

Hydrochemical characterisation of a coal mine plume detected by an airborne geophysical survey

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ABSTRACT

A trial airborne electromagnetic (AEM) geophysical survey was carried out across a 13 x 9 km area of the northern Nottinghamshire (UK) coalfield. One of the objectives was to examine the influence of coal mines (collieries) and associated spoil heaps situated above the Triassic Sherwood Sandstone aquifer. The conductivity models obtained from the AEM survey revealed extensive zones of enhanced subsurface conductivity in the vicinity of all the collieries in the survey area. The present study provides information regarding subsequent investigations (ground geophysics and borehole) to confirm the AEM results and to investigate the geochemical nature of the conductive zone identified in the vicinity of one of the collieries.

Following ground geophysical confirmation of the airborne results, three boreholes were drilled into one of the conductive zones to the east of a working colliery. Geophysical logs and analysis of pore fluid geochemistry demonstrate that there is a very strong correlation between the borehole induction logs (formation conductivity), total dissolved solids and chloride in the pore waters. The three, cored boreholes have confirmed that there is a groundwater plume with high concentrations of total dissolved solids, compared to background, moving east from the Thoresby Colliery on a hydraulic gradient of 0.023. Porewater geochemistry obtained from core has been compared with that of local aquifer waters and with samples obtained from the colliery. The results indicate that the plume chemistry could result from the mixing of a typical Sherwood Sandstone composition with colliery spoil leachate. The AEM conductivity models have been successfully correlated with ground geophysical models, borehole induction logs, total dissolved solids and chloride in the pore waters. By implication, the geophysical results obtained over a larger area indicate the wider extent of such impacts in relation to both former and current mining activities.

INTRODUCTION

Airborne electromagnetic (AEM) measurements, traditionally used for reconnaissance and mineral exploration, are playing an increasing role in the assessment of land quality and in environmental and hydrogeological studies. All available AEM systems, including time and frequency domain EM systems (both towed bird and fixed wing) are being applied to such studies. Large scale (regional) assessments have been undertaken (e.g. Fitterman and Deszcz-Pan, 1998; Munday *et al.*, 2001) together with site investigation scale studies (e.g. Puranen *et al.*, 1999; Doll *et al.*, 2000). Here trial data obtained in the East Midlands of central England using a frequency domain fixed wing system is used to investigate AEM data in relation to environmental assessments.

Airborne geophysical surveys conducted at low altitude (< 100 m) can simultaneously acquire multi-parameter data sets. The Geological Survey of Finland (GTK) in collaboration with the British Geological Survey (BGS) flew a series of four trial airborne environmental and geological surveys in 1999. 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 magnetic (gradiometer) measurements were also collected to see to what extent these techniques provide complementary information. The geophysical systems, mounted on a DeHavilland Twin-Otter aircraft, are described in detail by Poikonen *et al.* (1998). The surveys and initial results provided by all of the techniques are described by Beamish *et al.* (2000a,b). Environmental applications of the high resolution geophysical data sets in the U.K. are discussed by Beamish (2002) and by Peart *et al.* (2003).

Two wing-tip coil pairs, operating at 3 and 14 kHz, collect EM coupling ratios, which are converted (modelled) to provide a measure of the bulk subsurface conductivity. The two frequencies provide different depth measurement scales. In the case of the area discussed here, the system provides a sensitivity to conductivity changes to depths of about 60 m. The bulk conductivity in near-surface materials is largely dependent on geology (i.e. mineralogy) and the electrical conductivity of the pore fluids. The latter is sensitive to, and increases with, the amount of total dissolved solids (TDS). The measurement provides no geochemical discrimination so that ground-based, invasive sampling techniques must be employed to establish the cause of any enhanced conductivity variations.

One of the four areas, the Shirebrook survey, included a 13 km x 9 km area in northern Nottinghamshire. Here, one of the objectives was to examine the influence of coal mine (colliery) spoil heaps situated above the Triassic Sherwood Sandstone aquifer. The AEM survey data, when converted to conductivity, revealed extensive zones of enhanced subsurface conductivity in the vicinity of all the collieries in the survey area. The purpose of the present report is to provide information regarding subsequent investigations to confirm the geochemical nature of the conductive zone identified in the vicinity of Thoresby Colliery. This colliery currently extracts coal from seams at depths in excess of 800 m. The hydrogeochemistry of contaminating coal mine waters, including the effects of spoil tip leachates, from mines to the north and west of the study area is discussed by Banks *et al.* (1997).

A description of the general relationships between formation conductivity and groundwater quality is given first. The airborne survey results from northern Nottinghamshire are then described. Follow-up ground geophysical investigations, that provided confirmation of the airborne anomalies are presented. Three boreholes were drilled to further investigate the nature of the elevated conductivities. The data obtained from the downhole geophysical logging and geochemical analyses of pore fluids are described. Comparisons of the pore fluid chemistry, obtained from core, are then made with local aquifer waters (from producing wells) and with samples obtained from the colliery. The accumulated results are used to provide a summary of the evidence for colliery spoil impact on groundwater.

