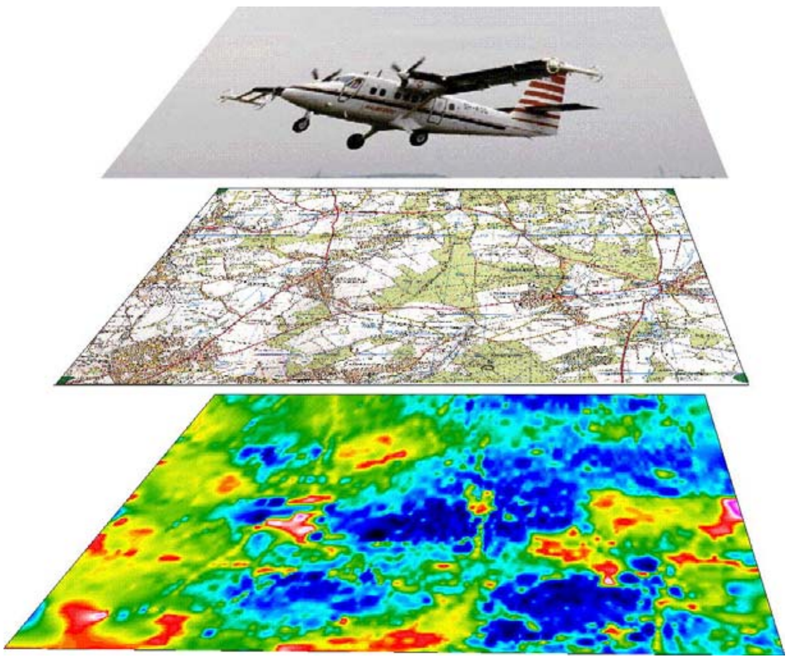
TECHNICAL REPORT WK/00/02

Regional Geophysics Series

Trial airborne environmental and geological survey of target areas in the English Midlands

D Beamish, R J Cuss, D G Jones and R J Peart



British Geological Survey
Natural Environment Research Council

Report on airborne geophysical surveys conducted by the Geological Survey of Finland in collaboration with the British Geological Survey and co-funded by the Department of the Environment, Transport and the Regions and the Environment Agency

TECHNICAL REPORT WK/00/02

Regional Geophysics Series

Trial airborne environmental and geological survey of target areas in the English Midlands

D Beamish, R J Cuss, D G Jones and R J Peart

Subject Index
Airborne geophysics, magnetic, radiometric, electromagnetic, UK

Bibliographic Reference
Beamish D., Cuss R.J., Jones D.G., and Peart R.J., 2000
Trial airborne environmental and geological survey of target areas in the English Midlands
British Geological Survey
Technical Report WK/00/02

 Keyworth Nottingham British Geological Survey

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desk at the Survey headquarters, Keyworth, Nottingham. The more popular maps and books may be purchased from BGS-approved stockists and agents and over the counter at the Bookshop, Gallery 37, Natural History Museum (Earth Galleries), Cromwell Road, London. Sales desks are also located at the BGS London Information Office and at Murchison House, Edinburgh. The London Information Office maintains a reference collection of BGS publications including maps for consultation. Some BGS books and reports may also be obtained from the Stationery Office Publications Centre or from the Stationery Office bookshops and agents.

The Survey publishes an annual catalogue of maps, which lists published material and contains index maps for several of the BGS series.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland) and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

Keyworth, Nottingham NG12 5GG
☎ 0115-936 3100 Telex 378173 BGSKEY G
Fax 0115 936 3200

Murchison House, West Mains Road, Edinburgh EH99 3LA
☎ 0131-667 1000 Telex 727343 SEISED G
Fax 0131-668 2683

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE
☎ 0171-589 4090 Fax 0171-584 8270
☎ 0171-938 9056/57

St Just, 30 Pennsylvania Road, Exeter EX4 6BX
☎ 01392-78312 Fax 01392-437505

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ 01232-666595 Fax 01232-662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491-838800 Telex 849365 HYDROL G
Fax 01491-692345

Parent Body
Natural Environment Research Council
Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793-411500 Telex 444293 ENVRE G
Fax 01793-411501

SUMMARY

A series of four trial airborne environmental and geological surveys was flown by the Geological Survey of Finland (GTK) in collaboration with the British Geological Survey (BGS) in June 1999; the trials were co-sponsored by the Department of the Environment, Transport and the Regions and the Environment Agency. The main objective of these surveys was to test the efficiency of the GTK airborne electromagnetic (EM) system in the mapping of potential pollution problems in the UK environment. Gamma spectrometric and magnetometric measurements were also collected to see to what extent these techniques provide complementary information.

The EM data are particularly encouraging and have identified anomalies which may relate to subsurface pollution. The data have identified conductive zones both on the 'local' scale (i.e. possibly emanating from domestic landfills) through to regional scale features up to many kilometres in length. The information obtained in relation to spoil tip drainage is of particular note. The data have provided a wealth of information on 'point source' anomalies (requiring ground truth information) and diffuse sources that may be connected with groundwater extraction. At two sites (Trent Valley and Langar) the EM technique appears to have met the challenge of detecting conductive targets in a conductive host. Many other features of the data will take time to assess.

The radiometric data indicate features of land fill and colliery spoil sites and allow comparison to be made rapidly with the EM data to define the lateral spread of conductive pore fluids beyond the site itself. They can also be used to map site-specific contamination where radioactive elements are present. The radiometric data also give direct indications of solid and drift geology and soil type, providing additional detail to that shown on geological maps (soil maps are not available for much of the UK).

The magnetic data have suggested the presence of significant volumes of metallic debris in the Langar landfill sites. This may be significant in terms of the leachates derived and the compaction (through time) of the contrasting fill materials. Compared with the EM and radiometric techniques, the applications of magnetics in environmental studies are rather limited, but such data is worthwhile collecting in view of the marginal additional costs involved.

CONTENTS

LIST OF FIGURES

1. INTRODUCTION

For some years the Geological Survey of Finland (GTK) have applied their airborne geophysical capability to the mapping and monitoring of potential environmental hazards. In particular they have achieved impressive results with their electromagnetic (EM) system, both mapping pollution plumes emanating from landfill sites and monitoring the integrity of other, better constructed and managed, landfills. Could a similar system be used for the rapid and efficient surveillance of pollution hazards in the UK?

When compared with the Shield areas of Finland, the typical UK environment suffers many more sources of cultural noise (both electromagnetic and magnetic) while it is predicted that a much reduced conductivity contrast will exist between the target and host material. However, early numerical modelling indicated that a detectable EM response could be observed at flying heights up to 100 m above a conductivity contrast as small as 3:1. This result was sufficiently encouraging for the British Geological Survey (BGS) to invite the GTK to undertake collaborative trial airborne surveys over a number of diverse sites in the UK. In addition to the EM measurements, gamma spectrometry and magnetometry were also to be employed to investigate to what extent these techniques yield useful complementary data.

The airborne trials were conducted during a one week period in June 1999 and were co-funded by the Department of the Environment, Transport and the Regions and the Environment Agency. As far as we are aware this is the first high resolution, airborne EM survey carried out in the U.K. The EM information obtained is of a new 'type' and a full understanding will take time and require extensive ground calibration and modelling.

2. AN OUTLINE OF AIRBORNE GEOPHYSICS

This section is included as a convenient reference for those readers not familiar with airborne geophysical surveying. We first describe how physical properties measured from an aircraft can help characterise both the nature and condition of the underlying soil and rock and we then highlight some of the main advantages of airborne geophysics.

EM: the raw EM data from this survey comprise coil-coil coupling ratios at two frequencies. The high frequency data relate to shallow depths and the low frequency data provide deeper information. The coupling ratios are processed and converted to apparent ground resistivities for interpretation purposes.

Airborne EM resistivity mapping systems exist in various forms (e.g. fixed-wing and helicopter) and with different technical specifications that can be chosen by the user to suit particular problems. It is the frequency content of the system that governs the depth of the investigation. The frequency range of the present system provides information *below* the near-surface (ie below the first few metres) and relates to concealed bulk resistivities on a vertical scale of tens of metres.

The bulk resistivity of subsurface formations provides a distinct measure of land and water 'quality'. For porous rocks that are either partially saturated (ie above the water table) or wholly saturated (ie within an aquifer) the electrical current flow is primarily controlled by ionic conduction. The ions, which conduct the current, result from the dissociation of salts. The conductivity of the in-situ electrolyte depends on both the number of ions present (concentration) and their mobilities. Common ion species with high mobilities include the

Na^{+}, SO_4^{-}, Cl^{-}, K^{+} and NO_3^{-} groups. The bulk resistivity measured by geophysical means cannot discriminate which ions are present. In certain specific cases (e.g. saltwater intrusion) the geophysical data can be calibrated (e.g. to provide equivalent chloride concentration), at various depths, by borehole measurements.

Other influences on the formation resistivity include porosity and certain mineralogical associations such as the presence of clays. In cases where the geological formation changes (in terms of these parameters) then the geophysically measured resistivity will also change.

Gamma-ray spectrometry*:* measures the total spectrum of gamma radiation from the ground. The different components of natural radioactivity, arising from potassium, uranium and thorium, are separated and quantified. Man-made sources, such as ^{137}Cs arising from the Chernobyl accident, can also be identified and quantified. The depth of investigation of the technique is restricted to the ground surface layer to a depth of about 30cm.

