Natural Environment Research Council

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TECHNICAL REPORT WK/00/03

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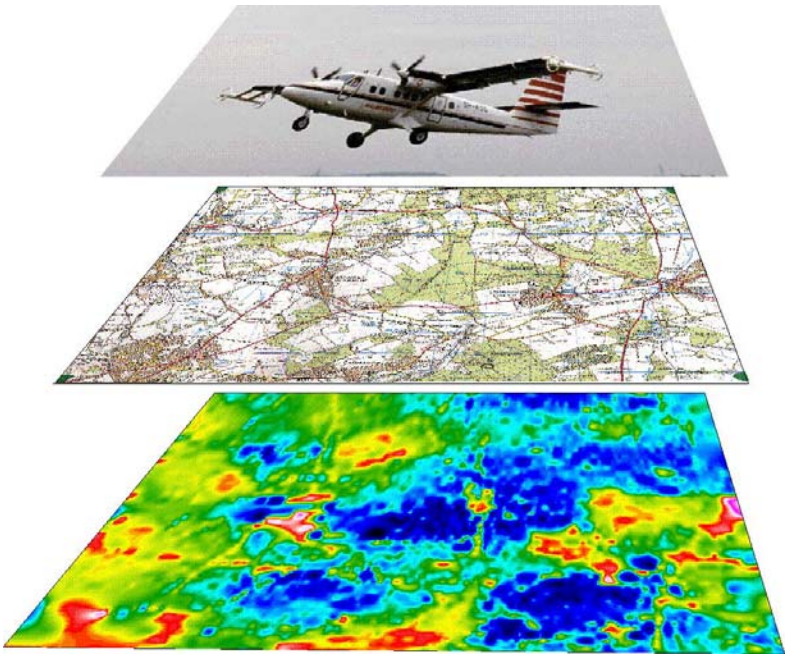
Trial airborne environmental and geological survey: an initial appraisal of relevance to land-use

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

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Trial airborne environmental and geological survey: an initial appraisal of relevance to land-use

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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 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.

This report is an initial consideration of the multi-parameter airborne geophysical data in relation to land-use issues. A variety of earth science information for planning and development already exists. The baseline information is reviewed according to scale and resolution. It is noted that the airborne data is of a new type with regard to both information content and spatial continuity. The specific characteristics and advantages of the airborne geophysical data are emphasised.

The trial survey data were obtained at high resolution and a large number of anomalous responses have been observed. Since the information is provided at a local-scale a number of issues concerning the nature of the responses observed and the underlying causes have been raised. It will be necessary to improve our understanding of the data before an unambiguous discussion of their specific relevance to land-use issues can proceed.

In advance of detailed interpretations of the trial data, the data are presented and discussed in relation to their potential relevance to five land-use issues: (i) Waste planning/Planning and pollution control, (ii) Minerals Planning, (iii) Water supply and water resource protection/Coastal zone management, (iv) Urban regeneration/Peripheral development and new communities and (v) Agriculture and Forestry.

It is acknowledged that there are differences between the information needed for planning the use of land, and information which is required for monitoring environmental strategies. The geophysical data appear to have greatest relevance to the latter requirement. Recommendations for ground and subsurface calibration of the data are made.

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1. INTRODUCTION

This report has been prepared by the British Geological Survey (BGS) for the Department of the Environment, Transport and the Regions (DETR). The report is an initial consideration of recently acquired multi-parameter airborne geophysical data in relation to land-use issues.

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 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? The BGS invited the GTK to undertake collaborative trial airborne surveys over a number of diverse sites in the UK. In addition to the electromagnetic (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 electromagnetic survey carried out in the U.K. It should be noted that there are no existing data and confirmed interpretations with which to compare and contrast the trial survey data.

The DETR has played a major role in promoting awareness of environmental geology issues as part of its Minerals, Land Instability and Waste Planning Research Programme. Between 1994 and 1998, the DETR commissioned a number of research projects to demonstrate the importance of environmental geology and the practical use of such Earth Science Information in a range of different planning situations (Reports [1], [2] and [3]).

The background to the discussion are the ‘attributes’ and ‘resolutions’ of existing earth science information and their relevance as discussed in the reference material. The specific characteristics and advantages of the high-resolution airborne geophysical data are emphasised here.

A brief description of the extent of the trial surveys is given first. Scale and resolution issues raised by a consideration of existing baseline information are then discussed. Prior to assessing the potential uses of the data, the nature of the information that was obtained using the three techniques is described and illustrated.

Five key *strategic* issues related to land use are discussed in [4]. They are:

- Sustainable land use
- Environmental appraisal
- Regional development
- Spatial development strategies
- Major development initiatives

All these issues include a need for earth science information in various forms and at an appropriate scale. Prior to release, either into map or database form, earth science information, being complex, is usually made fit-for-purpose. It is pointed out that the geophysical data are essentially raw and require additional inputs and ground-truth information to establish credibility. In advance of full interpretations of the trial results, the

data are presented and discussed in relation to their potential relevance to several land-use issues. The geophysical data appear to have greatest relevance in relation to the monitoring of environmental strategies. Based on the work to date, conclusions are drawn and recommendations are made.

2. THE TRIAL SURVEYS

The four survey areas included in the trials are shown in the location map (Figure 2.1). The survey collected 3324 line kilometres of data and required 31 hours of flying over 5 days. The four areas comprise:

East of Shirebrook (117km^2). The largest survey area encompasses part of the north Nottinghamshire coalfield and contains two active and two former collieries and associated spoil tips. The area also contains at least two domestic landfill sites and is underlain by the important Sherwood Sandstone aquifer.

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

Langar (6km^2). The area contains two landfill sites (one active, one closed) occupying worked-out Hydraulic Limestone quarries. There is no known pollution problem.

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.

Further details of the trial airborne survey and the techniques employed are provided in a companion report [5]. The companion report discusses the four areas, the results obtained and the detection of targets.

It is acknowledged that the current survey areas are clearly a limited basis on which to assess 'whole U.K.' issues of land-use information. However, reference is also made to results obtained from the much more extensive HiRES-1 airborne survey of the English midlands (a collaborative BGS-World Geoscience (UK) Ltd project).

The current airborne survey provided information from three techniques (Electromagnetic, Radiometric and Magnetic). The preliminary processed data were made available to BGS in September 1999.

3. EXISTING BASELINE INFORMATION

A guide to sources of earth science information for planning and development is provided in [2]. When discussing these matters it is important to understand the scale, resolution and nature of the information before assessing its potential use. Report [2] introduces three categories, which allow for the scale of involvement of existing information. The three categories are (1) Strategic level (e.g. national, regional and structure planning; environmental protection), (2) Local level (e.g. development control in local authorities; site selection by developers) and (3) site specific level (e.g. geotechnical and civil engineering; environmental statements). The scale and resolution of the airborne information appears to make it best suited to categories (2) and (3).