CONDUCTIVITY AND GROUNDWATER QUALITY

Geophysical measurements provide volumetric estimates of total formation resistivity (ρ_t , or its reciprocal, conductivity σ_t). The use of formation (or bulk) resistivity to investigate subsurface water quality relies on an ability to understand the factors that control it in a given hydrogeological setting. It has long been established that the formation resistivity (ρ_t) of a clean (a rock matrix that is perfectly insulating) saturated formation is proportional to the resistivity (ρ_f) of the fluid. The constant of proportionality is referred to as the formation factor (FF):

$$FF = \rho_t / \rho_f = \sigma_f / \sigma_t \quad \dots(1)$$

In practice, even the cleanest formations contain small amounts of clay, or mudstone bands, which can exert a significant influence on σ_t and the value of FF as σ_f increases. Assuming negligible clay content, an empirical relationship developed by Archie (1942) indicates the bulk material conductivity is related to pore fluid conductivity (σ_f) and fractional porosity (ϕ) as:

$$\sigma_t = a' \sigma_f \phi^m \quad \dots(2)$$

where σ_t and σ_f are in units of S/m and a' is an empirically determined constant. The exponent m is also an empirically determined parameter that depends on the geometric factor of grain shape and packing (typically in the range 1.2 to 2.0). In the absence of clays, measured bulk conductivity is determined by the fluid conductivity which may be expressed as a function of ion concentration and mobility as:

$$\sigma_f = F \left(\sum C_i M_i \right) \quad \dots(3)$$

where F is Faradays number (96500 coulombs/g equivalent) and C_i is the concentration (number of gram equivalent weights) of the charge carriers of mobility M_i (in $\text{m}^2/\text{s V}$). Common ionic species with high mobilities include: SO_4^- , Na^+ , Cl^- , K^+ , NO_3^- and HCO_3^- .

McNeil (1990) demonstrates that equation (3) is consistent with experimental data indicating conductivity values from 0.16 mS/m to 0.22 mS/m for ion concentrations of 1 mg/l

(or ppm), resulting in the expression between fluid conductivity and total dissolved solids (TDS) of:

$$\sigma_f \approx 0.16 \text{ TDS} \quad \dots(4)$$

Where TDS is expressed in mg/l and σ_f is measured in the common conductivity unit of mS/m. Pore fluid conductivity is thus linearly related to TDS. The effect of temperature on the conductivity of water bearing rocks is controlled by the temperature dependence of the aqueous electrolyte. The temperature sensitivity of typical electrolytes is sufficiently low such that, under typical near surface (~50 m) temperature gradients, the major influence on conductivity comes from TDS and not from temperature.

Equations (1) to (4) indicate some general relationships that exist between bulk conductivity and rock/fluid parameters. Howard (1990) indicates the errors that arise when the equations are used without due attention to the locally appropriate hydrogeological parameters. The formation factor FF has been estimated for Permo-Triassic sandstones in northwest England (Howard, 1990) as:

$$FF = 0.53 / \phi^{1.9} \quad \dots(5)$$

If the same relationship is valid for the study area in northern Nottinghamshire then equations (1), (2), (4) and (5) predict that: $\text{TDS} = 70\sigma_t$ for a porosity of 20% and $\text{TDS} = 33\sigma_t$ for a porosity of 30%. The estimates suggest that within the Permo-Trias, and in the absence of clays, changes in formation conductivity of a factor of 10 within the aquifer may be accounted for by changes in TDS of between 700 mg/l (20% porosity) and 330 mg/l (30% porosity).

AEM SURVEY RESULTS

The AEM regional scale results obtained using E-W flight lines spaced at 200 m are shown in Figure 1. The nominal flight elevation was 40 m above ground. Here a half-space conductivity model, based on the high frequency (14 kHz) AEM data, is shown selectively contoured. Black contours, with no infill, denote values in excess of 100 mS/m and three levels of grey infill then denote values decreasing to 20 mS/m. According to background studies (i.e. the typical values obtained in non-anomalous areas as seen in Figure 1), this cut-off level should identify anthropogenic sources of enhanced conductivities. It is clear from the results that highly conductive features (predominantly black contours) occur in association with all of the colliery spoil areas including the former pits of Clipstone (C), Langwith (L), Shirebrooke (S), Warsop Vale (Wa) as well as the active pits of Thoresby (T) and Welbeck (We). Away from the immediate vicinity of the spoil zones, less conductive anomalies with a plume-like geometry are observed.