Magnetometry: records local variations in the strength and direction of the earth's magnetic field and these variations in turn reflect the presence of contrasting magnetic susceptibilities. The susceptibility of a rock, a measure of how strongly magnetised it becomes in the inducing earth's field, is determined almost entirely by its content of ferrimagnetic minerals, principally magnetite. Quite subtle changes in the content of this auxiliary mineral results in the very large susceptibility variations displayed by different rock types and hence magnetometry can be a very sensitive tool for geological mapping. In general terms sedimentary units display low values of susceptibility and basic igneous rocks (such as basalt and dolerite) the highest.

The earth's magnetic field is dipolar and at UK latitudes the typical anomaly created by an east-west trending feature shows a positive peak with a lower amplitude negative trough to the north. North-south trending sources produce a more symmetrical positive peak. In practice, interference between adjacent anomalies can yield quite complex anomaly shapes. Magnetic anomalies can arise at any depth above the Curie isotherm (about 35km in Continental areas) but in the present work we are interested only in the short wavelength features (say less than 1 km) that reflect shallow sources. In addition to anomalies that reflect geological features, many man-made metallic objects (railways, powerlines, buildings etc) give rise to so called cultural anomalies and these are particularly intense at lower flight elevations. Typically such anomalies are removed during processing because they can obscure subtle geological features. In the context of environmental studies, however, such cultural anomalies are clearly significant in their own right.

The main advantages of airborne geophysics: these may be summarised as follows:

- Simultaneous acquisition of multi-parameter data sets.
- High spatial resolution, with quasi-continuous sampling (every 5 to 50m) along flight lines spaced between 50 and 200m apart (user specified).
- Continuous coverage over *all* areas, whether conurbations, landfills, forests etc.

It follows that airborne geophysics enjoys three major advantages over isolated, 'spot' sampling techniques (such as soil or water geochemistry): high density of coverage, the synergism of integrated data sets and the information gained on the depth extent of anomalous distributions. In addition, the geophysical techniques are non-invasive (although a sound interpretation will usually require some further ground sampling) and remotely sensed, two particular advantages when investigating potentially hazardous sites.

3. SURVEY AREAS

Four target areas were chosen. The selection criteria included: the presence of a known or potential pollution hazard, proximity to Tollerton Airport (Nottingham) where the survey aircraft was to be based, the avoidance of urban and sub-urban areas and busy air corridors adjacent to military and commercial airports. In addition it was decided to refly the Vale of Belvoir radiometric calibration range that had been established for the earlier HiRES-1 regional airborne geophysical survey of 1998. This would allow both more accurate conversion of airborne spectrometer readings into ground concentrations of the three naturally occuring radio-elements and also a comparison of the two different instruments used for these surveys. The locations of these survey areas are shown in Figure 3.1 while further details of the targets and the airborne coverage achieved at each site are given below. The terrain clearances listed are nominal; at all times during the survey the aircrew observed UK Civil Aviation Authority regulations.

Area A) East of Shirebrook (117km^2) Here there exist numerous colliery spoil heaps and it was feared that rainfall percolating through these could become contaminated and pollute the important shallow Sherwood Sandstone aquifer. In the central part of the trial area deep (800m) open fractures pervade this aquifer which is thus made more vulnerable. The area also contains at least two domestic landfill sites.

The entire block was flown with mean clearance of 40m in the east-west direction with 200m line spacing and tie-lines at 2 or 2.5km. In two sub-areas (A1 and A2) the flight line spacing was subsequently reduced to 50m.

Area B) The Trent Valley, from immediately north-east of Nottingham to the village of Bleasby (90km^2). Within this stretch of the valley there are numerous landfills (containing power station fly-ash and domestic waste) that occupy abandoned gravel pits.

This block was flown with north-east flight lines at a mean clearance of 92m. Flight line spacing over most of the area is 100m, increasing to 200m in a narrow north-west border zone. Seven north-west trending tie-lines were flown at 2.5km line spacing.

Area C) Wolvey Villa Farm, near Hinkley (6.25km^2). At this site seepage from shallow lagoons filled with industrial waste has created a well-documented contaminant plume in a shallow and thin sandy aquifer.

This small block was flown at three clearances (40m, 60m and 92m) with north-south flight lines and three east-west tie lines. Flight line spacing was 50m for the two lower level surveys and 100m for the high level survey. The reason for flying at three different heights was to enable the comparison between the actual and theoretical response attenuation, primarily for the EM data.

Area D) Langar (6km^2). Here there occur two landfill sites occupying worked-out Hydraulic Limestone quarries. There is no known pollution problem.

This area was flown with east-west flight lines at two mean clearances (40m and 92m). Line spacing was 50m with three north-south tie-lines.

Area E) The Vale of Belvoir 5km radiometric calibration range. Here three parallel lines 1.5km separate were flown at 4 different heights (40m, 91m, 152m and 244m). Monitoring of the radiometric background at these various heights was achieved by overflights of Rutland Water. The results obtained here are not considered further in this report.

4. SUMMARY OF RESULTS

4.1. Area A East of Shirebrook

Figure 4.1 shows the processed regional low frequency EM data obtained from 200m separation flight lines (insufficient coverage to adequately resolve domestic scale landfills). The results indicate that highly conductive zones are associated with all four spoil tips. A fifth related zone is identified as waste ground on the map. Other extensive zones of high conductivity are associated with a variety of recreational and industrial settings as indicated in Figure 4.1.

The results of more detailed survey (50m flight line separation) have revealed a plethora of anomalies. The most significant features remain the behaviour of conductive zones in the vicinity of the spoil tips. We hypothesise that the tips have acted as ‘sources’ for conductive leachate through several decades. The resistivity images appear to provide information on the preferential subsurface migration pathways although this remains only a hypothesis.

Figure 4.2 shows the detailed results obtained in the vicinity of Welbeck Colliery within a 3x3km area. The resistivity information is shown at shallow and deeper subsurface levels together with an insert of the topographic relief. The Welbeck spoil tip exists on the southern slope of a ridge and a conductive zone is evident below the Welbeck colliery village and in the valley system to the south. It should be noted that the anomalies exist *below* the river and surface drainage features. The zone appears to connect with the next spoil tip (North of Warsop Vale mine) just visible in the south-west corner. The results shown also illustrate one of the key problems facing the interpretation of the new data. In addition to the colliery/spoil feature, a major N-S linear conductive zone is observed that appears to ‘pool’ below the village of Cuckney in the next valley to the north. The linear feature shows an obvious correlation with the main N-S road through the area, however the source of the anomaly, and why it should pool to the north, is not self-evident. The relationships between many of the at-surface and near-surface installations (e.g. roads and pipelines), typical of populated environments, and the geophysical responses observed remain to be fully investigated by ground-truth surveys.

The remarkable detail of the results in the Shirebrook area (50m separation flight lines) require careful appraisal of location information on the ground. Both the domestic landfill targets exist as conductive anomalies. A major plume is associated with the landfill near Warsop. The second domestic land-fill is defined primarily in the shallow data set (inorganic components are vertically confined) but has a significant and well-defined lateral extension (see Figure 4.3).

The radiometric data are summarised in Figure 4.4. The four colliery spoil tips all stand out clearly as areas of relatively high K, U and Th. This is most probably a reflection of the strong radiometric contrast between the predominantly shaley Coal Measures spoil and the sandstone or dolomitic limestone on which the tips are sited. The extent of the spoil tips, as indicated by the radiometric data, does not always coincide exactly with the mapped boundaries on OS 1: 50k or 1: 25k maps. This suggests that, in the absence of up-to-date maps, or where a feather edge of spoil extends beyond the mapped boundary, the radiometric data may be used to accurately define the current extent of the spoil. The relationship between the tips and areas of conductive groundwater shown by the EM data can then be examined more closely. Lower count rate areas on the Edwinstowe tips indicate flooded portions of the tips.

The domestic land fills are not readily identifiable on the regional scale Shirebrook radiometric data.

The radiometric data show clearly the K-dominance of the major sandstone units, the Nottingham Castle Formation and parts of the Lenton Sandstone Formation. In contrast the lower part of the Lenton Sandstone and the older Permian rocks are relatively rich in U and Th but depleted in K. The major alluvium-filled valleys, especially that of the River Meden, are low K and relatively high U (and Th) features.

The radiometric ternary image of Figure 4.4 shows a number of intermediate K and Th features (identified by a yellowish hue) that stand out on the sandstone. These may relate to drift features not depicted on the Ollerton 1: 50k geological map. Forested areas are also clearly delineated as low activity areas (identified by dark hues), superimposed primarily on the Nottingham Castle Formation.

The regional north-south total magnetic field gradient (Figure 4.4) reflects the distribution of Palaeozoic granodiorite and/or folded Carboniferous volcanics at depth. There are strong dipolar anomalies apparently associated with the mapped colliery spoil heaps but when examined in detail these are seen to be compound features reflecting neighbouring metallic constructions (pit-head gear, extensive metal roofing etc). Neither of the landfill sites is characterised by a discrete magnetic anomaly. Linear anomalies reflect power lines and railways etc.

