible	X	X		
	Large (cobble sized) brick fragments visible	X			
Near-surface	Coal fragments visible 5–10%	X	X		
	Coal fragments visible >10%	X	X		
	Coal Measures mudstone fragments visible 5–10%	X	X		
	Coal Measures mudstone fragments visible >10%	X	X		
	Brick Fragments present	X	X		
	Large (cobble sized) brick fragments visible	X	X		
Other	Depression in ground			X	X
	Soft ground	X			
	Shaft lining visible			X	
	Circular, water filled depression with horizontal outer edge				X
Interpretation Shaft present? (Yes, no, probable, possible)		Prob	Poss	Yes	Prob

Figure 5.1 The three principal vegetation types found at the site. Note that the topographic high in the foreground of photo c is thought to be the remnants of the disused tramway.

agricultural equipment or even that the tree (or its predecessor) was utilised as a hoist support during mining operations. Equally plausible is that the area surrounding a tree was left fallow as a safety precaution or because of the presence of a depression and that in some cases this led to the development of tree growth.

5.2.3 Other topographic features

A circular mound, approximately 15 m in diameter and 0.5 m in height was mapped near to the western edge of the site at NGR 451475 342775, (Table 5.1) close to Shaft 15 and 16 (Figure 5.4). Although it could not be confirmed during mapping, this feature was thought, because of its size, shape and composition to be the remnants of a waste heap, possibly formed as a result of mining activity. At NGR 451525 342775 there appeared to be building remnants (Table 5.1).

A broad ridge, approximately 20 m in width and 0.5 m high and thought to be the remnants of the disused tramway was noted in northwest of the site.

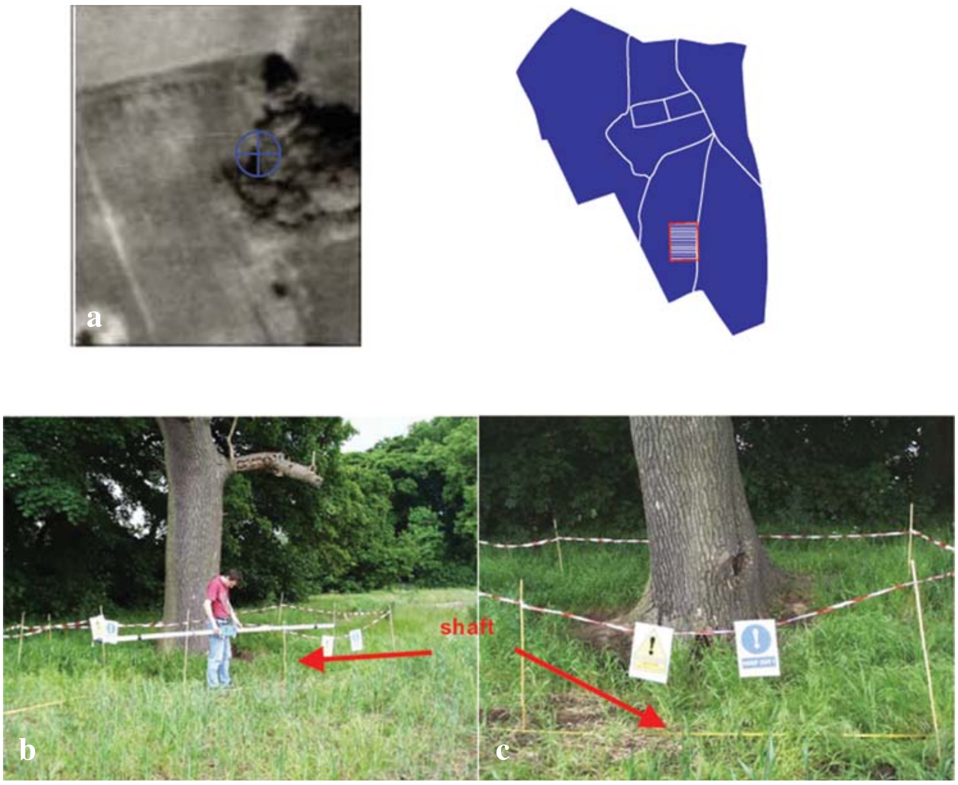


Figure 5.2 Showing the open mineshaft, Shaft 32, at NGR 451285 342342, obscured from aerial view by tree growth (a) and observed from a distance of approximately 10 m (b), D Gunn (carrying out an EM survey of the site) is stood at the outer perimeter of the 2.5 m radius exclusion zone observed by BGS staff throughout investigations. Even from distance of 3.5 m, (c), the shaft remains obscured from view. N.B. The safety perimeter was a temporary measure installed by BGS for the duration of BGS investigations. See also Figure 3.2.

Figure 5.3 Two examples of water filled topographic depressions, both of which were obscured by tree cover. Both locations are marked as known mineshafts on Coal Authority records.

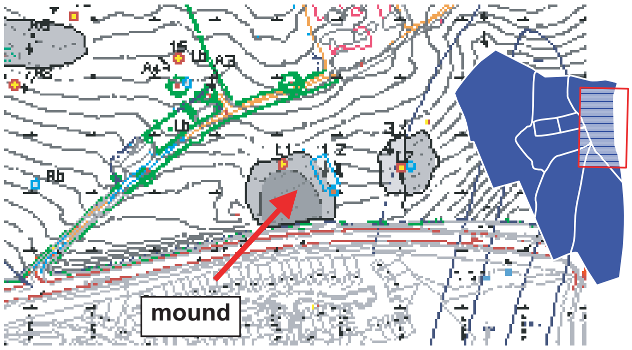


Figure 5.4 Showing the location of 15 m wide mound of debris SSE of the farm site.

Figure 5.5 Typical appearance of the red silt soil type, with (right) and without (left) a significant fraction of coal.

Figure 5.6 Typical appearance of the light to medium brown sandy silt with (right) and without (left) a significant coal fraction.

Some topographic variation in the site is attributable to geological factors. The boundary between the Lenton Sandstone and the Edlington Marl (Figure 3.1) is observed as a break in slope from the steeper gradient of the Lenton.

Sandstone to the more gentle slopes formed on the Edlington Marl. The highest part of the site forms an almost flat plain, marked on the geological map as an area of Glacial till. Although not investigated in detail, the very flat morphology and straight fence line along the northeast boundary of the site, leading to an old break in the boundary hedge, suggest that this has in the past, as a roadway and that the materials here have been re-worked, possibly by cut and fill.

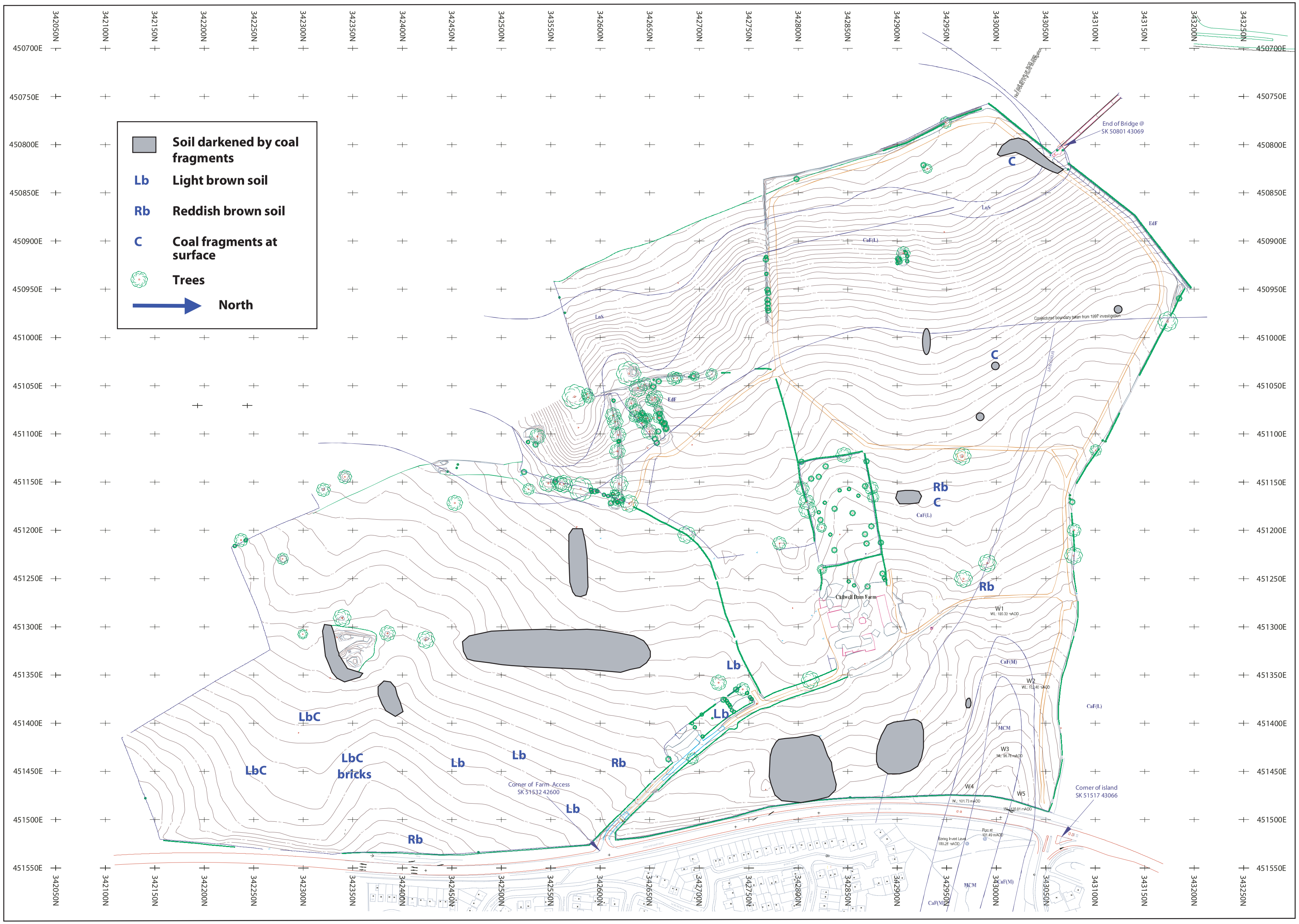


Figure 5.7 Map of the survey area showing the location of patches of darkened soil.

Figure 5.8 Coal Measures Mudstone at surface.

An north-south trending linear depression shown in the detailed contour map of the site is present in the area between NGR 451350 342375 and NGR 451550 342375. No detailed assessment of this feature was made, but it is thought that this could be the margin of a hill-wash deposit.

It is likely that other topographic features were present at the site, but that these were missed at the time of the survey as a result of vegetation growth.

5.3 Compositional features

5.3.1 Increased coal content

Coal-bearing strata are not exposed naturally within, or upslope of, the boundaries of the Chilwell Dam site. Therefore any coal fragments at surface must indicate activities associated with the nearby extraction, processing or use of coal.

In many locations it was noted that the 'clean' soil (a reddish brown silt with clay occurring in the north-western areas of the site and a light to medium brown sandy silt occurring elsewhere) contained a significant proportion of lignitic material, making the overall appearance of the soil surface darker (Figures 5.5 and 5.6).

On close inspection almost all of the soils inspected along the survey line contained a small proportion of very coarse sand- to small gravel- sized coal fragments, estimated at a few percent. In order to cause significant soil darkening, visible in the field, it was estimated that approximately 5–10% of the soil at surface had to be comprised of coal fragments. The distribution of these significantly darker areas is shown in Figure 5.7. Although the presence of coal fragments is almost certainly an indicator of some sort of mining activity it is difficult to attribute this coal to the location of mineshafts. Coal fragments could have been widely distributed across the site by a number of activities including extraction, storage and transportation. The fissile nature of coal fragments also means that they are susceptible to break up and re-distribution under normal agricultural practice. This was borne out by geophysical testing which located very few subsurface structures in the proximity of coal rich areas.

5.3.2 Increased coal measures mudstone content

It was also noted that in one location NGR 451035 342775, there was a significant proportion of weak, fissile light to medium grey mudstone, thought to be Coal Measures Mudstone (Figure 5.8), usually associated with increased coal content (Figure 2.3).

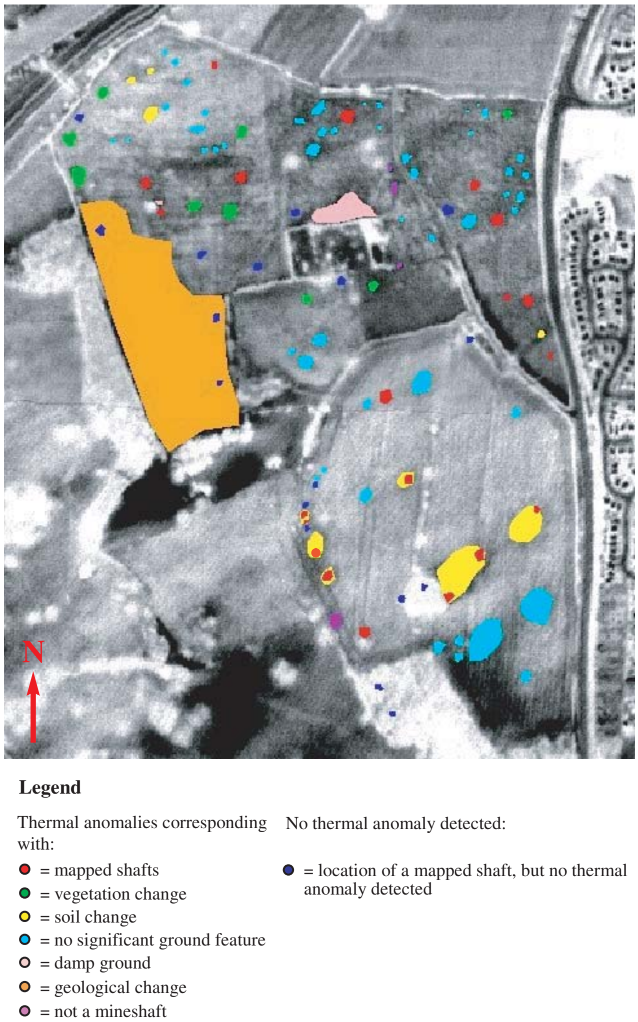


Figure 5.9 Classification of thermal anomalies at Chilwell Dam Farm.

The presence of mudstone of this type is considered to be a better indicator of mineshaft location than coal fragments. The mudstone extracted had little economic value and was essentially a waste product that would have been deposited as near to the point of extraction as practical.

5.4 Thermal image analysis post pre-soil strip site visit

Figure 5.9 provides a classification of the thermal anomalies identified (in Figure 4.2) within the pre-dawn thermal image of the site following the pre-soil strip site survey. 89 anomalies were identified within the thermal image. Of these, 18 corresponded with the location of mapped shafts, indicating that half of the 36 mapped shafts were detected. From the 71 anomalies that did not match the location of mapped shafts, 8 anomalies coincided with a vegetation change at the surface and 5 anomalies corresponded with a soil change at surface relative to the surrounding ground. The anomalous area immediately to the north of the orchard was identified as damp ground, a large thermally anomalous area to the west corresponded with a change in geology. It was apparent that a further 4 anomalies were not related to the location of a mineshaft. For instance the ground appearance at the two 'purple' anomalies to the east of the damp ground were patches of ground where trees had recently been removed. Detailed analysis of the thermal image is described in section 8.

6 Geophysical survey

6.1 Overview

Wilson Bowden Ltd. had scheduled soil stripping of the site to observe material changes indicative of abandoned mineshafts prior to development of the Nottingham Business Park. A soil map was prepared after the initial walk-over survey of the site. Using the thermal image and the soil map, interim sets of geophysical surveys were undertaken over the ground areas that formed localised thermal anomalies. It was anticipated that the exact localities of abandoned mineshafts or related dereliction might be identified as anomalous signatures along the geophysical profiles. In this way the geophysical surveys would verify the position of anomalies on the thermal image and provide selection criteria for potential soil strip areas.

6.2 Geophysical techniques

Two rapid methods to provide geophysical profile data were used to traverse over areas of ground that coincided with anomalies on the thermal image:

- Electromagnetic EM 31
- Magnetic

6.2.1 Electromagnetic EM 31

The electromagnetic method is based on the artificial production of a primary magnetic field by passing an alternating current through an electrostatically shielded coil or loop, which induces electrical eddy currents within the earth, (McNeil, 1979). These electrical eddy currents will create a secondary magnetic field and an electrostatically shielded receiving coil at the surface detects the net field resulting from the interaction between the primary and secondary magnetic fields, as shown in Figure 6.1a. The receiver signal comprises a part that is in phase with the alternating current, Ip, due to the primary magnetic field, Bp, and a part lagging by 90° due to the secondary magnetic field, Bs, that is generated by the induced current in the ground, Is, as shown in Figure 6.1b. The transmitter-receiver coil spacing, S, in Figure 6.2 is always much less than the skin depth of the current flow in the ground. The skin depth is the depth at which the current density is reduced to one third its direct current value. Skin depth is calculated from,

$$\delta = \sqrt{\frac{2}{\mu.\omega.\sigma}}$$

where $\mu \approx$ magnetic permeability of free space (8.85 × 10-12 Fm^{-1}), $\omega = 2\pi$.frequency of oscillation and σ = the conductivity of the ground (approximately 0.05 Sm^{-1} in Chilwell Dam). This gives a skin depth of several kilometres. Under these conditions, the induced current flow causing the secondary magnetic field is linearly proportional to the conductivity, σ of the ground, and is

$$Bs = j\frac{\omega.\mu.S^2\sigma}{4}Bp$$

where S = the transmitter – receiver coil spacing and j = √-1 and indicates the 90° phase difference between Bs and Bp. (Bp is measured directly by a small coil next to the transmitting loop).