The zone around Thoresby Colliery, shown as a 3 km x 2 km rectangle in Figure 1 was selected for further ground-based studies. The area was overflown with 'in-fill' flight lines thus providing an E-W flight line separation of 50 m. Figure 2 shows the AEM conductivity results obtained at high frequency (HF, from shallower depths) and low frequency (LF, a deeper depth of investigation) across the 3 km x 2 km area, centred on the Thoresby site. Conductivity values are only contoured between a low value of 20 mS/m and 70 mS/m. Values above 70 mS/m are shown in cross hatch. The highest conductivities detected (> 200 mS/m) are associated with a processing lagoon and are shown in black. It can be seen that

the lower frequency results (Fig. 2b) indicate a more extensive high conductivity anomaly (> 70 mS/m) to the east of the mine. The eastern-most area, largely beyond Easting 464 km, lies outside the mine perimeter. This area contains the locations of 4 ground-based Vertical Electric Soundings (VES, star symbols) together with the 3 borehole locations (borehole symbols). The borehole locations, all within the main anomaly (i.e. > 20 mS/m), were chosen on the basis of land access/permissions and to provide a groundwater flow direction.

GROUND GEOPHYSICS: VERTICAL ELECTRIC SOUNDING

A more detailed assessment of subsurface conductivity variations was made at the four VES locations, shown in Figure 2, to the east of the mine. The Schlumberger VES soundings were made with the ABEM SAS3000 Terrameter. Maximum AB/2 expansions (the half maximum length between current electrodes) were 200 m (VES 1), 160 m (VES 2), 160 m (VES 3) and 200 m (VES 4). Depth of investigation is normally between 0.3 and 0.5 of the maximum AB/2 distance.

The one-dimensional conductivity models obtained at the 4 locations are shown in Figure 3. Two types of model are used. A conventional 'discrete layer' inversion model is indicated by the dotted line with infill. This model assumes a discontinuous (layered) conductivity profile. A regularised 'minimum-structure' inversion model is indicated by the 'many-layer' single line. This form of modelling procedure forces the profile to be smoothly varying. The two types of modelling are discussed by Constable et al. (1987). The regularised models indicate that the most conductive parts of the profiles occur between 30 and 60 mbgl (VES sounding sites 1,2 and 3) and between 50 and 70 mbgl (VES sounding site 4). The most conductive zone in the models is that at VES sounding 3 (66 mS/m). The discrete layer models indicate transitions to a highly conductive zone at depths of : 17.3 m (VES 1), 12.6 mbgl (VES 2), 13.8 mbgl (VES 3) and 31.8 mbgl (VES 4). These depths are similar to the depths to the water levels in the nearest boreholes as indicated in the plot.

When comparing VES results with the results from borehole geophysical logging the distances between the centre of the VES sounding and the borehole locations should be noted. Distances range from 145 m (VES 1 to BH 1), 51 m (VES 2 to BH 2), 152 m (VES 3 to BH 2) and 280 m (VES 4 to BH 3). The ground geophysical programme confirmed that the high conductivity zone observed in the airborne conductivity data was genuine and that it was associated with depths within the aquifer.

BOREHOLE DRILLING PROGRAMME

The three boreholes sites (Fig. 2) were selected to provide information on hydraulic gradient and to recover core for pore water extraction. The boreholes were drilled using rotary-cored air flush and a temporary plastic casing was installed to prevent the upper twelve metres of unconsolidated material running into the hole. Table 1 provides details of the borehole locations and calculated elevations.

A suite of borehole geophysical logs was also run including gamma, resistivity, induction (formation conductivity), temperature and fluid electrical conductivity (EC). Using the induction log, which is a better indication of formation conductivity changes than the EC log, intervals of core were selected for pore water extraction by centrifugation. The pore waters were preserved and analysed for major and minor elements by ICP-AES.

Background geochemical information for producing groundwater wells was obtained from the Environment Agency. Thoresby Colliery permitted access onto their site to sample a borehole used to abstract process water and the settlement lagoons where process water and mine drainage are allowed to settle before discharge. For health and safety reasons it was not possible to sample the highly conductive lagoon feature indicated by the highest conductivities in Figure 2.

Lithological Description

Figure 4 provides an example (Thoresby 1) of the lithological logging of the boreholes. In general core recovery was of the order of 90%. In all three boreholes the upper part of the sequence consisted of soft sand with occasional pebbles. This is considered to be the weathered top to the underlying sandstone. The sequence is dominated by laminated and bedded pebbly sandstone. Because of the highly conductive nature of the sandstones due to pore fluid composition it has not been possible to interpret the resistivity log in terms of porosity or sand content.

The sandstones show a range of lithologies ranging from dominantly medium and coarse grained light brown to dark reddish brown sandstones to coarse granular moderate reddish brown to dark reddish brown pebbly sandstones. Sub-rounded to well-rounded, flat, elongate discoid and oblate pebbles range in size from 10 to 50mm and consist predominantly of quartzite. The sandstones are often bedded and occasionally bedding plane surfaces are micaceous. In borehole Thoresby 1 the sandstone becomes thinly laminated with micaceous partings between 24 and 34 mbgl.

