Airborne EM applied to environmental geoscience in the UK

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The British Geological Survey has been highlighting the need for modern, multi-sensor airborne geophysical data in the UK. Here David Beamish describes the first trial electromagnetic data acquired and its relevance to environmental geoscience.

Introduction

The lack of modern, multi-sensor (magnetic, radiometric and electromagnetic) data represents one of the most serious gaps in the geoscience knowledge base of the UK and a national, high resolution airborne survey has been a stated corporate objective for many years. In 1999, the fixed-wing, frequency domain, airborne EM (AEM) system developed and operated by the Geological Survey of Finland was used in a series of trials to acquire detailed EM data sets in addition to magnetic gradiometer (wing-tip) and radiometric information. The purpose of the trials was, in part, to assess the case for the inclusion of AEM in future strategic airborne geophysical surveying. The limited data acquired (3324 line km in 5 days flying) constitute the first high resolution AEM survey information to address specific environmental issues in the UK. It was anticipated that the AEM data would provide pathfinder information for general assessment of land quality issues such as planning and pollution control and water supply/resource protection.

AEM surveys

The information delivered by an AEM system is a volumetric average of the bulk subsurface conductivity, similar (except in scale) to its ground-based parent techniques. A view of the electric field induced by a vertical coil at a height of 40 m is shown in Figure 1. The parameters used (a frequency of 14 kHz and a 10 mS/m half-space) are appropriate for the data discussed below. The maximum electric field occurs directly beneath the transmitting coil and attenuates as shown by the contoured region (warm to cold colours). The distribution is asymmetric and is elongate perpendicular to the flight direction (x). The outer opaque volume defines three skin-depths while the central transparent volume is one skin-depth from the maximum value. The latter volume defines a region of maximum sensitivity. The bulk conductivity delivered by the measurement will, in this example, encompass over 60,000 m^3. Such large scale averaging is both a strength and weakness. When changes in the bulk average are detected, they must relate to a considerable volume of the subsurface.

The measured bulk conductivity is connected, through Archie's Law, to geological/lithological dependencies and to the conductivity of the pore fluid. This latter dependence often forms the basis for diagnostic environmental assessments. Fluid conductivity is linearly related to Total Dissolved Solids (TDS) and the level of each of these parameters forms a basis for regulatory control. To preempt an environmental FAQ, AEM, like its ground-based counterparts, provides no geochemical discrimination. The information is geochemically summed; typical ionic species with high mobilities include the Na, SO_4, Cl, K and NO_3 groups. AEM data need expert interpretation since geology, lithology and geophysical scale and depth averages are involved.

Four areas in the East Midlands were surveyed. Environmental targets included colliery zones in north Nottinghamshire together with a series of active and closed landfills. In practice we observed far more environmental responses than were ever anticipated. Of particular interest were AEM capabilities in conductive environments, some containing complex Quaternary sequences. Provision was also made, within the trials, for technical issues of flying height between 100 and 300 feet (i.e. 40 and 90 m) and flight line spacing (50 and 200 m) to be investigated. Some data sets were repeated at different elevations. Low level flying must adhere to regulatory controls and this may impact on signal/noise. In areas of modest population density, low level flying can only be achieved between conurbations. In practice, data obtained from elevations up to 120 m were found to be fit-for-purpose; signal/noise levels were, however, aided by the relatively conductive geology encountered in the trial areas.

In contrast to the more common towed-bird (helicopter) AEM systems, the fixed-wing system operates just two vertical wing-tip coil-coil pairs at 3 and 14 kHz. Thus, although the system can maintain adequate signal/noise at high elevations, the depth discrimination is inevitably more limited. Sampling along the flight line is typically between 10 and 15 m. The trial data were used to develop a modelling/inversion strategy to achieve reliable and consistent results. The conductivity estimates shown here are one-dimensional inversions of the data at each of the two frequencies. Data from only one of the four trial areas are used here to illustrate general relevance.

Regional data

Investigations into detectable environmental effects across the Permo-Triassic sandstone aquifer were conducted in northern Nottinghamshire. The 13 x 9 km Shirebrook survey area is shown in Figure 2. Here the geology is highly uniform (the Sherwood Sandstone with a typical thickness > 100 m) and the survey area contains a swathe of closed (Sh, Wa and Cl) and active (We and Th) collieries. Representative 'background' information was established using data obtained within the central 2 x 2 km red square. According to these data, background conductivities range from volumetric averages of 4 to 10 mS/m at high frequency and from 2 to 8 mS/m at low frequency. Even within this small area, differences between agricultural and historically forested zones were detectable. Centroid depths, meaning the depths that can be associated with these background values, increase from about 40 m at high frequency to about 70 m at low frequency.

