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A helicopter AEM survey providing an environmental assessment of the Eastfield quarry/landfill site, West Lothian, Scotland

National Geoscience Framework Programme

Internal Report IR/05/095

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/05/095

A helicopter AEM survey providing an environmental assessment of the Eastfield quarry/landfill site, West Lothian, Scotland

David Beamish

Key words airborne, electromagnetic, conductivity landfill, Polkemmet

Front cover

Helicopter and towed bird during survey

Bibliographical reference

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Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Foreword

This report is the published product of a study by the British Geological Survey (BGS) using data acquired by the HiRES Geophysical Surveys project. It describes an airborne electromagnetic survey carried out in February 2004 in the vicinity of the Eastfield quarry, former landfill situated in West Lothian, Scotland. The survey consisted of 54 km of line coverage. The purpose of the survey was to investigate the capabilities of the technique in relation to mapping subsurface leakage and migration of conductive materials from a former waste disposal site.

Acknowledgements

The assistance of Greg Paleolog and Mike Cain (Project Geophysicist) of Fugro Airborne Surveys is much appreciated. Mike Raines and Rhys Cooper of the BGS conducted the ground geophysical surveys.

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Summary

This report describes an airborne electromagnetic survey carried out in February 2004 in the vicinity of the Eastfield quarry, former landfill situated in West Lothian, Scotland. The landfill is situated on the former Polkemmet colliery site. The survey consisted of 54 km of line coverage. The purpose of the survey was to investigate the capabilities of the technique in relation to mapping subsurface leakage and migration of conductive materials from a former waste disposal site. The survey took place some 24 years after closure of the landfill.

The landfill, occupying a former quarry, is situated among shallow, worked-out coal seams (pillar and stall workings) and was located over at least two mineshafts that occupied the quarry floor. The landfill was known to be leaking from an extensive borehole investigation that took place in the 1970's, when the landfill was active. Redevelopment issues and associated, proposed surface extraction of coals have renewed interest in the possible pollution threat of waste products. Of particular concern is the extent to which pollution has, potentially, transgressed a fault to the north and entered the area of proposed regeneration. The airborne survey data (EM and magnetic) were obtained using the six-frequency RESOLVE bird and a flight line spacing of 40 m. The data acquired have been subjected to 1D regularized inversion to enable a 3D conductivity model to be assessed. The main site assessment covers a 600x600x100 m volume in the immediate vicinity of the landfill and Polkemmet Fault to the north. The model clearly identifies the landfill as a source term of highly conductive materials. At conductivities that are a factor of 3 above background, evidence is obtained for a variety of vertically compact, lateral migration pathways, largely below the base of the quarry. A limited amount of ground geophysical follow-up (Vertical Electric Sounding) has provided a degree of confirmation of the airborne conductivity model.

1 Introduction

A number of airborne geophysical surveys have now been conducted in the UK using a fixed-wing system operated jointly by the British and Finnish Geological Surveys. The system provides magnetic, radiometric and frequency domain electromagnetic (EM) survey measurements (Peart et al., 2001). Application of the Airborne Electromagnetic (AEM) technique to landfill investigations is reported by Beamish (2003) and Beamish and Mattssson (2003). In the UK, regulatory survey permissions force a variety of flight elevations typically between 54 to 244 m above ground level. In addition to fixed-wing surveying, helicopter (towed-bird) survey configurations can also be undertaken. The survey bird usually acquires magnetic and electromagnetic data. The bird must be flown at very low altitude, typically 30 m, in order to provide adequate signal-to-noise. The survey and data presented here provide, to the best of our knowledge, the first detailed environmental application of helicopter EM surveying in the UK. The system used here is the RESOLVE bird developed by Fugro Airborne Surveys.

The study presents results obtained from a remarkably small-scale helicopter AEM survey of a closed solid and liquid waste disposal landfill. The landfill, occupying a former quarry, is situated among shallow, worked-out coal seams (pillar and stall workings) and was located over at least two mineshafts that occupied the quarry floor. The landfill was known to be leaking from an extensive borehole investigation that took place in the 1970's, when the landfill was active. Redevelopment issues and associated, proposed surface extraction of coals have renewed interest in the possible pollution threat of waste products. Of particular concern is the extent to which pollution has, potentially, transgressed a fault to the north and entered the area of proposed regeneration. The airborne survey data (EM and magnetic) were obtained using the six-frequency RESOLVE bird and a flight line spacing of 40 m. The data acquired have been subjected to 1D regularized inversion to enable a 3D conductivity model to be assessed. The model clearly identifies the landfill as a source term of highly conductive materials. The conductivity models provide no geochemical discrimination. At conductivities that are a factor of ~3 above background, evidence is obtained for a variety of vertically compact, lateral migration pathways, largely below the base of the quarry.

A degree of broad confirmation of the airborne conductivity model has been established by ground geophysical (Vertical Electric Sounding) follow-up. Background conductivities within the Lower Coal Measures sequence appear low and, although we only have 3 such soundings, we could anticipate non-geological influences being detected at conductivity levels in excess of, say, 15 mS/m. Elevated conductivities, at all depths, are confirmed within the quarry/landfill area.

2 The AEM survey

The AEM survey was carried out using the 6 frequency (0.4 to 110 kHz) RESOLVE HEM system (Fugro Airborne Surveys) as part of a research project into the application of AEM in the UK environment. Magnetic data from the Caesium magnetometer mounted in the RESOLVE bird were also acquired. The survey was carried out by Fugro Airborne Surveys (Toronto Office). The survey took place on the morning of February 11, 2004; the total line coverage achieved amounted to about 54 km. Outline specifications were provided by the BGS. The survey coverage achieved is shown in Figure 1.

The main survey area covers a 1 x 1.5 km block taking in the target landfill and a regional fault to the north. Several issues relating to detailed towed-bird AEM data acquisition were revealed. Overflights above the local village (Fauldhouse) were not permitted so that flight lines just to the south of the target were curtailed by climbs and veers. Although a N-S line separation of 20 m was specified, only a 40 m separation could be achieved using a relatively inexperienced pilot.

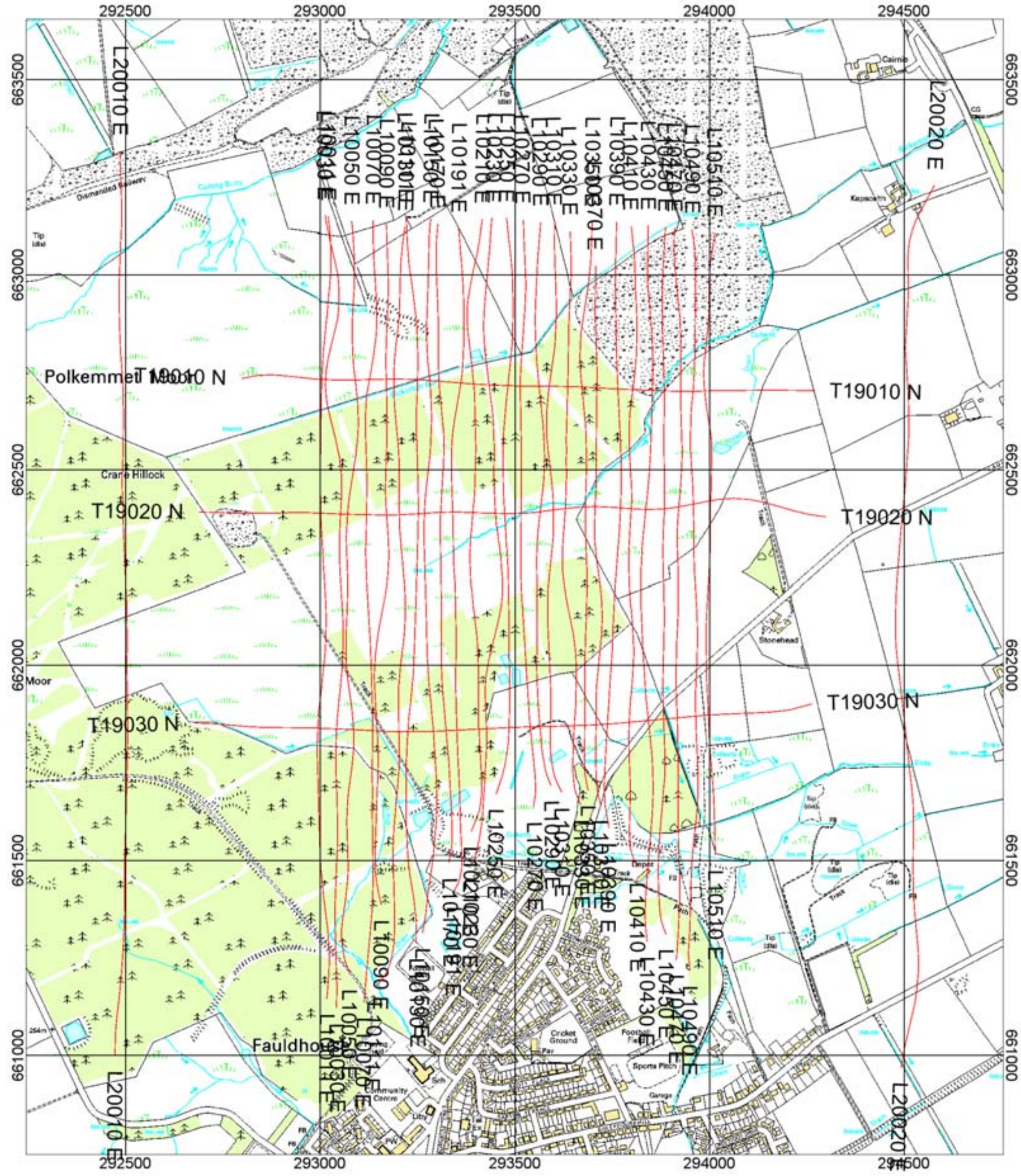

Figure 1. Survey flight lines (red lines) on background OS 1:10k map (©Crown copyright. All rights reserved).