An example of a scale issue is now provided in the context of groundwater vulnerability. Report [2] discusses sources of aquifer data including information on groundwater vulnerability and flood risk. Groundwater vulnerability maps are being prepared at a scale of 1:100 000 for the Environment Agency. Sheet 18 of the series covers the groundwater vulnerability of Nottinghamshire. The information provided for the Shirebrook survey area indicates that the aquifer (Sherwood Sandstone) is a highly permeable major aquifer. The soil class is H2 and thus indicates deep permeable coarse textured soils, which readily transmit a wide range of pollutants because of their rapid drainage and low attenuation potential. The vulnerability maps involve an acknowledged compromise between the representation of natural complexity and ease of interpretation. The map legends state ' *The maps only represent conditions at the surface and therefore where the soil and/or underlying formations have been disturbed or removed, for example during mineral extraction, the vulnerability class may have been changed. Hence where there is evidence of disturbance there will be a need to determine groundwater vulnerability using site-specific data.*' The EM data, as discussed later, provide subsurface information that appears to relate to leachates that may originate within individual colliery/spoil zones. It is suggested that such data may be used to assist with the determination of groundwater vulnerability at the site specific scale. This is also the 'scale' at which vulnerability may reach its highest level (it may go unrecorded in the existing baseline information).

A further issue of scale relates to the radiometric survey information and existing baseline information on radon potential as discussed in [2]. The arguments again follow those above, although the context and the agencies differ. It is again suggested that high-resolution airborne data may allow the development of mapped information for users under category (3) e.g. those required to make an environmental statement at the site-specific level.

Two of the techniques (Electromagnetic and Magnetic) have an existing portfolio of surface applications at the site-investigation scale i.e. highly detailed ground investigations at the metre and sub-metre scales to scan sites (e.g. for physical and chemical hazards) in connection with development/redevelopment of land. One of the techniques (magnetic) possesses existing baseline information under categories (1) and (2) however the new information is more sensitive, more accurate and is obtained at a much higher spatial resolution than the existing baseline data. The radiometric technique, which, in the airborne application, provides multi-spectral information on a range of radionuclides, has only limited baseline information (various ad-hoc surveys). The largest and most detailed survey is the HiRES-1 data set across the English Midlands. The information obtained from the EM technique is of a new 'type' and no comparable baseline information exists.

4. THE NATURE OF THE AIRBORNE INFORMATION

The present airborne trials provided data from three techniques. All three techniques provide diagnostic information on geology. The geological component is an attribute that has been discussed extensively in the DETR reviews. It does not seem appropriate to review this well defined range of background material here. The three techniques involve different scales and depths of subsurface assessment and sample very different properties. Here we emphasise the specific environmental attributes of the three techniques:

4.1.The electromagnetic data

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 applications. 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 (i.e. below the first few metres) and relates to concealed bulk resistivities on a vertical scale of tens of metres.

For porous rocks that are either partially saturated (i.e. above the water table) or wholly saturated (i.e. 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. 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.

4.2.The radiometric data

The radiometric data provide information on the radioactive composition of the ground to a depth of about 30cm. The gamma-ray detectors used respond to naturally radioactive potassium and decay products of uranium and thorium, as well as to any man-made isotopes, such as ^{137}Cs. The data can be interpreted in terms of the rock, drift or soil type as well as identifying certain types of minerals and the distribution of radioactive and related contaminants.

4.3.The magnetic data

The magnetic data are processed to highlight anomalies; these are local departures from the regionally uniform earth's magnetic field. Anomalies reflect the presence of contrasting contents of (principally) the accessory mineral magnetite in different rock types, and hence aeromagnetics can be a very sensitive tool of geological mapping. The earth's magnetic field is also distorted locally by certain man-made metallic objects (such as steel frameworks, railway lines and power lines) and these features give rise to so-called cultural anomalies. These are usually considered to be noise (and are excised from the observed data) but in environmental surveys they may assume special significance. The wavelength of the anomaly indicates the source depth, with deep features displaying long wavelengths. In the present work we are interested only in anomalies with wavelengths of less than about 1 km.

In the context of existing information, the main advantages of airborne surveying should be noted:

- Simultaneous acquisition of multi-parameter data sets
- Non-invasive assessment of subsurface properties at hazardous sites
- High spatial resolution. Quasi-continuous sampling along flight lines (observations every 7 to 15 m for electromagnetic/magnetic and 60-70 m for radiometric) and with flight line spacings of 50 to 200 m (user specified).
- Continuous coverage over *all* areas, whether conurbation, landfills, forests etc.

The latter two points allow the data to be translated from the local site scale to the regional scale. Such information can be highly significant when dealing with environmental problems involving 'flow' e.g. from source to sink in both point and diffuse senses. As an example, Figure 4.1 shows EM apparent resistivity results across a 3x3 km area in the vicinity of Welbeck colliery and spoil tip. The issue is one of spoil tip drainage. In one of many possible interpretations, the warm colours (high conductivities) appear to trace flowpaths of enhanced conductivity pore fluids (within the subsurface) from a probable source location (the spoil zone) into other areas. 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.

5. POTENTIAL RELEVANCE TO LAND-USE ISSUES

The trial survey data appear to have potential application across a range of land-use issues as discussed in the DETR reports [1]-[4]. The issues discussed in [4] include:

- Waste planning / Planning and pollution control
- Minerals Planning
- Water supply and water resource protection / Coastal zone management
- Urban regeneration / Peripheral development and new communities
- Agriculture and Forestry

All these issues include a need for earth science information in various forms and at an appropriate scale. Prior to release either into map or database form, earth science information, being complex, is usually made fit-for-purpose.

The trial survey data are raw and were obtained at high resolution. In the case of the EM data, the data are of a new type. Since the information is provided at a local-scale a large number of issues concerning the nature of the responses observed and the underlying causes have been raised. It will be necessary to improve our understanding of the data before a full discussion of their specific relevance to land-use issues can proceed. Such research, which includes ground-truth investigations, forms part of the recommendations of this report.

In advance of detailed interpretations of the trial results, the data are presented and discussed in relation to their potential relevance to the five issues noted above. It is acknowledged that there are differences between the information needed for planning the use of land, and information which is required for monitoring environmental strategies. The geophysical data appear to have greatest relevance to the latter requirement.

5.1.Waste planning / Planning and pollution control

In the context of the avoidance of adverse environmental impacts, the EM data may provide specialist information on the nature and extent of **existing** subsurface contamination. Figure 5.1 is an example of a possible plume of conductive pore fluids in the vicinity of a domestic landfill.

The radiometric data provide background geological data at the site and regional scale which may be used to assess the geological suitability of sites for waste disposal. They can also provide information on the extent of landfills and any associated contamination, although this is clearly not always the case. The disposal sites in the Langar area are broadly defined as radiometric lows (Figure 5.2), with the flooded areas standing out, and there appear to be radiometric highs (i.e. slightly above background) associated with fly ash tipping into former gravel workings in the Trent Valley. However, the landfill sites in the Shirebrook area are not readily apparent in the radiometric data.

Radiometric data would directly indicate any radioactive contaminants at surface in and around radioactive waste disposal sites and could reveal the presence of such material, accidentally or illicitly placed, in other waste disposal sites; for example radioactive sources have been discovered in scrap yards and landfill sites. Processing of raw materials for certain industries (e.g. phosphates, glass and ceramics) can also lead to wastes enhanced in radioactivity. Such sites, and facilities such as radium luminising plants, may have long since ceased to exist but their legacy of contamination may remain and could be detected by airborne radiometric surveying.