The higher frequency conductivity results obtained from the regional scale survey (200 m E-W line spacing) are selectively contoured on the base topographic map in Figure 2. Black contours denote values in excess of 100 mS/m and three levels of colour (red, yellow, blue) then denote values decreasing to 20 mS/m. According to the background study, this cut-off level should clearly identify anthropogenic sources of enhanced subsurface conductivities. It is evident from the results that highly conductive features (predominantly black contours) occur in association with colliery spoil zones. Away from the immediate vicinity of the at-surface mineral concentrations, less-conductive anomalies with a plume-like quality are observed. In the case of Welbeck mine (We) an apparently continuous conductive zone can be traced eastwards for over 3 km following a topographic low. Other large-scale conductive features detected by the survey (the Cuckney and Thoresby Lake anomalies) are not yet understood.

Many other smaller scale features were found to provide significant conductivity signatures. Types of land-use giving rise to detectable conductive anomalies in the Shirebrook area include agricultural waste/slurry pits, sewage works and former landfills. Three isolated landfills are labelled L1, L2 and L3 in Figure 2. All three are classed as unengineered (i.e. they used the dilute and disperse principle) and closed during the 1970’s. Limited ground geophysical surveys at sites L1 and L3 (L2 is inaccessible) confirm the airborne results. The amplitude observed in association with L1 is some 160 mS/m indicating that it probably constitutes a significant bioreactor some 25 years after closure.

High resolution data

Infill flying, using 50 m flight lines, provided higher spatial resolution data in two areas of the Shirebrook survey. Figure 3a shows a portion of the higher resolution conductivity results across a central swathe (1 x 4.5 km, red rectangle Fig. 2) of the former Sherwood Forest. Contour lines denote the 10, 20 and 30 mS/m levels. Figure 3b comprises the 1:50k Ordnance Survey map with water pipeline routes superimposed. Both images are draped on exaggerated topography. The pumping/blending station (silver cylinder) takes nitrate enriched waters from the north and mixes these with cleaner waters from five newer (1992) extraction boreholes in the forest (Fig. 3b). Towards the north, enhanced conductivities, associated with an E-W trending regional scale feature are observed in detail. The extensive 10-20 mS/m zone probably represents a marginal increase in TDS levels with the main enhancements (> 20 mS/m) occurring in association with, but well below, the topographic low. An extensive conductivity high is also centred on the extraction boreholes. The results imply a possible association between water extraction and the regional scale movement of pore fluids with enhanced conductivities. Like so many of the results obtained, the observations warrant further study.

High resolution results obtained across a 3 x 2 km area (blue rectangle Fig. 2) centred on the working Thoresby mine are shown in Figure 4. The upper frame displays an air photo mosaic draped over exaggerated topography. The pithead appears in the centre of the image surrounded by exposed coal working/processing areas. To the east and south east, topographic highs indicate landscaped spoil zones. The conductivity distribution is selectively contoured and draped over the same topography in the lower frame. The gray area denotes conductivity values < 15 mS/m; this level, chosen as a local background, defines a series of strong gradients outlining the perimeter of the mine in the west and north. Within the mine, conductivity values increase from 20 mS/m (blue) through increasingly warmer colours to red (~50 mS/m) and beyond to values in excess of 150 mS/m (areas with cross-hatch). The latter values partially trace at-surface mineral concentrations. Pooling of localised high values is observed towards the base of the isolated spoil heap in the foreground of the image. Elevated conductivities continue to the east of the mine and trace a surprisingly complex pattern. This apparent eastward migration may be a regional scale effect (e.g. Fig. 2) associated with the main stratigraphic dip of the sandstone.

Ground truth

Airborne conductivity models must be supplemented by ground truth studies in order to arrive at a more complete and reliable understanding of the information. This is particularly true for our first trial surveys. In the case of the sandstone, information is required to depths in excess of 40 m. Available, moderately deep, boreholes rarely provide either the geochemical or the geophysical sampling required. Projected cost figures for even a quite limited borehole programme indicate that costs would soon exceed those of the entire trial airborne survey. In practice, a modest amount of targeted surface geophysical investigation can, at least, enhance the interpretation of the airborne data. One of the main requirements is to provide a greater degree of vertical discrimination than that obtained from the airborne survey.