4.2. Area B The Trent Valley

The sand and gravel pit targets in the Trent Valley area are associated with conductive anomalies (Figure 4.5). The present day working boundaries need to be defined more accurately in order to establish the lateral migration of conductive components implied by the results. Localised zones with higher conductivities than the gravel pits are apparent throughout the valley floor. Two large-scale zones of high conductivity exist on the southern margin of the river (Figure 4.6), on a topographic high. The first is associated with agricultural land to the south of the village of Kneeton while the second is framed by the outline of the military airfield of Syerston.

The fly ash filled former sand and gravel workings appear to be associated with higher total count rates (high in K, U and Th) coincident with the conductive anomalies seen in the EM data (Figure 4.6). Areas of flooded gravel workings are clearly distinguished by their lower count rates in all radiometric channels. It seems probable that degrees of waterlogging of the ground can be distinguished by the different shades of blue on the radiometric plots in Figure 4.6.

There is a good deal of geological information in the radiometric data. Different types of alluvium can be seen, the most prominent feature being a presumed oxbow in the centre of the area with higher K, U and Th. This most probably reflects finer grained (muddy) sediments within a region of predominantly sands and gravels with lower radiometric values. There are clear distinctions between the solid geology north and south of the valley: the Gunthorpe and Radcliffe Formations (to the north) show higher values, particularly for K and Th, than the Edwalton Formation south of the river. This is in accord with observations of natural gamma borehole logging of these formations. The siltstone bands ('Skerries') within these formations can also be picked out as paler regions on the ternary image. These are also indicated as zones of higher conductivity on the EM plots.

Again, the regional total magnetic field gradient probably reflects the distribution of deep Carboniferous volcanics. The fly-ash filled sand and gravel pit targets are not characterised by discrete magnetic anomalies.

4.3. Area C Wolvey Villa Farm

The EM results obtained at this site are highly detailed and reveal subtle features of the Quaternary geology. The target in this area consists of a former waste lagoon hydraulically connected to a shallow sand aquifer between 3 and 12 m thick. The plume contains both organic and inorganic constituents. Limited BGS surface surveys suggest the conductive anomaly is largely confined to the upper 7.5 m in the vicinity of the former lagoon. The target did not provide any significant response in the low altitude data and it is assumed that the plume is too confined (vertically) and at too shallow a depth to generate an anomaly at the frequencies employed in the airborne survey. Elsewhere several highly conductive zones are defined by the data. The zones do not correlate with geology and are located on agricultural land (Figure 4.7).

The target here occupies a low total count area (but with fairly high K) and does not have a distinctive radiometric signature (Figure 4.8). The lowest total count areas represent saturated zones, in the northern part of the area, and a wood in the south west corner. The north west corner of the area displays generally lower values. This broadly correlates with a change in the drift lying on the Mercia Mudstone Group. The lack of a close match with the different drift types identified on the geological map suggests the possibility that the radiometric division noted above may reflect sub-divisions of the Mercia Mudstone Group which are not identified on the 1: 50k geological map.

The regional SW-NE total magnetic field gradient possibly reflects vertical displacement of the Caldecote Volcanic Formation of the pre-Cambrian Charnian Supergroup (upthrown to the SW) along the NW striking Polesworth Fault (as indicated on the 1:50K geological map (Sheet 169: Coventry) (Figure 4.8). All the isolated high-amplitude features can be correlated with mapped farm buildings etc (including Wolvey Villa farm and its environs).

4.4. Area D Langar

The broad trends in the resistivity distribution obtained from the Langar survey reflect transitions in the geological sequence across the area (Figures 4.9 and 4.10). The two landfill targets here are located in a conductive zone of enhanced clay content that forms a trend across the survey area. The first is a large working domestic landfill site while the second is a former capped waste site that ceased operation in the 1970's. It is far easier to resolve and trace conductive zones in a geologically resistive environment (e.g. the Shirebrook area).

Despite the limited resistivity contrasts at Langar, the two land-fill targets appear as zones of enhanced conductivity and are compact and localised (no plumes are apparent). Two other, equally conductive, zones are associated with works areas.

The landfill sites are clearly seen as low radiometric areas (Figure 4.10), particularly where flooded. The major features relate to the geology. The Mercia Mudstone Group and overlying alluvium form a higher radiometric zone in the north west corner. To the south east of this is the basal Barnstone Member of the Lias; the interbedded limestones and mudstones of this unit form a distinctly lower radiometric feature. Further to the south east and south, a predominantly mudstone member shows higher count rates, but does not reach the levels of the Mercia Mudstone Group.

There are a number of man-made features also apparent in this area. The most notable (at 473750, 335200) appears to be related to stock piles of raw materials within the Barnstone cement works site. This exhibits above background Th and U, but low K. A similar feature (474000, 334200) is probably caused by foundation material for an old runway at Langar airfield.

Figure 4.10 includes a comparison of the raw- and manually de-cultured total magnetic field images. The manual de-culturing process involves the recognition of possible cultural sources on either OS maps or survey flight video film and the excision (by minimum curvature interpolation) from the observed aeromagnetic profile of any coincident anomaly. At least two of the main dipolar anomalies (centred at 474000 335000 and 473400 334600) had no visible expression on the OS maps and we concluded that they may reflect Carboniferous volcanics (that had adversely affected the nearby mining process at the Asfordby Coal Mine). However, numerical modelling suggested a shallow source for these features and subsequent field investigations indicated that the anomalies are due to, respectively, the much extended landfill operations (than shown on the OS map) and a capped landfill completed during the early 1970’s.

The regional magnetic field at Langar, a broad N-S striking ridge, probably reflects folded Carboniferous volcanics at depth.

5. CONCLUSIONS

The EM data are particularly encouraging and have identified anomalies which may relate to subsurface pollution. The data have identified conductive zones both on the ‘local’ scale (i.e. possibly related to domestic landfills) through to regional scale features up to many kilometres in length. The information obtained in relation to spoil tip drainage is of particular note. The data have provided a wealth of information on ‘point source’ anomalies (requiring ground truth information) and diffuse sources that may be connected with nitrate movement in response to groundwater extraction. At two sites (Trent Valley and Langar) the EM technique appears to have met the challenge of detecting conductive targets in a conductive host. Many other features of the data will take time to assess.

The radiometric data indicate features of land fill and colliery spoil sites and allow comparison to be made rapidly with the EM data to define any possible lateral spread of contaminant plumes beyond the site itself. They can also be used to map site-specific contamination where radioactive elements are present.

The radiometric data also give direct indications of solid and drift geology and soil type, providing additional detail to that shown on geological maps (soil maps are not available for much of the UK).

The magnetic data have suggested the presence of appreciable volumes of metallic debris in the Langar landfill sites. This may be significant in terms of the leachates derived and the compaction (through time) of the contrasting fill materials. Compared with the EM and radiometric techniques, the applications of magnetics in environmental studies are rather limited, but such data are worthwhile collecting in view of the marginal additional costs involved.

6. RECOMMENDATIONS

The trial survey data were acquired as a speculative data set and, as far as we are aware, they include the first high resolution airborne electromagnetic surveys to address specific environmental issues in the U.K. The data obtained are of excellent quality and the results, when examined in detail, have highlighted a number of issues. It is suggested that the data be thoroughly assessed before further airborne trials are conducted.

The EM data have revealed a range of anomalies that require calibration. The exercise is non-trivial since information on the geochemistry of the pore fluids and their distribution is ultimately required. In order to make the problem tractable, it is suggested that a generic approach be adopted. Specific anomalies associated with:

a) spoil tip and/or minerals drainage
b) working domestic landfill
c) industrial landfill (gravel beds/fly ash in the Trent valley)
d) water pipeline route
e) urban anomalies

would seem appropriate generic targets. The two main issues are anomaly source distributions (vertical and lateral) and associated geochemical pore fluid distributions (vertical). The calibrations would therefore require:

- site-specific information to establish appropriate historical and current land-use parameters

- ground geophysical surveys

- borehole geochemical sampling

In addition to the above, the BGS needs to develop and put in place processing and interpretation algorithms for airborne EM. The data presented here have been processed by GTK to a certain level. The level achieved has known limitations and may lead to pitfalls when applied to a complex and three dimensional subsurface. A valid interpretational capability should be investigated in tandem with the ground calibrations of the data.

Features revealed in the radiometric data also require ground investigation. The apparent association of higher count rates with fly-ash filled gravel workings in the Trent valley and relatively low radiometric responses over the Langar landfills require further assessment. The precise relationships between higher K, U and Th values in the airborne data and colliery spoil in the Shirebrook data needs to be examined. In addition, several radiometric features have been interpreted in relation to solid and drift geology. All such aspects should be investigated by ground gamma spectrometry to confirm the initial interpretations.

In terms of follow-up to the aeromagnetic data, we recommend performing several surface traverses over the closed landfill site at Langar. It is anticipated that these will reveal several high amplitude isolated anomalies reflecting discrete magnetic items in the fill. These data, when continued upwards by numerical procedures, should match the observed airborne anomaly.

7. ACKNOWLEDGEMENTS

We were particularly impressed by the dedication and professionalism shown by Mrs Maija Kurimo and her GTK team throughout the survey period. We also acknowledge with thanks the close co-operation during the flying operations of Mr Leatherland (General Manager) and his staff at Truman Aviation Limited, Tollerton Airport. Messrs Rob Metcalfe and David Beaven of the General Aviation Department of the Civil Aviation Authority provided much useful guidance on the airborne operations. We are grateful to the Department of the Environment, Transport and the Regions and the Environment Agency for their co-sponsorship of these trials. This report is published with the permission of the Director, British Geological Survey.