Over a homogeneous or horizontally stratified half space, a coil with its axis either horizontal or vertical produces only horizontal current flow. In horizontal strata, the contribution to Bs from each individual layer is linearly dependent on the conductivity of the layer. Thus the response in the measuring equipment to a horizontally layered earth is the sum of the contribution from each layer weighted to the coil spacing and orientation. Figure 6.3 shows that the relative signal contributions from coil axes orientated vertically occur at slightly deeper depth intervals than from coil axes orientated horizontally. Electromagnetic field equipment utilises fixed coil and moveable coil systems to vary S, the inter-coil spacing, and thus the depth intervals within the earth that contribute to the conductivity measurement. The Geonics EM 31 was used in this project; equipment shown in Figure 6.4, has a coil spacing is 3.66 m, and thus the peak response on the vertical dipole is 1.46 m

Electromagnetic methods are employed along profiles or in a gridded fashion. These methods can be very effective in the detection of mineshafts that contain a mixture of materials with highly contrasting conductivities. A void, for example, would have no conductivity but metal mining artefacts within the shaft infill would have very high conductivities. In the case of vertical sheet conductors, eddy currents tend to be induced within the vertical plane of the conductor and not within a horizontal loop within the ground, as Parasnis (1980) explains. Figure 6.5 shows a

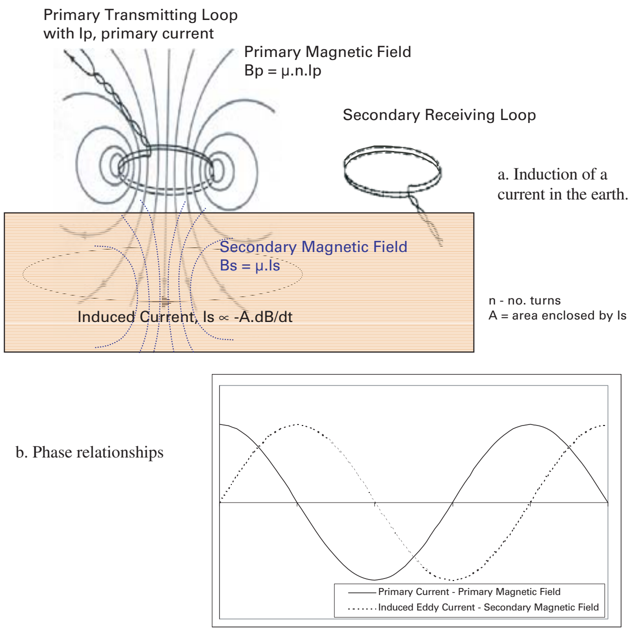


Figure 6.1 Earth conductivity measurement using an electromagnetic technique.

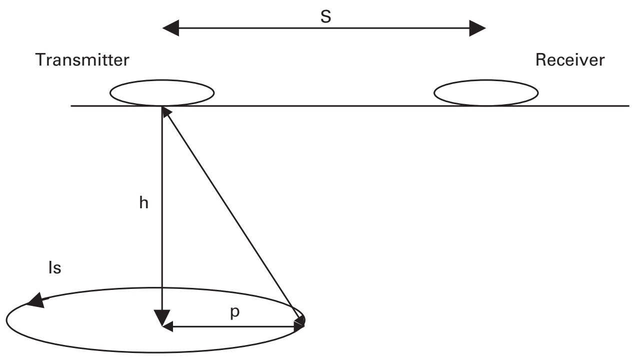


Figure 6.2 Parameters used to calculate the earth's electrical conductivity (After McNeill, 1979).

vertical dipole system with the transmitter to the right of a vertical sheet (extending in and out of the page). When the oscillating dipole is directed downwards, the primary magnetic field cuts the vertical sheet conductor, inducing a current to flow into the page at its top and out of the page at its bottom. This causes the secondary field to flow such that a receiver at point R_1 detects a constructive superposition of primary and secondary magnetic fields causing a maximum response in the profile. Where the receiver and transmitter straddle the vertical sheet conductor with the receiver at R_2, there is a destructive superposition of primary and secondary fields causing a minimum response in the profile. The two points where the profile plot crosses the 100% line are when the receiver and transmitter are over the sheet. The two maxima are usually a distance 0.7S from the 100% crossover points. Figure 6.5 also shows the equivalent response of a horizontal dipole system. Telford et al. (1990) suggested that the size of the maxima give some indication of the depth of the conductor, and that the maximum detectable depth is one-half the coil separation, S. Figure 6.6 shows how a dipping sheet produces an asymmetric profile where the down-dip maximum is broadened.

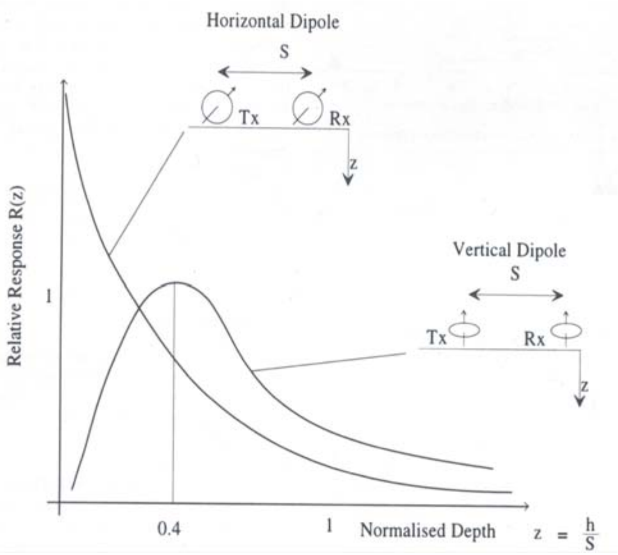


Figure 6.3 Theoretical responses for horizontal and vertical dipole orientations.

6.2.2 Magnetic

The magnetic method detects variations in the geomagnetic field strength caused by contrasts in the magnetisation of different rocks. The magnetisation of rocks is a vector quantity containing several components, of which two predominate. Magnetisation can be in the same direction as the earth's magnetic field, called induced magnetism, (McCann *et al.* 1987a, b). The strength of the induced magnetism depends upon the magnetic susceptibility of the rock. Most rocks owe their magnetic properties to the presence of magnetite and their magnetic susceptibility is largely controlled by the total content of magnetite that they contain. In addition to induced magnetism, rocks can have a remnant magnetism that they acquired under the geomagnetic field that prevailed at the time of their formation. The direction of remnant magnetism is dependent upon the rock's history of formation and movement to form the present day earth's crust.

The strength of the earth's magnetic field varies from about 0.38×10^{-11} T (or 0.0038 nT) near the tropics to about 0.65×10^{-4} T (or 65 000 nT) near the magnetic poles (where T = Tesla). Additionally, its vector angle relative to the earth's surface varies from 0 to 90°. In England, its strength is about 47 000–49 000 nT at an angle of about 67°. The field strength just above the ground is measured by the field magnetometer equipment, for example, the Scintrex IG-2 apparatus as shown in Figure 6.7. This is a proton precession magnetometer that measures the oscillations of protons in the earth's magnetic field after they have been temporarily polarised by a strong field applied using a coil. The frequency at which the protons precess is proportional to the total magnetic field strength. Often, field equipment measures the field strength in two units at different heights above the ground to produce the vertical magnetic field gradient. (This negates the requirement to account for temporal variations of the magnetic field strength during the survey.)

Magnetic anomalies due to natural cavities are caused by the susceptibility contrast between the void and the rock. Magnetic detection of voids is unlikely in low susceptibility rocks like chalk, but becomes more likely in rocks of increasing magnetic susceptibility like ironstones. Mineshafts can be detected where either brick linings or metallic objects such as rails, nails, carts and so on have been abandoned. Bricks generally contain a significant

Figure 6.4 Geonics EM 31 system with an inter-coil spacing of 3.66 metres.

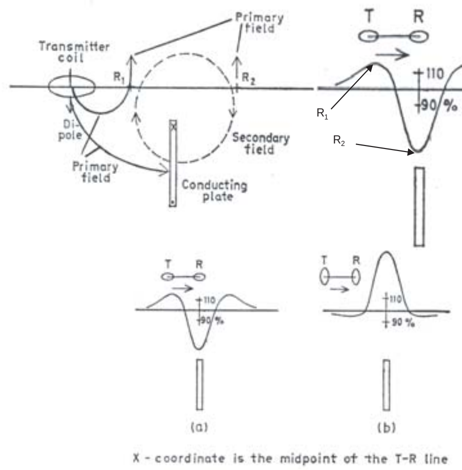


Figure 6.5 Profile using an electromagnetic two coil system to a vertical sheet conductor (After Parasnis 1962).

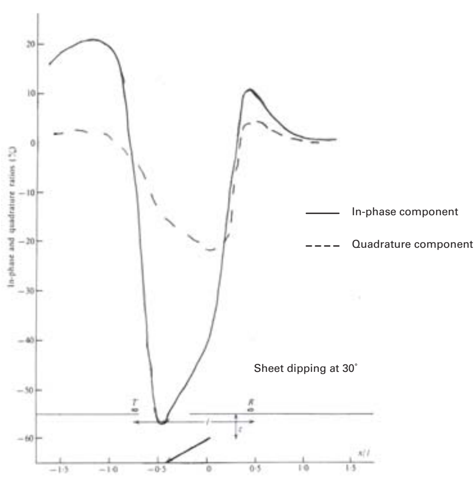


Figure 6.6 Profile using an electromagnetic two coil system to a dipping sheet conductor (After Telford et al. 1990).

amount of magnetite, and have a strong remnant and induced magnetism. (As complete alignment of the remnant magnetic fields of all the bricks is unlikely, they are usually detected by the induced magnetic fields they cause.)

Shafts can be approximated by a dipole model. Assuming that the shaft contents are magnetised by the earth's magnetic field, Figure 6.8, shows the anomaly produced by a dipole that is inclined at 45° to the surface. The width, x* of the Z-curve (the vertical field) at $Z_{max}/2$ is approximately equal to z_m, the depth of the dipole. The same relationship holds for the F-curve (total field or sum of the magnitudes of the horizontal and vertical fields) in the range $30° \leqslant I \leqslant 90°$. For I = 90°, or a vertical dipole, the total and the vertical magnetic field anomalies are identical, as shown in Figure 6.9. For I = 0°, or for a horizontal dipole, the profile is sharper and $x^* \approx 0.7\ z_m$ at Fmax/2 which is shown in Figure 6.10.

When surveying for cavities or mineshafts a profile or even a series of parallel profiles can be undertaken such that a grid of measurements is established. Anomalies associated with the shafts can then be identified on profile or contour plots of the field data.

Figure 6.7 The Scintrex IG-2 field magnetometer equipment. (The staff has two proton precession units at approximately 1.5 m and 2.0 m above the ground.)

6.3 Geophysical survey lines

The locations of the geophysical survey lines were planned to coincide with as many of the following features, where the list order indicates the priority given to a feature when locating the lines:

i thermal anomaly on the thermal image,
ii soil colour change or lush vegetation on the soil map,
iii mineshaft located on Coal Authority records, or,
iv open mineshaft to calibrate response of geophysical tools.

Figure 6.11 shows the location of the geophysical lines, and Tables B.1 and B.2 in Appendix B summarise the line statistics and the features found on each of the electromagnetic survey and each of the magnetic survey lines respectively. The resultant profiles over five of the most interesting geophysical lines are reported in detail in the main text. Plots of the geophysical profiles and summary interpretations are provided for all survey lines in Appendix B.

6.3.1 Line C–D Profile over the brick-lined shaft

This line was traversed from north to south, (*c.f.* Figure 6.11), over the open mineshaft shown in Figure 3.4, (mineshaft no.32 in Appendix A). The line is 30 m in length and the mineshaft is positioned at its centre. No coal spoiling was observed in the reddish-brown soil immediately surrounding the shaft. Heating from the tree above the shaft would have masked any thermal anomaly caused by the ground at this locality. This traverse provides an 'expected profile' over a lined mineshaft that can be used as a comparative signature when interpreting the geophysical profiles over thermally anomalous ground.

In the vertical dipole orientation, the EM 31 profile shows the averaged conductivity of the ground down to about 5.5 m depth (Figure 6.12). This profile has a peak of higher apparent conductivity (around 8% higher than the end line conductivity) that coincides with the centre of the shaft. In the horizontal dipole orientation, the EM 31 profile shows the averaged conductivity down to about 2 m depth. This has a peak of higher apparent conductivity (around 35% higher than the end line conductivity) that coincides with the

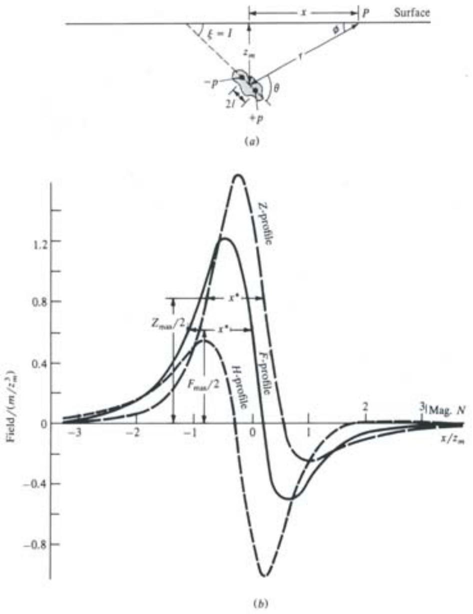


Figure 6.8 Magnetic anomaly caused by an isolated dipole dipping at 45° to earth's surface (After Telford et al. 1990).

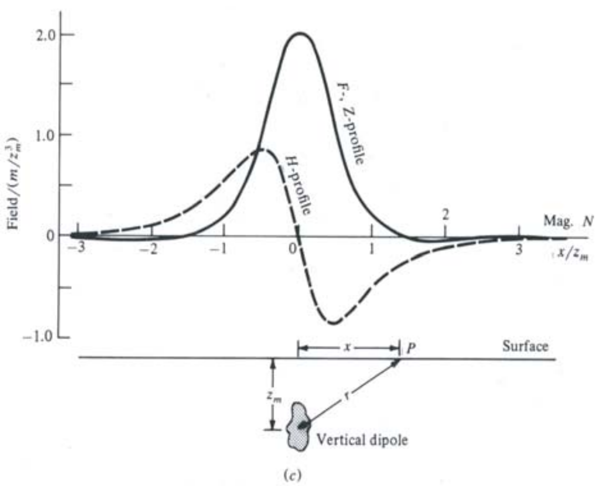


Figure 6.9 Magnetic anomaly caused by an isolated vertical dipole (After Telford et al. 1990).

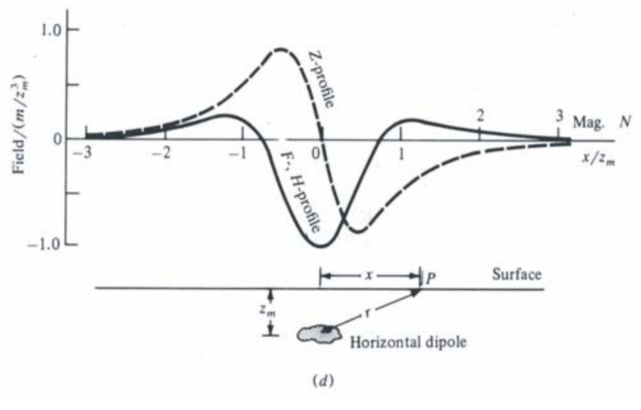


Figure 6.10 Magnetic anomaly caused by an isolated horizontal dipole (After Telford et al. 1990).

centre of the shaft. The horizontal dipole survey is strongly affected by the metal objects at the top of the mineshaft and has a similar signature to that caused by an extended conductor. Many of the metal objects had rusted indicating the presence of ferrous materials. There is a very strong magnetic anomaly over the mineshaft, which indicates a sub-vertical magnetic dipole within the mineshaft. A near-vertical standing iron, scaffolding bar was observed in the shaft. It should be noted that kiln baked brick wall structures within the ground can also produce geophysical anomalies of a similar character (Figure 6.13). However, because of the strength of this peak, it is suspected that the metal objects have a very significant influence on this magnetic anomaly.

6.3.2 Lines A–B Thermal anomaly associated with a coal darkened area

Line A-B was traversed from the north, in a soil that had been darkened by coal mixing, to the south where the soils were lighter in colour. Soil samples were taken along this line at the 0 m , 75 m, 100 m and the 150 m stations. PIMA tests on these samples showed significant differences in the reflectance spectra due to coal darkening. (PIMA is a portable infra-red Mineral Analyser that evaluates the mineralogy of a rock sample from the spectral content of the reflected infra-red radiation). There is a marked ridge of higher apparent conductivity values from around the 100 m to the 170 m station as this line is traversed from north to south, Figure 6.14. Apparent conductivities measured across the ridge of around 26 mSm^{-1} for the vertical dipole (investigation to 5.5 m depth) and around 21 mSm^{-1} for the horizontal dipole (investigation to 2 m depth) are similar in end values along Line C-D.

The lower apparent conductivities measured at the ends of Line A-B of up to 10 mSm^{-1} for the vertical and around 5 mSm^{-1} for the horizontal dipole are also observed over the Cadeby 'carbonate facies' along Lines E–F, Q–R, U–V and AA–BB. Thus, there is much geophysical evidence to suggest that a transitional ridge of high conductivity follows an east to west trending topographic ridge to the south of the site, (as shown in Figure 6.11). The transition from low to high apparent conductivity coincides with the edge of a thermal anomaly associated with a soil change on Lines A–B and I–J. The Coal Authority indicate an abandoned mineshaft at NGR 451375, 342385, (no.28 in Appendix A) about 30 m west of the 50 m station on Line A–B, and also a mineshaft at NGR 451180, 342360 (no.30 in Appendix A), which coincides with the 56 m station of line I–J. These are likely sources of the coal spoil that caused the darkening of the soils. The 1978 aerial photograph also indicates former crop boundaries without a hedgerow running very close to the low to high conductivity transition. One possible interpretation is that different soil properties encouraged growth of different crops either side of this boundary. Borehole logs from the Seagrave Borehole drilled at NGR 451600, 342600 indicate less than a 2 m thickness of drift and topsoil at this point, (National Coal Board, 1959b). The shallow depth of the topsoil and the significant effect on the deeper investigating vertical dipole along Line A–B is consistent with these anomalies having a geological cause, possibly a ridge of altered or clayey material within the Cadeby 'carbonate facies'.