Figure 5 shows a series of conductivity models obtained from five vertical electric soundings across the Shirebrook area. The models are based on smooth first derivatives rather than conventional layered constructions. An estimate of the rest water table (25 to 35 mbgl), based on regional borehole information, is indicated. Profiles A and B were obtained in the control area (Fig. 2). Profile A is taken to represent the behaviour of clean background sandstone. Profile B is taken to represent the behaviour of an agricultural zone. The conductivity differences between the two responses are small but detectable in both the ground and airborne measurements. The remaining group of three profiles were obtained across the nature reserve to the east of Thoresby mine. The sounding centres are shown in Figure 4. Below about 15 m, the conductivity displays a ramp-like increase through the unsaturated zone to reach a maximum within the aquifer at depths of about 50 m. The variation in the maximum amplitudes reflect variations also observed in the airborne results. At a depth of 50 m, the conductivity values translate to TDS estimates of A) 278, B) 586 and C) 2480 to 3653 mg/l. The value of 278 mg/l for Profile A is within the commonly reported range of normal groundwater values for Nottinghamshire. The most important conclusion is, however, that the airborne data, at both frequencies, are mapping enhanced conductivities primarily within the aquifer.

Conclusions

The AEM data acquired in the trials appears to offer potential for a range of applications in the environmental geoscience sector. The continuity of information for problems involving flow from source to sink and from the local to the regional scale is particularly appealing. In other data sets, not discussed here, the background geological response is more prominent. The inclusion of AEM in future multi-sensor airborne surveying appears warranted. In the UK, the AEM data, alongside the magnetic and radiometric data sets, are provided in the context of a large amount of existing information on land and groundwater qualities. The low level AEM data can be understood as part of a continuum of electromagnetic remote sensing that includes higher level airborne and satellite sensing through the optical and thermal bands. Much of this information, including many of the direct geochemical sampling/monitoring systems that are in place, provide data that constitute at-surface diagnostics. Two of the key roles of AEM which ***uniquely*** define its value to environmental geoscience are:

- Lifting the lid. AEM provides subsurface information of environmental diagnostics on a scale that can extend to many tens of meters in depth.

- Fluid geochemistry. AEM provides bulk conductivity information, which exhibits a high degree of sensitivity to pore water geochemistry.

We are aware that much remains to be done to translate the data obtained into firmer and possibly geochemically-related interpretations. In mitigation we offer the following definition: **Path~finder**: *explorer, aircraft (or pilot) sent ahead of others to guide them to their objective and mark out their targets*.