Both the landfill targets at Langar are characterised by strong magnetic anomalies, which implies that both contain significant volumes of metallic debris. This may be important in terms of both the derived leachates and the compaction (through time) of the contrasting fill materials. The remaining investigated landfill sites are not characterised by discrete magnetic anomalies.

The colliery spoil heaps in the Shirebrook Area all *appear* to give an anomalous magnetic response but, when examined in detail, these observed compound anomalies are seen to reflect neighbouring cultural features (pit-head gear, peripheral railway lines and buildings etc).

5.2.Minerals Planning

Target spoil tips in the Shirebrook area have proved ideal candidates in relation to the issue of spoil tip drainage as described earlier. The environmental impact of coal extraction is exemplified at the Thoresby mine/spoil as shown in Figure 5.3. Here the EM data may be interpreted as an intense conductive zone associated with the spoil cover (but clearly more extensive) at shallow depth. The deeper information suggests that leaching may generate conductive pore fluids that extend downward and undergo lateral migration that can be detected several kilometres away. Although only spoil tip issues were addressed by the current trial survey areas, the wider and more extensive issues of drainage from all mineral extraction/reprocessing industries are relevant.

The radiometric data can provide information on both the location of mineral resources, whether bulk resources, such as sand and gravel or limestone, or radioactive minerals such as phosphates or rare earths. This can be of value both directly (by locating the resource) and

also by preventing the sterilisation of minerals through other types of development. An example of mineral resource identification is provided by the Trent Valley data (Figure 5.4) which distinguishes areas of potentially extractable sand and gravel from finer grained (mud-rich) alluvium.

The second aspect of the radiometric data relates to the environmental impact of mineral extraction. Colliery spoil tips east of Shirebrook are clearly identifiable from their relatively high levels of K, U and Th (Figure 5.5). It should be borne in mind, however, that, where spoil heaps are landscaped and covered with imported topsoil, the distinctive radiometric signature may be masked.

Although not seen in the present trials, radiometric data would be of direct relevance to establishing the degree of contamination where radioactive minerals (e.g. uranium) are being extracted or where enhanced levels of radioactivity are associated with the minerals being worked (e.g. uranium associated with tin mining in Cornwall, or with phosphates, and thorium associated with zircon and rare earths).

Again, although not demonstrated in the present trials, magnetic surveys have frequently mapped the distribution of concealed bulk- and metallic minerals. The HiRES-1 survey revealed numerous previously un-mapped shallow Carboniferous volcanic rocks in the Matlock area of Derbyshire. Aeromagnetic surveys worldwide have also detected various metallic ores, either directly or through their association with magnetic accessories.

Magnetic data can also indicate areas that are potentially unsuitable for mining development. Again, although not demonstrated in the current trials, the presence (and, in favourable circumstances, even the thickness) of intrusive volcanics and the density and alignment of faulting may be indicated by detailed airborne survey.

5.3.Water supply and water resource protection / Coastal zone management

Figure 5.6 shows an interesting relationship between EM data anomalies and water abstraction locations. A swathe of non-continuous conductive anomalies detected along a water pipeline route in a forest area is shown. Superimposed on the map are the main elements of the pipeline information obtained to date. Although there appears to be an association between the pipeline route and the anomalies, the reasons for the association are not yet understood. The type of information obtained will require quite detailed assessment and will likely entail input from the appropriate water company. The EM results in relation to spoil tip drainage are also important; they may indicate natural flowpaths *below* the surface drainage. This has implications with regard to existing ‘at-surface’ risk assessments (e.g. river/stream sampling). Although not studied here, saltwater intrusion is known to influence water quality at a number of coastal extraction locations. The EM data would provide information on the nature and extent of such intrusions in relation to coastal zone management.

The main potential input of radiometric data under this heading, although not apparent in the present areas, would be in assessing radioactive contaminants at surface, which may have the potential to impact on water supplies. The data also give a regional view of coastal zone contamination; this can clearly be seen in the HiRES-1 dataset that shows Sellafield-derived ^{137}Cs at relatively high levels around the Dee and Mersey estuaries. This dataset also shows the higher contents of ^{137}Cs from the Chernobyl accident over upland watersheds, particularly in north Wales and the Peak District.

Shallow concealed doleritic dykes were not encountered in the current trial areas but such features are common in many parts of the UK and are readily detected by aeromagnetic survey. Cleaved and fissured dolerite dykes can provide hydraulic continuity between the near surface and deeper lithologies or may provide hydraulic barriers.

5.4.Urban regeneration / Peripheral development and new communities

The first context here is one of brownfield site development. The EM data provide information on a number of ground condition problems such as ground and water contamination. The data have revealed a plethora of anomalies (equivalent ionic concentrations to landfills are implied in some cases) in both urban and semi-urban environments. At this stage we have no knowledge of the source/sink relationships. The continuous nature of the information also provides 'linkage' diagnostics from the local to the more regional scale. The information could be used strategically to determine the suitability of individual sites for particular types of treatment or avoidance. In terms of peripheral development in out-of-town/rural locations, the data may be used to identify existing hazards in relation to new development.

As stated under previous headings the radiometric data can be used to identify any radioactive contamination of sites under consideration for development. This includes radioactive materials derived from the nuclear industry as well as radioactive wastes from other industrial processes including luminising, glasses and ceramics, phosphate processing or other mineral processing. Such sites were not targeted in the present survey.

The radiometric data also serve as an excellent means of mapping solid and drift geology and soils. The geological mapping capability is well illustrated in all the survey areas [5]. This mapping capability would ensure that appropriate sites are developed while hazards associated with particular geological situations are avoided. These would include, for example, rocks prone to landslips or associated with high radon emanation, which may require protective measures to be incorporated into new buildings. The HiRES-1 data define very clearly the radon prone areas of limestones in Derbyshire and associated with parts of the Jurassic sequence in the East Midlands. Soil mapping, and the mineral resource delineation possibilities alluded to earlier, may be used to prevent the sterilisation of mineral resources and prime agricultural land.

High resolution *ground* magnetic surveys have been applied to the rapid mapping of concealed foundations and infrastructure (rails, pipelines etc) in brownfield sites. These features are revealed by the magnetic response to the steel reinforcing bars in the foundations and other linear cultural responses. Although we have no evidence from the present airborne trials, it is possible that concealed large volume re-inforced foundations etc. could be detected by detailed low-level airborne magnetics.

5.5.Agriculture and Forestry

The protection of good agricultural land is enabled through codes of practice for farmers and landowners. The EM survey data have identified a number of localised concentrations of high conductivities in farmland environments. Figure 5.7 shows results obtained across a 1x1 km area around an isolated anomaly together with pictures taken when visiting the location. Whilst the individual 'source' in each case requires investigation, the survey information may have a bearing on good and bad practice.

The primary use of the radiometric data in this context is in soil mapping and thus the recognition of soil types suited to different kinds of agriculture. This application is currently being evaluated as part of a MAFF-funded project, led by the Soil Survey and Land Resource Centre, which will test the use of radiometric data from HiRES-1, used in conjunction with geological mapping and slope information. Preliminary indications are that the potassium data are particularly useful in this respect.