6.3.3 Line I–J Thermal anomaly associated with a coal darkened area

Line I–J was also traversed from the north in a soil that had been darkened by coal mixing to the south where the soils were lighter in colour. Conductivity values of 6 mSm^{-1} for the vertical dipole and 3 mSm^{-1} for the horizontal dipole are similar to the respective values on the northern

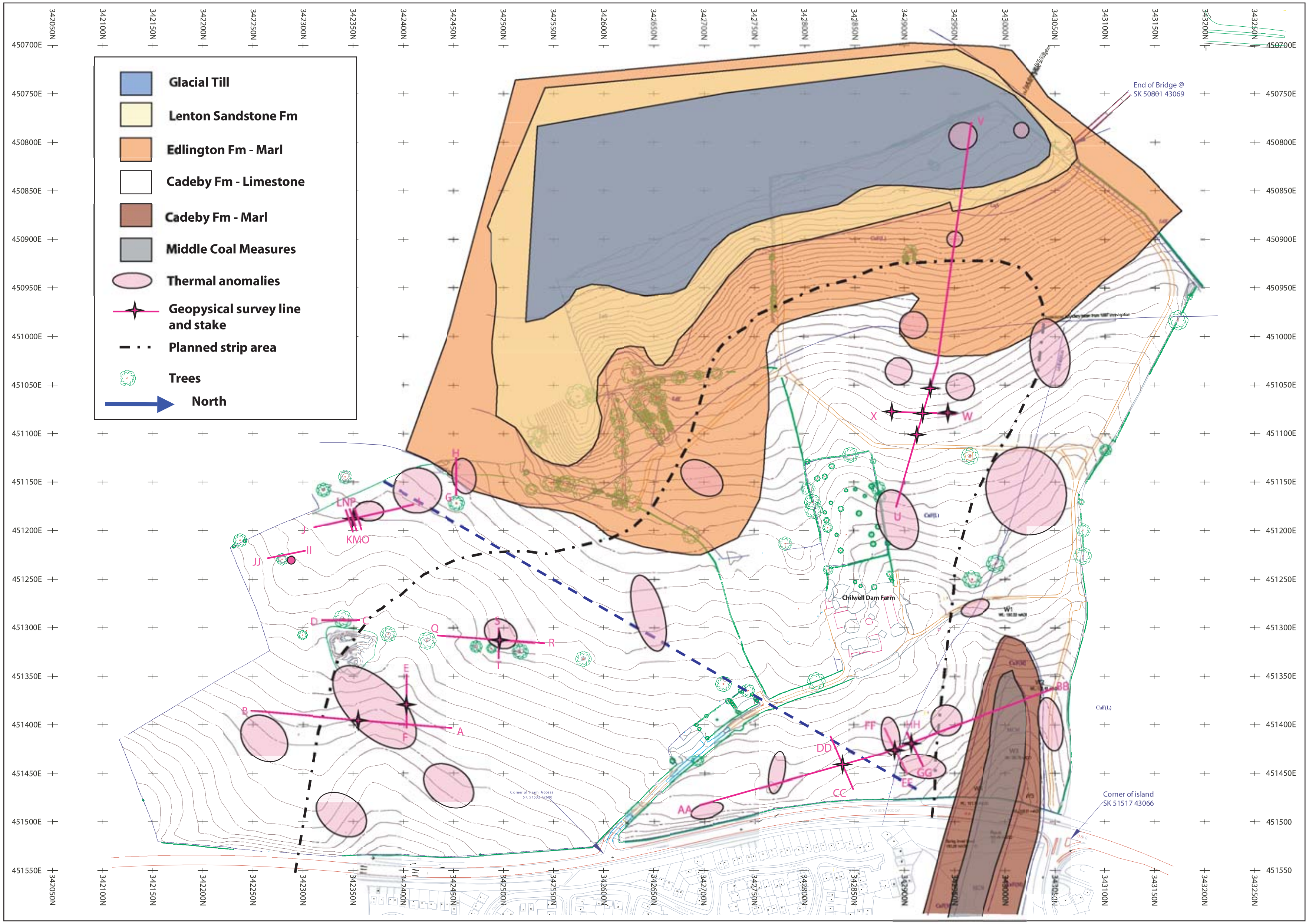
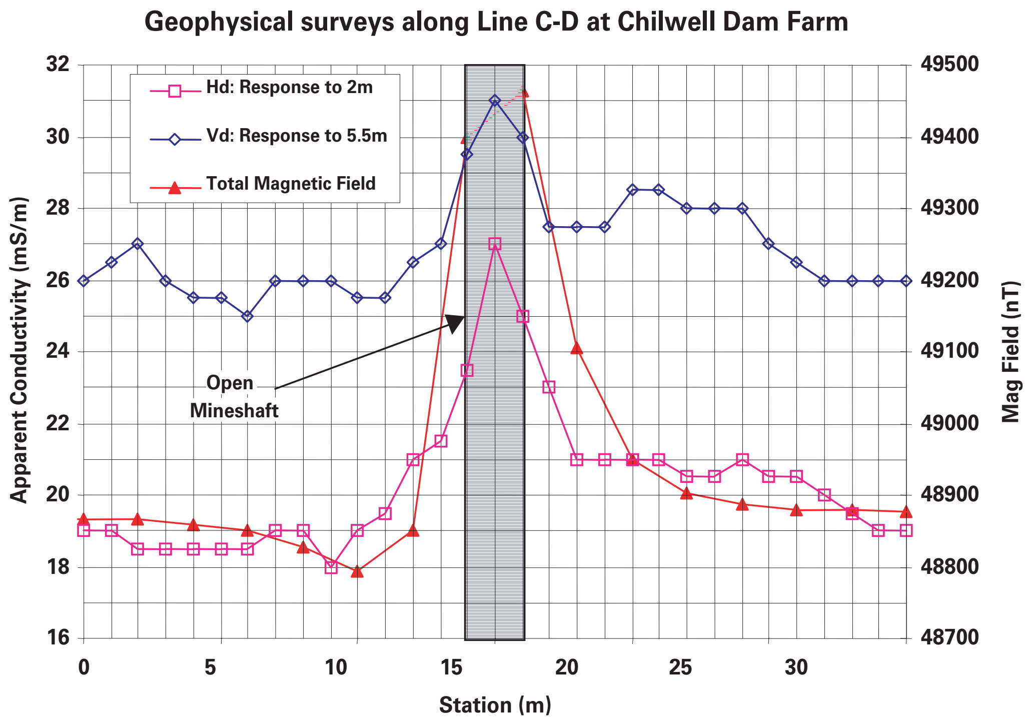


Figure 6.11 Location of the geophysical survey lines at Chilwell Dam Farm.

Figure 6.12 Geophysical profiles over a brick-lined mineshaft on line C–D.



end of Line A–B (Figure 6.15). A higher apparent conductivity ridge also occurs along this line from about the 10 m to the 70 m station. However, this ridge has a more complicated structure than that on Line A-B, with a local trough at about the 42 m station and a local maximum at about the 56 m station. Plots of the apparent conductivities of surfaces constrained by ± 10 m E/W and by ± 5 m N/S of the 56 m station indicate a low conductivity hollow just west of Line I–J at station 56 m (Figure 6.16). The Coal Authority records indicate abandoned mineshafts at NGR 451180, 342380 and NGR 451180, 342360 (nos.29 and 30 in Appendix A), which would coincide at the 40m and the 60 m stations along the line respectively. It is possible this dual peak feature is caused by the ground disturbances of two mineshafts in close proximity of one another. The magnetic profile along Line I–J from north to south across station 56 m indicates

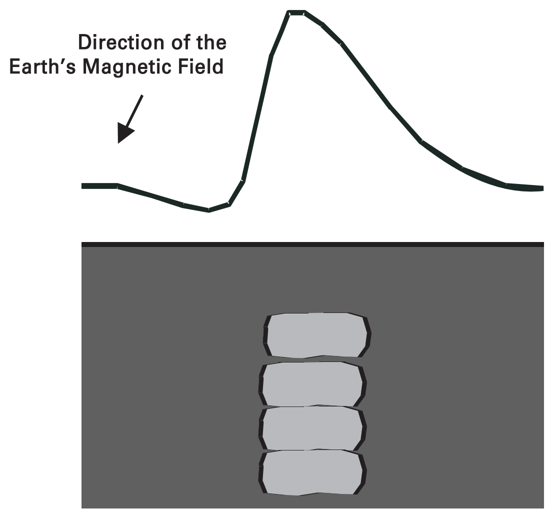


Figure 6.13 Response in the total magnetic field response over a brick-lined mineshaft (after Breiner 1973).

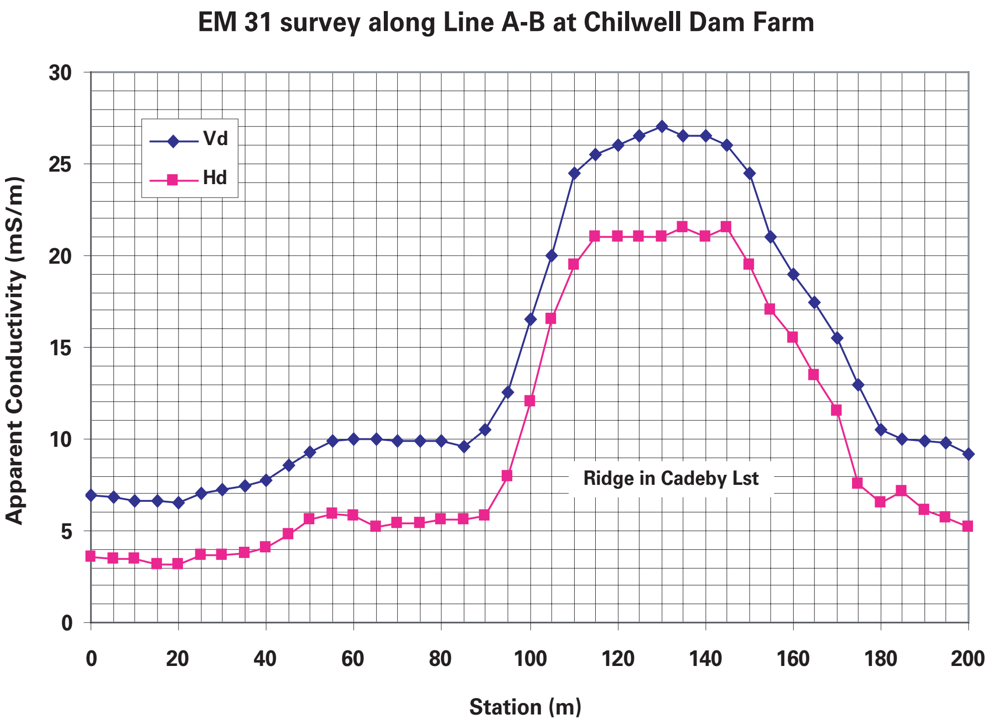
a transitional magnetic regime from smooth, low noise signals to the north, to more erratic noisier signals to the south (Figure 6.17). The 1978 aerial photograph indicates a limited ground disturbance feature of about 20 m diameter in the vicinity of this point. Also, there is an area of soil darkening that obscures a crop boundary to the north of station 56 m on this line. All this evidence is consistent with the presence of an abandoned mineshaft at this location as indicated by the Coal Authority records.

6.3.4 Line U–V Small thermal anomalies and geological variation

Line U–V was traversed from the east in an area of damp ground in the Cadeby 'carbonate facies', up-slope to the west, over the Edlington Marl, the Lenton Sandstone and finally onto the Glacial Till. Along this line, the Coal Authority records indicate the location of three abandoned mineshafts, and the thermal image indicates several thermal anomalies on the line. The mineshafts are indicated at NGR 451145, 342895, NGR 451030, 342930 and NGR 450875, 342945 (nos.8, 6 and 5 in Appendix A and NGR 450875, 342945 is coincident with a thermal anomaly *c.f.* Figure 2.5). The apparent conductivity values over the Cadeby 'carbonate' facies at the beginning of the line are consistent with Lines A–B, E–F and Q–R (Figure 6.18). Neither the thermal anomaly associated with damp ground nor the mineshaft within 30 m (NGR 451145, 342895, Shaft 8) of the beginning of the line caused any noticeable fluctuations on the profiles.

There is a very large anomaly centred at the 90 m station. The character and strength of the response on the vertical dipole on both E/W and N/S traverses suggests that a sheet conductor is buried close to the ground surface (Figures 6.19 and 6.20). The absence of a significant fluctuation on the horizontal dipole of the EM 31 on the N/S traverse across the 90 m station may be caused by the sheet conductor having a N/S orientation and being just offline. The strengths of the magnetic anomalies produced by this feature are a tenth of the strength of the anomalies caused by the iron objects in the open mineshaft. The magnetic anomaly produced across the 90 m station on the

Figure 6.14
Geophysical profiles over a soil change thermal anomaly on line A–B.



N/S along Line W–X could have been produced by baked kiln bricks. It is possible that very iron (magnetite) rich materials were used to produce the bricks that could be lining a concealed mineshaft, or an old wall section.

The abandoned mineshaft indicated at NGR 451030, 342930 (Shaft 6) coincides with a localised depression on the apparent conductivity profile between 140 and 150 m (as shown in Figure 6.18). This is also very close to transition to higher conductivity values across the geological boundary between the Cadeby 'carbonate facies' and the Edlington Marl. The geophysical depression could be a geological feature but observations of gravel-sized coal fragments within 20 m support existence of a mineshaft. However, this hypothesis could have been tested with additional profiles traversed parallel to and either side of Line U–V. This would test for a limited lateral extent of the depression feature that would be consistent with a mineshaft.

The Edlington Marl appears to comprise at least two units with different apparent conductivities. Between stations 150 m and 200 m the horizontal and vertical dipole values are at about 5 mSm^{-1} and 10 mSm^{-1} respectively. Between stations 200 m and 250 m the horizontal and vertical dipole values are at about values 11 mSm^{-1} and 21 mSm^{-1} respectively. From station 250 m to the faulted

Figure 6.15
Geophysical profiles over a soil change thermal anomaly on line I–J.

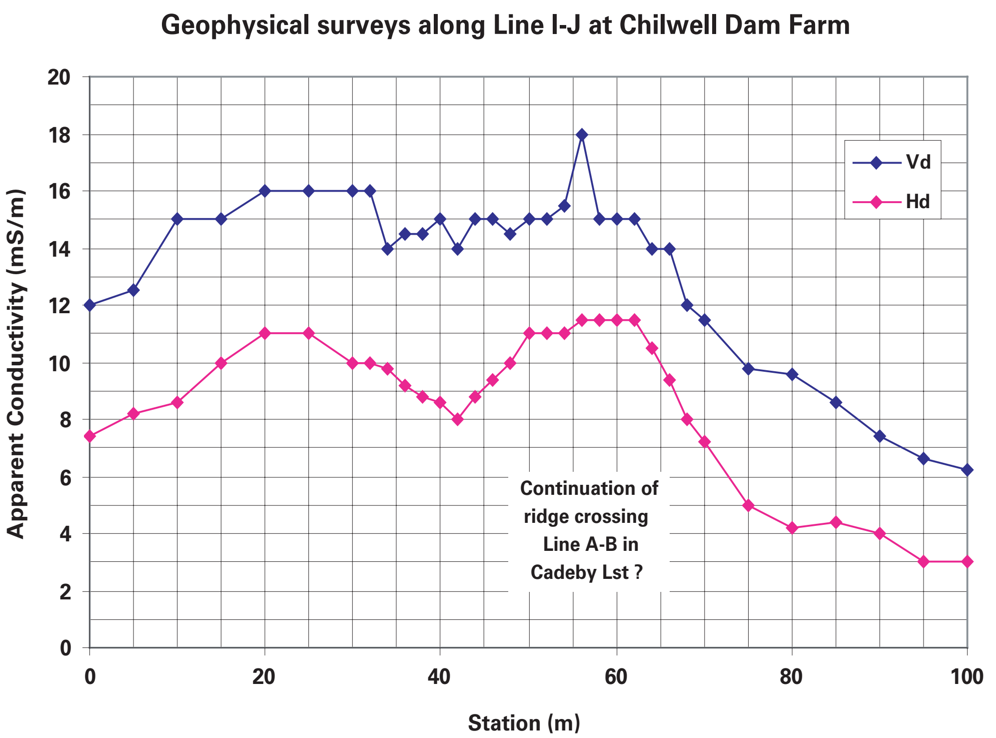
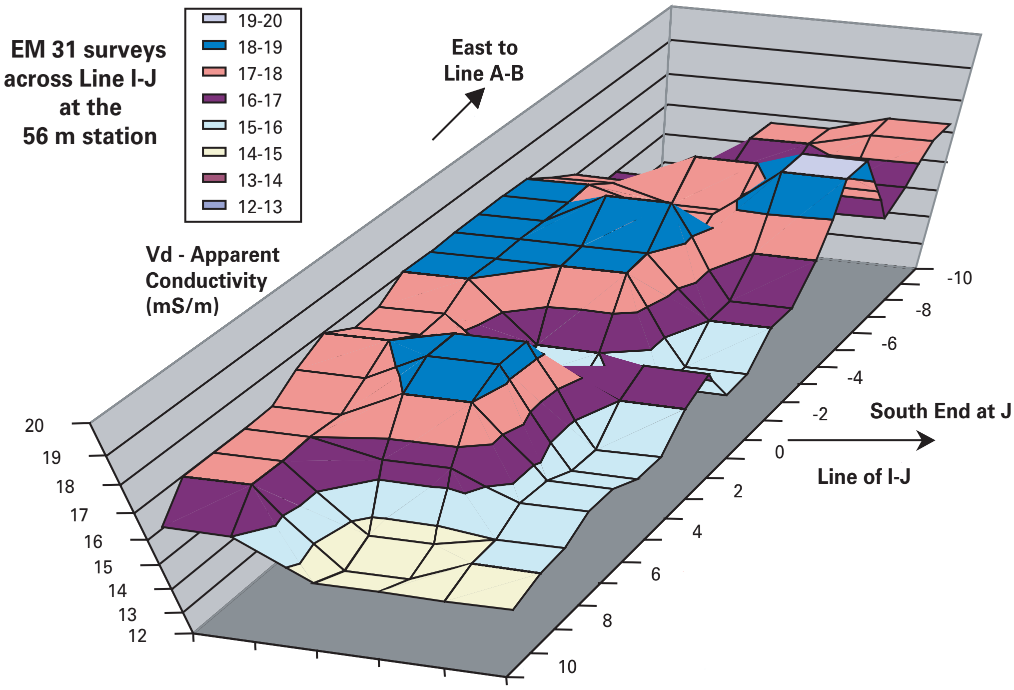
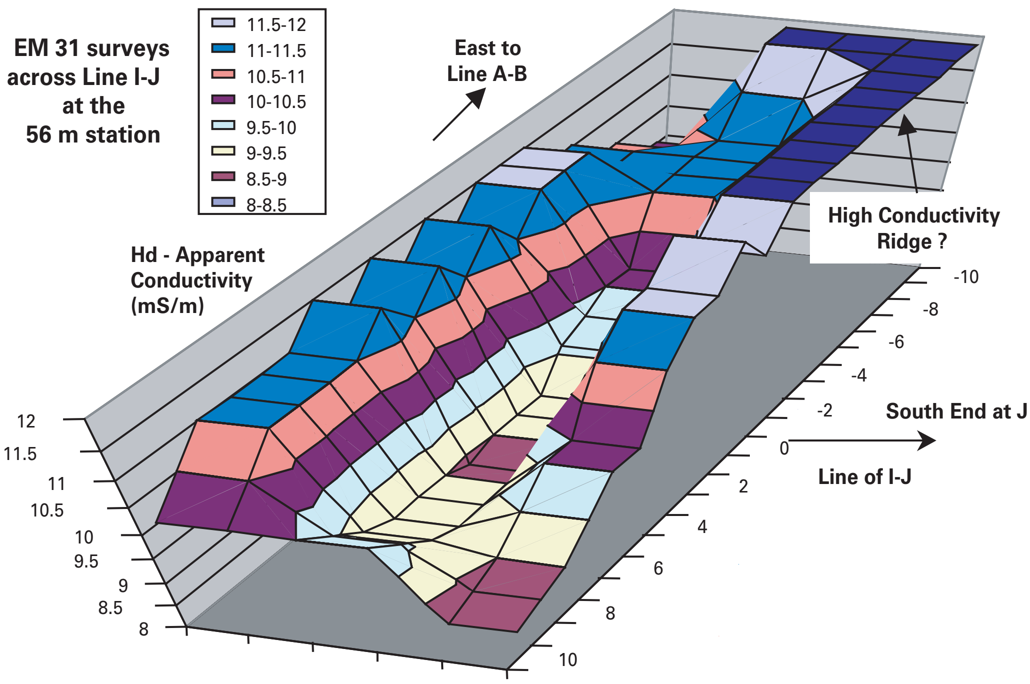


Figure 6.16
Geophysical profiles over a suspected mineshaft on line I–J, NGR 451180, 342350.



a. EM 31 vertical dipole: surface plot of apparent conductivity at station 56m on line I-J.