Two additional N-S control lines, outside the main, area were obtained together with 3 E-W tie lines for the magnetic data (Fig. 1). The final processed data were obtained by BGS at the end of March 2004. The data were accompanied by a Fugro survey report (Fugro, 2004). This technical report provides a complete description of the survey and the acquired data.

Of particular concern was the spatial sampling achieved in the vicinity of the former Eastfield landfill. A 600 x 600 m area in the vicinity of the former quarry/landfill (red polygon) is shown in Figure 2 with the flight line sampling, surface trace of the fault, two recent borehole locations (two pairs) and the centre position of 3 follow-up Vertical Electric Soundings (described later). The landfill polygon was manually digitized from the site plan of Harrison et al. (1981, Fig. 2). The fault trace was digitised from the 1:10k geological map. The borehole locations shown are 35/35A north of the fault and 36/36A south of the fault. Borehole information was obtained from ENTEC (2003). The area considered covers Eastings from 293100 to 293700 m and Northings from 661700 to 662300 m.

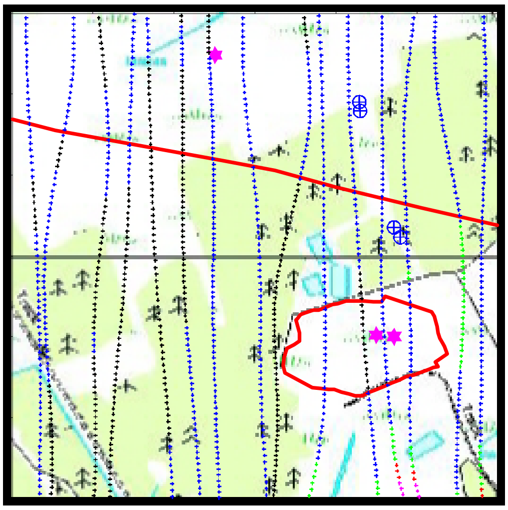

Figure 2. 600 x 600 m area within the larger survey area showing quarry/landfill polygon (red), surface trace of fault (red line), recent boreholes (circled cross symbols) and centre locations of 3 VES measurements (star symbols). Flight lines superimposed on background topographic map(©Crown copyright. All rights reserved).

3 The Eastfield Quarry Landfill

The following is a summary of the more detailed historical information found in Harrison et al., (1981). Eastfield quarry worked a sandstone outcrop within the Lower Coal Measures to a depth of 31-32 m. The quarry was located on former (early 19'th century) colliery shafts. Two of these are known and another is suspected. Landfill operations began in the 1950's when the site was leased for domestic refuse. Industrial waste disposal began in 1963 and the type industrial wastes included paints, solvents, oils, sludges and treated cyanide i.e. large volumes of liquid waste products. From 1972, the Deposit of Poisonous Waste Act allowed for greater control and since that date, 47,000 m^3 of liquid waste (33,500 m^3 containing oils) were deposited. A permanent liquid waste lagoon formed, perched above one of the 19'th Century shafts. Input of solid waste ceased in 1979 and the landfill was covered and graded. The AEM survey took place some 24 years after closure.

Historically the active landfill was the subject of a detailed BGS hydrogeological characterization research programme (Harrison et al., 1981).

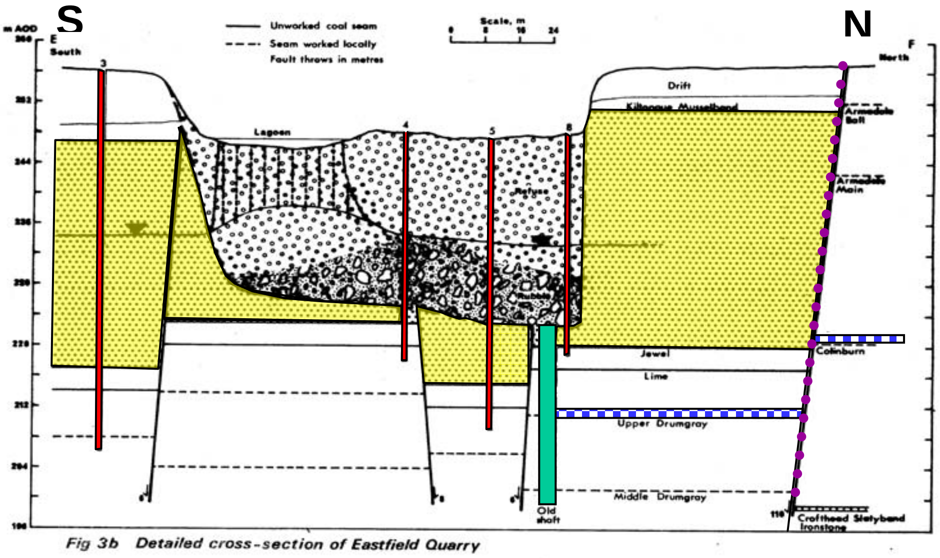

Figure 3. N-S cross section through the landfill, adapted from Fig. 3b in the report by Harrison et. al., undated), showing sandstone (yellow), boreholes (red), shaft (green) and Polkemmet Fault.

Eleven boreholes were drilled; three of the boreholes were drilled into the landfill. At that time (1974), aqueous wastes were found to have migrated through the shafts and into shallow worked coal seams surrounding the site. Oils and acidic leachates were found in fractures within the underlying sandstone and also 300 m down dip (west) within the highest worked seam (the Upper Drumgray seam ~46 mbgl). A north-south cross-section through the quarry developed during the borehole investigation is shown in Figure 3 (after Harrison et. al., undated).

A large area to the north of the landfill is due for regeneration in an ambitious scheme to develop the former colliery site. Initial phases of the scheme involve surface extraction of coal and fireclay. The environmental/technical issues of redevelopment have renewed interest in the extent of possible migration of source materials. One of the main issues of concern is the possibility of any leachate migration northwards from the landfill and the degree of any transgression across the fault, as discussed in the environmental statement (Entec, 2003) for the regeneration site.

4 Magnetic Results

The magnetic survey data, restricted to the main survey area, reveal two main anomalies as shown in Figure 4. The main anomaly is a 1000 nT dipolar perturbation associated with the landfill. This N-S oriented feature appears due to remnant magnetization within deposited ferrous materials. A further small anomaly (100 nT) appears in association with a long-term burn area across the coal spoil heap (Polkemmet Bing No. 3). A picture of the bing taken, from the south looking north, on the day of the survey is shown in Figure 5.

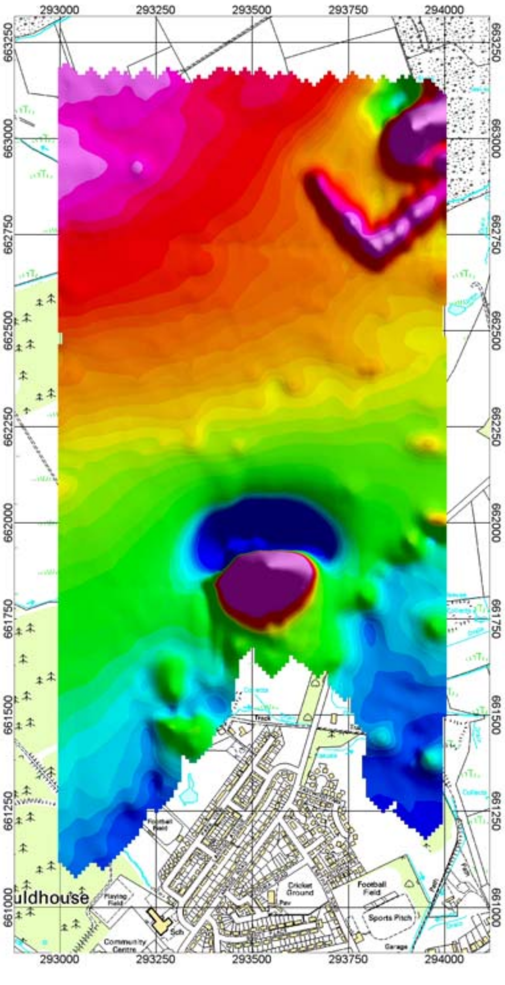

Figure 4. Total magnetic intensity (coloured contours with shaded relief) on background OS 1:10k map (©Crown copyright. All rights reserved).

Figure 5. Photograph of Bing No. 3 from the south looking NE, taken on day of survey (©BGS. Fergus McTaggart).

The two main magnetic anomalies have been contoured separately and draped on a Digital Terrain Model (DTM) of the area. The results are shown in Figure 6 in relation to the fault trace and quarry/landfill polygon. The L-shaped small magnetic high on the southern, lower flanks of the bing correspond to a zone of persistent burn noted in the report of Entec (2003). The magnetic data, although of scientific interest, have not been processed further.