APPENDIX A : EQUIPMENT

Electromagnetics:

Model GSF-95, dual frequency unit with vertical coplanar coil configuration (wing-tip mounted) and coil separation of 21.36 m.

- frequencies: 3 125 Hz 14 368 Hz
- sensitivity: 1 ppm
- noise (STD):
  3 125 Hz frequency: 3 ppm quadrature and 4 ppm in-phase components
  14 368 Hz frequency: 8 ppm in both quadrature and in-phase components
- measurement range: 0 - 50 000 ppm
- cycling rate: 4 Hz (equivalent to about 12.5 meters of traverse)

Gamma-ray spectrometer :

Exploranium GR-820/3:

- 2 sets of NaI crystals, each containing 4 downward and 1 upward looking crystal (42 L in total)
- energy range 0.01 - 3.0 MeV, with 256 channels (each of width 12 keV) and cosmic channel measuring energies greater than 3.0 MeV.
- cycling rate 1 Hz (equivalent to about 50 m of traverse)

Magnetometers:

Scintrex MAC-3 Caesium vapour magnetometers (with two wing-tip sensors):
- automatic compensating unit (RMS AADCII)
- resolution: 0.001 nT
- sensitivity:0.005nT
- cycling rate: 10 Hz (equivalent to about 5 m of traverse)
- sensor separation: 21.36 m
- maximum gradient tolerance: 50 000 nT/m
- measuring range 20 000 - 100 000 nT
- noise density 0.0006 nT/sqrt Hz

Base station magnetometer (at Tollerton Airport):

Scintrex CS-2 sensor + MEP-710 base station processor

Navigation and flight path recovery:

Ashtech GG-24, 24 channel GPS+GLONASS receiver. Accuracy 7 m/16 m (50%/95%)
- real time DGPS with RDS,
- visual navigation with maps and left-right navigation indicator (GPS)
- Collins radar altimeter with resolution of 0.1 m, accuracy 0.5 m and maximum cycling rate 10 Hz

Base station GPS (at Tollerton Airport):

Ashtech Ranger GPS receiver, 12 channels, for DGPS correction. Accuracy after correction +/-1 m (lateral)

Auxiliary equipment:
- barometer
- thermometer
- accelerometer
- spherics monitor
- flight path video

Data logging:

- all data was recorded on a PC in flight and subsequently copied to Iomega Zip disk.
- there is provision for analog monitoring of all observations in flight

All equipment listed above is owned by the Geological Survey of Finland.

Aircraft:

DeHavilland (Canada) DHC-6/300 Twin Otter (registration: OH-KOG). A STOL fixed-wing, twin engined aircraft built in Canada in 1979.
Speed during data acquisition: 160 - 220 km/h
Rate of climb: 7.5 m/sec

This aircraft is owned and maintained by Finnair and is operated by Malmilento Oy, a subsidiary of Finnair.

APPENDIX B : CALIBRATION AND DATA PROCESSING

Electromagnetics:

The EM system was calibrated initially in Finland by flying over the sea at different altitudes. The conductivities and temperatures at different depths were measured simultaneously and the EM data has been corrected using the derived calibration coefficients. For the primary levelling the zero level was measured before and after each sortie at an altitude of 300 m. A later processing stage involves the conversion of observed coupling ratios to apparent resistivities (assuming a half space model). This conversion corrects for the effect of variations of ground clearance.

Gamma-ray spectrometrics:

Dead time, aircraft background, cosmic background, temperature, air pressure, radon and stripping corrections were made according to IAEA recommendations. The radiometric data have been downward continued to a uniform 30 m clearance and the airborne measurements have then been converted to ground concentrations using calibration parameters observed over a test range in Finland prior to the survey.

Magnetometrics:

The constants for the automatic compensation of aircraft pitch, roll and yaw movements were obtained by overflying a quiet magnetic zone to the north-east of Nottingham. The observed figure of merit was 2.0 nT for the left sensor and 3.1 nT for the right sensor. Values below 5 nT are regarded as acceptable. The diurnal variation was measured at the Tollerton Airport base station and used to correct the observed in-flight data.

Navigation:

Real time navigation along the survey lines was based on GPS and GLONASS, adjusted by RDS signal. In subsequent processing differential base station data was used to derive the coordinates BNG) of each measuring point. The final coordinate accuracy is estimated at better than 1 m (lateral).

Quality control:

The data were monitored throughout acquisition and their acceptability was checked immediately after each flight. At this time the Geosoft Airborne QC package was used to confirm that elevation and flight path were within the specified tolerances. The main processing was completed by GTK during the survey period with final levelling of the data completed in Finland. The final processing included statistical, interactive and tie line levelling.