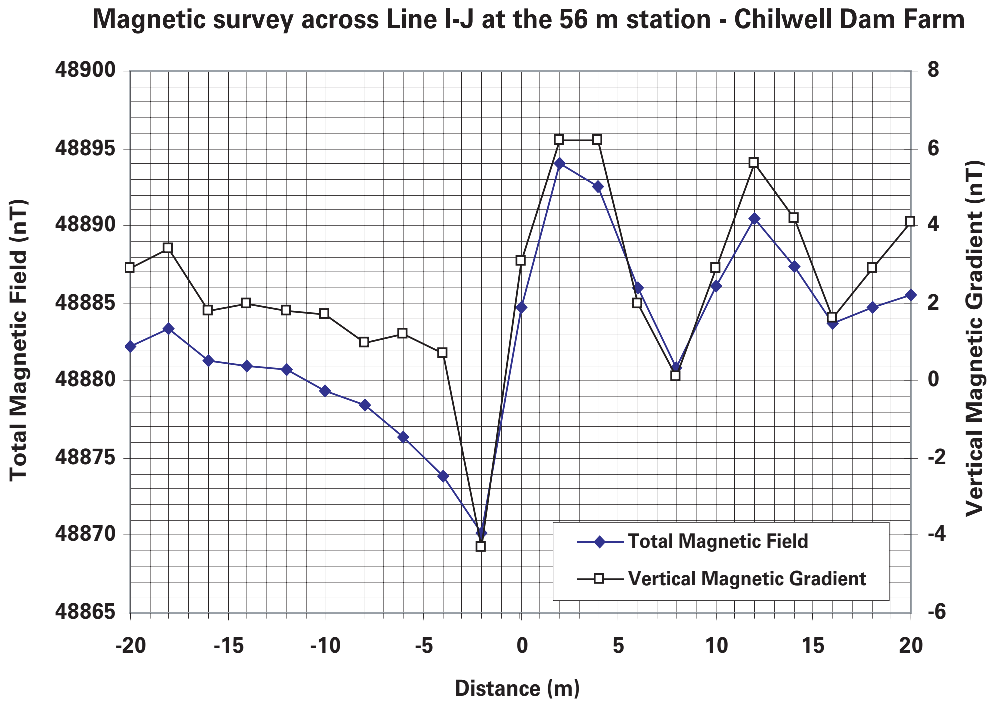


b. EM 31 horizontal dipole: surface plot of apparent conductivity at station 56m on line I-J.

boundary with the Lenton Sandstone the values fall to about 7 mSm^{-1} and 17 mSm^{-1} respectively. A localised vegetation change above a suspected abandoned mineshaft at NGR 450875, 342945 (Shaft 5) produces a thermal anomaly that coincides with the localised minima in the conductivity profiles at station 290 m. A geological fault also intersects the geophysical profile at this point, and could be an addition factor in causing the thermal anomaly. Again, the geophysical survey corroborates the identification of disturbed ground on the thermal image, and the existence of a mineshaft cannot be ruled out.

The values of apparent conductivities measured by the horizontal and vertical dipoles over the Lenton Sandstone are about 25 mSm^{-1} and 38 mSm^{-1} respectively. Values in the Glacial Till fall from 27 mSm^{-1} and 40 mSm^{-1} to as low as 20 mSm^{-1} and 31 mSm^{-1} for the horizontal and vertical dipoles respectively. Again, these low values appear as localised minima that are coincident with a

Figure 6.17 Magnetic profile over the 56 m station on line I–J.



thermal anomaly associated with a vegetation change. No abandoned mineshaft is indicated on Coal Authority records, but again there appears to be good corroboration between the thermal and geophysical responses.

6.3.5 Line AA–BB Small thermal anomalies and geological variation

Line AA–BB was traversed from the south to the north for 200 m before traversing NNW for a further 200 m. Along this line, the Coal Authority records indicate mineshafts at NGR 451515, 342685 (mineshaft no.19 in Appendix A, near the very beginning of the line), two shafts at about NGR 451455, 342785 and NGR 451485, 342790 (nos.15 and 16), one at NGR 451430, 342880, (no.10) and one at NGR 451395, 342955, (no.4). A mound of approximately 20 m diameter of disturbed ground with fragments of coal and grey mudstone is located at NGR 451455, 342790, and lies just south of the shaft pair. A thermal anomaly and an associated vegetation change with an increase of clovers and nettles also occurs at this site, as shown in Figure 2.5a. Another thermal anomaly coincides with an area of approximately 25 m diameter of discoloured ground due to fragments of limestone, grey mudstone and coal (up to cobble sizes), located at NGR 451430, 42890 near the mineshaft at NGR 451430, 342880, (Shaft 10) as shown in Figure 6.21. A small mound coincides with the shaft at NGR 451395, 342955 (Shaft 4).

Figure 6.18 EM 31 profiles along line U–V: showing variation to geology and ground disturbances.

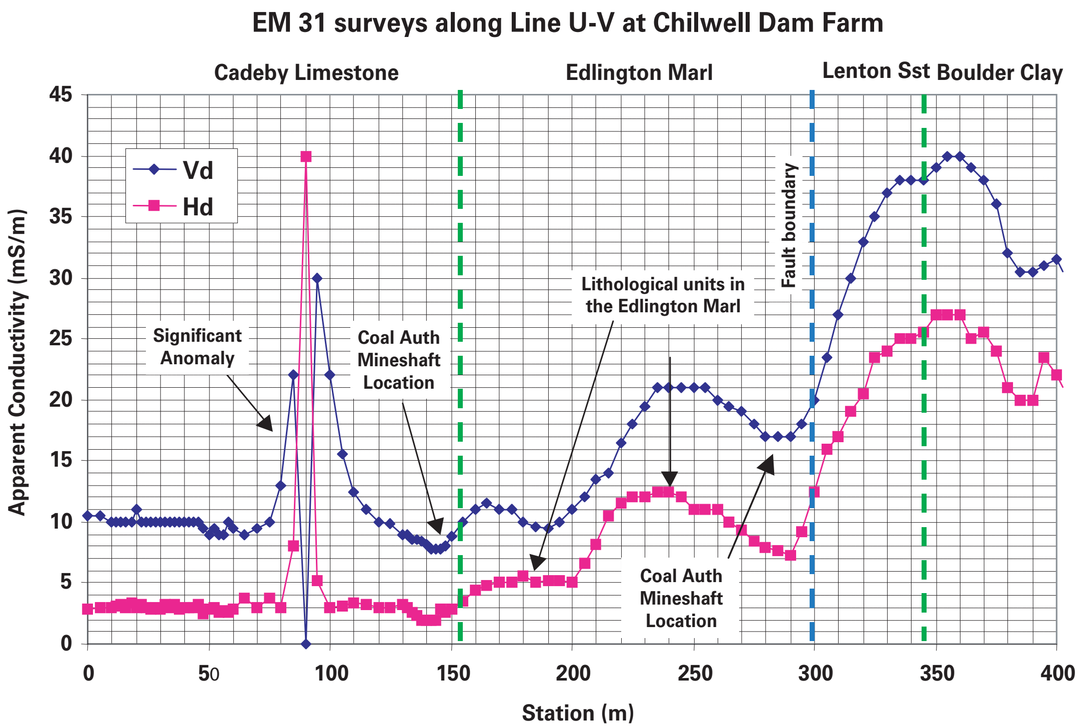
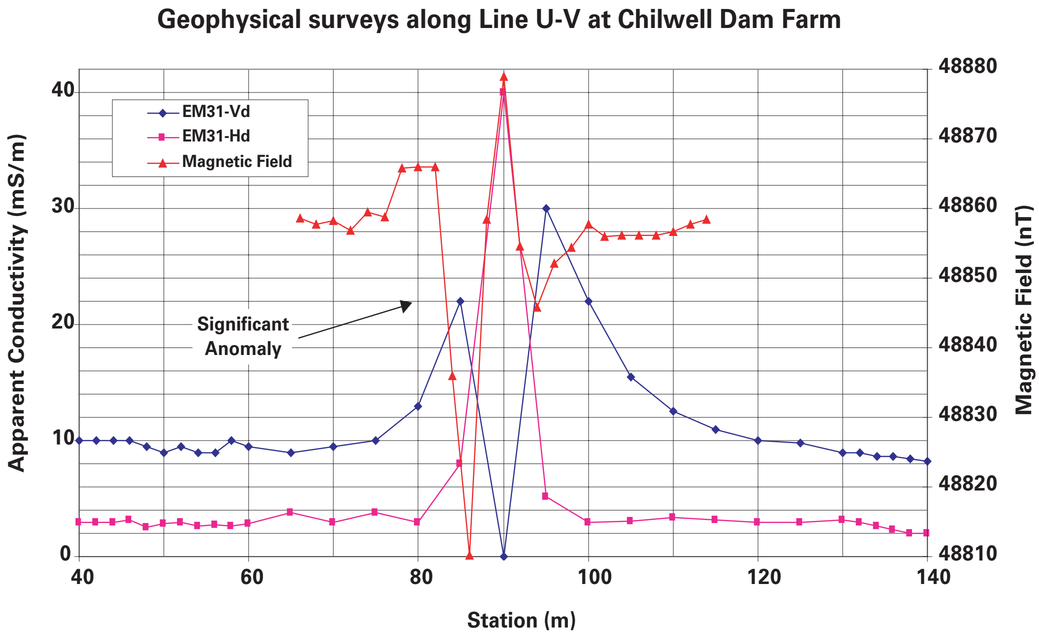


Figure 6.19 Geophysical profiles in the E/W direction over the 90 m station on line U–V.



A dominant feature on the EM 31 profiles is a large peak at the 155 m station caused by interference from the actively conducting power cables, (Figure 6.22). However, there appears to be no significant interference on the magnetic profile. At the south end of the line, the apparent conductivity values over the Cadeby 'carbonate facies' up to the fault are similar to the values on Lines E–F, Q–R and A–B. The fault boundary is clearly defined as an abrupt increase in the conductivity measured on the horizontal dipole from the 60 m station. Between the 90 m and the 110 m stations the horizontal dipole values are consistent at about 9 mSm^{-1}, and this may be representative of a measurement over the Cadeby 'carbonate facies' without interference. The fluctuations on the EM 31 profiles between the 80 m and the 90 m stations could be due to the ground disturbances, possibly caused by mineshafts. The coincidence of a fairly strong local maximum on the magnetic profile at 95 m is further evidence of the existence of a mineshaft, which is corroborated by the thermal anomaly and the ground observations. Similarly, a thermal anomaly and the ground disturbances at the 190 m station coincide with local maxima on the EM 31 and the magnetic profiles. Again, there is much evidence that an abandoned mineshaft is very close by. Fluctuations on the EM 31 and the magnetic profiles also occur around the 270 m station, which coincides with the mound and mineshaft indicated at NGR 451395, 342955 (Shaft 4). It is possible that a former tramway embankment that would have intersected the geophysical profiles at about this point has also affected the measurements. For, example, this may be the cause for the additional peak in the magnetic profile at the 260 m station. The boundary between the Cadeby 'carbonate' and 'mudstone' facies is marked by an abrupt increase in the

Figure 6.20 Geophysical profiles in the N/S direction along the line W–X and across the 90 m station on line U–V.

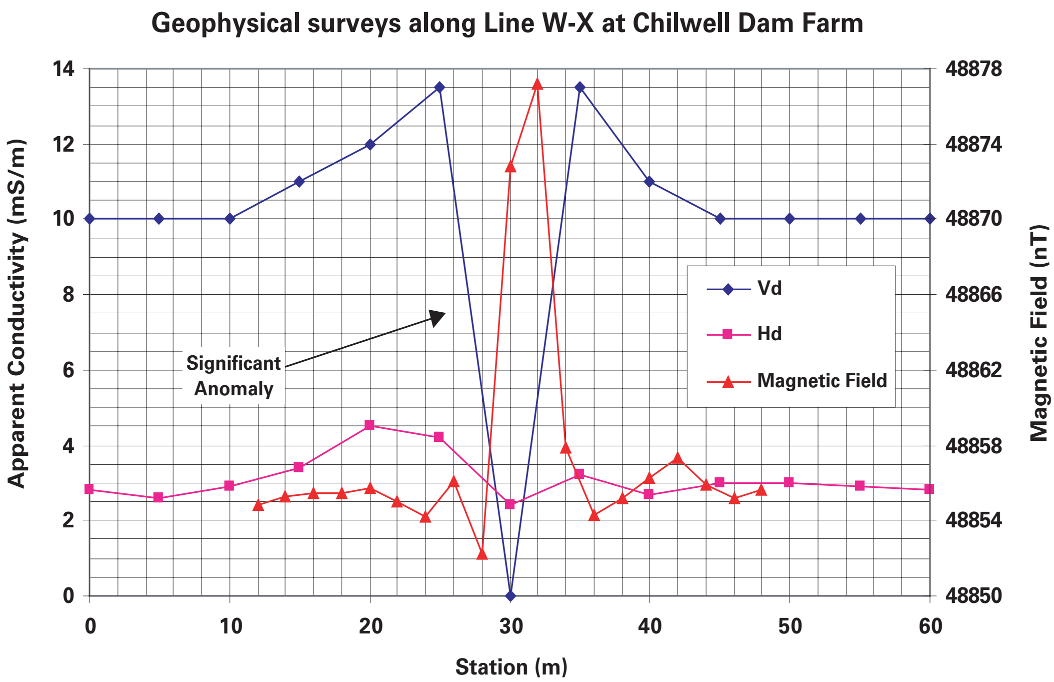


Figure 6.21 Soil disturbances over mineshafts at Chilwell Dam Farm, (NGR 451430, 42890).

a Soil discoloration over an area of approx. 25 m diameter.

b Colour change due to cobble sized limestone, mudstone and coal fragments.

conductivity values on the vertical dipole at the 290 m station. The small dip in the conductivity values measured on the vertical dipole between the 340 m and the 360 m stations maybe coincident with Middle Coal Measures outcrop. (This would have to be verified by a series of short orthogonal traverses across the 340 m, the 350 m and the 360 m to identify different conductivity values in the Cadeby and the Middle Coal Measures.) The cause of the strong magnetic peak at the 360 m station is not known. Dense patches of very tall nettles made ground observations very difficult in this area. Small iron objects or bricks may have been in the soil or there could have been a disused pathway that intersected the line at this point.

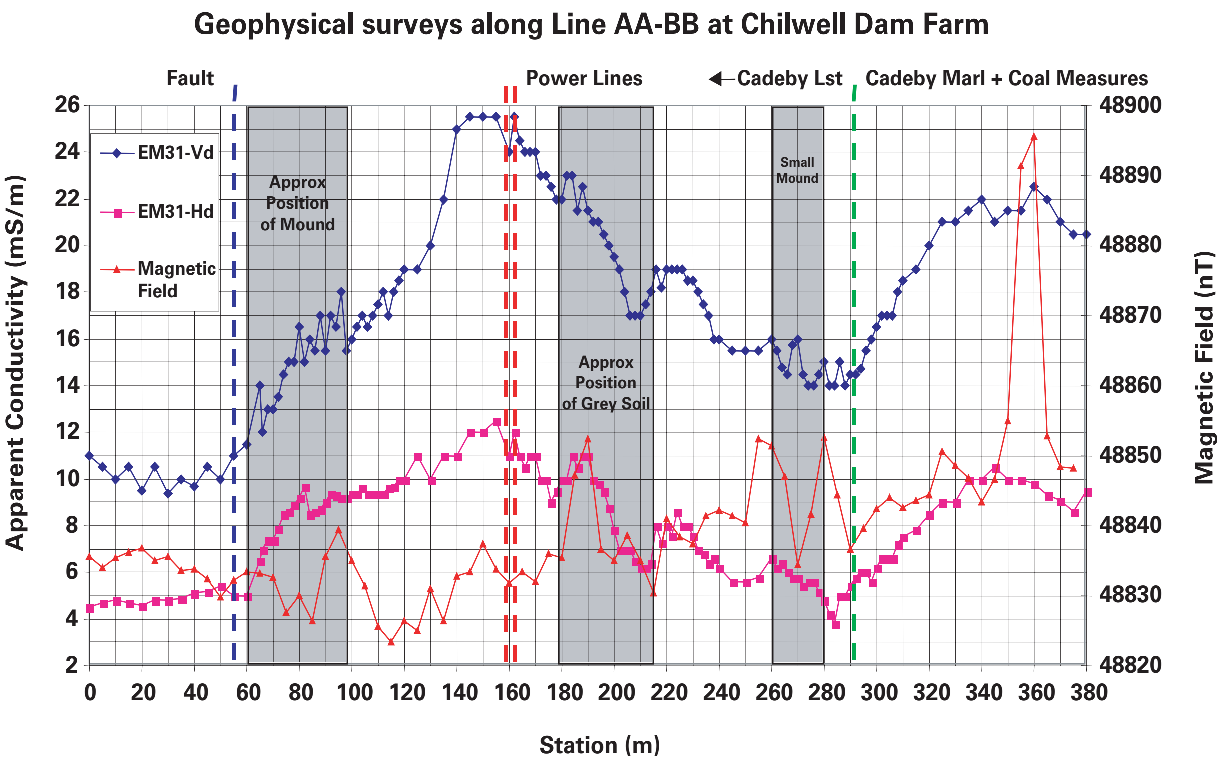


Figure 6.22 Geophysical profiles in the S/N direction along line AA–BB.

7 Soil stripping

7.1 Appearance of the site post-soil stripping

Stripping of the Chilwell Dam site commenced in July 2001 using a variety of earth moving equipment including scrapers and excavators. The extent of cut and fill observed at the time of investigation on 24 August 2001 is shown on Figure 7.1. Where cut, the excavation was typically less than 0.5 m in depth.