Different lithologies may be grouped together on the geological map, but be readily distinguishable using the radiometric data. The HiRES-1 data are being used to assist current geological mapping in the Melton Mowbray and Ollerton areas and there is a close link between geology and soil type. The Trent Valley data (Figure 5.4) appear to delineate zones of different wetness, an important factor in soil classification. The Shirebrook data (Figure 5.5) also show the effect of different woodland types in modifying the ground signature.

6. CONCLUSIONS

The EM data 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. 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 landfill and colliery spoil sites and allow, in conjunction with the EM data, the identification of the lateral spread of conductive zones beyond the site itself. They can also be used to map site-specific contamination where radioactive elements are present as well as depicting regional-scale effects such as the anomalous distribution of ^{137}Cs following the Chernobyl accident.

The data 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 information can be used to define hazard-prone areas, mineral resources and prime agricultural land and help ensure appropriate development.

Magnetic data in the present trials have suggested the presence of significant volumes of metallic debris in the Langar landfill sites. Although not demonstrated in the present surveys, other potential environmental applications of aeromagnetics include the mapping of concealed foundations etc in brownfield sites, mineral exploration and the detection of shallow concealed doleritic dykes that may provide hydraulic pathways for leachates. Compared with the EM and radiometric techniques, the applications of magnetics in environmental studies are rather limited but such data are worthwhile collecting given the marginal costs involved.

7. 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. The data require additional information and ground-truth studies to establish firm interpretations. Only when these are

achieved can more specific assessments of their relevance to land-use and environmental monitoring strategies be made.

The EM data have revealed a plethora 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 a fuller 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.

8. 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.

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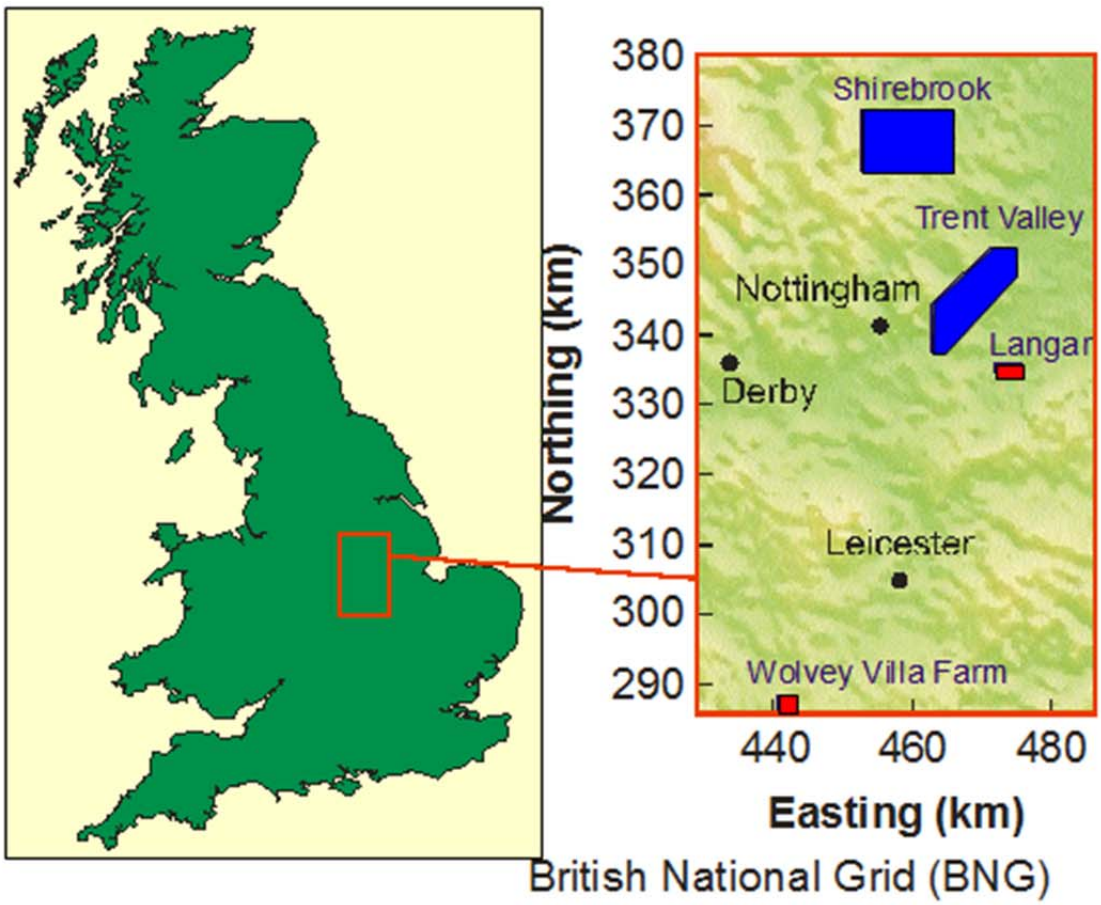


Total of 3324 line km (112 km of tie lines).
31 flight hours over 5 days

Figure 2.1 BGS/GTK airborne trial areas. 4 survey areas comprise (1) Shirebrook, (2) Trent Valley, (3) Langar and (4) Wolvey.