Acknowledgements

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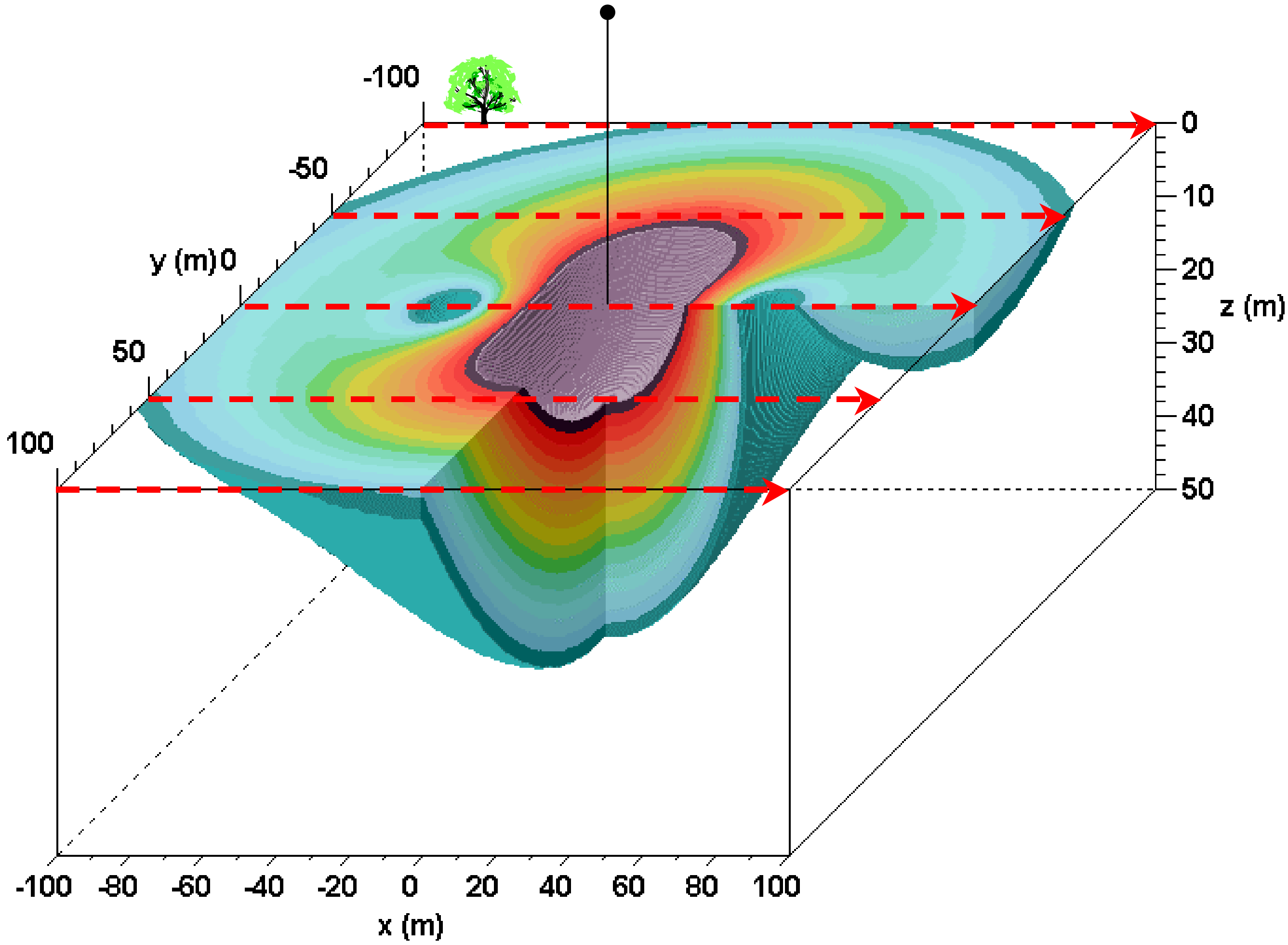

Figure 1	Scale of information delivered by an airborne vertical coil (height 40 m). Induced electric field is a maximum directly below the coil. Contoured region is 3 skin-depths, central transparent zone is 1 skin-depth. Red arrowed lines indicate 50 m flight line spacing.