7.2 Topographic features

7.2.1 Building remnants

Many more fragments of brick and concrete were visible at surface after stripping in the area of the mound at NGR 451475 342775 (Figure 7.2), and in the area thought to be building remnants at NGR 451525 342775. These fragments are thought to confirm the presence of building remains at the site.

The stripping process had uncovered only one new upstanding topographic feature at the time of investigation. A section of red-brick walling, 3 m in length and exposed to a depth of 0.5 m, was located at NGR 451255 342730 (Figure 7.3). The brick bond was of two brick widths indicating that the wall was part of a low construction such as a low storey building or wall.

7.2.2 Soft ground

Areas of soft ground were located at NGR 451255 342730 (Figure 7.4a), 451325 342975 (Figure 7.4b), and 451110 343000. These were indicated by depressions in the ground surface where passing vehicles have sunk into the ground. These depressions were typically 0.5–1.0 m deep, with an outline following the shape of the vehicle tracks within a broad area of soft ground approximately 10 m in diameter. Fragments of Coal Measures mudstone, bricks and yellow stone thought to be weathered Sherwood Sandstone were found in each of the depressions.

7.3 Compositional features

Stripping had the effect of revealing the colour of the near-surface soils within the site (Figure 7.5), indicating that agricultural processes and weathering have had a significant effect upon soil composition and appearance at surface.

7.3.1 Areas of increased coal content

Stripping the topsoil from the site also had the effect of enhancing the contrast between 'clean soil' and soil enriched with coal fragments (Figure 7.4). Although contrast between the two soil compositions is made clearer by stripping, it was difficult to estimate to what extent the two had been intermixed and to locate the exact boundary between soil types with any accuracy. The method of stripping the topsoil using mechanical scrapers had the additional effect of 'smearing' the surface, especially where soft coal or mudstone fragments were present.

7.3.2 Areas of increased mudstone and brick fragment content

As shown in Figure 7.2 the stripping process also enhanced the contrast between areas of clean soil and areas with increased levels of Coal Measures mudstone. In every location that a significant quantity of mudstone was encountered (Figure 7.6), there was an increased level of coal fragments and brick fragments. The combination of these was thought to be a good indicator of nearby coal workings.

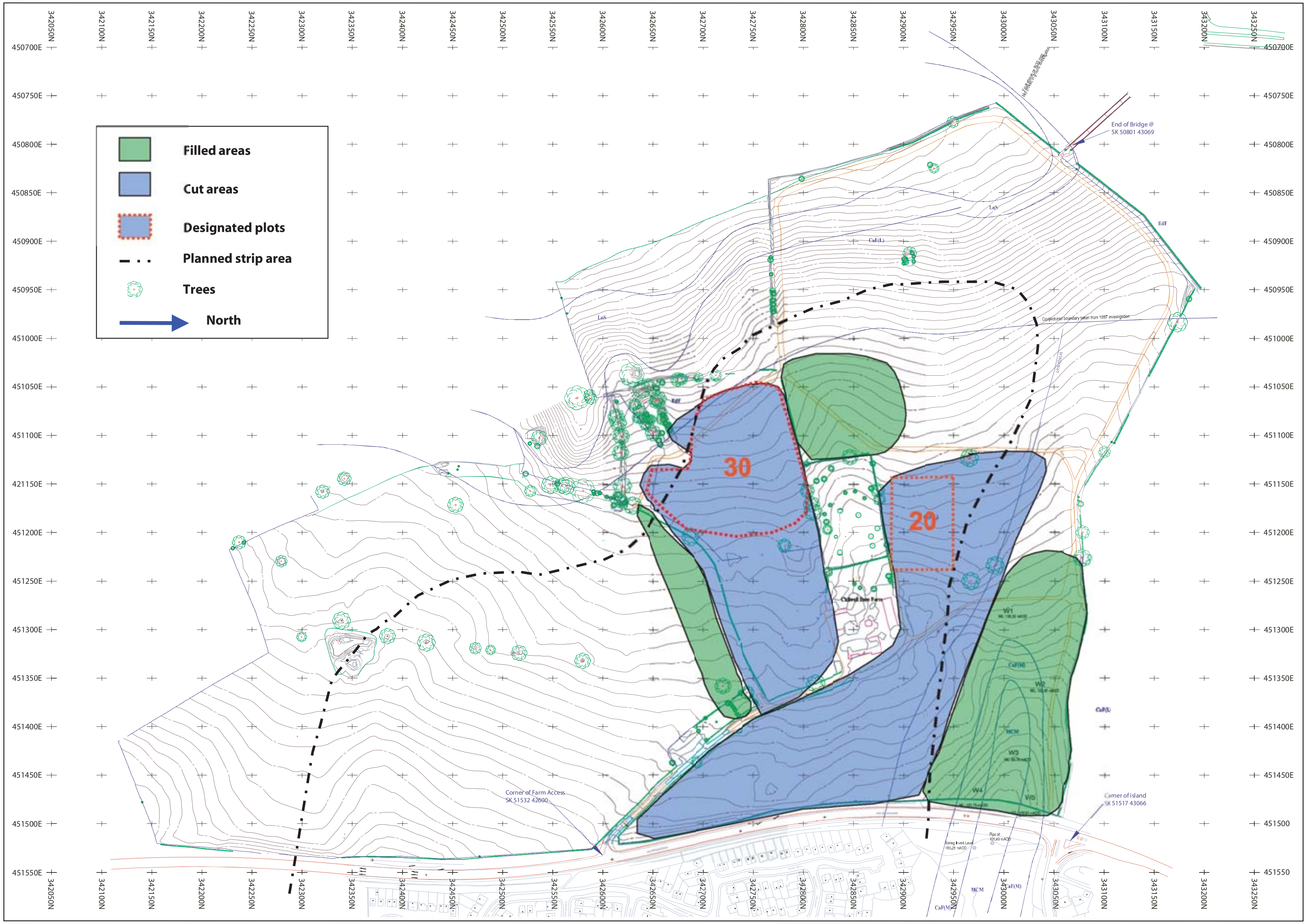


Figure 7.1 Extent of cut and fill at the time of the post-strip investigation.

Figure 7.2 Coal, mudstone and brick fragments at NGR 451475 342775.

Figure 7.3 Brick walling uncovered by stripping and traffic movements at NGR 451255 342730.

Figure 7.4a Soft ground at NGR 451255 342730 denoted by a series of ruts caused by the passage of site vehicles. Note the sharp boundary between 'clean' soil in the upper part of the image and darker, coal enriched soil in the foreground.
b Rutting of the ground at NGR 451325 342975 caused by the passage of site vehicles.

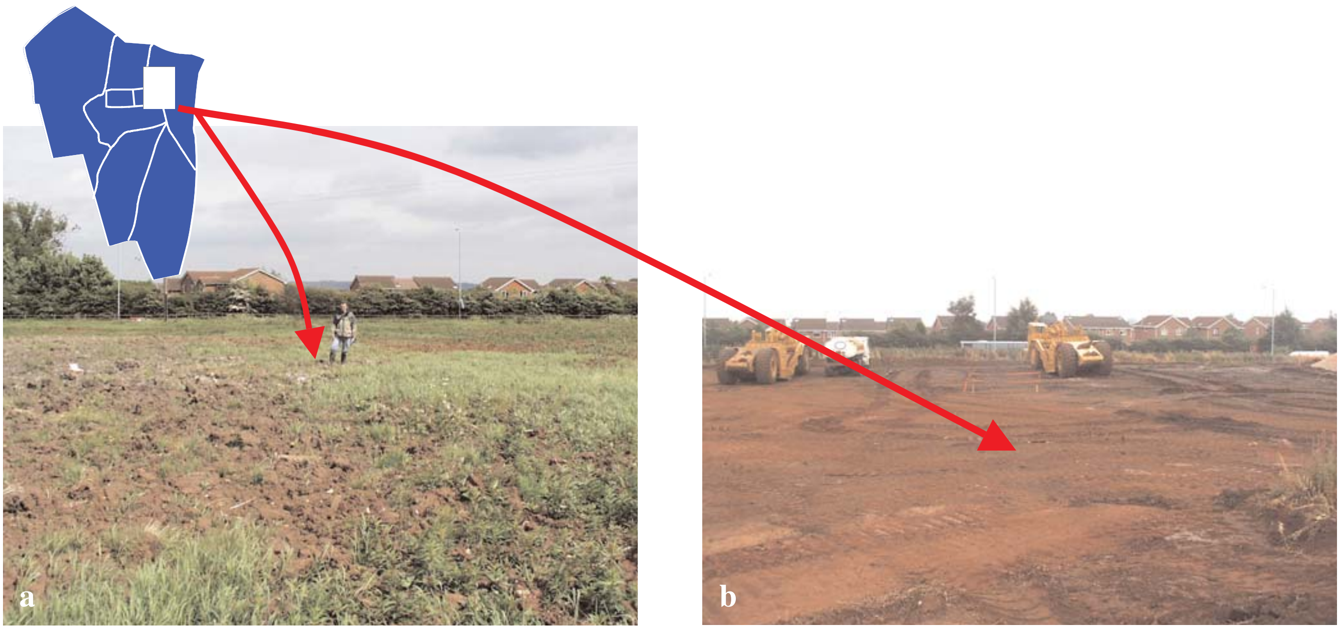


Figure 7.5 The effects of stripping on soil colour within the site; both images are of the same location.

Figure 7.6 Stripped surface showing increased levels of Coal Measures mudstone, coal and brick fragments at NGR 451120 343000. The area was also identified as an area of soft ground.
b The brick fragments in this area occurred as a number of patches 2 m in diameter, in a regular grid spacing. This was thought to indicate the possible locations of either a number of shafts or a number of colliery-related buildings.

8 Analysis of the thermal image with reference to the ground and geophysical surveys

8.1 Overview

This section brings together the results from the site investigations, the geophysical surveys, and the thermal image analysis. At the location of each mapped shaft and each thermal anomaly with potential to be a shaft, a description is made of the pre-soil strip ground appearance and the geophysical results, and any significant feature observed post-soil stripping is noted. For this purpose the site is split into 3 areas, which are considered in relation to thermal anomalies corresponding firstly to mapped shafts and secondly to areas of vegetation and/or soil change but not to a mapped shaft. Finally locations are discussed where mapped shafts were not detected in the thermal image.

8.2 Shafts evident in the thermal imagery (Red annotation, Figure 8.1)

8.2.1 Area 1

The soil over Shaft 19 (Appendix A) was observed to differ from the surrounding soil, being less red in colour, and the geophysics at AA confirmed the existence of a shaft.

Shaft 15 had a striking appearance in the field, being a mound, approximately 30 m across with a slight depression in the centre. The vegetation was different to the surrounding vegetation, with nettles around the edge and clover, dandelions, and broad-leaved weeds in the central core (Figure 2.5a). The soil was a dull grey colour with gravel-sized coal spoils, compared to the general red colour of the field (Figure 8.2). Shaft 15 was located close to 16, but the surface expression was not as apparent, perhaps masked by the mound of Shaft 15. Mudstone was detected around Shaft 15 and 16 post-soil stripping, indicating the presence of a mineshaft, and the geophysics along line AA–BB confirmed the presence of a mine-shaft in the vicinity of Shafts 15 and 16.

At Shaft 10 there was a marked change in soil colour from red, silty soil to white grey soil over the shaft, perhaps due to mine-waste of coal and ash, or limestone (Figure 8.3 and Figure 8.4). The lighter soil covered an oval shaped area approximately 30 m by 25 m diameter. The geophysics along line AA–BB indicated the presence of a mineshaft.

The ground above Shaft 4 was a depressed circular area having clover within and thistles on the outside. The geophysics along line AA–BB confirmed the existence of a mineshaft at this location.

8.2.2 Area 2

Thermal anomalies and mapped shafts within the north-west fields, area 2, are displayed in Figure 8.5.
At the location of Shaft 1 there was a slight soil change, differing in colour from the general red colour of the field. No geophysical investigations were carried out.

There was a vegetation change over Shaft 5, where a patch of nettles occurred, approximately 15 m in diameter. Geophysics along line U–V indicated the existence of a mineshaft.

Over Shaft 6 there was a vegetation change to longer grass, which was confined to a relatively small, 2–3 m diameter area (Figure 8.5). Geophysical investigation along line U–V confirmed the existence of a shaft.

Shaft 9 occurred near a pond that was under a tree. A change in vegetation took place approximately 10–15 m from the tree, where there was a circular zone of buttercups and weeds within the surrounding grass vegetation (Figure 8.6). No geophysical investigation took place.

8.2.3 Area 3

The south field differed in nature from the other fields. Ploughed furrows were evident, soil was much more visible and the vegetative cover was largely restricted to straw stubble.

At the location of Shaft 21 the soil was an orange brown colour, compared to the brown colour of the surrounding soil, and contained coal fragments ranging in size from gravel- to cobble size. Geophysical investigations were not carried out.

The soil over Shaft 23 comprised many coal fragments, predominantly coarse gravel sized, with some smaller angular coal fragments (Figure 2.3). The geophysical investigation

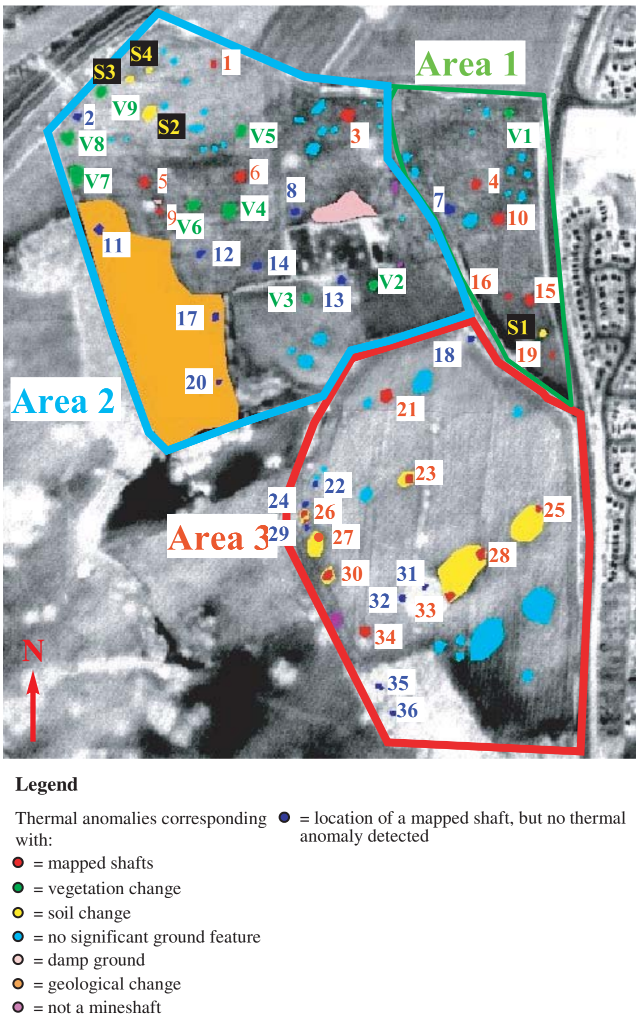


Figure 8.1 Classification of the thermal anomalies within area 1, area 2 and area 3.

Figure 8.2 The general red colour of the soil within the north-east field compared to the grey coloured soil at Shaft 15.

Figure 8.3 Soil colour change over Shaft 10.

along line Q-R did not show much variability along the line, and therefore did not identify the existence of Shaft 23.

There was coal spoil on the ground over Shaft 28 and Shaft 33, which suggested a mineshaft origin. Geophysical investigation was carried out over Shaft 28 along line A–B that indicated the existence of a mineshaft. A similar geophysical response would be expected over Shaft 33.

At the location of Shaft 34 the existence of a mineshaft was suggested by a circular area of ground with soil predominantly composed of angular, gravel sized coal fragments. The geophysical survey along line II–JJ also indicated the presence of a mineshaft.

Over Shaft 25 the soil was darkened by coal fragments; no geophysics were conducted.

The soil was dark coloured over Shaft 30. Several geophysical lines traversed the location of the shaft. Line I-J for example indicated the existence of a mineshaft.

At the locations of Shafts 26 and 27 the soil colour was very dark. No geophysical surveys were conducted over Shaft 27, and the geophysical survey conducted along line G-H did not produce evidence of a mineshaft at the location of Shaft 26. However the geophysics responded to anomalous material in the track to the east of the line and to a geological boundary to the west, which may have masked the geophysical response to mineshaft 26. The significant variability in the ground level along line G-H may also have masked the geophysical response. Alternatively, perhaps the shaft was not actually at the recorded position.

8.3 Thermal anomalies associated with vegetation and/or soil change (Green and yellow annotation, Figure 8.1)

8.3.1 Area 1

V1 was an area that exhibited subtle vegetation change at the surface. Geophysical investigations were not conducted here.

At location S1 the soil was brown rather than the red brown colour of the surrounding soil. However the geophysical investigation along line AA–BB did not suggest that a mineshaft was present at this location.

8.3.2 Area 2

At V2 there was both a pronounced depression and vegetation change to thistles (Figure 8.7). Further investigation revealed that the location corresponded with that of a former trial pit. Hence the thermal anomaly related to a trial pit rather than a mineshaft.

At V3 there was a subtle vegetation change. This site was not subject to geophysical investigations.

V4 corresponded with a vegetation change, but no geophysical investigations were conducted here.

V5 coincided with an approximately 5m diameter circular area that contained longer and different variety of grass to the surrounding vegetation, and some coal fragments were found at surface. No geophysical investigation was carried out.

V6 was another area of relatively long grass. It was not subject to geophysical investigation.

A vegetation change was also observed at V7. Geophysical investigation was conducted here, which indicated that a mineshaft may be present.

V8 was an area of subtly different vegetation where there was also a scattering of coal fragments. No geophysical investigations were carried out. It is possible that this area related to shaft number 2 that was mapped close to the location of V8. No geophysical investigation was carried out.

Figure 8.4 White grey soil over Shaft 10.

Figure 8.5 Vegetation over Shaft 6.

Figure 8.7 Depressed surface and vegetation change over V2.

V9 related to an area of fine grass and thistles with light, greyish brown silty soil with about 10% coal fragments, plus sandstone fragments. No geophysics were conducted.

At the location of S2 the soil was darker than the surrounding soil, and pebble-sized angular coal fragments were found at the ground surface. S3 and S4 also corresponded with darker soil, S4 also exhibiting 5% coal fragments of gravel size. No geophysical investigation was conducted at S2, S3 or S4.

Figure 8.6 Area of buttercups and weeds at the location of Shaft 9.