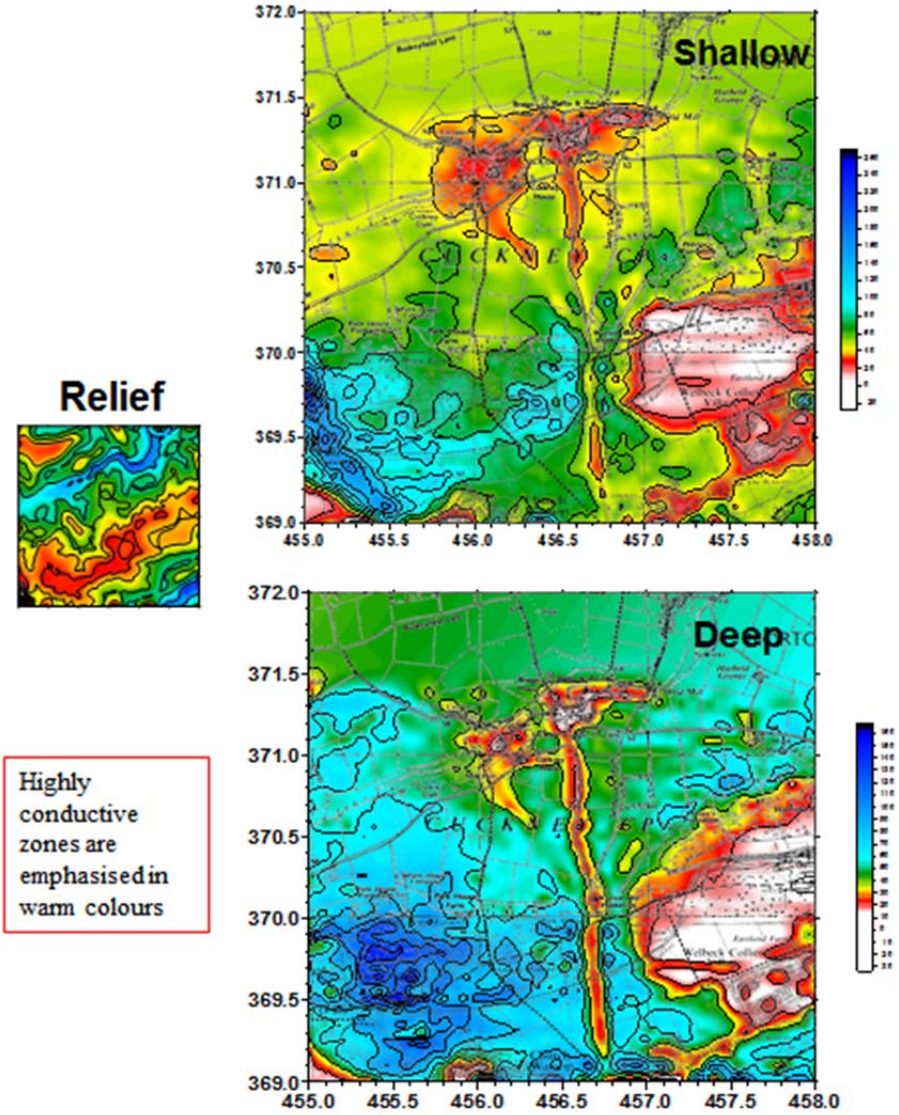


Figure 4.1. Shirebrook EM. 3 x 3 km detail. Shallow and deep resistivities (ohm.m). Conductive zones to the south and west of Welbeck colliery. The source/sink relationships involved in the linear Cuckney anomaly are not known. 50 m flight lines.

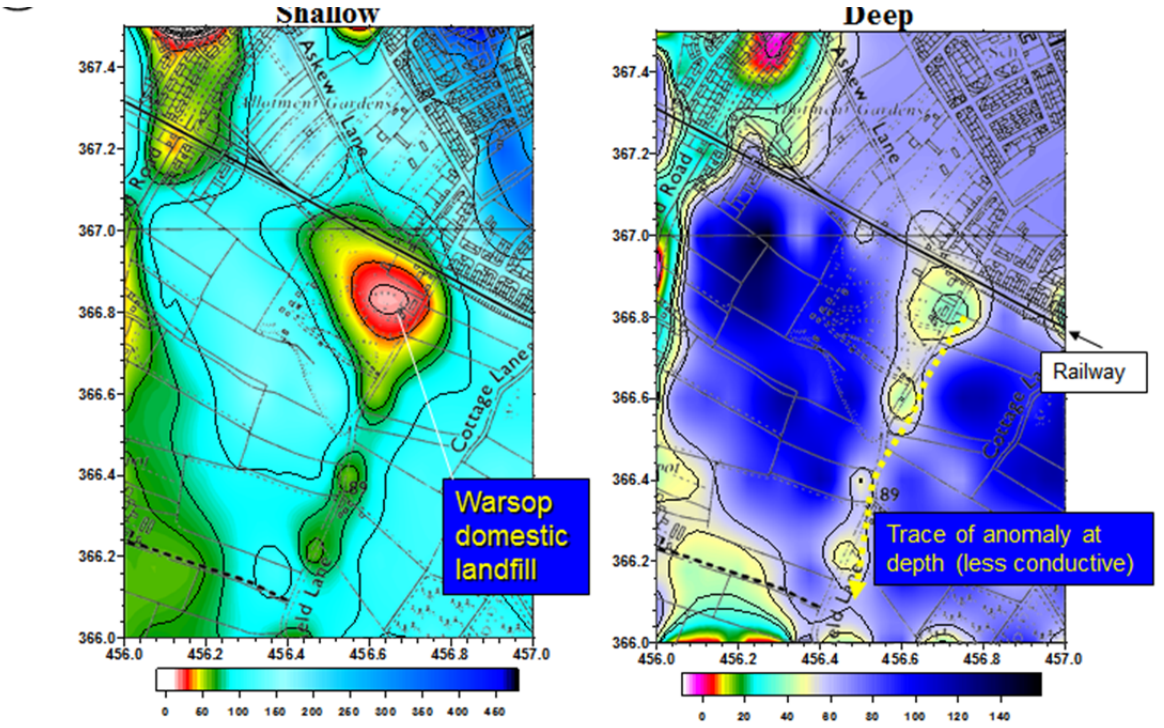


Figure 5.1 Shirebrook EM. Detail 1 x 1.5 km. Possible plume from domestic landfill. Shallow and deep resistivities (ohm.m). 200 m flight lines.