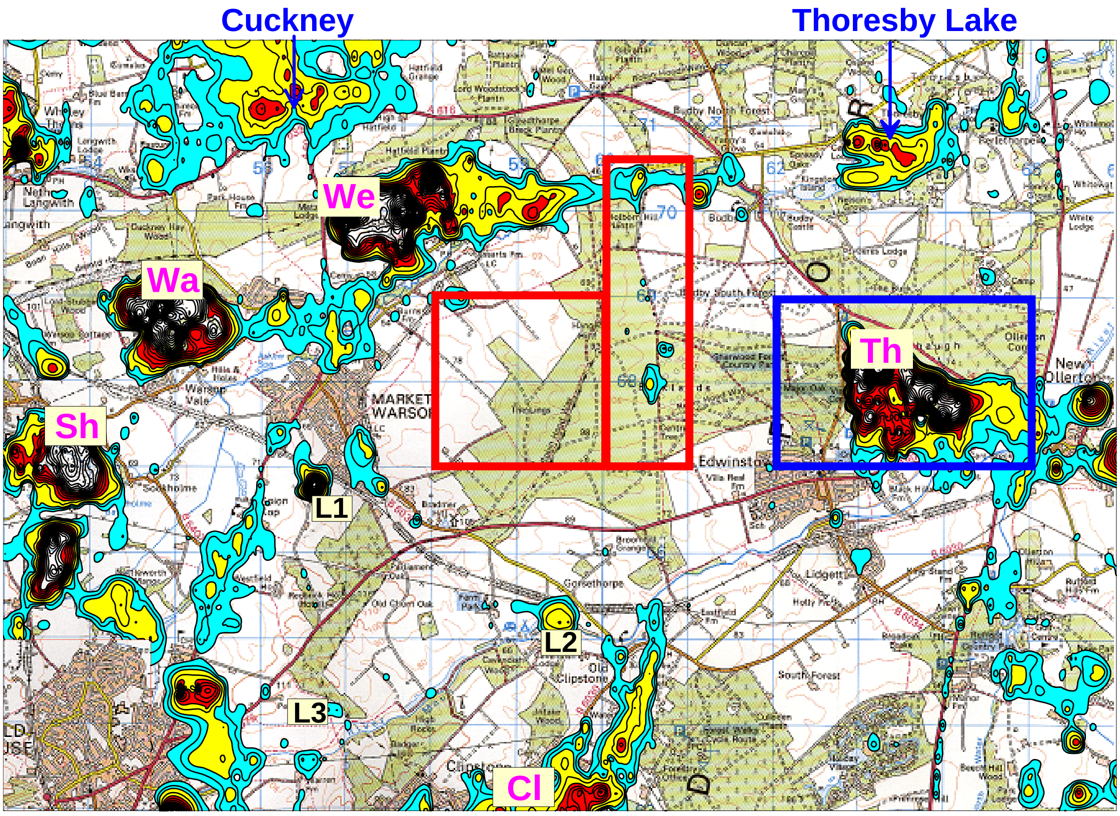

Figure 2	Shirebrook survey area (13 x 9 km). Conductivity results
selectively	contoured on OS base topographic map (© Crown copyright.
All rights	reserved). Black >100, red 50–100, yellow 30-50, blue 20-30