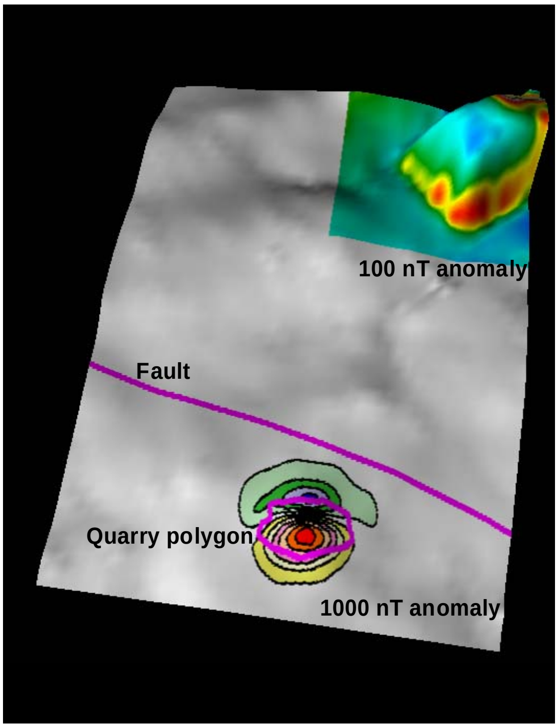

Figure 6. Total magnetic intensity values draped on digital terrain values. The main area shown covers Eastings from 293000 to 294000 m and Northings from 661700 to 663100 m. A 500 x 500 m area in the NE covering Bing No. 3 uses a different colour scale.

5 Electromagnetic/Conductivity Results

The RESOLVE electromagnetic data comprise coupling ratios from 5 horizontal coplanar coil pairs (nominal frequencies of 400, 1500, 6400, 25000 and 11500 kHz) together with a coaxial pair operating at 3300 Hz. Sampling of all data is at 10 Hz providing data every 3.2 m along flight lines. These data can be used to provide a variety of half-space apparent conductivity maps together with approximate frequency-depth transform models (Beamish, 2002).

The standard form of mapping is in terms of the half-space model derived from the coupling ratios at each frequency. The basic (original) procedure is described by Fraser (1979). The conductivity mapping information obtained by this type of procedure is shown in Figure 7. The sequence is from high to low frequency (shallow to deep penetration depths). Figure 7a shows the results for 115 and 25 kHz, Figure 7b shows the results for 6200 and 3300 Hz and Figure 7b shows the results for 1500 and 400 Hz. Centroid depths, meaning the depth of the 'centre-of-gravity' of the induced in-phase current system, have been calculated from the statistics across the main survey area. Mean values are 6.9 m (115 kHz), 14.5 m (25 kHz), 27.5 m (6200 Hz), 54 m (1500 Hz) and 106 m (400 Hz). The induced current system for the coaxial coil pair at 3300 Hz is different to that of the other 5 coil geometries and a centroid depth calculation at this frequency is omitted.

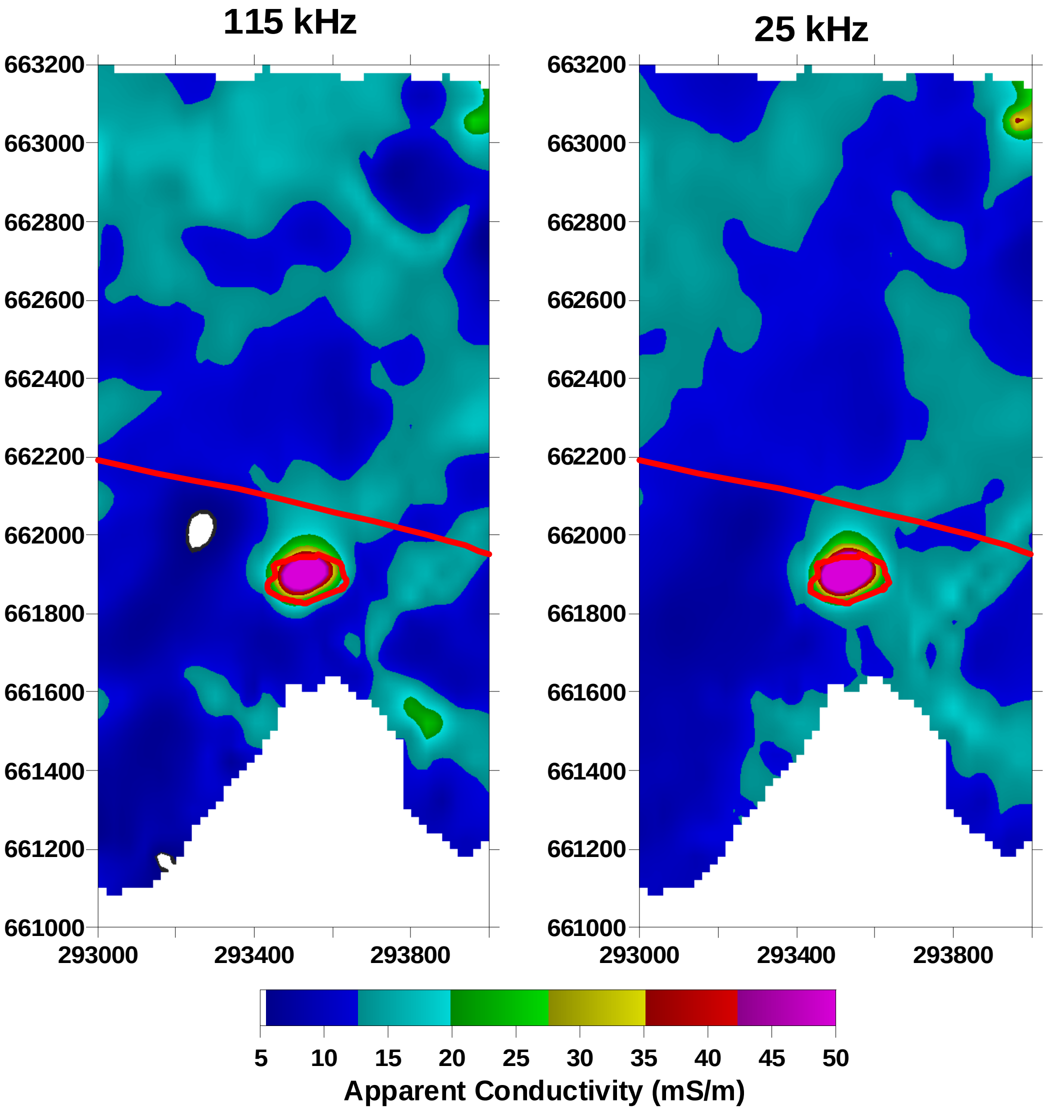

Figure 7a. Half-space apparent conductivity distribution at frequencies of 115 and 25 kHz

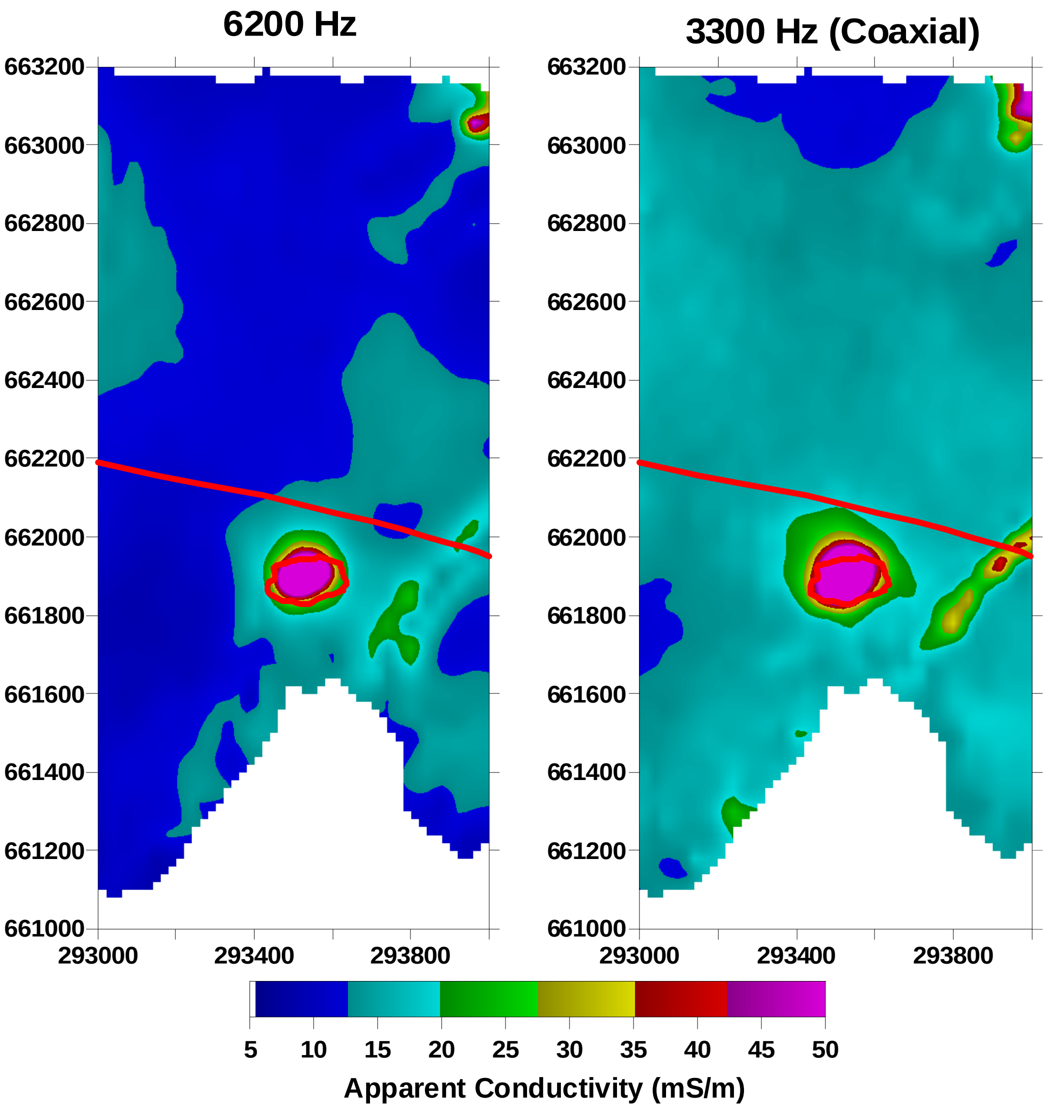

Figure 7b. Half-space apparent conductivity distribution at frequencies of 6200 and 3300 Hz