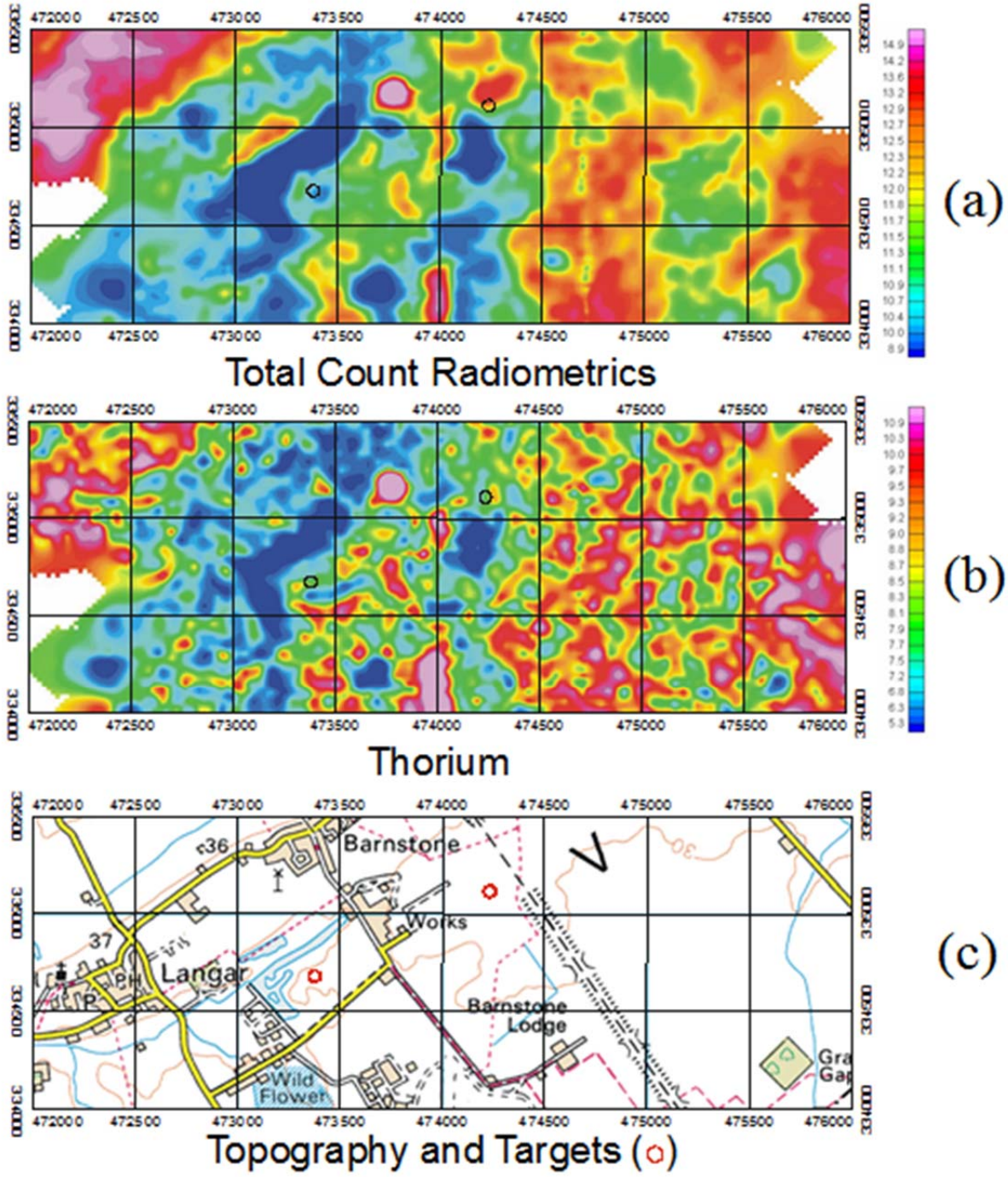


Figure 5.2 Radiometric images for the Langar area: a) Total count in counts/sec b) Thorium in ppm c) Ordnance Survey map and targets. Landfill targets stand out as flooded areas with very low counts. Most other features are related to geology: higher values in the NW reflect Mercia Mudstone, lower values in the centre mainly Jurassic limestones and higher values further east reflect Jurassic mudstones.

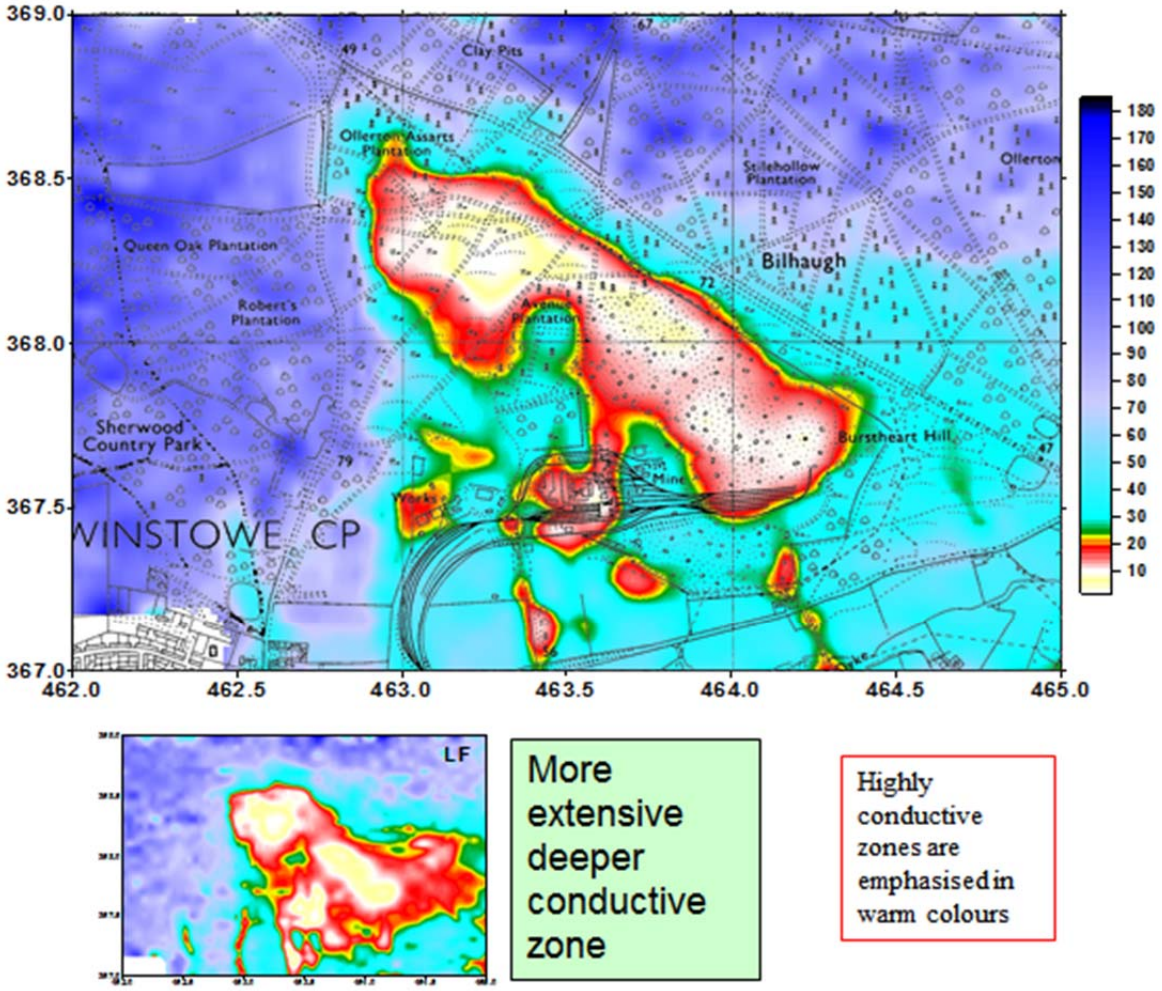


Figure 5.3 Shirebrook EM. Thoresby mine/spoil. 3 x 3 km detail. Possible conductive plume migration around Thoresby colliery. The conductive zone appears far more extensive at depth. 50 m flight lines.