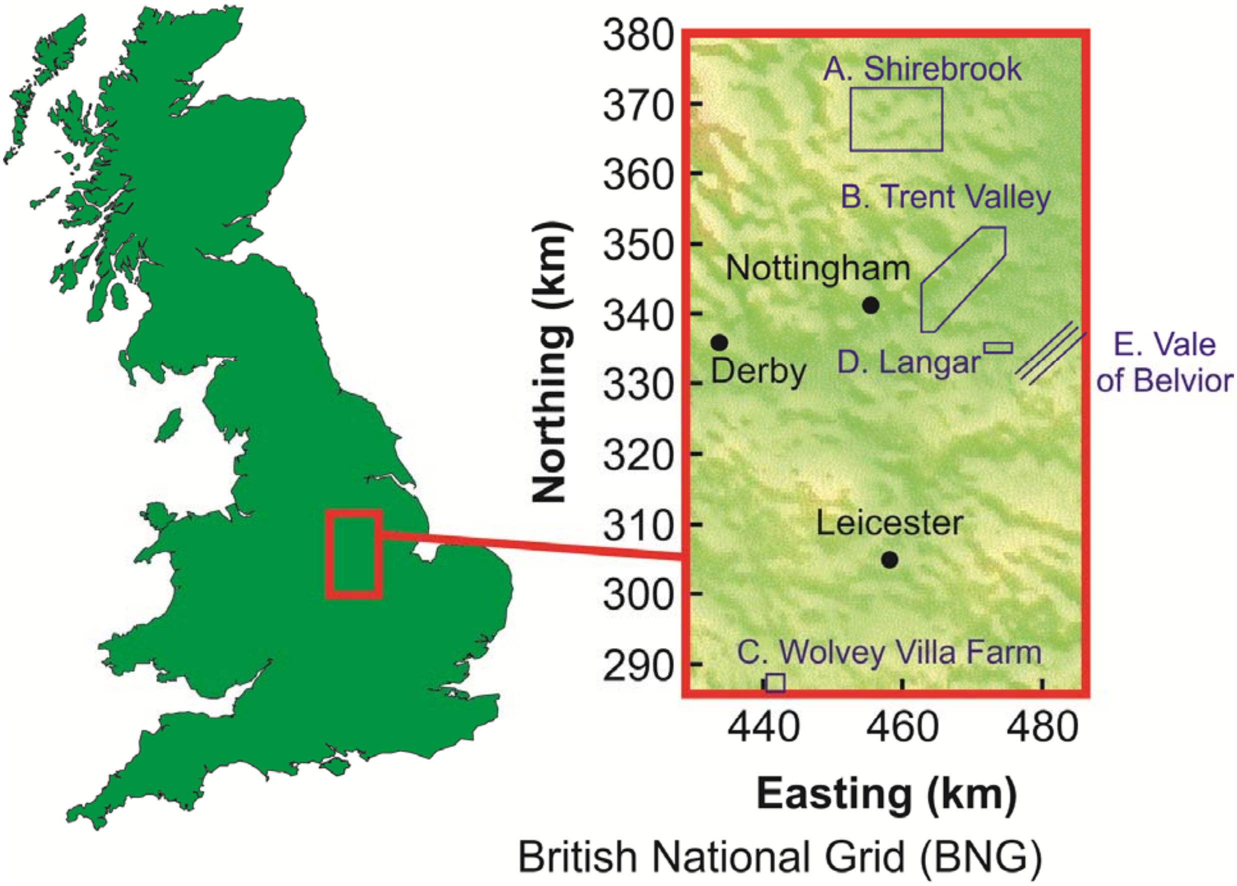


Figure 3.1: BGS/GTK survey areas

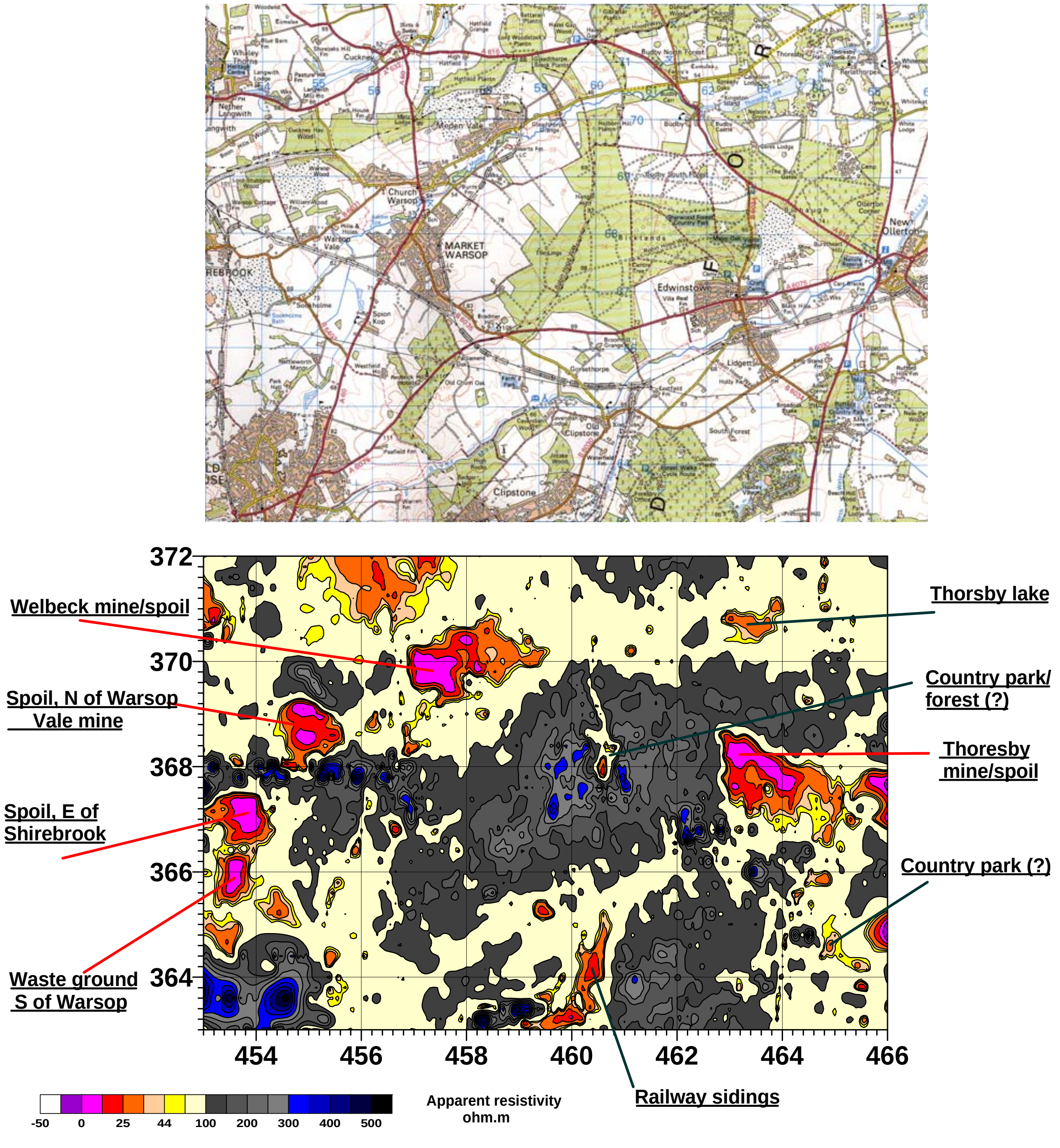


Figure 4.1 **Shirebrook EM**. 13 x 9 km. Low frequency apparent resistivity. 200 m flight lines

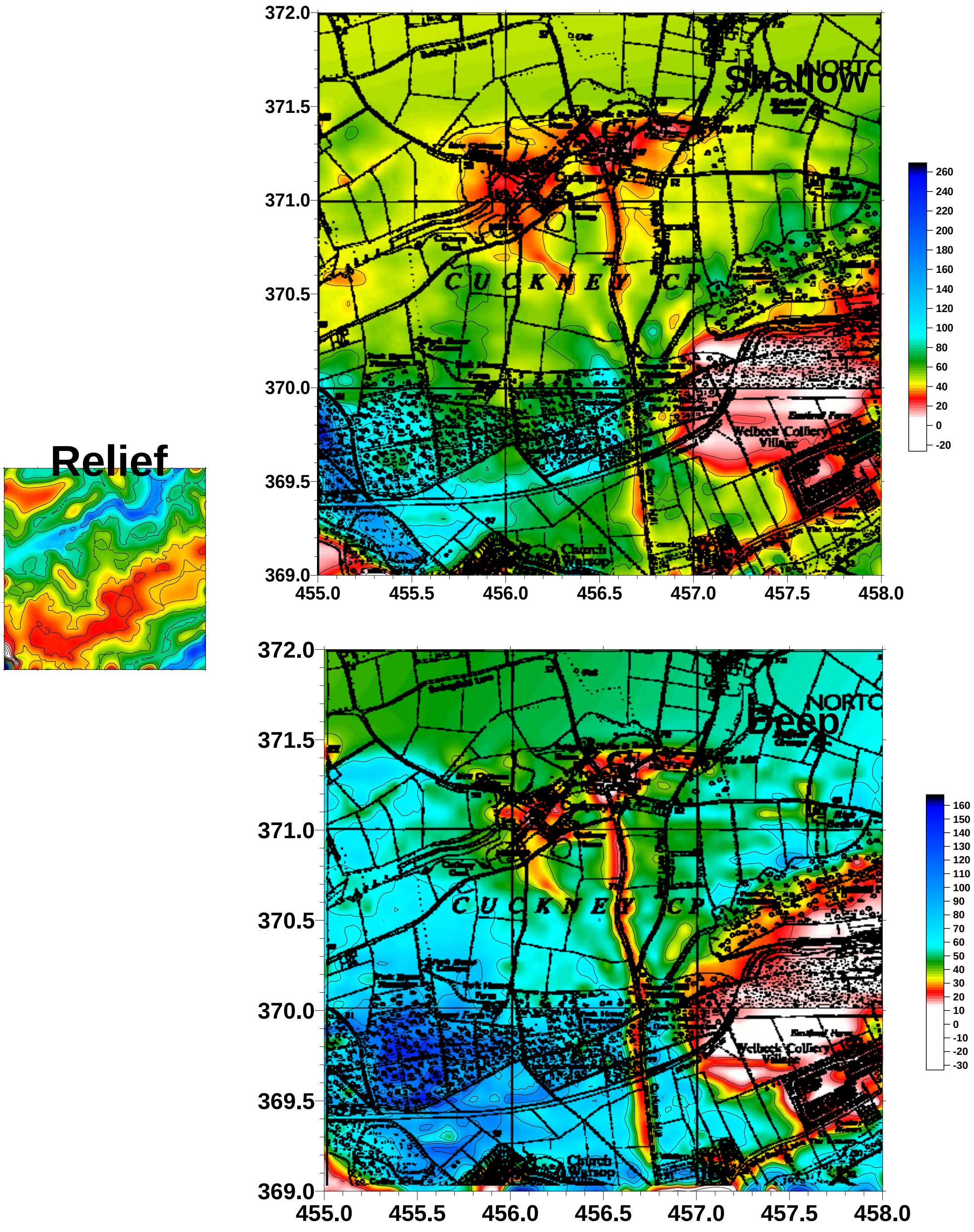


Figure 4.2 **Shirebrook EM**. 3 x 3 km. Shallow/deep resistivities.
50 m flight lines