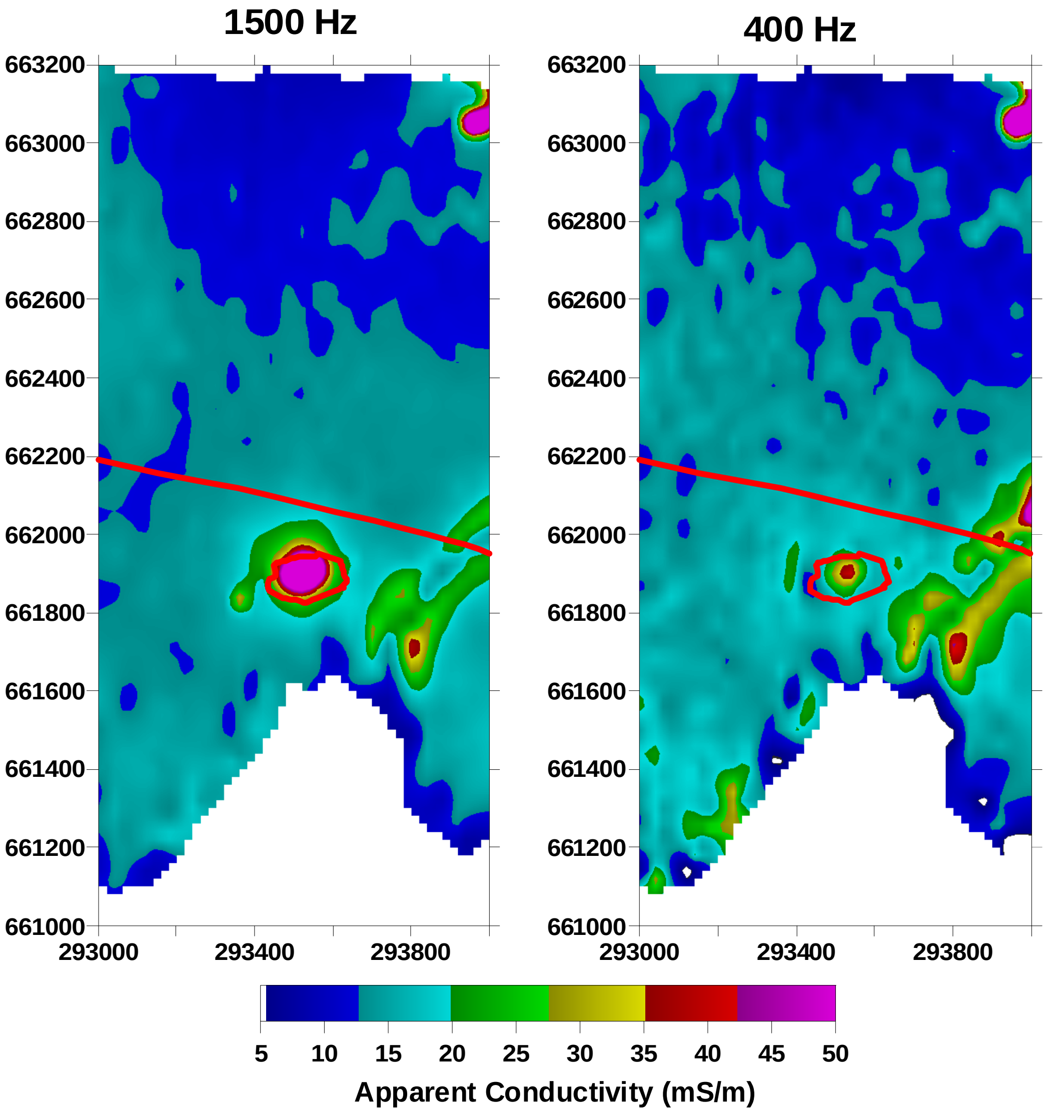

Figure 7c. Half-space apparent conductivity distribution at frequencies of 1500 and 400 Hz

The colour contour scale in Figure 7 has been set to a constant range of 5 to 50 mS/m (a factor of 10) throughout. The lowest half-space conductivity obtained is 4.85 mS/m at 115 kHz (Fig. 6a). Maximum values of conductivity occur within the landfill site and are 77 mS/m (115 kHz), 117 mS/m (25 kHz), 145 mS/m (6200 kHz), 138 mS/m (3300 kHz), 125 mS/m (1500 Hz) and 41 mS/m (400 Hz). Clearly the landfill shows a peak conductivity response at 6200 Hz. Centroid depths within the conductive landfill area, at this frequency, range from about 13 to 20 m.

The results shown in Figure 7 reveal that the conductivities of the Lower Coal Measure sequence range from about 5 to 20 mS/m (a factor of 4). The regional scale Polkemmet Fault shows no readily discernable conductivity expression. This is to be expected since, although the fault downthrows the solid geology by ~100 m to the south, similar geological materials exist to the north and south.

With decreasing frequency (Figures 7b and 7c), a NE-SW striking conductivity anomaly, to the east of the landfill, becomes increasingly apparent. The form of the anomaly, most pronounced at 400 Hz, conforms to an ‘M’ shaped feature (high-low-high amplitude) orthogonal to strike. At 3300 Hz (Fig. 7b), in which the transmitter/receiver are horizontal dipoles, the feature comprises a single high amplitude. This is the classic response of a line-current (power line). The RESOLVE power-line monitor channel is shown as a posted value plot in Figure 8a. The area shown is 500 x 500 m and a trace of high values is observed sub-parallel to the road. A picture taken from the track entrance (visible in Fig. 7a) along the road to the NE shows the overhead power line responsible for the anomaly. As indicated in the conductivity maps of Figure 7, the perturbation increases with decreasing frequency and has a large spatial influence on the models derived from the coupling ratios.

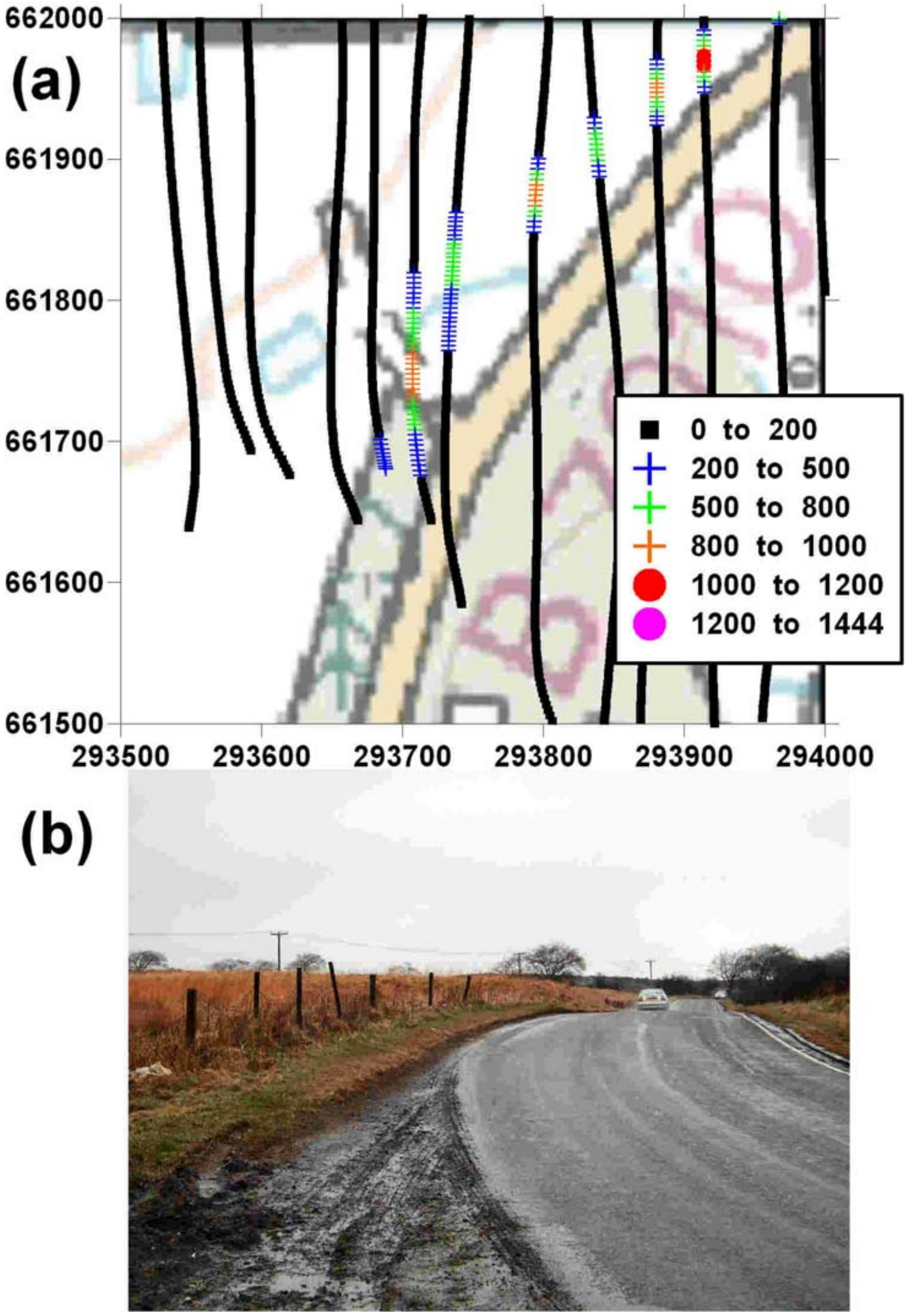

Figure 8. (a) Posted values of coplanar power-line monitor channel (CPPLR) along flight lines in vicinity of B7010. (b) Photograph, taken from the track entrance, looking NE along B7010 (©BGS. Rhys Cooper).