8.4 Locations where mapped shafts were not detected in the thermal image (Dark blue annotation, Figure 8.1)

Eighteen mapped shafts were not detected in the thermal imagery. Six of these were either very close to or immediately under trees and bushes, which could have masked the thermal anomaly associated with the mineshaft. Trees and bushes appear as bright, relatively warm features in pre-dawn thermal imagery. The shafts masked by trees and bushes were 13, 18, 31, 32, 35 and 36. Three mapped mineshafts occurred on the large patch of cold within the western section of the thermal image that was related to a rock type change. The general dark shade of this area made it difficult to identify the expected cold ground over the shafts. These shafts were 11, 17 and 20. Shaft 20 also occurred beneath a tree. The mapped positions of a further 4 shafts, Shafts 3, 22, 24 and 29, were very close to the location of an anomaly on the thermal image. A further shaft, Shaft 2, was close to a thermal anomaly associated with a vegetation change at the surface, V8. The map of known mineshaft locations is considered accurate to +/- 20 metres and there are inaccuracies inherent in the thermal image from the geocorrection process. Therefore it is possible that these 5 shafts were identified in the thermal image. The reasons that the remaining four mapped shafts (7, 8, 12 and 14) were not detected are not clear. There was no noticeable surface expression of a mineshaft over Shafts 7, 12 and 14. There was a small hollow however at the location of Shaft 8 and the soil contained small coal fragments sized from coarse sand to fine gravel.

9 The effectiveness of shaft detection using thermal imagery at the Chilwell Dam Site

9.1 Detected shafts

Almost two thirds of the mapped shafts (23 out of 36) were detected from the thermal image, taking into account the thermal anomalies that were close to the location of a mapped shaft. If allowance is made for the shafts located under or very near to trees and bushes and the shafts masked by the underlying rock type, then only four mapped shafts were not detected from the thermal image (shafts 7, 8, 12 and 14). The detected shafts all had a subtle surface expression on the ground in the soil or vegetative cover, and in some cases a mound or small depression, whilst three of the four undetected shafts did not have a surface expression.

The anomalies relating to the shafts were consistently cold, which may suggest that they are, in part, an expression of the cold air in the shafts relative to the surrounding ground. However, they are more likely to be related to thermal conditions at the ground surface. The thermal sensor will have detected the differences in surface soil and vegetative conditions that are related to mining processes (as detailed in section 2.2.), and in the relief over the mineshafts relative to the surrounding ground, all of which can produce cold anomalies. For example, soil compacted by mining processes would be poorly drained, damp ground producing a cold anomaly at night. The predominant vegetative cover over the shafts was long grass and weeds spaced densely relative to the general vegetative cover of the fields. This could conceivably trap more air and moisture relative to the general vegetation of the fields. Both scenarios would produce ground that would appear relatively cold in the pre-dawn thermal image.

9.2 Undetected shafts

Shaft 8 (Figure 8.1) was the mapped shaft that was not located from the thermal image but which had a surface expression in the field. The reason it was not detected may have been its proximity to damp ground, which being relatively cold pre-dawn would have masked the cold thermal anomaly relating to the shaft. Shafts were missed in the dark patch of the image that was related to a change in rock type because the dark thermal anomalies could not be distinguished from the general dark colour of the area. For future studies, in order to increase the likelihood of shaft detection within such dark patches of thermal imagery, the dark patches need to be contrast stretched and analysed separately from the rest of the image.

9.3 Soil stripping

Fourteen thermal anomalies related to surface vegetation and soil change, V1-V9 and S1-S5. Of these only V7 was subjected to geophysical investigation. The geophysical survey gave a strong indication that the thermal anomaly at V7 was related to a mineshaft. However it is not clear whether the anomalies identified at V1-V6, V8-V9 and S1-S5 coincide with mineshafts. Similarly, it was not clear whether the anomalies that had been identified from the thermal image but not found to correspond to significant features in the field (anomalies coloured pale blue in Figure 5.9) had any connection with mineshafts or related features. It was anticipated that the soil stripping process would reveal the true location of all mineshafts and related features on the study site. However the post soil-stripped site was confusing to interpret. Mixing of the soil had taken place during the stripping process and the original soil location was not clear. There were zones of coal-enriched soil that suggested proximity to mineshafts, but the soil stripping process had largely obliterated rather than added to the task of locating mineshafts.

9.4 Mis-identified anomalies

Fifty six anomalies were identified in the thermal image that did not appear to relate to mineshafts (coloured pale blue and purple in Figure 5.9). Twenty eight anomalies could be discounted on the basis that they were too small to correspond to a mineshaft. Four anomalies clearly related to a different feature on the ground, such as the site of a former tree. A further anomaly was discounted through study of a former mine plan which showed it coincided with the location of a former trial pit. Twenty three anomalies remained for which the cause was not clear.

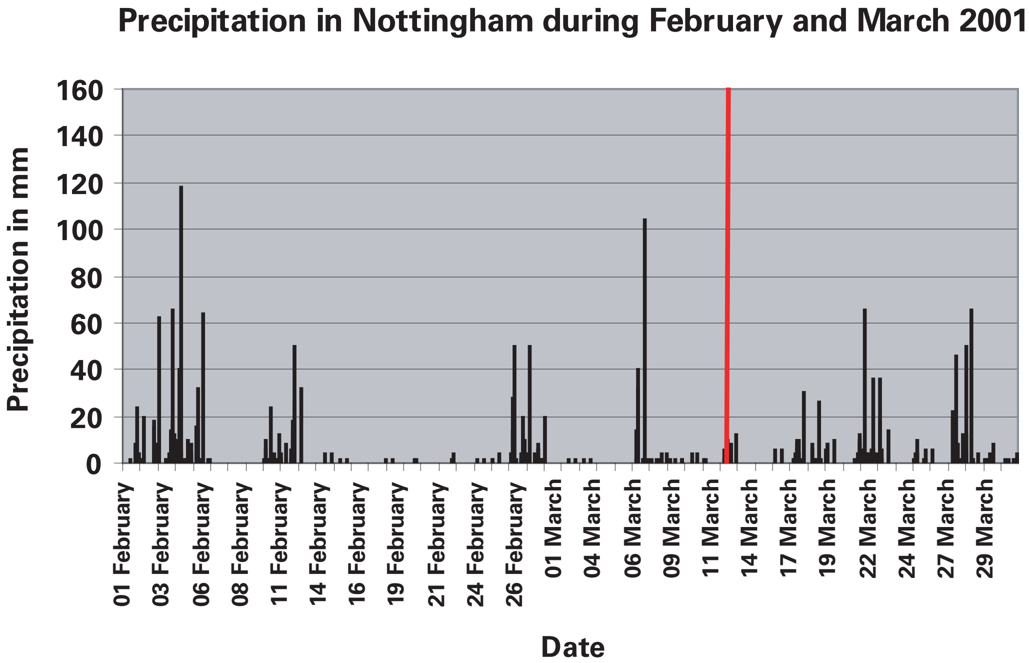
There are several possible causes of the thermal anomalies that did not appear to relate to mineshafts. Cold air may collect in topographic depressions and lead to thermal contrast. However, the sloping topography and low relief of the Chilwell Dam site mean that it is unlikely that ponds of air, cold and persistent enough to affect the thermal character of the ground surface could have formed. Patches of longer vegetation can trap cold air. In addition a good correlation has been found between the un-calibrated thermal band of some airborne imagery and soil moisture content of the near-surface layer (Davidson and Watson, 1995). An increase in soil moisture content will normally result in an increase in thermal inertia (Kahle, 1980), which may lead to contrast within a thermal image. Pre-dawn, areas of high soil moisture content tend to be cold relative to areas of lower soil moisture. Such factors may be responsible for some of the thermal contrast in the image. The walkover survey showed areas of high soil moisture content to be widespread across the site, occurring in topographic hollows, for instance at the geological boundary between the Sherwood Sandstone and Lenton Limestone and in association with soft ground.

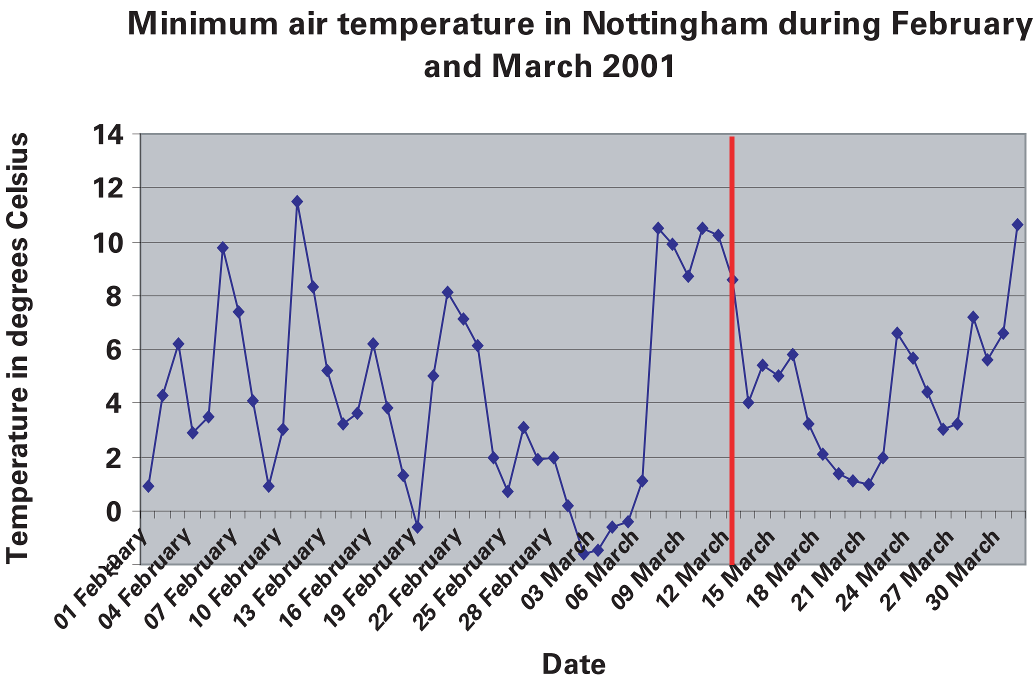
In order to minimise confusion in future studies, the acquisition of daytime data would be invaluable. Daytime thermal data is complimentary to night-time thermal data by providing information on the thermal nature of the surface during different heating conditions. Daytime data, in combination with the pre-dawn data, enables calculation of the thermal inertia of materials at a site and the application of spectral band ratios, which aid in the characterisation of ground above a mineshaft. A future option may be multi-band thermal data, which would enable improved differentiation between features. NERC hope to have this capability from 2005.

9.5 Aerial Photograph Interpretation

The aerial photograph interpretation revealed sixteen features with potential to relate to a shaft, compared to

Figure 9.1 Meteorological Conditions at the time of data acquisition at Chilwell Dam Farm on 12 March 2001 (BADC, 2002).



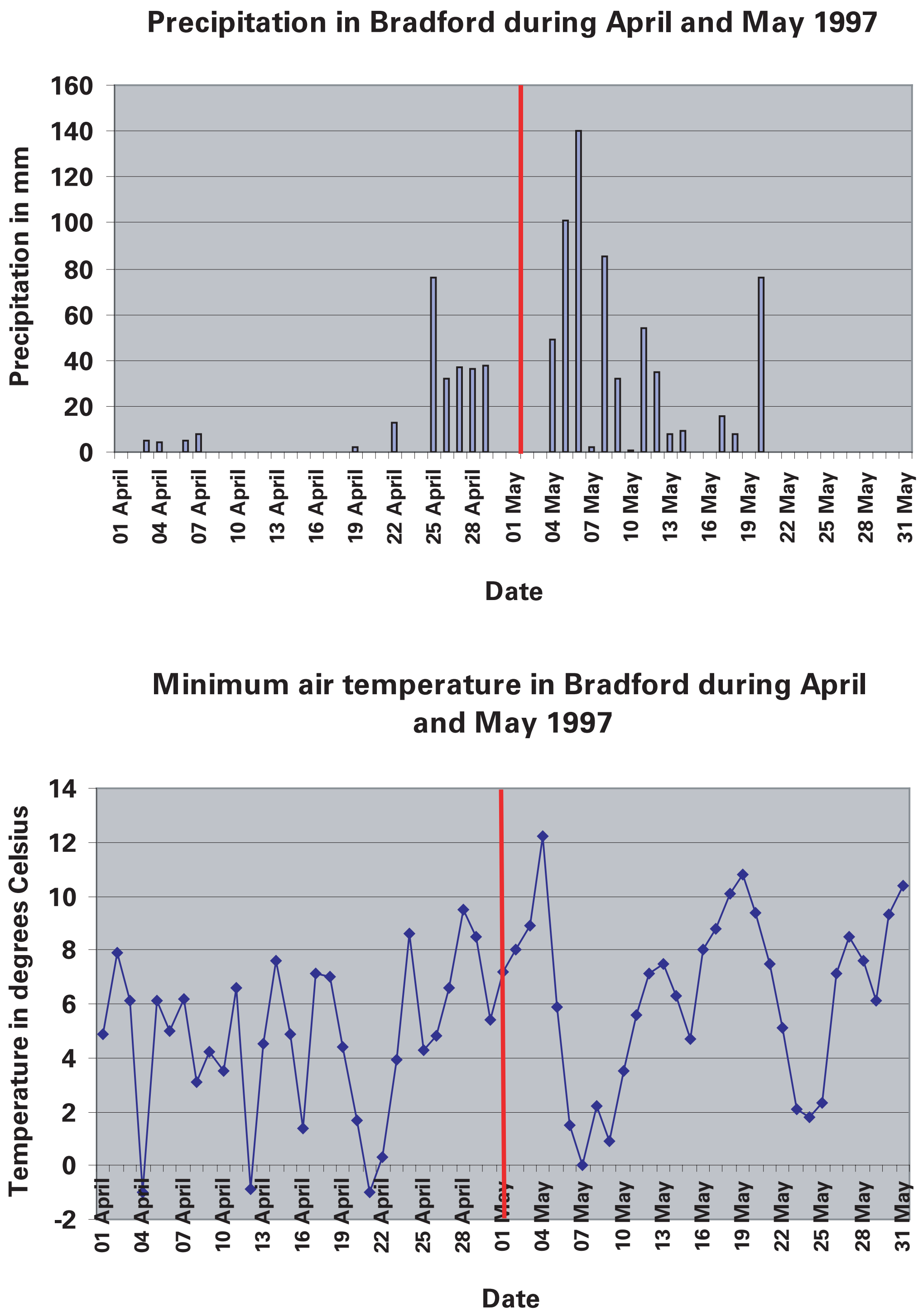


the much higher number of anomalies with potential to relate to a shaft that were detected in the thermal image. Nine of these sixteen features corresponded with the location of a mapped shaft, the remaining seven did not. At this site the thermal image had greater potential for locating abandoned mineshafts than the aerial photography. This is due in part to the lack of ground surface expression of the mineshafts and in part to the small 1:25 000 scale monochrome nature of the photography, as well as the different properties of the two image types. Larger scale colour aerial photography is more likely to aid mineshaft identification. The acquisition of colour, large-scale (around 1:10 000 scale) aerial photography is recommended for future shaft identification studies.

9.6 Comparison of two different sensors for shaft detection (Chilwell and Baildon Moor)

The Chilwell data was acquired by a commercial firm, Infoterra, whilst the data was acquired at Baildon Moor by NERC. The respective thermal sensors both acquire a single channel of thermal infrared data between 8 and 14um. The main difference between the sensors is that the Infoterra sensor acquires 8-bit (binary computer coding scale) data whereas the NERC sensor acquires 16-bit data. Significantly the Digital Numbers (DNs) constituting a digital image are recorded over the numerical range 0-255 (2^8) with 8-bit data and 0-65535 (2^{16}) with 16-bit data. Hence there are many more grey levels in 16-bit data.

Figure 9.2 Meteorological Conditions during acquisition of thermal data at Baildon Moor on 2 May 1997 (BADC, 2001).



It was easier to discern features in the NERC-acquired16-bit data. There was more contrast between features and the image was clearer and sharper. However, the differences between the imagery may be attributable to factors in addition to the disparity between the thermal sensors. These include: the ground appearance of the shafts, meteorological conditions and the aircraft flying height.

The shafts at Baildon Moor are more visible in the field than they are at Chilwell, hence the expectation would be for shafts to be more visible in the Baildon thermal imagery.

The weather conditions prevailing at the time of, and in the period leading up to, a flight can impact on the shaft detection capability from thermal data. During the acquisition of the two thermal data sets, there was a similar wind speed of approximately 9 knots, and similar precipitation conditions, with no precipitation occurring for several days prior to the Baildon flight whilst only minimal precipitation fell in the days before the Chilwell flight (Figures 9.1 and 9.2). A possible contributory factor to the difference in data quality between the two datasets was the slightly higher temperature both during and immediately preceding the Chilwell flight compared to the Baildon flight (Figures 9.1 and 9.2), colder conditions being preferable for this type of survey.

Greater shaft visibility would be expected in data acquired at a lower flying height, in relation to the more accurate spatial resolution. The Infoterra data was acquired at the lower flying height of the two datasets, at a height of

762 m compared to 1067 m for the Baildon data. Therefore, the flying height has not contributed to the difference in data quality between the two datasets.

The shaft detection capability of the 2 datasets has been affected by the appearance of the shafts on the ground, and to a lesser extent by the meteorological conditions preceding the thermal data acquisition. However, it is apparent that the NERC sensor is considerably more sensitive to temperature change than the Infoterra sensor, and it is preferable for thermal data acquisition to be made by the NERC sensor. Recent improvements to the NERC data acquisition and pre-processing procedure have added to the advantages of NERC data acquisition. The NERC aircraft has an inertial navigation system that enables semi-automatic image geocorrection to a high level of accuracy. Better positional accuracy can be achieved more rapidly than with data acquired by a commercial sensor, which must be geocorrected via manual control pointing.

10 Conclusions and recommendations for future work

10.1 Conclusions

The research conducted at Chilwell Dam Farm has further demonstrated the potential for rapid detection of abandoned mineshafts using the airborne thermal surveying technique. In particular, the study has confirmed that shafts without an obvious surface expression on the ground can be detected from an airborne thermal sensor.

Almost two thirds of the mapped shafts at the site were detected by the thermal survey, and the remaining third were not detected due to their close proximity to either trees or damp ground or due to their occurrence within a zone of rock that had a dark appearance in the thermal image. In addition, several thermal anomalies were identified which had potential to relate to a mineshaft.

Only one previously undetected mineshaft was indicated by the study, as a result of the geophysical investigations. At all other locations where a thermal anomaly was detected and had the potential to relate to an unmapped mineshaft the outcome was inconclusive due to the failure of the soil-stripping process to verify the location of mineshafts across the site. Ideally these sites would be subjected to geophysical investigation, but further geophysical survey at the site was not possible because construction work had commenced and also due to time and cost constraints.