The natural gamma log indicates that some mudrocks are present in the sequences. In general these were not recovered during coring. In Thoresby 1, a gamma peak is associated with the laminated sandstone sequence that has higher clay content than the sandstones and pebbly sandstones in the rest of the sequence.

Groundwater flow direction

Based on the data provided in Table 1 the hydraulic gradient is 0.0203 on an azimuth of 91.6°. The elongated shape of the conductivity anomaly is consistent with flow in this direction, away from Thoresby Colliery, of a dissolved contaminant plume. The temperature and electrical conductivity logs of the well bore fluid are reproduced in Figure 5. On the whole, the flow appears to be homogeneous in boreholes Thoresby 1 and Thoresby 3. In Thoresby 1 at around 45 mbgl there is a very slight increase in temperature and a reduction in fluid EC that possibly corresponds to a slight increase in flow at that depth. In Thoresby 2 the pattern is different and there is inflow at around at 25 and 27 metres that may be fissure controlled, or alternatively due to a perched condition of different composition on the postulated mudstone band at around 25 metres. The main body of the contaminant plume is below 27 metres.

HYDROCHEMISTRY

Sections of core and unconsolidated sand were selected from each borehole for pore water extraction; core selection was based on features seen on the induction logs. Three other water samples were obtained from Thoresby Colliery. These were a sample of borehole water that is used for processing on the colliery site and that is completed in the Sherwood

Sandstone (BGS Well Record SK66 NW /30), a sample from the Storm Tank, and a sample from the final settlement pond.

Background Water Quality

In order to determine the impact of the colliery spoil on groundwater quality it has first been necessary to establish the background hydrochemistry of the Sherwood Sandstone in the vicinity of the site.

Hydrochemical information has been provided by the Environment Agency (EA) for a number of production boreholes completed in the Sherwood Sandstone. Table 2 provides details of the EA monitored boreholes used in this study.

The Durov Plot in Figure 6 illustrates the compositional range of these groundwaters. Kirton and Boughton boreholes are on the down gradient side of the site and the Budby boreholes are on the up gradient side of the site. The water types classify as a Ca-Mg-HCO₃-Cl type.

Source Term Water Quality

A literature search has provided information on colliery spoil leachate quality for tips in neighbouring Derbyshire and Yorkshire areas, (Banks et al., 1997). This study demonstrated that mine waters in general are characterised by low chloride (typically between 10 and 40mg/l), unlike colliery spoil leachates that tend to have chloride concentrations in excess of 1000 mg/l. These values are in sharp contrast to Coal Measure formation brines reported by Downing and Howitt, (1969) with chloride concentrations in excess of 14000 mg/l.

Although it was not possible to collect any leachate from the Thoresby spoil tips two process-water samples were collected. This water derives from borehole water that is used in dust suppression and coal washing. Effluents are first led to a concrete bunded storm tank where some settlement occurs and finally to a lagoon where some of the water is recirculated into the processing loop. The main feature of the storm tank effluent is high potassium and high chloride concentration, reduced iron of 5 mg/l and aluminium below detection, values more typical of diluted formation water. The effluent is net alkaline with a pH of 7.17.

Plume hydrochemistry

The chemical profiles for the three investigation boreholes are presented in Figures 7a, 7b and 7c. The profiles selected are the induction log, which gives a good representation of the formation conductivity, total dissolved solids (TDS), (i.e. the sum of anions and cations), and chloride. It is evident from the plots that in all three cases the plot of chloride mirrors the induction log most closely. This is expected, as chloride is the main contributor to the TDS. In Thoresby 1 the induction log and the chloride concentration confirm that a chloride plume occupies the whole water column, the maximum concentration is about 450 mg/l. In borehole Thoresby 2 (Fig. 7b) the chloride/TDS contaminant plume shows an increase in concentration at about 20mbgl and the overall shape of the curve suggests some density stratification. Maximum chloride concentration is 1083 mg/l.

Thoresby 3 borehole (Fig. 7c) has a distinct profile with a pronounced chloride plume in both the unsaturated and saturated zones. In the unsaturated zone chloride concentration gradually increases to 1165 mg/l near the water table where it rapidly drops off. This feature is believed to be related to road salting run off rather than infiltration of colliery spoil leachate as this borehole is very close to the main road. There is also high total organic carbon and ammonium content suggesting a possible anthropogenic source. In the saturated zone the contamination appears to occur as a lens at about 35mbgl with a maximum concentration of 857mg/l chloride.

Evidence for a colliery spoil impact on groundwater

As well as the high chloride a number of other chemical parameters indicate a colliery spoil leachate source for the dissolved plume in particular barium, potassium and sulphate. The latter two ions occur at concentrations in excess of background.