5.1 CONDUCTIVITY MODELS

The above procedures, while useful, do not provide sufficient resolution or discrimination to fully address the technical issues posed by the landfill. In order to fully exploit the information provided by any multi-frequency EM system it is necessary to undertake formal inversion of each 'sounding'. At present, routine procedures for airborne data are limited to 1D assessments. These models may then be stitched together to allow a consideration of the conductivity distribution within a subsurface volume.

Various forms of regularized (Occam) 1D inversion have been applied to the data. The results described here were obtained using the algorithm described by Zhang and Oldenburg (1999). The goal of the inversion is to find a model that reproduces the data and exhibits certain desired characteristics. The desired characteristic is a 1D conductivity model that has minimum structure in the vertical direction and, at the same time, is close to a reference model. The reference model used here is the best fitting half-space. Although the algorithm can perform parameter inversion for conductivity and magnetic susceptibility, either separately or jointly, only conductivity inversion models are considered. It is acknowledged that the conductive landfill will provide a) magnetic and b) three dimensional influences that are not taken into account in the modelling procedure. The paper by Zhang and Oldenburg provides an assessment of 3D effects on 1D modelling.

While necessary limiting resolution in the vertical direction, such models are highly useful in mapping lateral changes within the subsurface volume. Using a realistic assignment of data errors (5%) and a 25 layer model (extending to a depth of 100 m), chi-squared misfits around the expectation of 12 (from 6 frequency coupling ratios) are achieved except on one central line through the landfill zone. The resulting conductivity models have been incorporated into a 3D visualization program (Geoexpress, IGM Ltd) that allows conductivity isosurfaces and isovolumes to be realized. In order to provide a detailed assessment of the conductivity distribution associated with the landfill and in order to avoid the perturbation introduced by the power-line, a zone of 600 x 600 x 100 m, as shown in Figure 2 is considered first.

Figure 9a shows the complete conductivity distribution within the selected volume. The values range from ~1 to > 60 mS/m as defined by the colour scale bar. The visualization allows the user to select and display regions with specific values of conductivity. Figure 9b shows a conductivity isovolume at 200 mS/m across the selected volume in which other additional elements have been incorporated into the visualization. The high value of 200mS/m defines only highly conductive materials and, as shown in Figure 9b, this material is confined to a localized volume within the former landfill. The blue skeleton box, extending to 30 m, is a crude representation of the extent of the quarry/landfill. Vertical yellow lines denote the locations and depths, below surface, of the borehole investigations carried out in the 1970’s (Harrison et al., 1981). Horizontal coloured discs denote water levels. The two sets of blue vertical lines denote borehole locations: 35/35A north of the fault and 36/36A south of the fault. Borehole information was obtained from ENTEC (2003). Borehole 36 was drilled 13 m to the north of 36A to a depth of 43 m and appeared to intersect the fault at its base. The dip on the fault plane (the transparent sub-vertical plane within the visualization) was estimated on this basis.

Figure 10 shows two views of the same conductivity isovolume as the level is reduced to 75 mS/m. This high level of conductivity is likely to be associated with source material with high levels of Total Dissolved Solids (TDS). As can be seen in Figure 10, breakout appears below the base of the quarry to the north and west. As the conductivity is further reduced, pathways containing lower levels of TDS are revealed. A lower conductivity level of 35 mS/m appears to provide a level that is x2 to x3 above background geological levels and hence attributable to enhanced TDS from landfill source materials.

Figure 11 attempts to summarise the main attributes of the conductivity model. An isosurface of 35 mS/m is used. A confined area of conductive breakout appears at a depth of about 8 m to the north of the landfill. The major northward breakout occurs at depths > 30 m and a conductive tongue traverses the fault largely below the base of recent investigation boreholes. To the west and south-west, deep breakout appears to correlate with the location/depth of the worked Upper Drumgray seam. The feature appears consistent with the interpretations derived from the borehole investigations noted previously.

Since there is a total lack of control information regarding the ‘background’ conductivities of geological formations at the site, it was considered prudent to carry out a limited ground geophysical assessment, to provide a degree of confirmation of the models obtained from the airborne survey. These are described below.

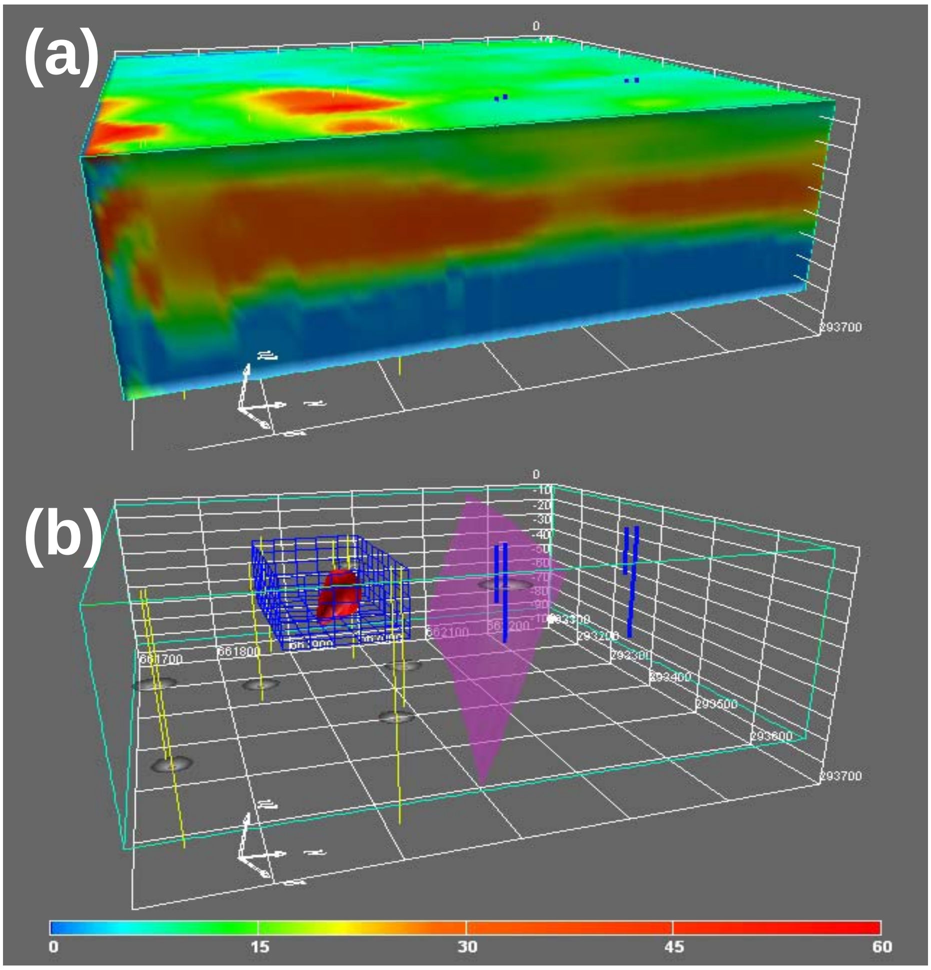

Figure 9. 3D perspective views of conductivity model (colour scale bar in mS/m) within 600x600x100m selected volume, looking west to east. V.E. x 2.5. (a) complete distribution. (b) 200 mS/m isovolume. Descriptions of other objects are in the text.