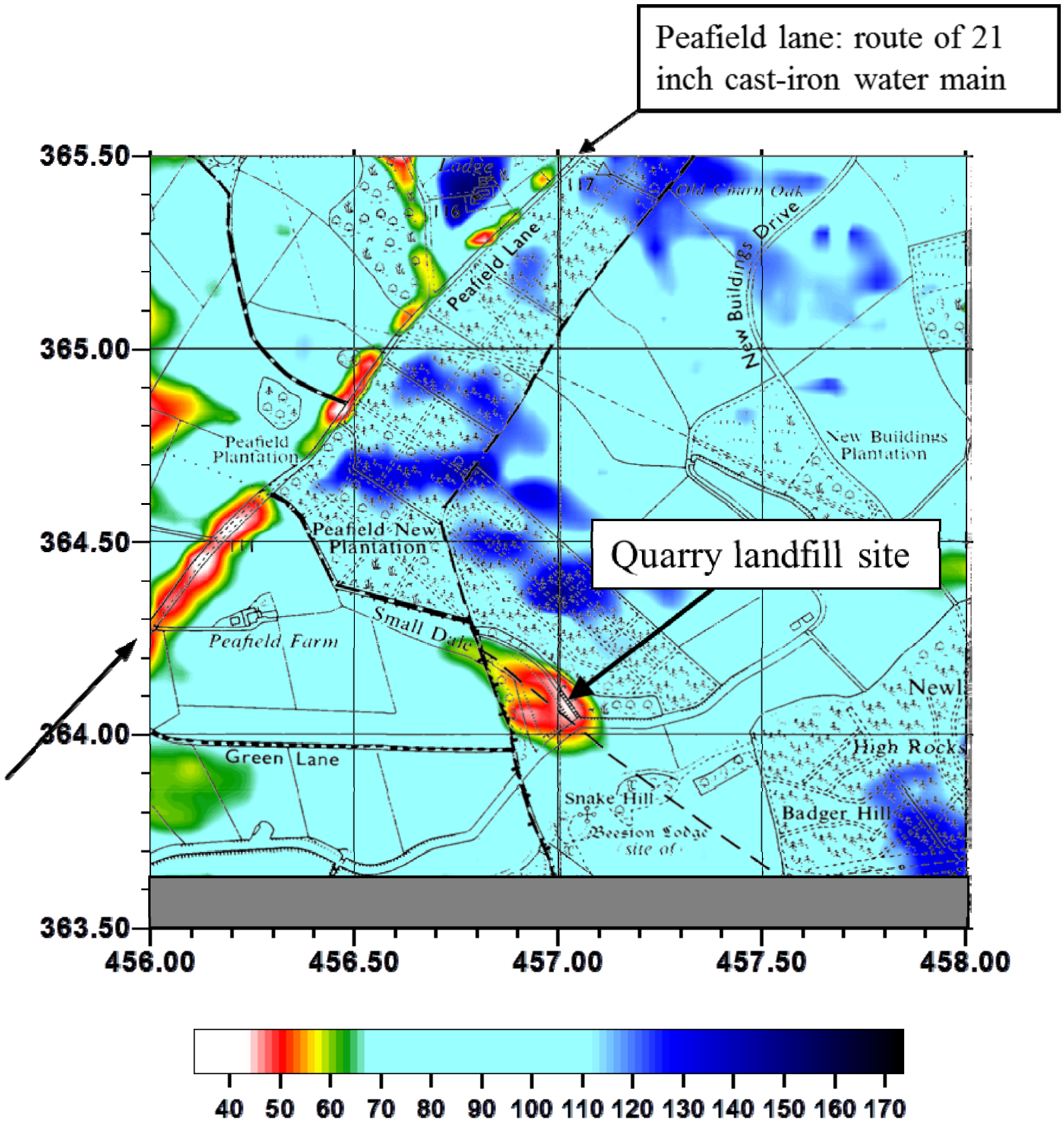
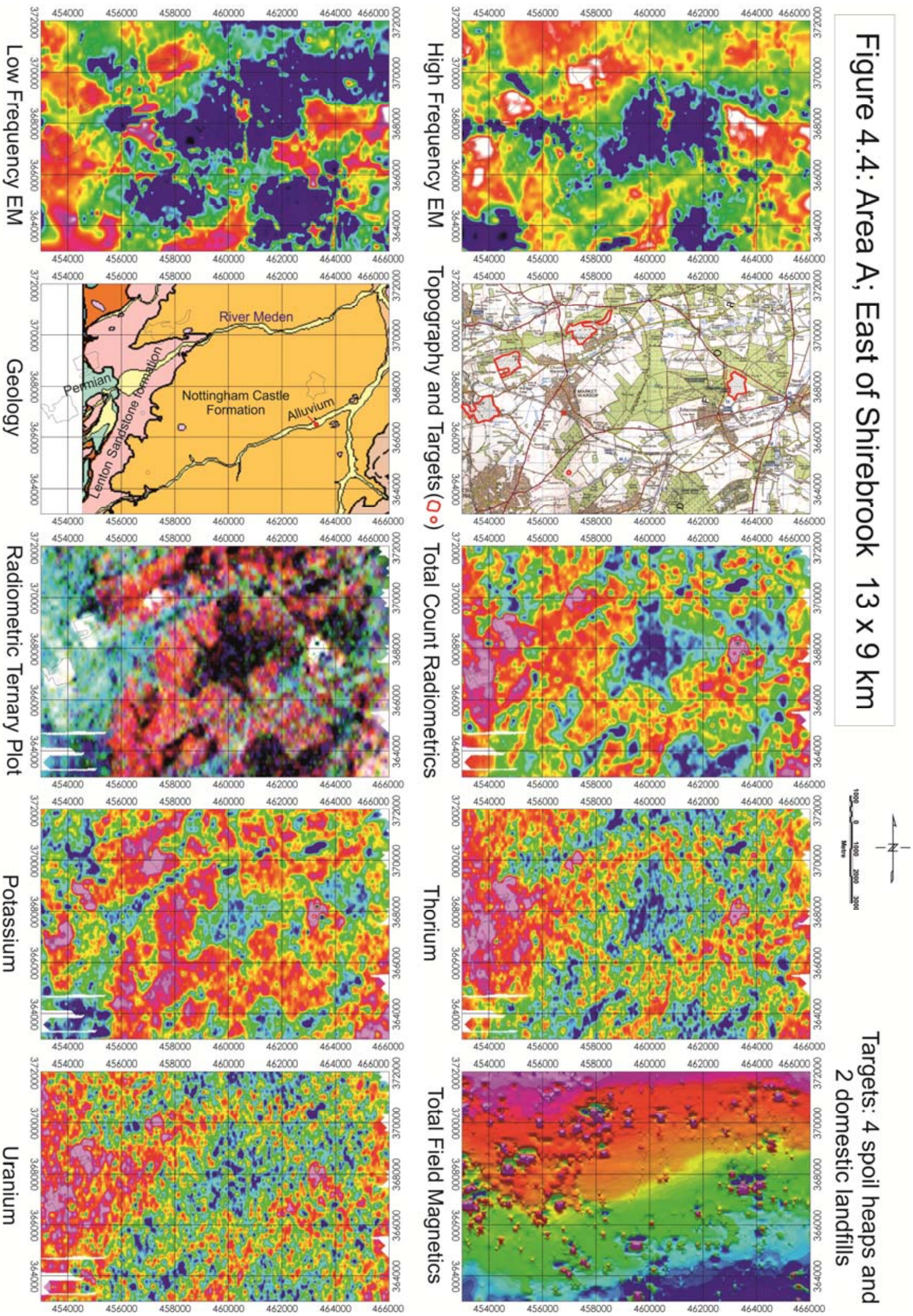


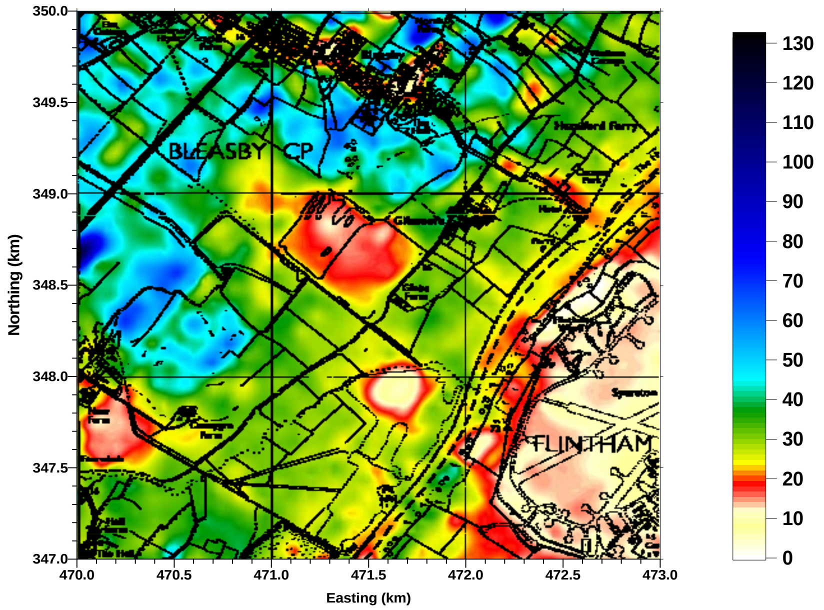
Figure 4.3 **Shirebrook EM**. 2 x 2 km. Shallow resistivity (ohm.m) 50 m flight lines

Figure 4.4: Area A; East of Shirebrook 13 x 9 km

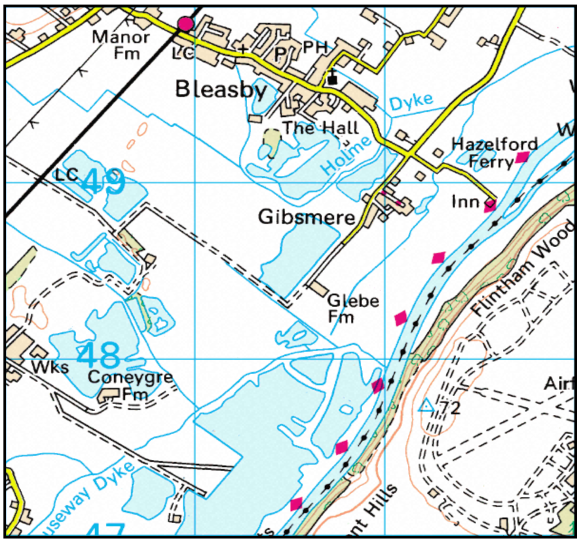


Warm colours are high values, cold colours are low values (except Ternary, Topography and Geology plots)
Topography based on the 1995 Ordnance Survey 1:50 000 Landranger Series map with the permission of The Controller of Her Majesty's Stationary Office Crown Copyright. Ordnance Survey licence number GD272191/1995.

Altitude is 90 m. Targets are gravel pits, some containing power station fly ash & domestic waste. Confirmation of current land/pit useage not yet available. Complex patterns with 25k and 50 k OS maps providing different information. At surface features (power line, railway, Trent river) do not provide responses.