10.2 Recommendations

The study has highlighted refinements to the technique that should be adopted for future shaft detection:

- Acquisition of 16-bit data
- Data acquisition using an aircraft with an inertial navigation system
- Both pre-dawn and daytime data should be acquired to enable thermal inertia and spectral band ratio studies to be conducted
- Multi-band thermal data should be acquired if the capability is available
- Colour aerial photography should be acquired at approximately 1:10 000 scale
- Where a shaft produces a cold thermal anomaly, dark areas of an image should be analysed separately, such as areas of damp ground
- Mapping of the geomorphology, vegetation and soil at a site should be carried out
- Wider application should be made of geophysical surveys
- More careful soil stripping should be conducted
- Construction of a GIS would facilitate integration and visualisation of the varied datasets generated by a shaft detection study.

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Appendix A — Transcription of abandoned mineshaft locations

Unless otherwise stated, these mineshaft locations are transcribed from a British Geological Survey field slip, which itself is the result of the transcription from British Coal Authority Records. The precision in their location should *not* be taken to be less than ± 20 m on either the easting or the northing.

No.	NGR Grid Reference	No.	NGR Grid Reference
1	451005, 343135	19	451515, 342685
2	450815, 343015	20	451030, 342650
3	451220, 342985	21	451290, 342635
4	451395, 342955	22	451150, 342495
5	450875, 342945 ‡	23	451310, 342485
6	451030, 342930	24	451145, 342460
7	451335, 342910	25	451480, 342455
8	451145, 342895	26	451145, 342440
9	450920, 342890	27	451150, 342425
10	451430, 342880	28	451375, 342385
11	450830, 342875	29	451180, 342380
12	450995, 342830 ‡	30	451180, 342360
13	451220, 342815	31	451325, 342355
14	451075, 342805	32	451285, 342340
15	451485, 342790	33	451365, 342320
16	451455, 342785	34	451215, 342280
17	451015, 342740	35	451235, 342215
18	451380, 342730	36	451245, 342180

‡ Identified from aerial photograph

Appendix B — Summaries of the geophysical profiles

B.1–Summary Description Profile Features

Line A–B: Figure 6.14. Large conductivity profile associated with a ridge. Believed to be a geological feature. Not sure whether this feature continues on to Line I–J.

Line C–D: Figure 6.12. Open mineshaft detected by both the EM 31 and magnetic. The magnetic response could be interpreted as either of the two scenarios (amongst others) indicated in plots B.3 and B.4.

Line E–F: Plot B.3. Thermal anomaly associated with a soil change. EM 31 didn't show much variation along the line.

Line G–H: Plot B.4. 8m diameter by 1.5 m deep depression at the south end of the hedgerow near a soil change thermal anomaly. Believed to be on the Cadeby Limestone — Edlington Marl boundary. The EM 31 may have responded to materials in the track to at the east side of the line and also to the geological boundary towards the west side. Unsure, as there was significant variability in the ground level along this line.

Line I–J: Figure 6.15. Thermal anomalies associated with a soil changes to west of line. Coal authority records suggest mineshafts within the run of the line. EM 31 indicated a high conductivity early line section falling towards J. Continuation of high conductivity ridge detected along A–B?? The value of 18 mS/m at the 56 m station on the vertical dipole could be an anomalous reading.

Lines K–L, M–N and O–P: Figure 6.16. These cross I–J at about the 56 m station. These surface plots indicate a high conductivity ridge at to the SE of I–J falling off to the NW. Believed to be geological; Cadeby Limestone–Edlington Marl boundary could be one possible explanation?? the magnetic survey in Figure 6.17 seems to indicate differing magnetic regimes across I–J.

Line Q–R: Plot B.5. Coal authority records suggest a mineshaft along line. Thermal anomaly associated with soil change along line towards R. Neither the magnetic nor the EM 31 have large variability along the line. EM 31 survey repeated due to spheric noise experienced on the Vd on first run (dark blue line).

Line S–T: Plot B.6. Run to check the minimum in the Line Q–R EM 31 Hd profile at the 60 m station. No large variation was detected.

Line U–V: Figures 6.18 and 6.19. Relatively long line with several mineshafts located on coal authority records within it. Damp ground thermal anomaly at U; vegetation change thermal anomalies at 140 m station and at V. This line picks out much geological information. The Hd especially can be interpreted as the Cadeby Limestone being of low conductivity — 3 mS/m, the Edlington Marl around 5 mS/m to 12 mS/m with some layering possible within, the faulted boundary with the Lenton Sandstone whose conductivity may be masked by the high conductivity values over 25 mS/m of the glacial till. There is a very significant geophysical anomaly at the 90 m station. Plot B.14 indicates large EM 31 and magnetic responses. It is possible that the feature causing this anomaly may have a westerly dip.

Line W–X: Figure 6.20. Profile over large geophysical anomaly. The magnetic response could be interpreted as either of the two scenarios shown in plots B.3 and B.4. However, given the response of the EM 31 Vd, a mass of highly conductive material at shallow depth is suspected.

Line AA–BB: Figure 6.22. Line over fault then mound in the south, under overhead power cables, over grey soil feature with coal and shale fragments, over mound and into hollow at the north end. Soil change thermal anomaly at AA in the south and vegetation change thermal anomaly at the mound just south of the hollow at station 270 m. The fault and the mound in the south are detected by the EM 31 as a sharp increase in conductivity at about 60 m. There may be a small response on the magnetic profile due to the mound. Interestingly, both the area of grey soil at about 200 m and the small mound at about 270 m have fairly large changes in the EM 31 and the magnetic responses. These could indicate ground disturbances. There is a very large magnetic anomaly at the north end of the line near BB. Could this be an old tarmac pathway?? Unsure how much the electricity power cables affect these data. Suspect the maxima on both EM 31 horizontal and vertical profiles underneath the power cables are interference effects. The Cadeby Marl and Middle Coal Measures can be differentiated from the Cadeby Limestone by higher conductivity values. Features in the EM 31 profiles: maximum at 150 m, local minimum at 210 m and the local maximum at 222 m were all cross-surveyed to decide if these features were localised.

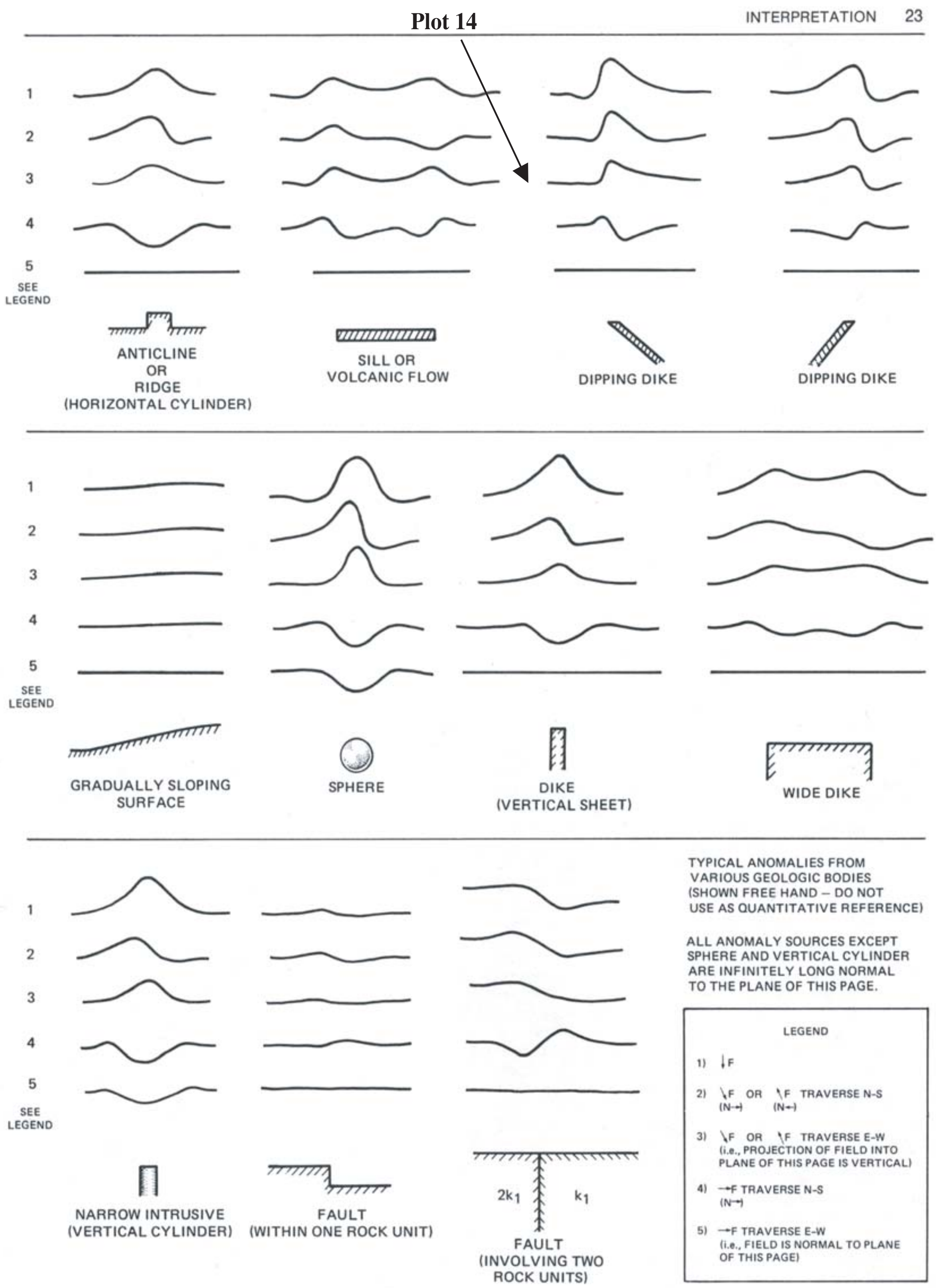
Line CC–DD. Plot B.7. Cross-line at 150 m. AA–BB crosses at the 25 m point. Unsure about the cause of the reducing conductivities as the power cables are approached.

Line EE–FF. Plot B.8. Cross-line at 210 m. AA–BB crosses at the 25 m point. Fairly consistent conductivity values. Lends weight to the local minimum being a geological feature.

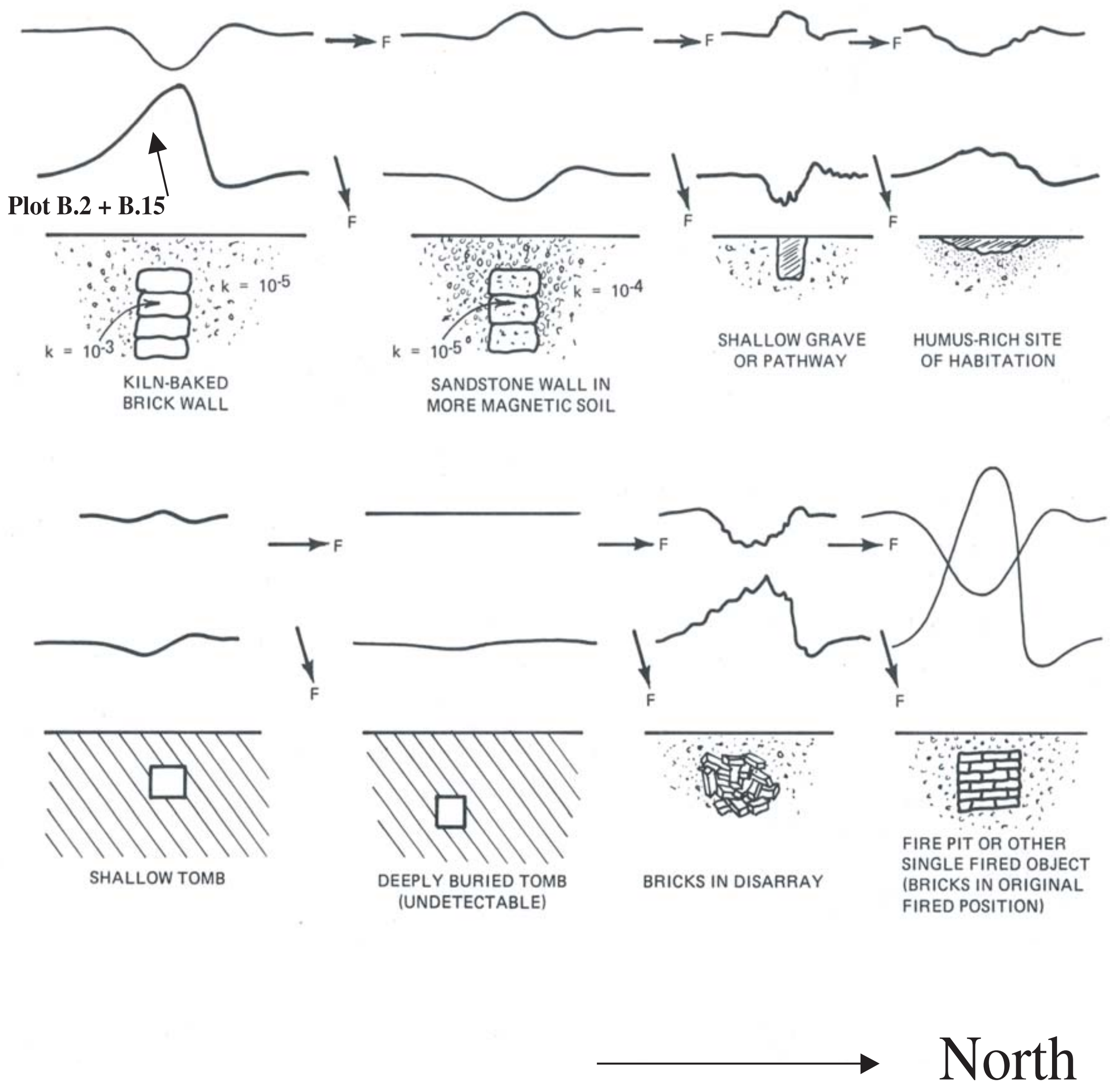
Line GG–HH: Plot B.9. Cross-line at 222 m. AA–BB crosses at 25 m point. Fairly significant rise in the Vd conductivities as Line AA–BB is approached from the east. Going upslope away from power cables. Unsure of this feature especially as Line EE–FF does not show similar increases in the Vd.

Line II–JJ: Plot B.10. Line roughly N–S 20 m either side of tree. Weak magnetic low slightly larger than background noise levels. Unsure. Disturbed ground??

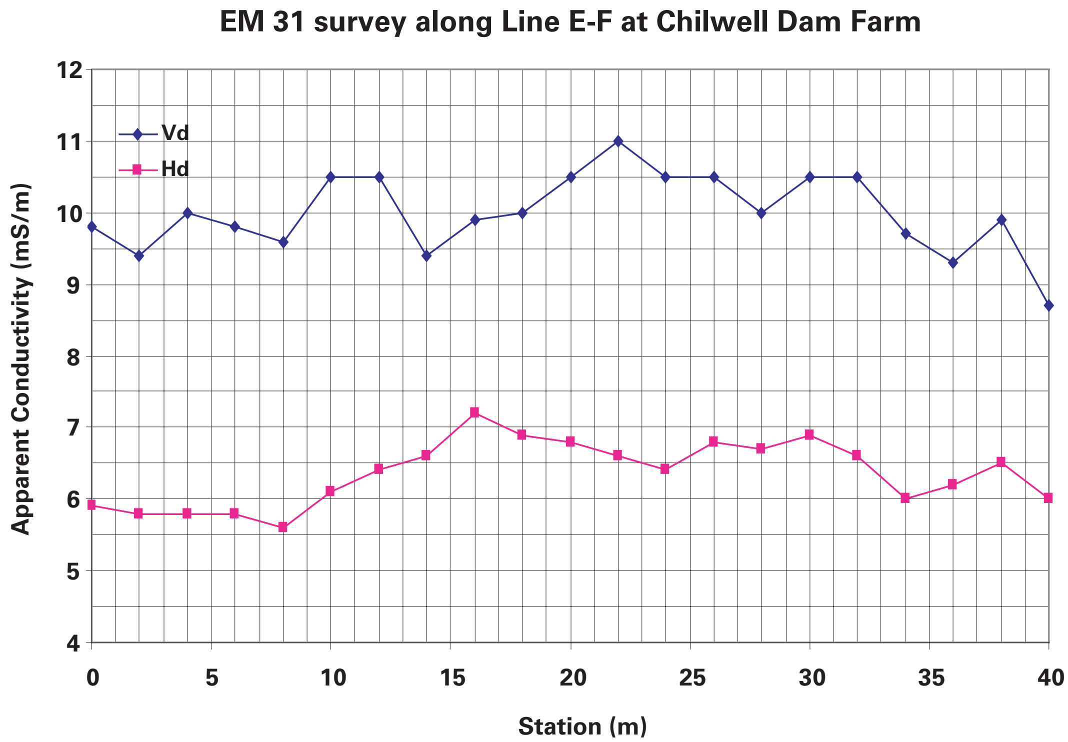
Plot B.1 Geophysical anomalies for geologic bodies. (Breiner, 1973).



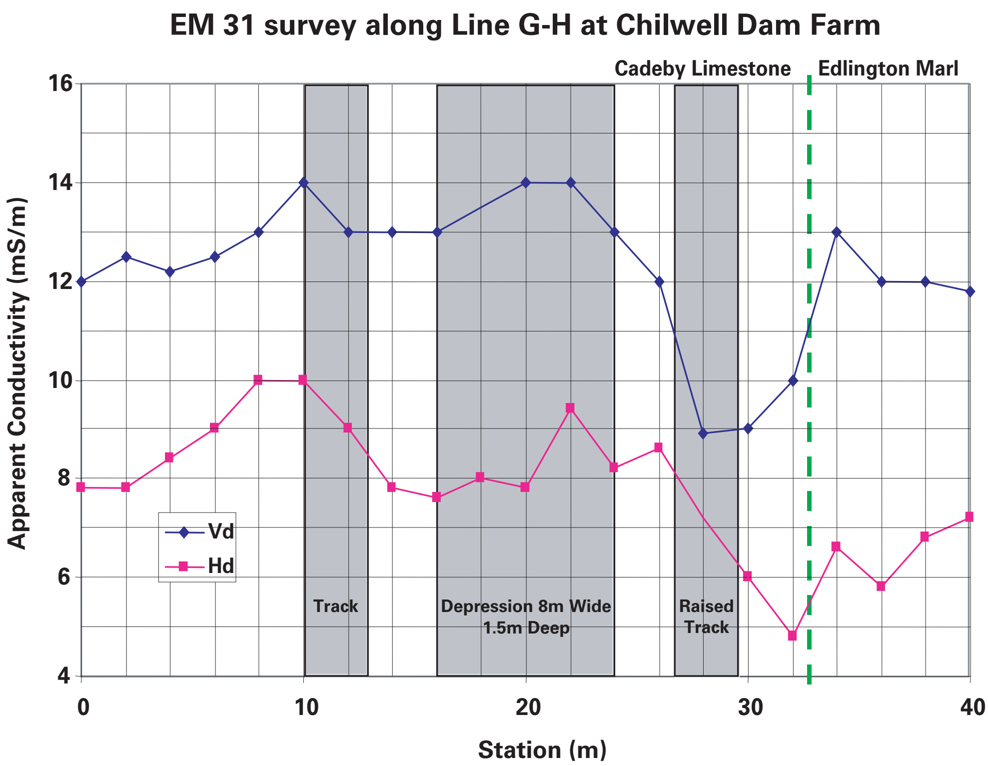
Plot B.2
Typical magnetic anomalies of common archaeological features. (Breiner, 1973).