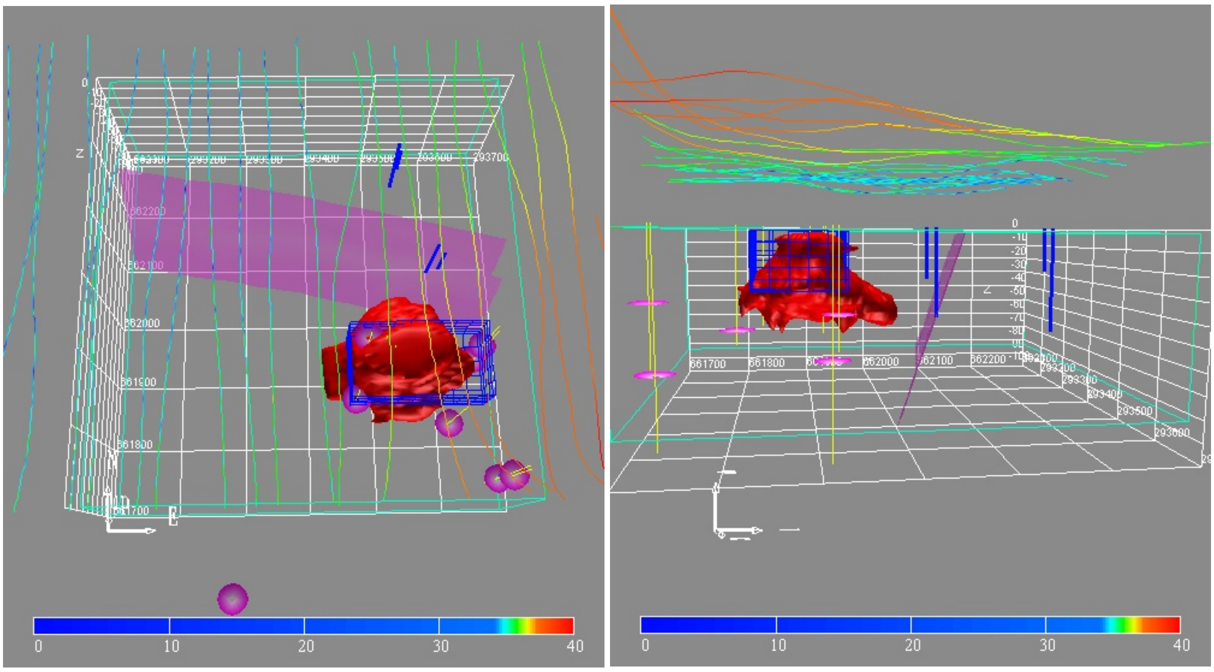

Figure 10. Two 3D perspective views of same conductivity isovolume of 75 mS/m. Uppermost lines are flight lines. Other details as previously.

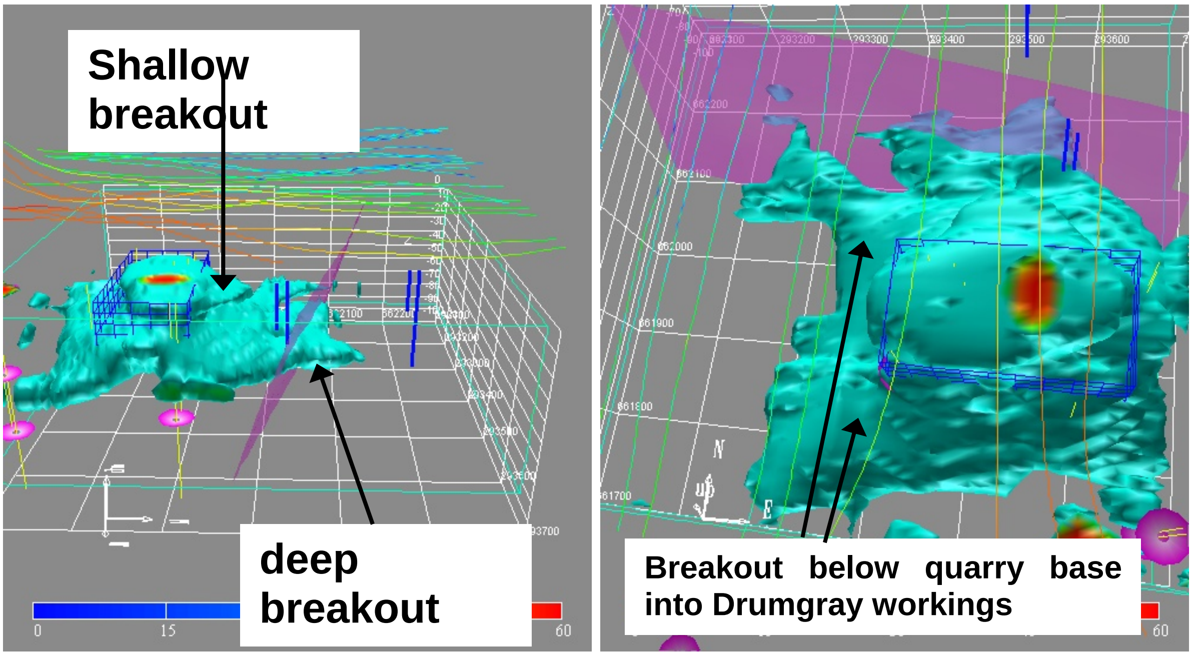

Figure 11. Two 3D perspective views of same conductivity isovolume of 35 mS/m. Uppermost lines are flight lines. Other details as previously.

6 Ground geophysical follow-up

As a follow-up to the airborne survey, a set of five Schlumberger Vertical Electric Soundings (VES) were obtained across the survey area. The data were acquired between 15 and 18 March 2005 using the ABEM SAS3000 Terrameter. The sounding locations are shown in Figure 13 as sounding centres with maximum geometrical extents. Table 1 provides sounding centre coordinates and lateral extents of the five soundings.

Sounding	Easting (m)	Northing (m)	AB/2 m
01	292929	662074	200
02	293550	661902	50
03	293351	662248	160
04	293503	662346	200
05	293572	661900	64

Table 1. Centre coordinates of VES soundings and one-sided, lateral extents (AB/2)

Depth of investigation is normally between 0.3 and 0.5 of the AB/2 distance. Two soundings (02 and 05) are contained within the former quarry/landfill. Sounding 01 lies to the south of the Polkemmet Fault and the remaining 2 soundings form a geometrical cross to the north of the fault. The location and geometry of the soundings were determined by access and safety considerations (water-logged moor land).

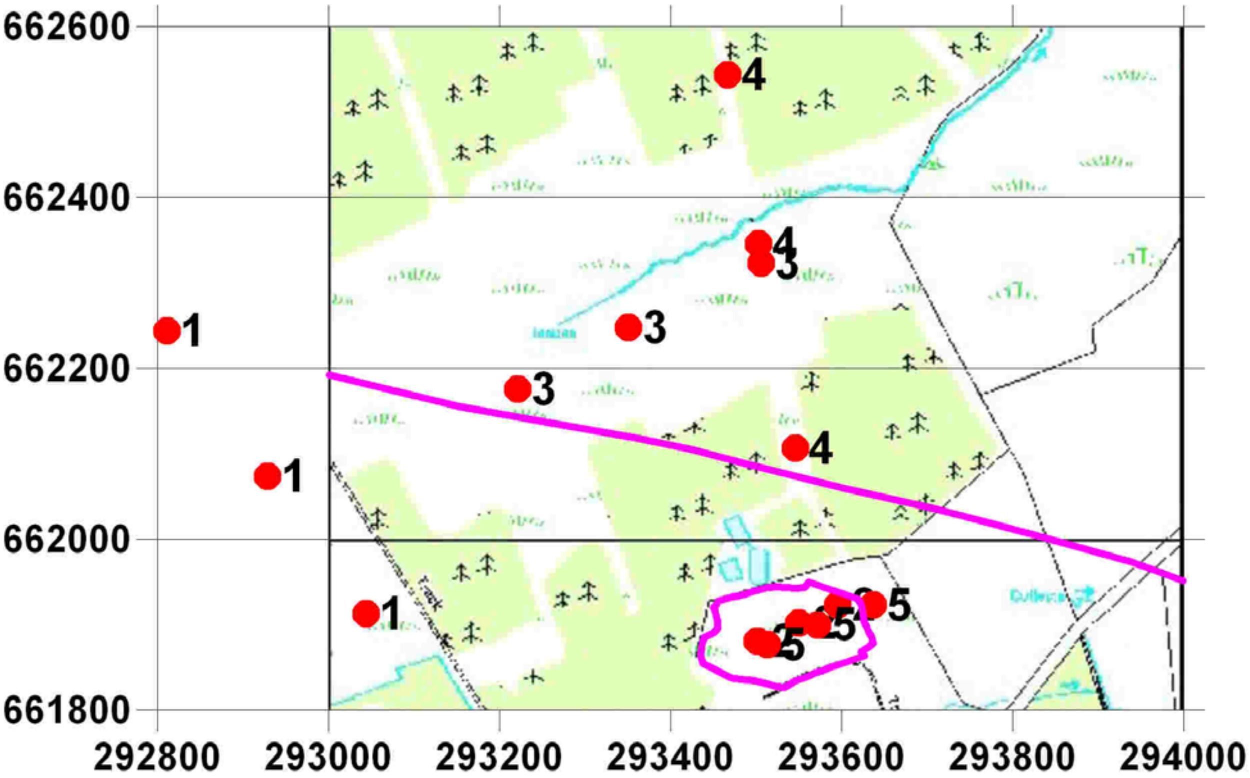

Figure 12. Locations (centres and end points) of five VES soundings.

Figure 13 shows the one dimensional conductivity models obtained at all 5 sounding locations. Both depth and conductivity are shown using a logarithmic scale. The models shown with symbols were obtained using an Occam regularized inversion. This form of inversion procedure forces the profile to be smoothly varying and the resulting profile has 'minimum structure'. The results were obtained assuming all the data had errors of 5% and the data were fitted to an rms error of 1%.

The 3 soundings (01, 03 and 04) represent 'background' profiles for the Lower Coal Measure sequence. The two soundings (03 and 04) to the north of the Polkemmet Fault are mutually consistent and provide a small variation of between 4 and 8 mS/m over the depth range shown. Sounding 01 to the south of the fault displays persistently higher conductivities although the overall form of all 3 profiles is similar. The two soundings within the quarry/landfill area (02 and 05) display consistently higher values than background particularly at depths > 1 m. Both profiles ramp to high values in the depth range 15 to 20 m. The limited lateral extent of these soundings means that the depth of investigation is more restricted than soundings 01, 03 and 04. A conventional 'layered' conductivity for sounding 05 (black line) is also shown for comparison. This model achieves a misfit error of 2.1% and indicates a high conductivity zone (95 mS/m) between depths of 8 and 41 m. Equivalence studies indicate that the base of the conductive zone is not well resolved, however.