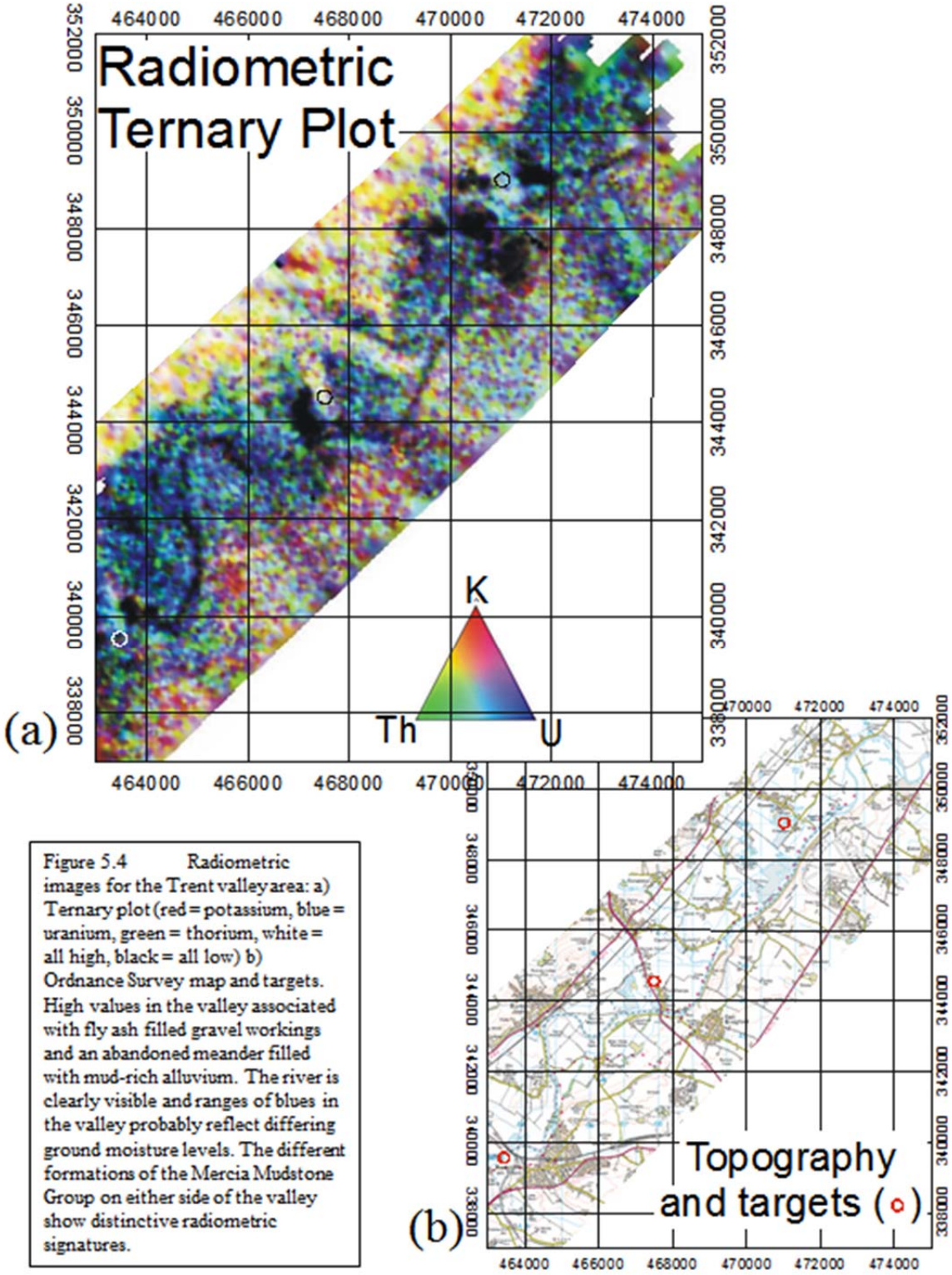


Figure 5.4 Radiometric images for the Trent valley area: a) Ternary plot (red = potassium, blue = uranium, green = thorium, white = all high, black = all low) b) Ordnance Survey map and targets. High values in the valley associated with fly ash filled gravel workings and an abandoned meander filled with mud-rich alluvium. The river is clearly visible and ranges of blues in the valley probably reflect differing ground moisture levels. The different formations of the Mercia Mudstone Group on either side of the valley show distinctive radiometric signatures.

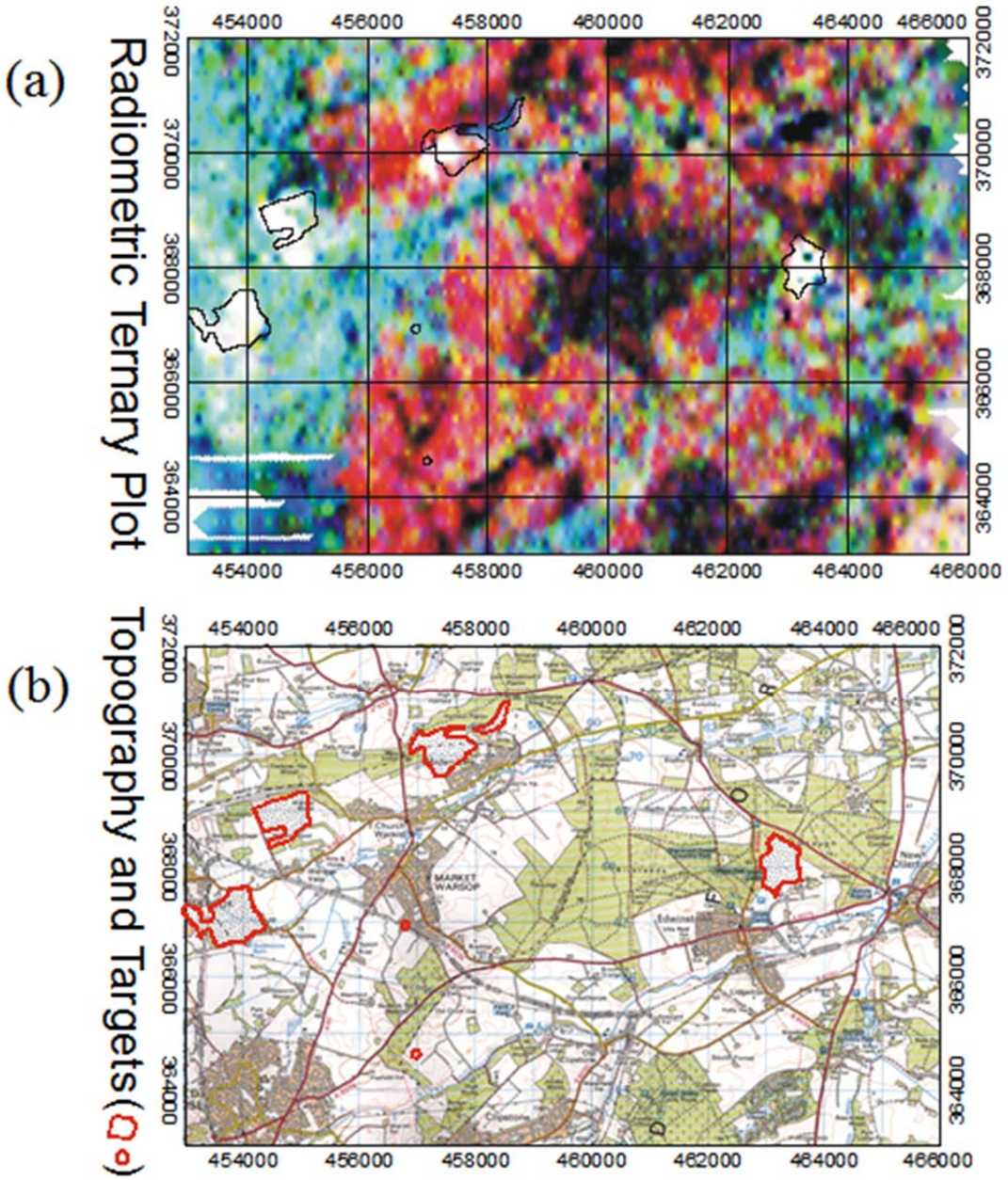


Figure 5.5 Radiometric images for the Shirebrook area: a) Ternary plot Ordnance Survey map and targets. Colliery spoil tips are clearly seen as higher values (white). Wooded terrain attenuates the ground signal and appears darker. There is clear demarcation of the Sherwood Sandstone Group (red) from older rocks to the W (blue). Strips of alluvium (blue) and probable patches of drift cover (yellow/green) on the Sherwood Sandstone are clearly visible.