Figure 8 shows a Durov plot for Thoresby 2. The plot summarises the average major element composition for the Environment Agency boreholes (shown in Figure 6), data on colliery spoil leachates from the paper by (Banks et al., 1997), the chemistry of the Thoresby Colliery production well, and the chemistry of the pore water fluids for each borehole. A close inspection of the plot indicates that the pore water chemistry tends to fall in a field defined by the colliery spoil samples with some overlap with the background wells. The results for boreholes 1 and 3 display similar behaviour. Thus there is strong supporting evidence that the groundwater in the Thoresby boreholes is a mixture of a colliery spoil type and typical Sherwood Sandstone groundwater. The Thoresby Colliery production borehole tends to fall within the field of the pore waters indicating some impact from the colliery due to increased chloride and sulphate.

The anions chloride and bromide are generally considered to behave conservatively, i.e. they do not undergo attenuation processes in the aquifer matrix. Since the only effect of the aquifer flow on the colliery leachate is dilution, the ratio of chloride to bromide should remain constant.

Figure 9 shows the chloride/bromide ratio profile obtained at the Thoresby 2 borehole. The vertical red dashed line at 100 corresponds to the process waters analysed from the colliery site. It is evident that the chloride/ bromide ratio in the plume (as indicated by the chloride profile also shown on the plots) is strikingly constant at around 100. Similar behaviour was observed in the ratios at the other two investigation boreholes.

COMPARISON OF RESULTS

The ground VES and borehole geophysical investigations together with the geochemical results obtained from borehole core samples allow further inter-comparisons to be made. Such results may also be compared with vertical profile estimates of the conductivity distribution obtained from the airborne data.

Thus far the information obtained from the AEM data has been displayed as half-space conductivity models at each of the two frequencies currently available. The information essentially forms a conductivity distribution map. The full nature of the data and the models pertaining to them is, however, intrinsically volumetric. The higher frequencies probe a shallower volume than the lower frequencies. With multi-frequency EM data it is always possible to construct multi-layer models. This can be undertaken even with only two

frequencies but the vertical resolution must be acknowledged to be limited. A variety of mathematical modelling experiments have been carried out to optimise the procedures (regularised inversion) for the type of data and targets under consideration.

Figure 10 shows the conductivity distribution obtained along a single E-W flight line that passes close to BH02. The cross-section is limited to 1 km in length between Eastings of 464000 and 465000 m. The cross-section is constructed by stitching together the one dimensional models obtained along the profile.

The conductivity distribution is contoured between the limits of 10 and 50 mS/m. Values in excess of 50 mS/m are shown in white. Within the area of the mine, at-surface mineral spoil provides conductivity values in excess of 100 mS/m and the airborne data are unable to resolve any subsurface structure. To the east of the mine, the highly conductive zone (> 50 mS/m) is resolved within the upper aquifer below the more resistive unsaturated zone.

The vertical profile obtained from the airborne data in the vicinity of BH02 is compared with corresponding ground based information in Figure 11. Figure 11a shows the regularised (smooth) airborne conductivity model. It should also be noted that the airborne model is obtained across a large area footprint that, in this case, is of order 50 x 50 m (Beamish, 2003). Figure 11b shows two equivalent models (one smooth and one layered) obtained from the VES 02 sounding. The borehole induction conductivity log from BH02 is shown in Figure 11c. The borehole tool is inaccurate at low conductivities (< 2 mS/m) so that, in this case, information is obtained only below 16 m (below the water table depth of 12.8 m). Comparing the airborne and ground geophysical models (Figures 11a and 11b), it is evident that the airborne model cannot resolve the true low conductivities associated with the unsaturated zone. This is a limitation of the frequency range of the airborne instrumentation. It is also evident that the borehole induction tool cannot resolve the true low conductivities due to technical limitations. The chloride profile obtained from pore fluids in the core samples of BH02 is also shown for reference in Figure 11d.

SUMMARY AND CONCLUSIONS

A trial airborne EM (AEM) survey was carried out across a 13 x 9 km area of the northern Nottinghamshire (UK) coalfield. One of the objectives was to examine the influence of collieries situated above the Triassic Sherwood Sandstone aquifer. The conductivity models obtained from the AEM survey revealed extensive zones of enhanced subsurface conductivity in the vicinity of all the collieries in the survey area.

An area to the east of one of the active collieries (Thoresby) was selected for further investigation by ground geophysics, borehole logging, core sampling and geochemical analysis of the pore fluids obtained from the core. The ground geophysical programme confirmed that the high conductivity zone observed in the airborne conductivity data was realistic. The vertical electric soundings provided greater depth discrimination than the airborne data and they confirmed that the conductive zone was associated with the saturated zone of the aquifer.

Three boreholes sites were selected to provide information on hydraulic gradient and to recover core for pore water extraction. A suite of borehole geophysical logs was obtained including gamma, resistivity, induction (formation conductivity), temperature and fluid electrical conductivity (EC). The rest water levels indicated a hydraulic gradient of 0.0203 on an azimuth of 91.6° . The elongated shape of the conductivity anomaly is consistent with flow in this direction, to the east of Thoresby Colliery.