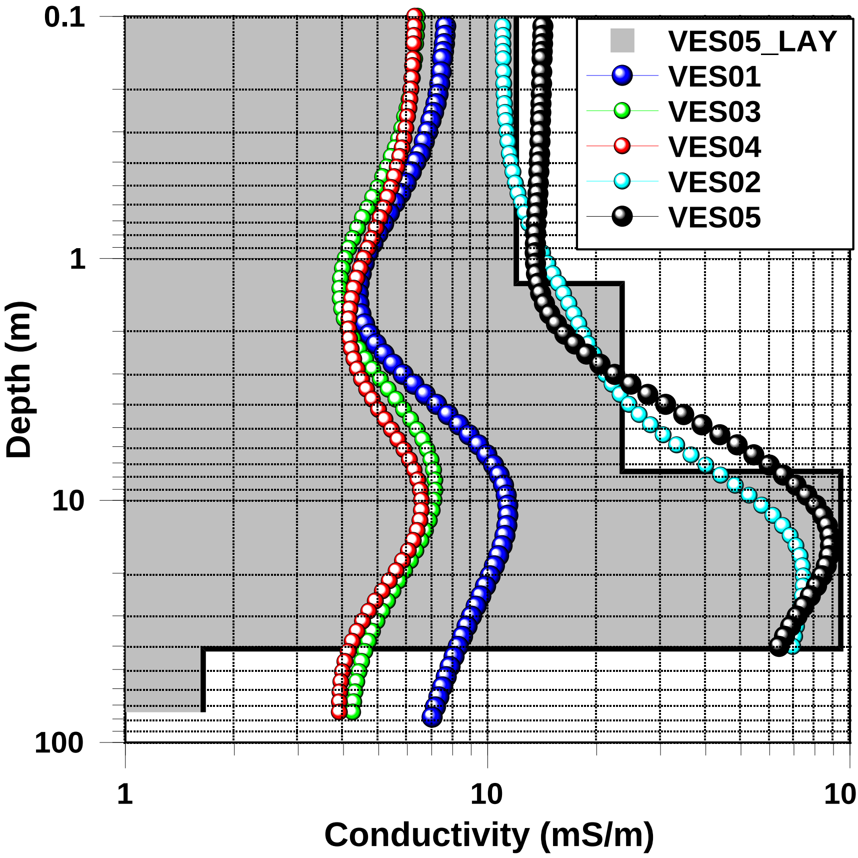

Figure 13. Conductivity models obtained by 5 VES soundings. Soundings with symbols denote smooth-model inversions. The single layered profile (with infill) obtained on the quarry site (VES05_LAY) is shown for comparison.

Overall the ground investigations have provided a broad degree of confirmation of the airborne model. Background conductivities within the Lower Coal Measure sequence appear low and, although we only have 3 such soundings, we could anticipate non-geological influences being detected at conductivity levels in excess of, say, 15 mS/m. Elevated conductivities, at all depths, are confirmed within the quarry/landfill area. Very high conductivities appear at depths > 8 m however the base of the conductive zone is not well resolved. One estimate of 40 m is consistent with the form of the model obtained from the airborne data.

7 Whole Survey Conductivity Model

A preliminary conductivity model has been produced for the main Resolve survey area shown in Figure 1. The model covers a 1 x 1.450 km area between Eastings of 293000 to 294000 m and Northings of 661700 to 663150 m. The model was obtained using the same regularised inversion procedures described previously. The 1D conductivity models were then incorporated into the same 3D visualization program. The mesh contains 67 elements, each of length 15 m, in the x (Easting) direction and 288 elements, each of length 5 m, in the y (Northing) direction. The model again extends to a depth of 100 m

A plan view of the 3D perspective model obtained for the 35 mS/m conductivity isovolume is shown in Figure 14. The previous information obtained across the detailed 600x600 m area of the quarry/landfill is repeated. Several other conductive features are apparent:

- SW corner. The double conductive features traversing the area SW to NE are the result of the power line perturbation. They are a known artefact (see previous discussion) and should be disregarded.
- NE corner. The at-surface (red colour) and more northerly (and deeper) conductive features follow a trace around the base perimeter of the previously discussed Bing No. 3.
- Central eastern edge. A relatively deep, spatially coherent, conductive unit is apparent. This area shows some correlation with the outline of the worked Colinburn seam to the north of the Polkemmet fault.
- Various. Several ‘along-line’ conductive features appear that are associated with individual survey lines. The lack of across-line spatial coherence suggests that these may be artefacts rather than valid subsurface features. These features would benefit from further investigative modelling of the data.

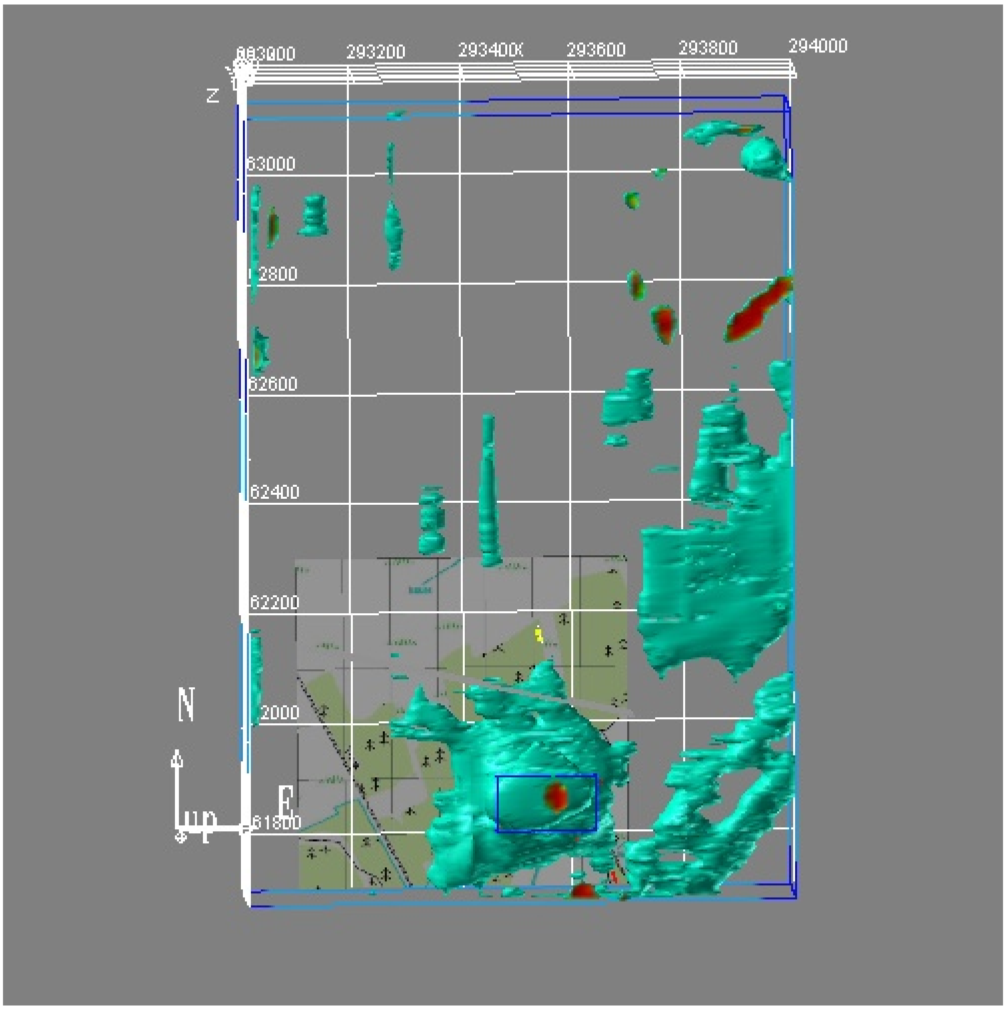

Figure 14. 3D perspective plan view of conductivity model across 1000x1450x100m main survey area, showing conductivity isovolume of 35 mS/m.

The extent of the Colinburn workings has been digitised from Figure 7 of Harrison et al. (1981). According to Entec (2003) the Colinburn seam on the northern side of the Fault is at a similar elevation to the Upper Drumgray seam on the south side of the Fault. A horizontal plane containing the outline polygon of the workings has been placed at a reference depth of 40 m. A detailed view of the eastern conductive feature and reference plane is shown in Figure 15.