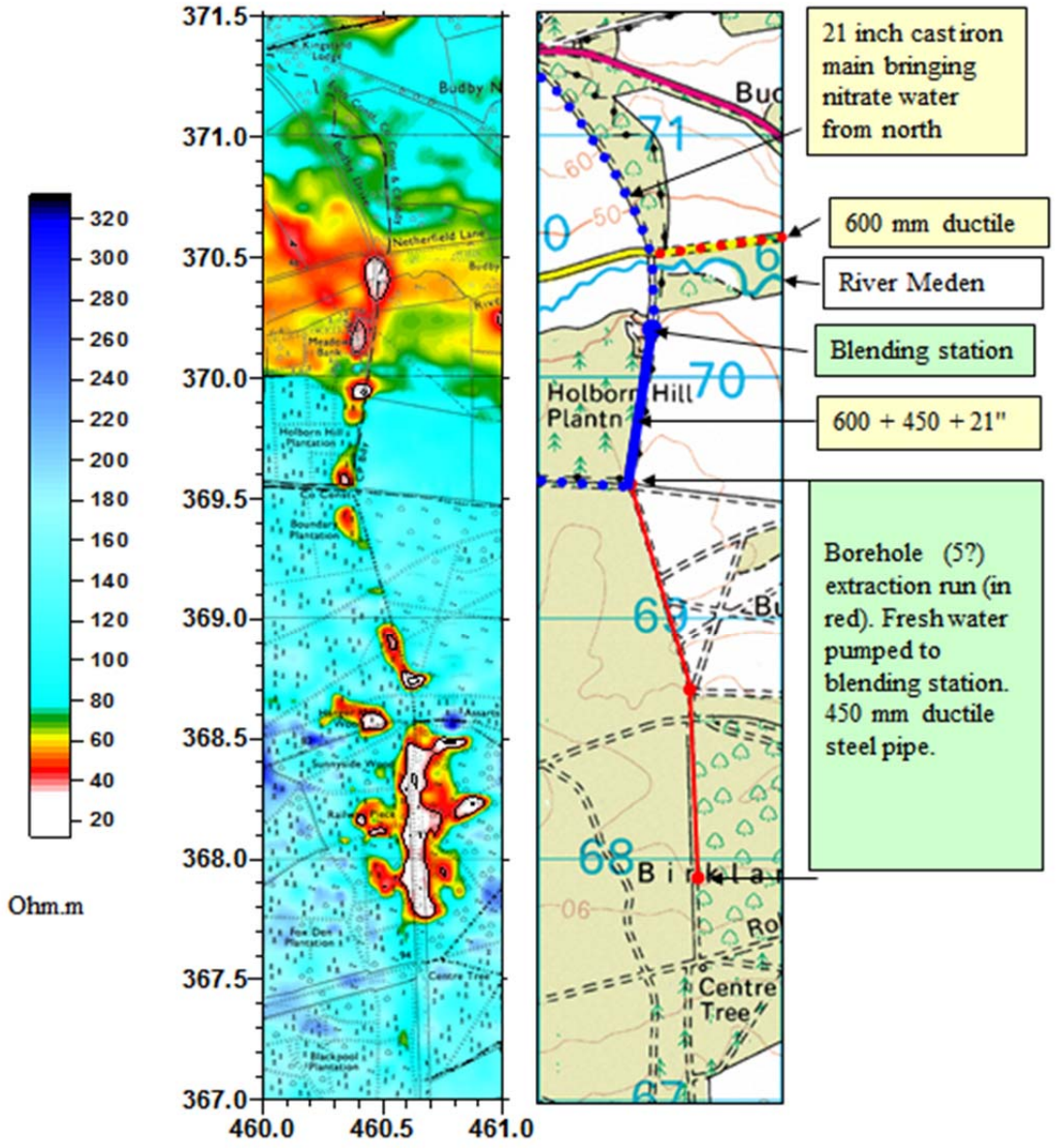
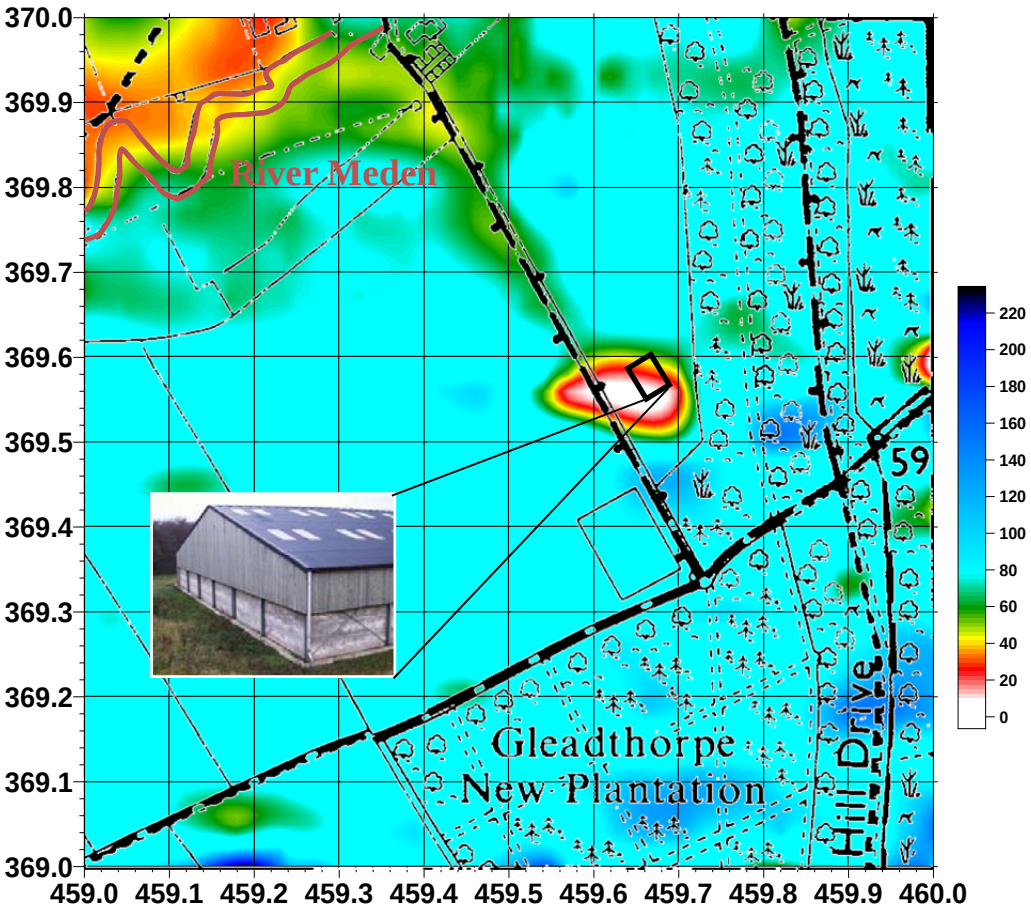


Figure 5.6 Shirebrook EM. 1 x 4.5 km detail. Water extraction, blending and distribution route.



Bridleway anomaly :barn and waste pit (to SE)

Highly conductive zones are emphasised in warm colours

Figure 5.7 Shirebrook EM. 1 x 1 km detail. Northern margin, Sherwood Forest. Deep resistivity (ohm.m).