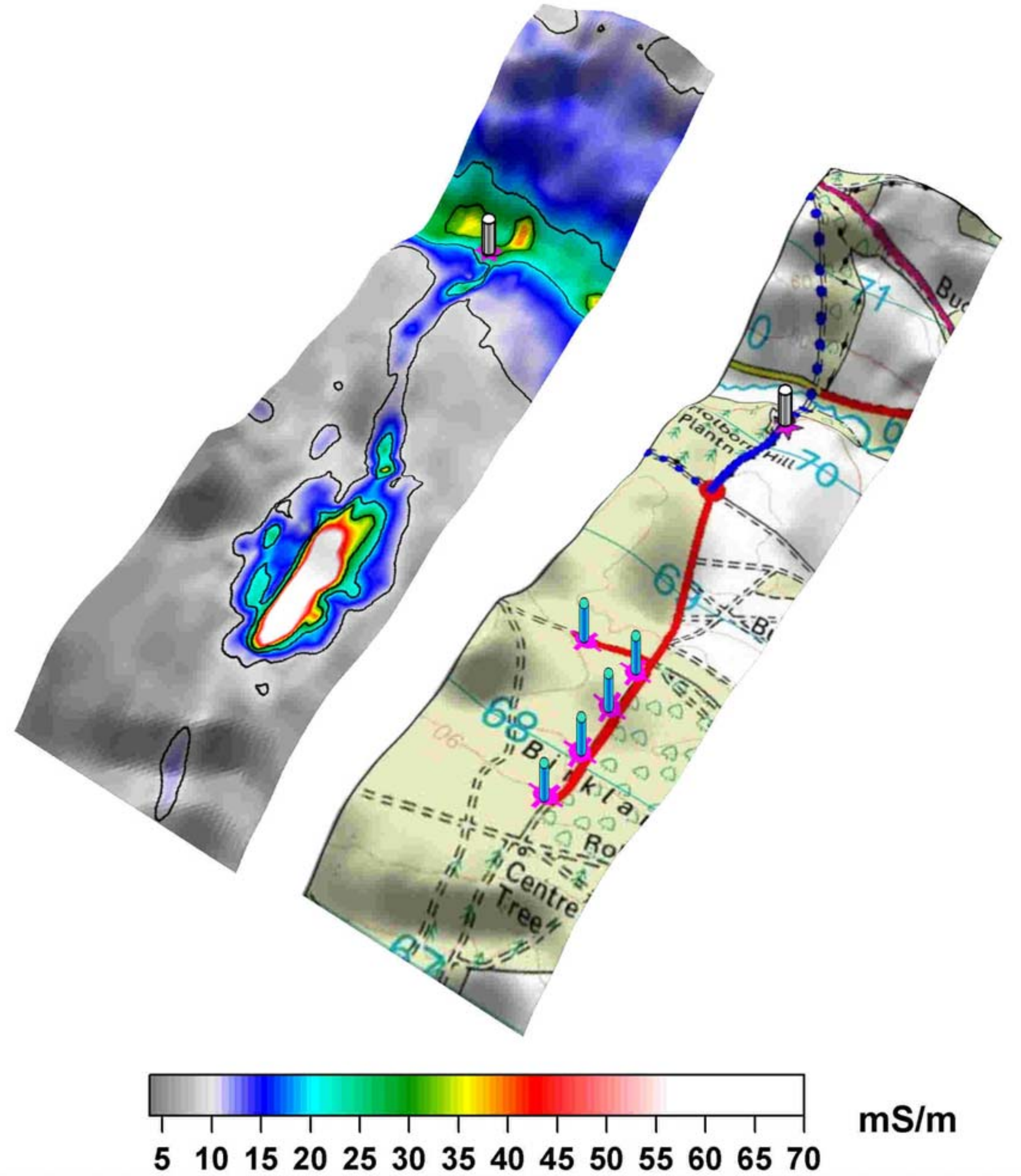

Figure 3 (a) High-resolution conductivity results across 1 x 4.5 km area. Five water extraction boreholes (blue) are indicated. (b) water pipelines on OS base topographic map (© Crown copyright. All rights