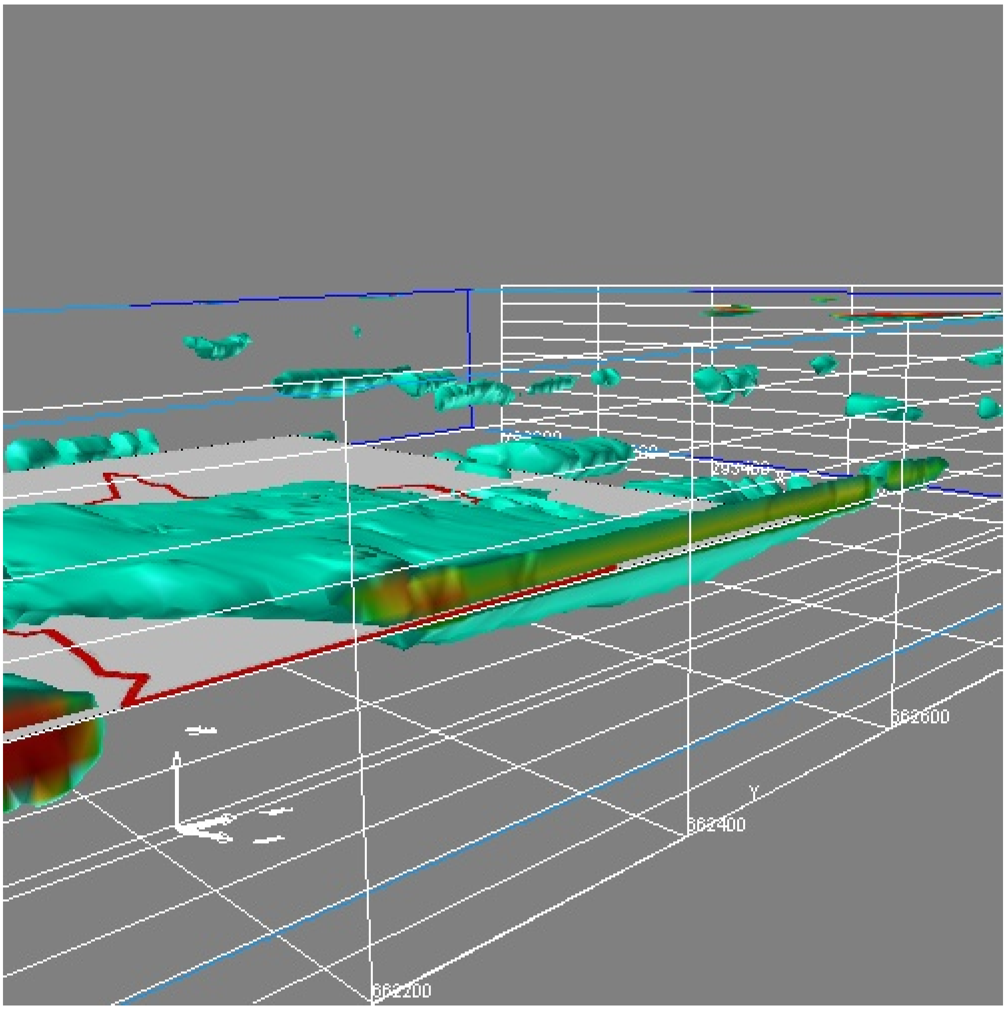

Figure 15. Detail from 3D perspective view of conductivity model across 1000x1450x100m main survey area, showing conductivity isovolume of 35 mS/m. Horizontal plane containing outline polygon of Colinburn workings shown at a depth of 40 m.

The conductive feature can be seen most clearly along the eastern margin. The feature here appears at depths between 35 and 40 m. Using the same isovolume conductivity level, the feature appears largely confined to depths greater than 30 m and less than 50 m over the lateral extent shown. In reality, the 1D models we are considering are not capable of resolving sharp boundaries in the vertical direction. It is likely that the actual feature may be vertically compact on a thickness scale of between 5 and 10 m. The lateral extent of the conductive feature in relation to the Colinburn seam reference polygon is shown in more detail in Figure 16.

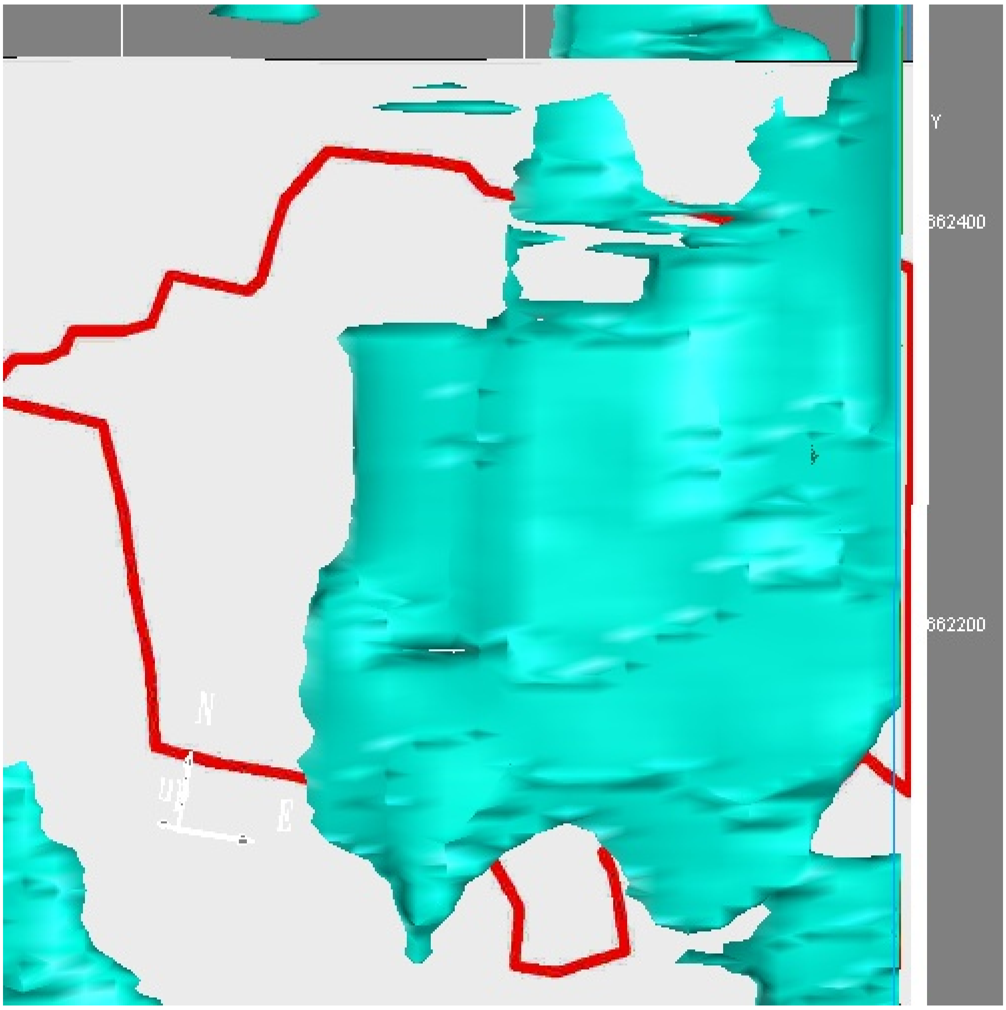

Figure 16. Detail (approximate plan view) from 3D perspective view of conductivity model across 1000x1450x100m main survey area, showing conductivity isovolume of 32.5 mS/m. Horizontal plane containing outline polygon of Colinburn workings shown at a depth of 40 m.

8 Conclusions

The Eastfield helicopter AEM survey probably represents the first UK application of such technology to a detailed site assessment. The survey has highlighted a number of issues related to data acquisition at the site investigation scale. These include the difficulties of achieving adequate flight line coverage and, also, the significant interference from a single overhead power line.

The magnetic survey data reveal two main anomalies across the site. The main anomaly is a 1000 nT dipolar perturbation associated with the landfill. This N-S oriented feature appears due to remnant magnetization within deposited ferrous materials. A further small anomaly (100 nT) appears in association with a long-term burn area across the coal spoil heap (Polkemmet Bing No. 3).

In order to extract pertinent information (in this landfill site context) from the 6 frequency AEM data it was necessary to perform 1D inversion. Adequate misfits were achieved using regularized, Occam procedures. The main volume investigated covers a 600x600x100m taking in the landfill and Polkemmet Fault.

The resulting conductivity model appears to ‘represent’ a leaking landfill. A confined area of conductive breakout appears at a depth of about 8 m to the north of the landfill. The major northward breakout occurs at depths > 30 m and a conductive tongue traverses the fault largely below the base of recent investigation boreholes. To the west and southwest, deep breakout appears to correlate with the location/depth of the worked Upper Drumgray seam. The depth of the feature appears consistent with the interpretations derived from the borehole investigations.

A degree of broad confirmation of the airborne conductivity model has been established by ground geophysical (Vertical Electric Sounding) follow-up. Background conductivities within the Lower Coal Measure sequence appear low and, although we only have 3 such soundings, we could anticipate non-geological influences being detected at conductivity levels in excess of, say, 15 mS/m. The inferences on breakout have been made using an isovolume conductivity level of 35 mS/m. Elevated conductivities, at all depths, are confirmed within the quarry/landfill area.

A preliminary conductivity model for the main survey has also been presented. The model contains a number of known and suspected artefacts. To the north of the Fault a relatively deep, spatially coherent, conductive unit is apparent. This area shows some correlation with the outline of the worked Colinburn seam. The feature occurs largely between depths of 30 and 50 m. Due to the nature of the modelling procedure employed, the anomaly could represent a thin conductive unit.

Due to the low conductivity of the Coal Measures, only the conductive component of leachate migration is resolved. According to Harrison et al. (1981), the main potential pollutants are heavy metals, acids and organic matter (principally oils). Biological degradation within the mine workings is unlikely to be significant since conditions for efficient aerobic breakdown are lacking. Oils, perhaps accounting for only 10% of the liquid wastes, should remain resistive. The cause of the conductive component is therefore likely to derive from the highly acidic and mobile sulphate component found in high concentrations (typically > 1000 mg/l) in the pore waters extracted by the borehole study in the 1970's. The precise geochemical nature of the conductive breakout remains speculative until further modern control information can be provided.

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