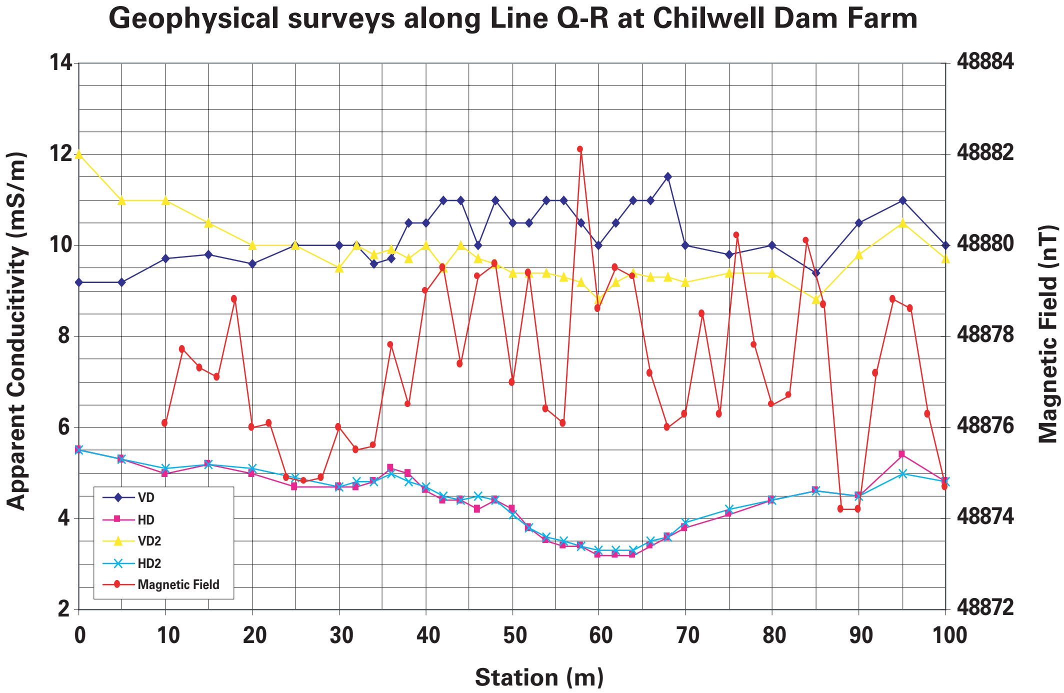
Plot B.3



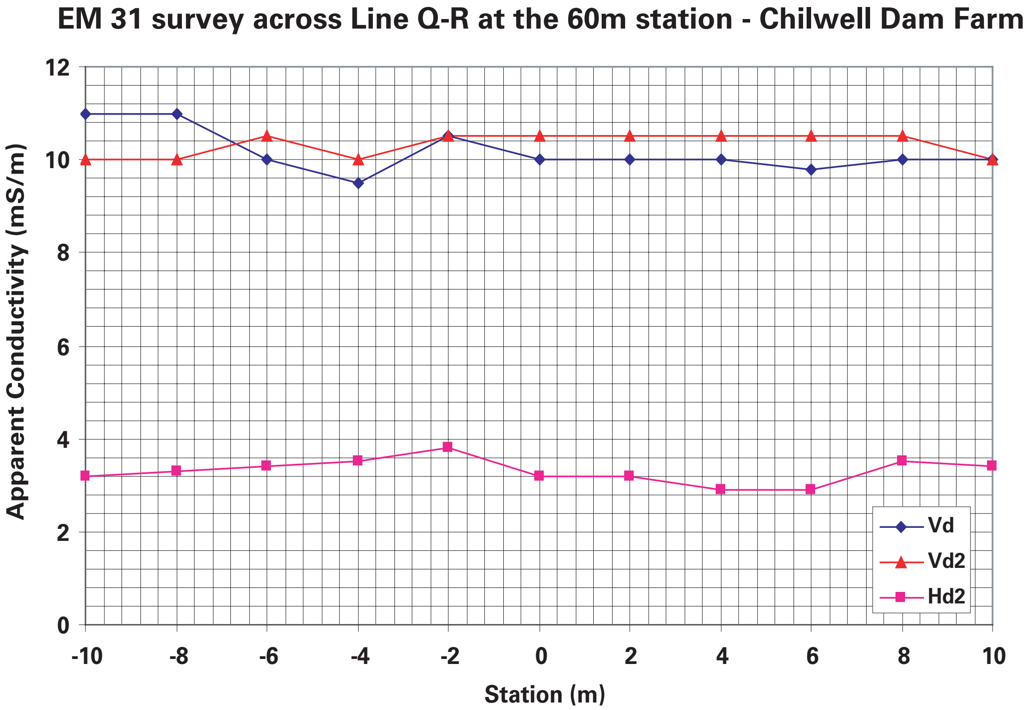
Plot B.4



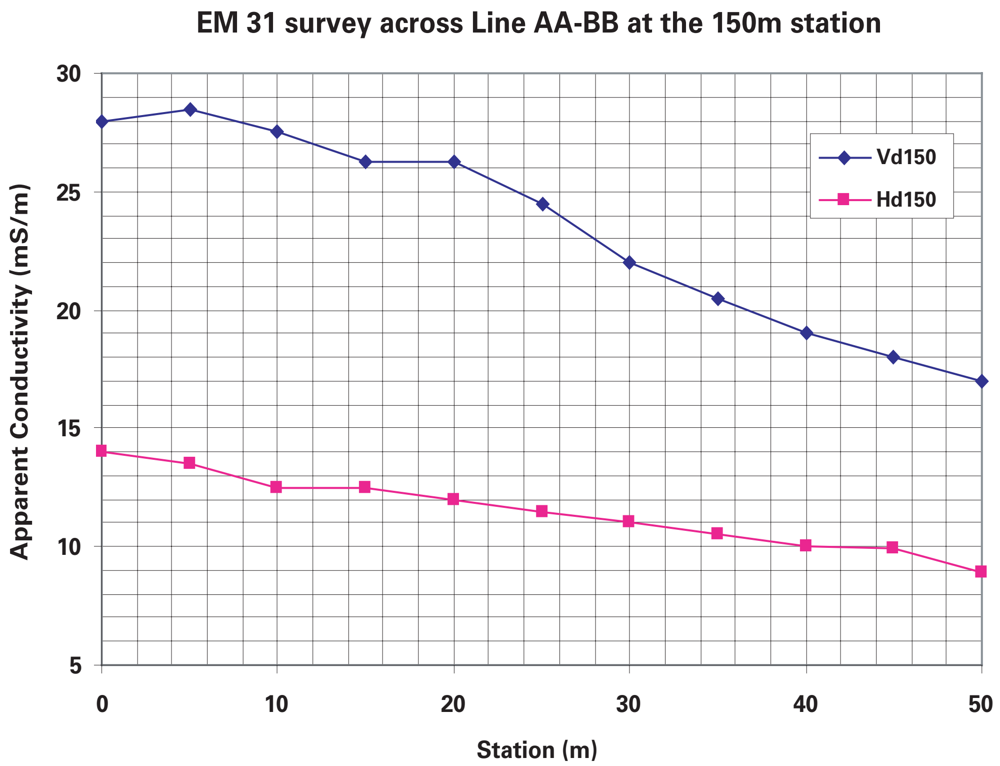
Plot B.5



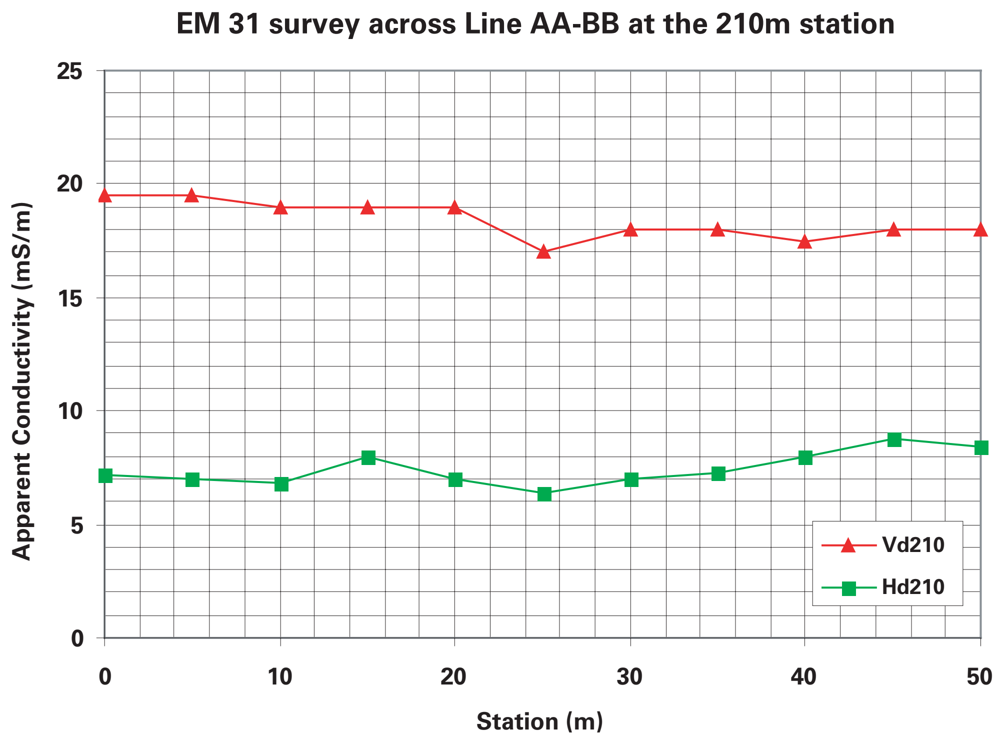
Plot B.6



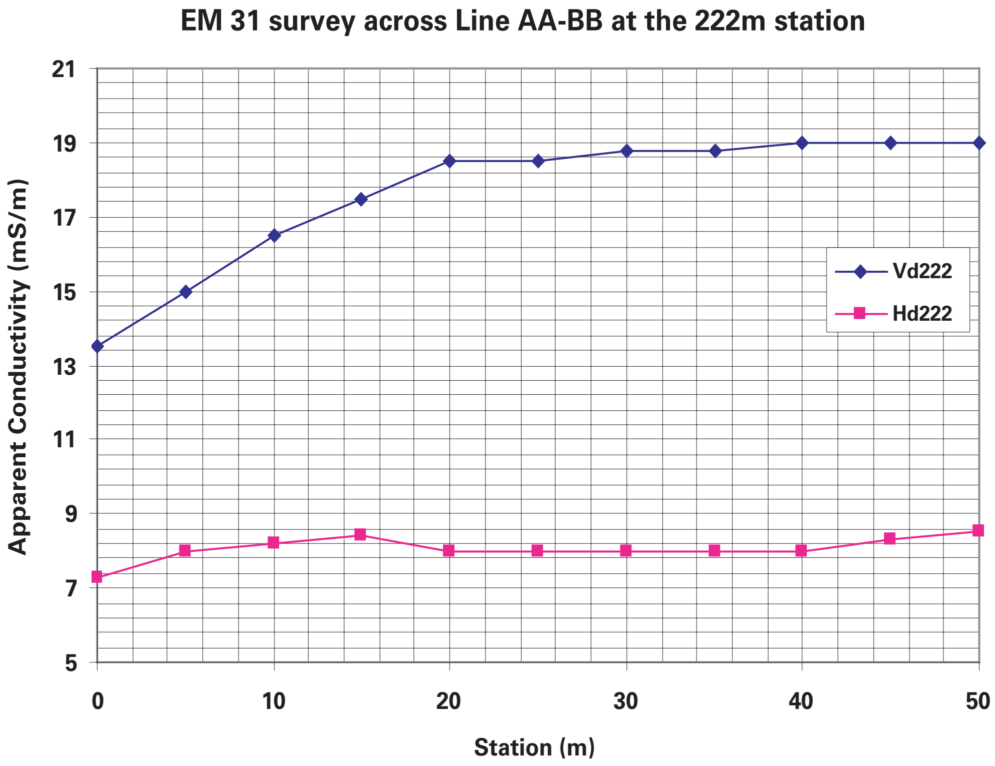
Plot B.7



Plot B.8



Plot B.9



Plot B.10

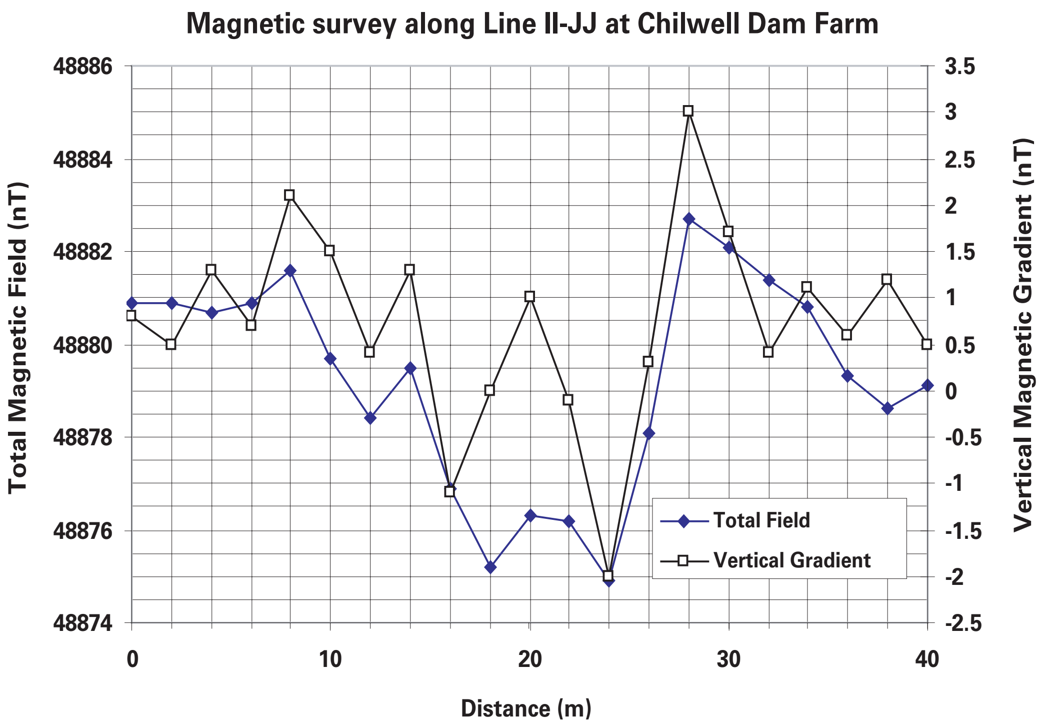


Table B.1 Statistics and features for the EM 31 survey lines.

EM31 Geophysical Lines

Line Name	Line Begin	Line End	Line Length (m)	Stake Stations (m)	Stake Location	Thermal Anomalies
A–B	51402, 42446	51377, 42249	200 m	85 m	51392, 42362	Soil change associated with ridge.
C–D	51285, 42363	51286, 42334	30 m	Open Mineshaft at	51285, 42342	
E–F	51350, 42398	51388, 42398	40 m	19 mm	51368, 42401	Soil change associated with ridge towards F.
G–H	51158, 42449	51120, 42444	40 m	8 m dia x 1.5 m deep depression at	51137, 42450	Soil change/Cadeby Lst — Edlington Boundary.
I–J	51169, 42419	51194, 42322	100 m	56 m	51185, 42365	Soil change west of I and soil change west of the 56 m station.
K–L	51194, 42368 Across I–J at	51175, 42362 56 m station	20 m	-10 m -E, 10 m -W		
M–N	Across I–J at	51 m station	20 m	-10 m -E, 10 m - W		
O–P	Across I–J at	61 m station	20 m	-10 m -E, 10 m -W		
Q–R	51307, 42440	51320, 42538	100 m	60 m	51313, 42497	Soil change west of line towards R.
S–T	Across Q–R at	60 m station	20 m	-10 m -W, 10 m -E		
U–V	51176, 42897	50776, 42960	405 m			Damp ground at U. Vegetation change north of line at 140 m station. Vegetation change at V.
	Stakes along the	Line are at Large Geophys	E side Anomaly W side	70 m 90 m 120 m	51112, 42918 51091, 42920 51060, 42933	
W–X	510090, 42954 Across U–V at	51078, 42900 90m station	60 m	-30 m, N, 30 m - S 0 m (N) 60 m (S)	 510090, 42954 51078, 42900	
AA–BB	51475, 42700	51340, 43072	380 m	150 m (S) 210 m 222 m (N)	51445, 42842 51424, 42900 51421, 42913	Soil change at AA. Vegetation change on the mound at the 270 m station.
CC–DD	51463, 42849 Across AA–BB at	51415, 42835 150 m	50 m	-25 m - E, 25 m -W		
EE–FF	51449, 42905 Across AA–BB at	51398, 42892 210 m	50 m	-25 m -E, 25 m - W		
GG–HH	51442, 42914 Across AA–BB at	51402, 42909 222 m	50 m	-25 m -E, 25 m -W		

Table B.2 Statistics and features for the Magnetic survey lines.

Magnetic Geophysical Lines

Line Name	Line Begin	Line End	Line Length (m)	Stake Stations (m)	Stake Location	Thermal Anomalies
C–D	51285, 42363	51286, 42334	30 m	Open Mineshaft at	51285, 42342	See entries in EM 31 section above.
I–J	51169, 42419	51194, 42322	100 m	56 m	51185, 42365	
M–N	?	?	40 m	Roughly 20 m N	51230, 42280	
				and 20 m S of tree at		
U–V	51176, 42897	50776, 42960	405 m			
	Stakes along the	Line are at	E side	70 m	51112, 42918	
		Large Geophys	Anomaly	90 m	51091, 42920	
			W side	120 m	51060, 42920	
W–X	510090, 42954	51078, 42900	60 m	-30 m - N, 30 m - S		
	Across U–V at	90m station		0 m (N)	510090, 42954	
				60 m (S)	51078, 42900	
			380 m	150 m (S)	51445, 42842	
AA–BB	51475, 42700	51340, 43072		210 m	51424, 42900	
				222 m (N)	51421, 42913	
II–JJ	?	?	tree			
	Roughly N–S line	20 m either side of				