Geophysical logs and borehole geochemistry have further identified the nature of the geophysical anomalies at the three borehole locations. The geophysical logs demonstrate that there is a very strong correlation between the borehole induction logs (formation conductivity), total dissolved solids and chloride in the pore waters.

Although spatially variable, the plume appears to occupy a substantial fraction of the water column, to depths of the order of 60 m. The maximum chloride concentration observed exceeded 1000 mg/l. The geochemistry of the borehole pore fluids was compared with background aquifer water values in the vicinity of the site and with process water samples obtained from the mine. The plume is characterised by being net alkaline with chloride concentrations falling somewhere between typical Sherwood Sandstone Group, background water compositions and fluid chemistry more typical of colliery spoil leachates. The results indicate that the chemistry of the pore waters could result from the mixing of a typical Sherwood Sandstone composition with a colliery spoil leachate. Weight is added to this interpretation by the fact that the chloride/ bromide ratio in the plume is very similar to the process water Cl/Br ratio found at the Colliery.

In conclusion we note that the AEM conductivity models have been successfully correlated with ground-based VES models, borehole induction logs, total dissolved solids and chloride in the pore waters. The correlation has been performed in the vicinity of one, active colliery. By implication, the geophysical results obtained over a larger area (e.g. Fig. 1) indicate the wider extent of such impacts in relation to both former and current mining activities.

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Table 1 Borehole Details. Coordinates are British National Grid (m).

Borehole	Easting	Northing	Elevation (m aod)	Water Level (m bgl)	Date Dipped
Thoresby 1	64182	67345	53.38	15.99	7/04/03
Thoresby 2	64591	67664	48.76	12.80	7/04/03
Thoresby 3	64223	60064	61.92	25.40	8/04/03

Table 2 Environment Agency boreholes used for background information. Coordinates are British National Grid (m).

EA Reference	Name	Data used	Easting	Northing
39480880	Budby Forest	12/12/95- 21/3/01	60400	70700
39480870	Budby	10/10/88	61700	70704
39770700	Kirton	24/7/92-28/1/03	68300	68800
38480450	Boughton	13/6/75-12/6/95	67000	69800

Figure Captions

Figure 1. High frequency (14 kHz) AEM conductivities (mS/m) across 13 x 9 km Shirebrook area in northern Nottinghamshire. Only values above 20 mS/m are contoured. Values above 100 mS/m are shown with no infill. Letters denote collieries described in the text.

Figure 2. High frequency (a) and low frequency (b) AEM conductivities (mS/m) across 3 x 2 km Thoresby colliery site. Only values above 20 mS/m are shown. Values above 70 mS/m are shown in cross-hatch. Values above 200 mS/m are shown in black. Area to the east of the mine contains locations of 3 boreholes (BH01, BH02 and BH03) and 4 VES sounding locations (star symbols).

Figure 3. 1D conductivity models obtained at Vertical Electric Sounding sites (a) VES 01, (b) VES 02, (c) VES 03 and (d) VES 04. Dotted line with infill denotes a few layer conventional model, line without infill is a smooth model fit to the observed data. Horizontal line with arrowheads indicates water level in nearest borehole.

Figure 4. Lithological and geophysical gamma-ray log obtained from borehole BH01.

Figure 5. Temperature (deg. C) and fluid conductivity (EC in $\mu\text{S}/\text{cm}$) logs at (a) BH01, (b) BH02 and (c) BH03.

Figure 6. Durov plot of hydrochemistry of 3 Environment Agency monitoring wells. Budby = square, Boughton = diamond and Kirton = cross symbols.

Figure 7. Lithology, induction log (formation conductivity S/m), TDS (meq/l) and chloride (ppm) for (a) BH01, (b) BH02 and (c) BH03.

Figure 8. Durov plot of hydrochemistry of BH02 (crosses) compared with that of background waters (squares), Thoresby Colliery borehole (diamond) and colliery spoil leachates (circles).

Figure 9. The weight ratio of Chloride/Bromide (line with diamond symbols) for BH02 with reference to the value (100) obtained from colliery waters. The depth of the water table (solid triangle) and the behaviour of the chloride profile are also shown.

Figure 10. Conductivity cross-section (1 km x 60 m) obtained across an E-W flight line traversing the mine and BH02. Values in mS/m with values > 50 mS/m in white.

Figure 11. Comparison of vertical profiles of information obtained for BH02. (a) Smooth conductivity model obtained from AEM data (mS/m), (b) smooth (single line) and discrete (line with infill) VES conductivity models (mS/m), (c) induction log (formation conductivity in mS/m) and (d) chloride (ppm). Horizontal dash line indicates water table in BH02.