Backdrop is 25k OS map



50k OS map showing gravel pits, all previously flooded

Figure 4.5 **Trent Valley EM**. 3 x 3 km detail Deep resistivity (ohm.m) 100 m flight lines

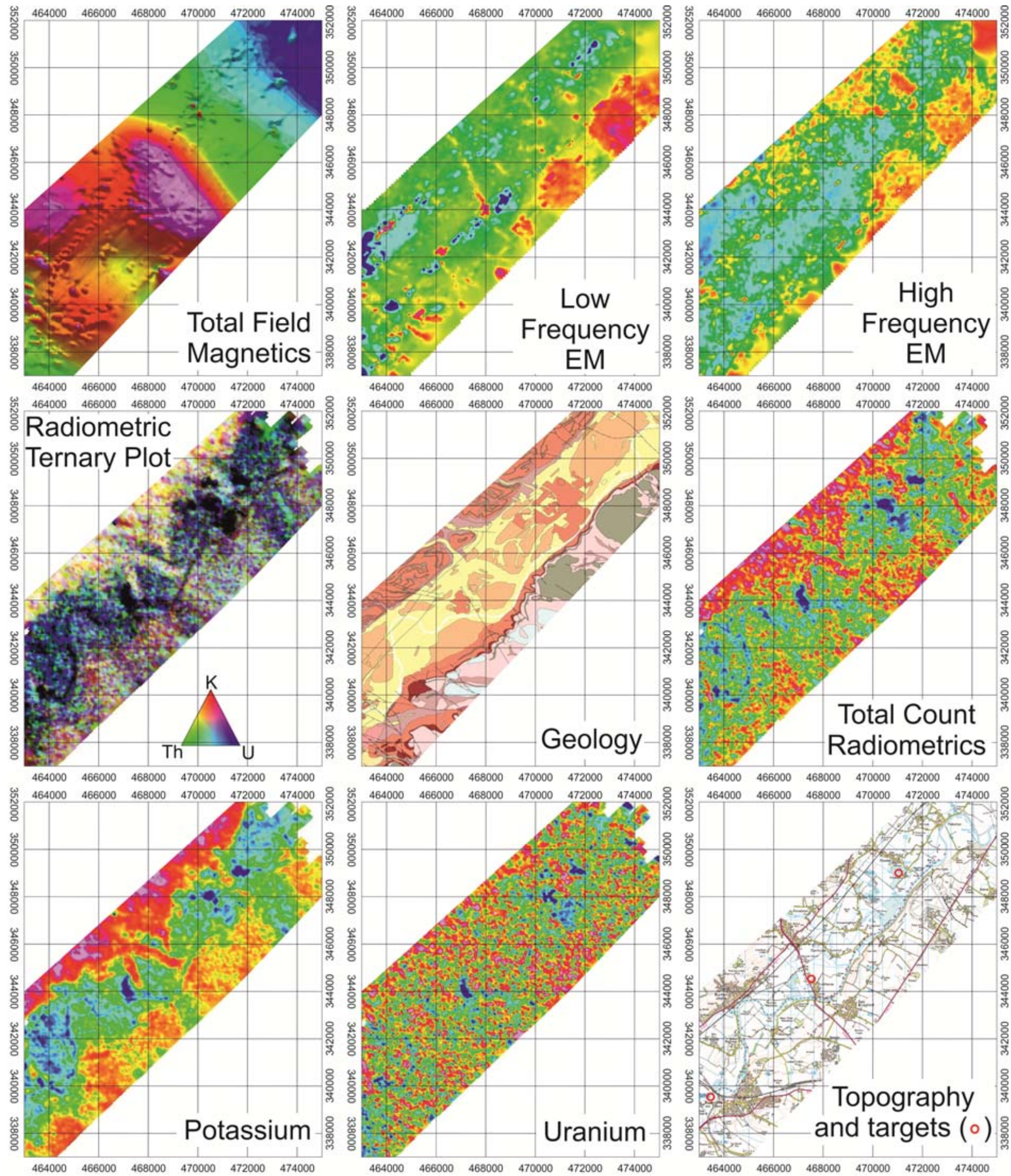


Figure 4.6: Area B; Trent Valley

6 x 18.5 km

Targets: 3 former sand/gravel pits infilled with fly ash

Warm colours are high values, cold colours are low values (except Ternary, Topography and Geology plots)

Topography based on the 1996 Ordnance Survey 1:50 000 Landranger Series map with the permission of The Controller of Her Majesty's Stationary

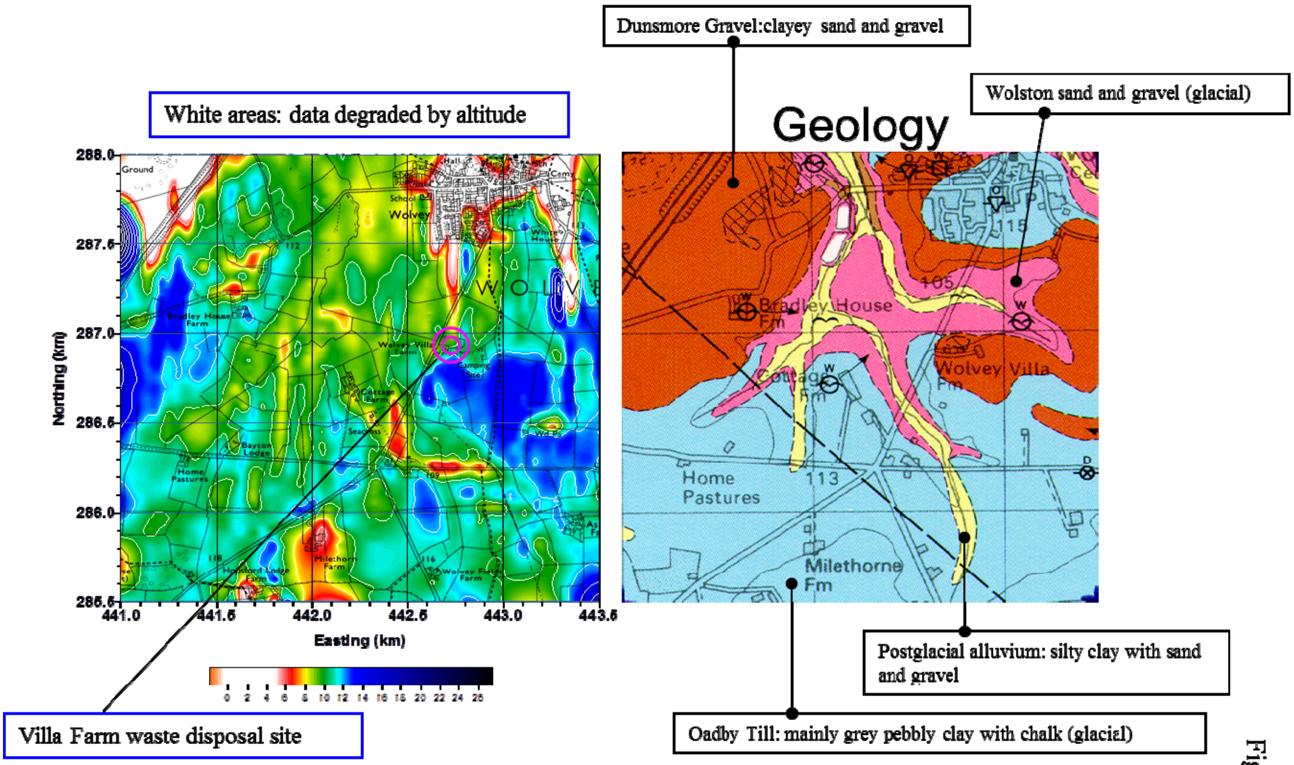


Figure 4.7 **Wolvey EM.** 2.5 x 2.5 km. Deep resistivity (ohm.m). 50 m flight lines