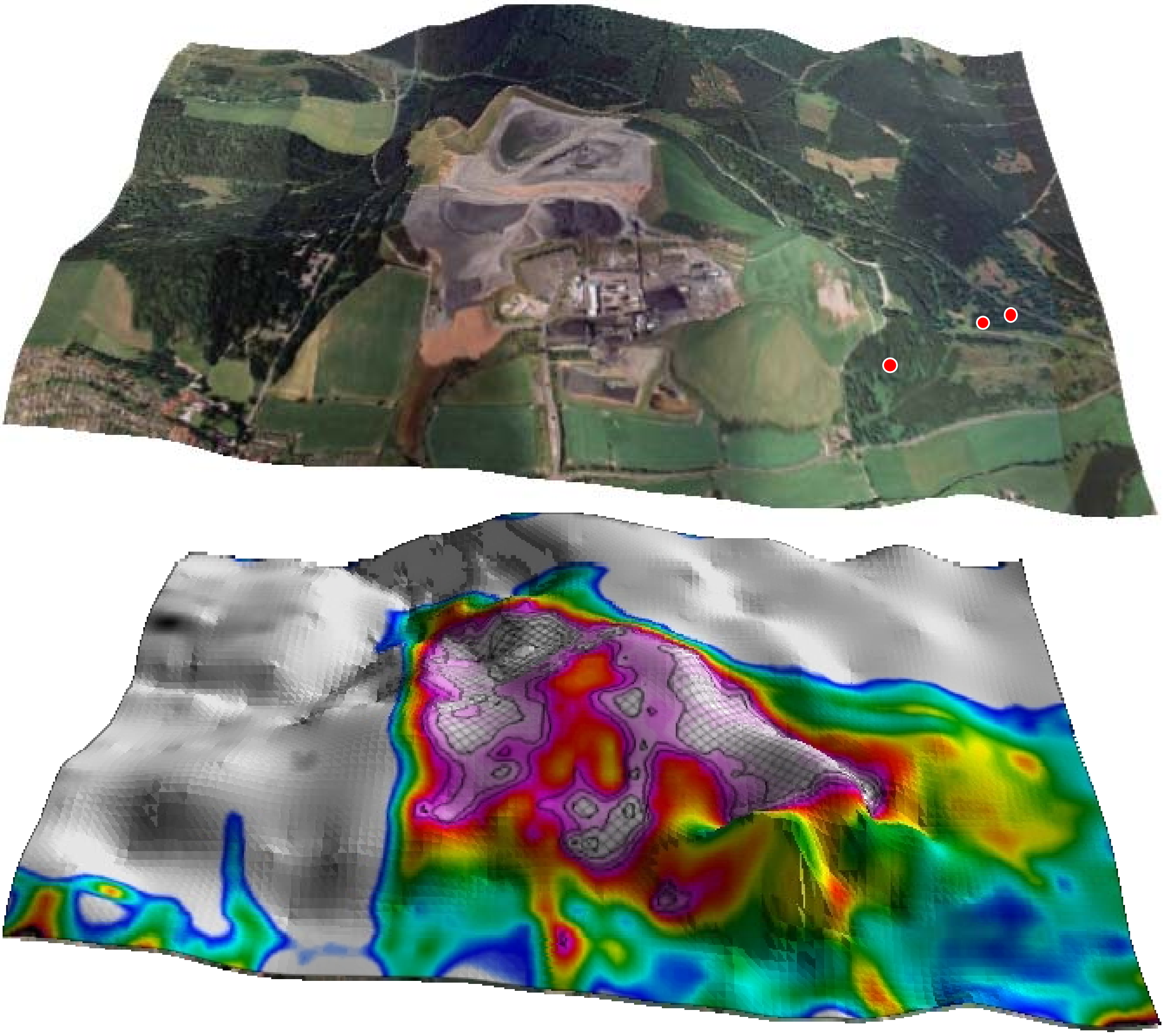

Figure 4	3 x 2 km area centred on Thoresby mine. Upper frame: aerial photograph draped on exaggerated topography. Red dots indicate Vertical Electric soundings. Lower frame: Conductivity results draped over same topography.

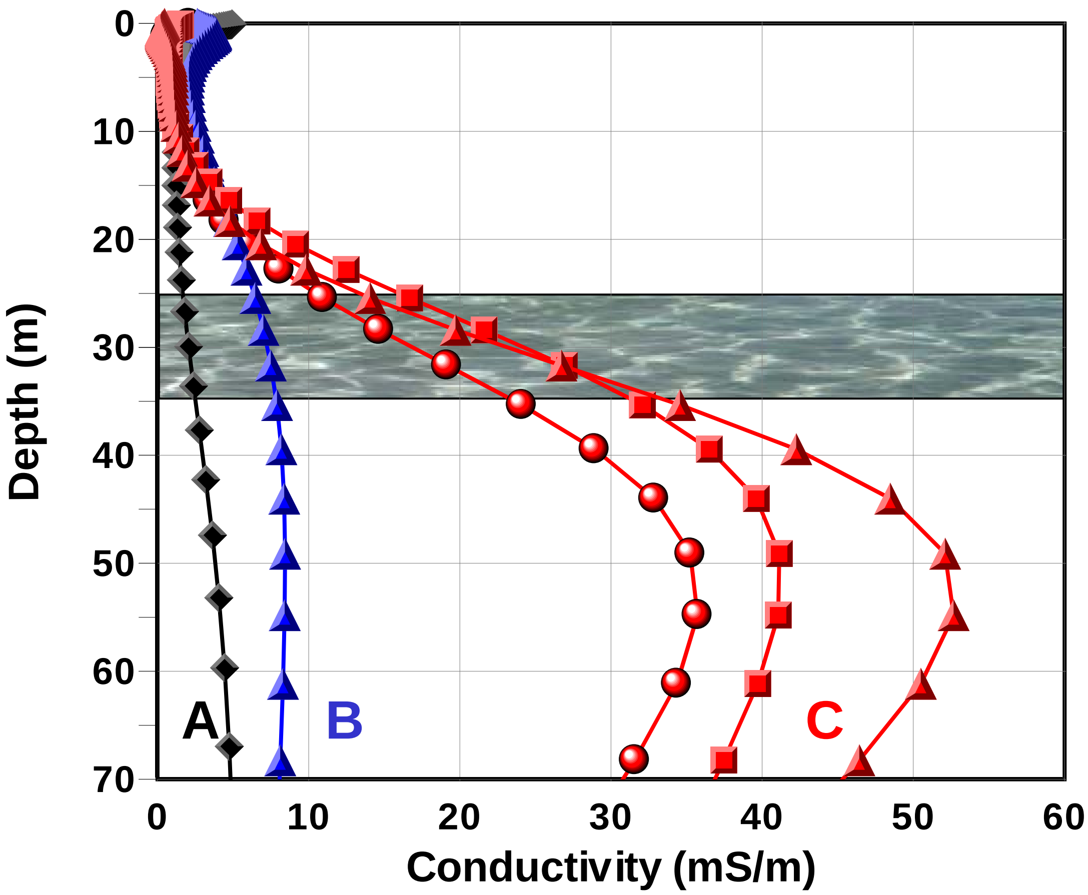

Figure 5	Vertical electric sounding results obtained across the Shirebrook area. Profile A: background. Profile B: agricultural. Profiles C obtained to the east of Thoresby mine.