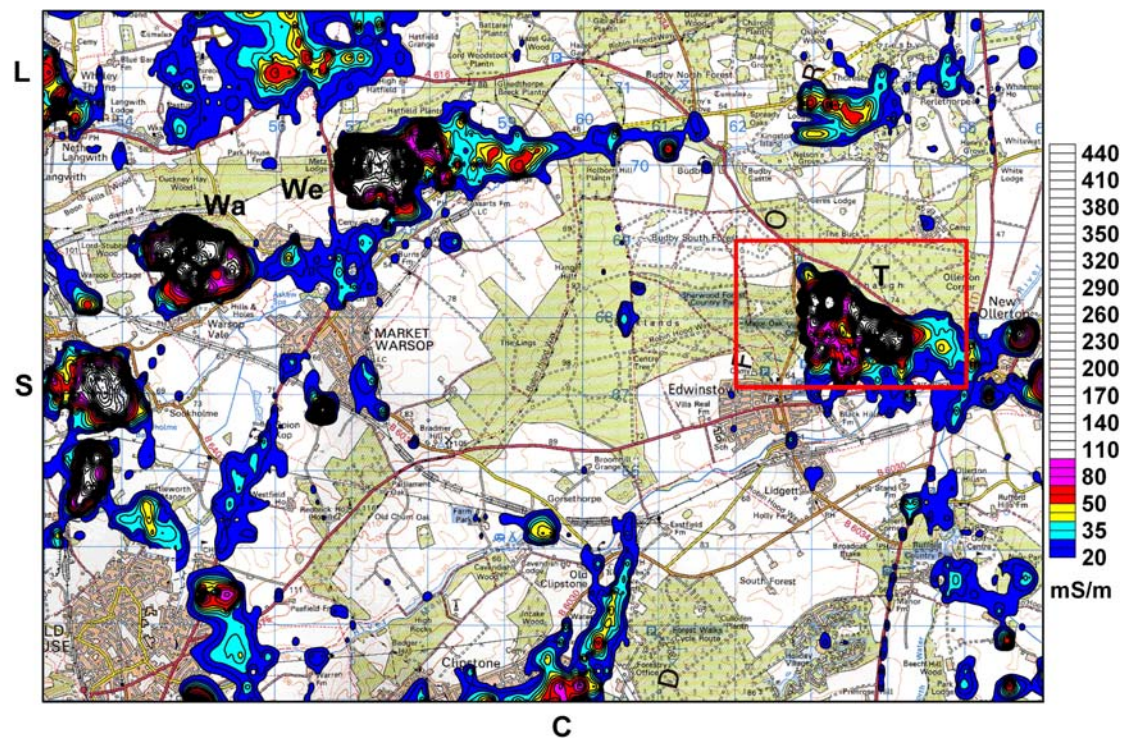


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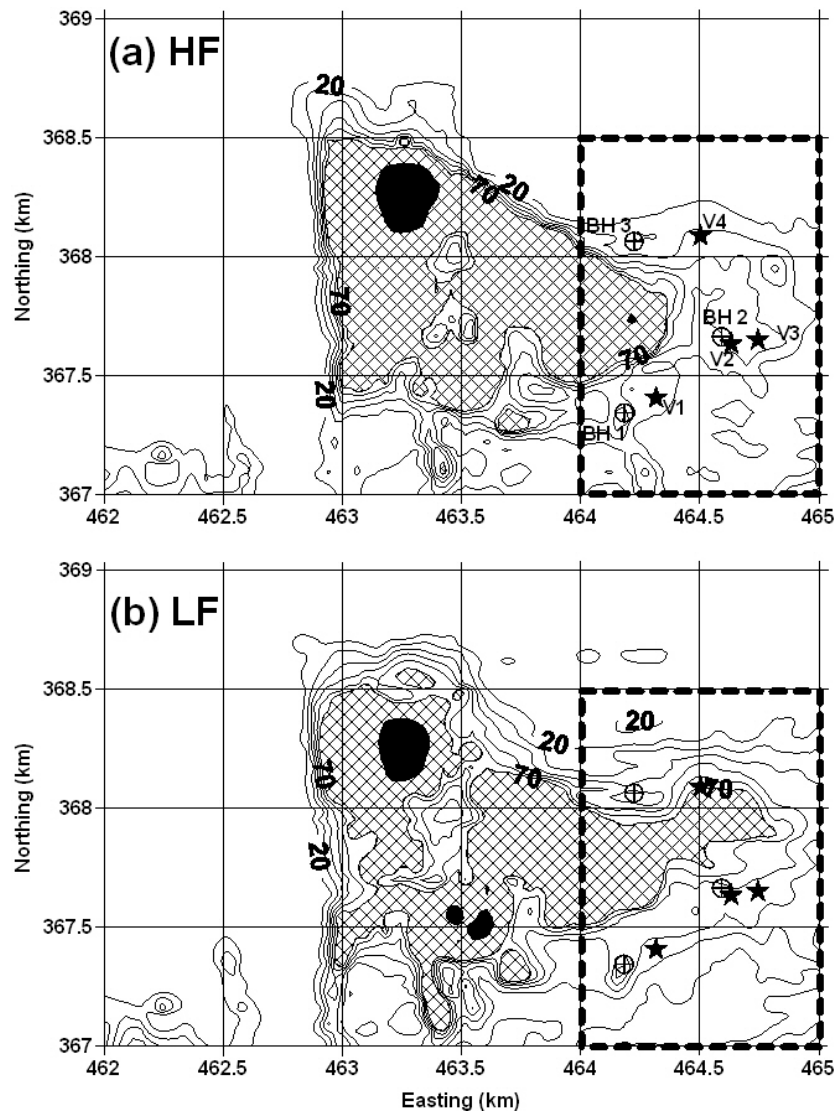