Figure 4.7

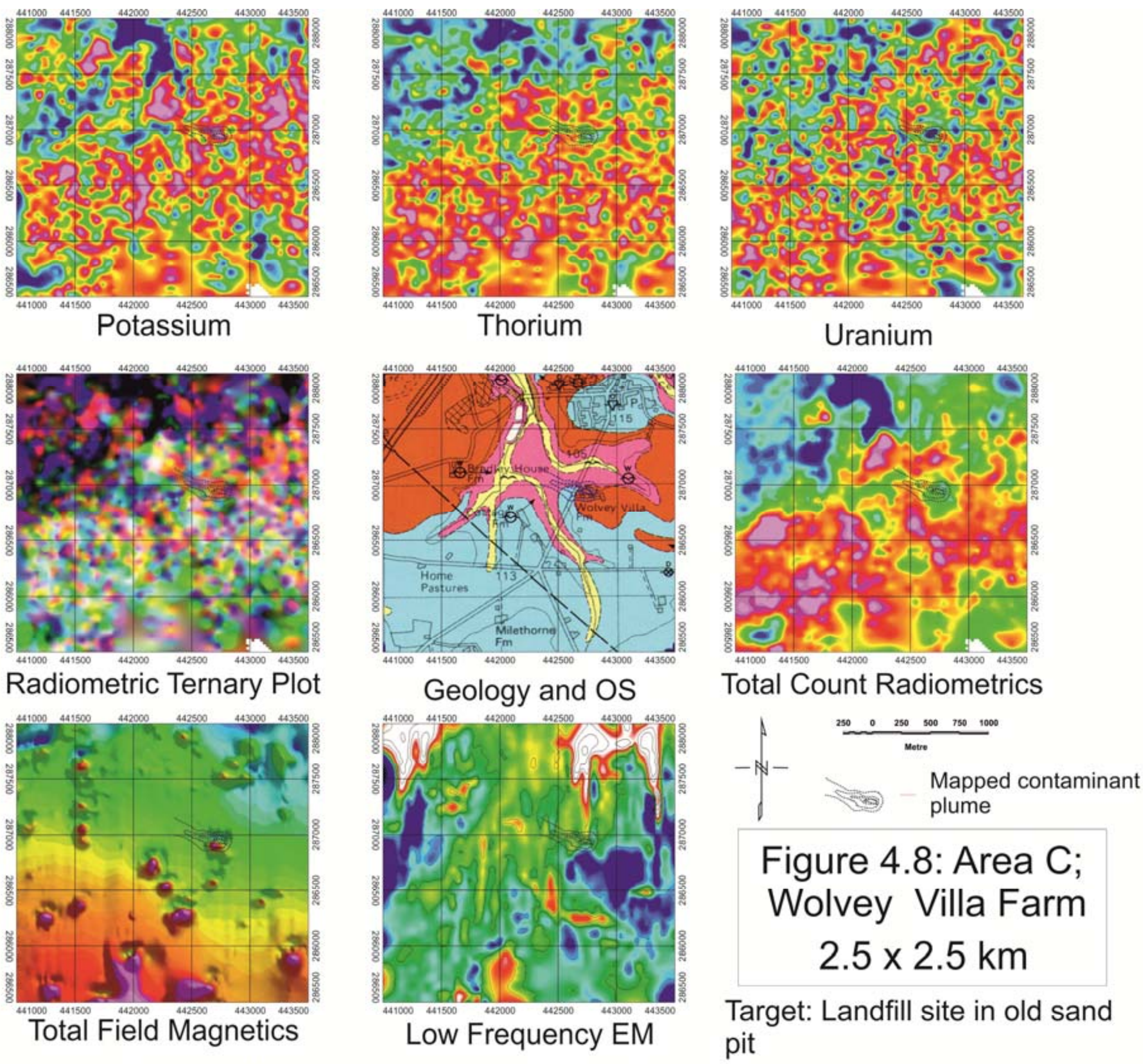


Figure 4.8: Area C; Wolvey Villa Farm 2.5 x 2.5 km

Warm colours are high values, cold colours are low values (except Ternary and Geology plots)

Topography based on the 1994 Ordnance Survey 1:50 000 Landranger Series map with the permission of The Controller of Her Majesty's Stationary

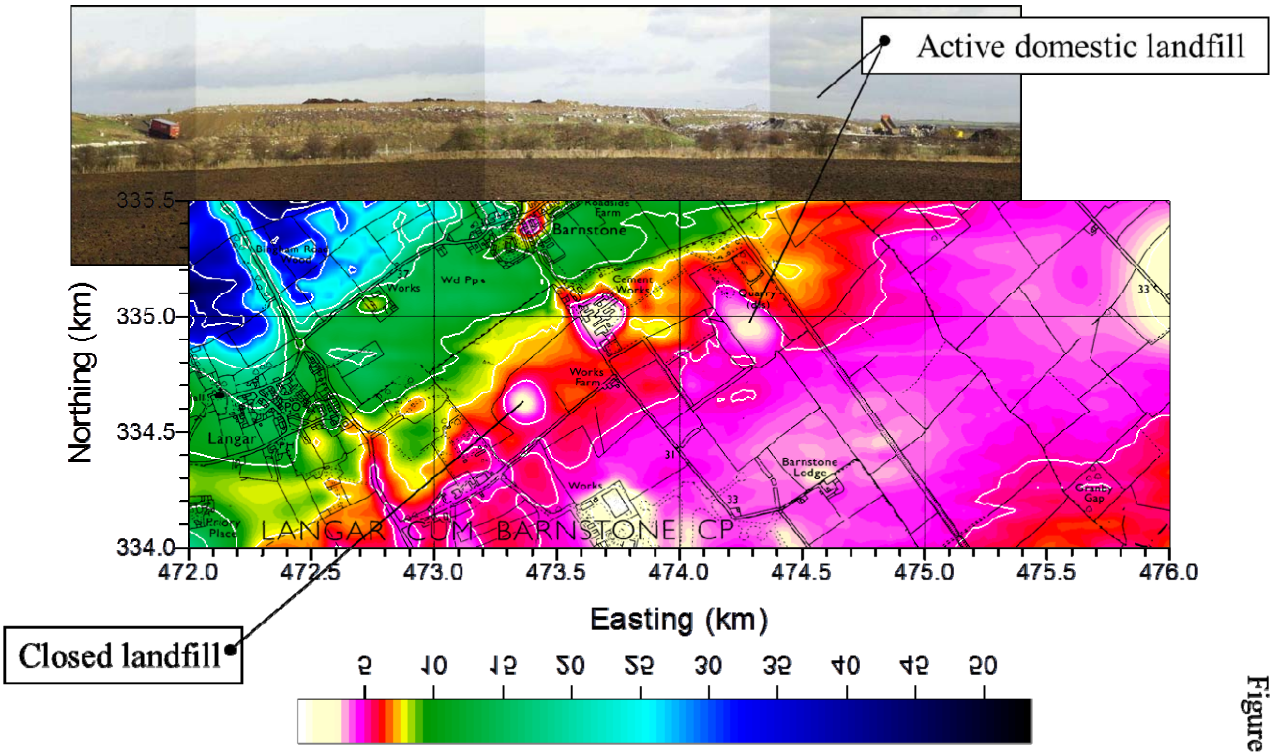


Figure 4.9	**Langar EM.** 4 x 1.5 km. Deep resistivity (ohm.m). 50 m flight lines

Figure 4.9

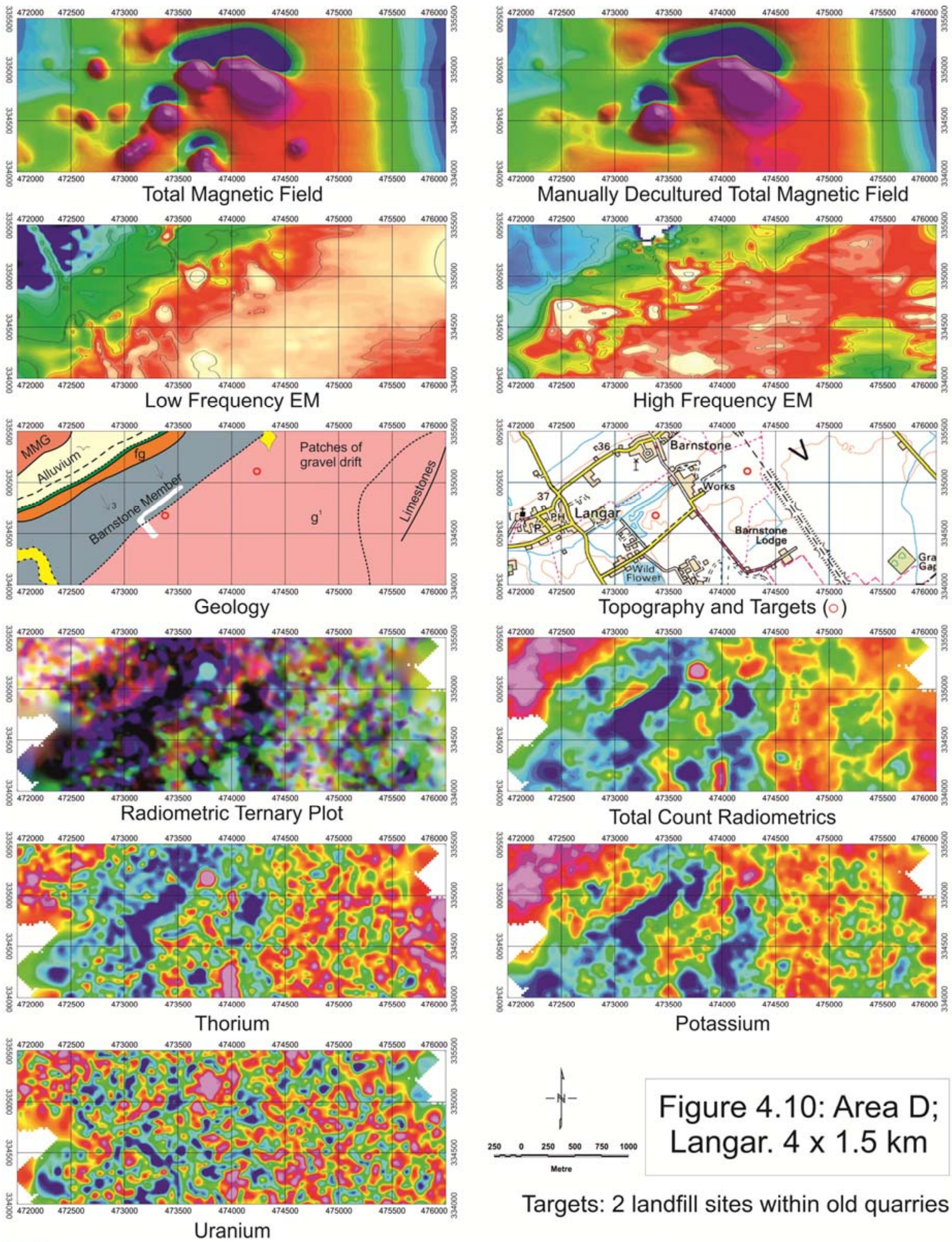


Figure 4.10: Area D; Langar. 4 x 1.5 km

Targets: 2 landfill sites within old quarries

Warm colours are high values, cold colours are low values (except Ternary and Geology plots)

Topography based on the 1996 Ordnance Survey 1:50 000 Landranger Series map with the permission of The Controller of Her Majesty's Stationary