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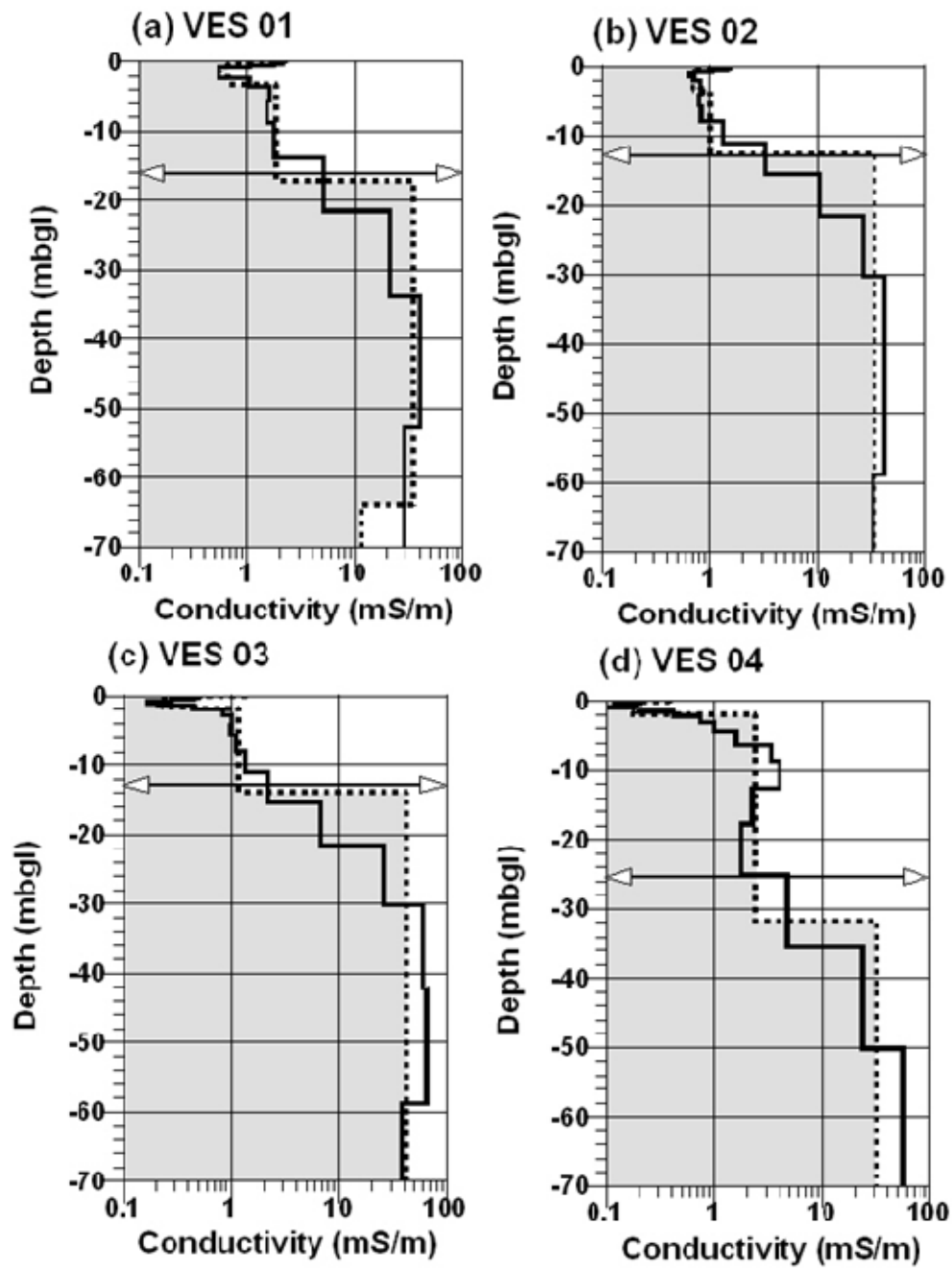


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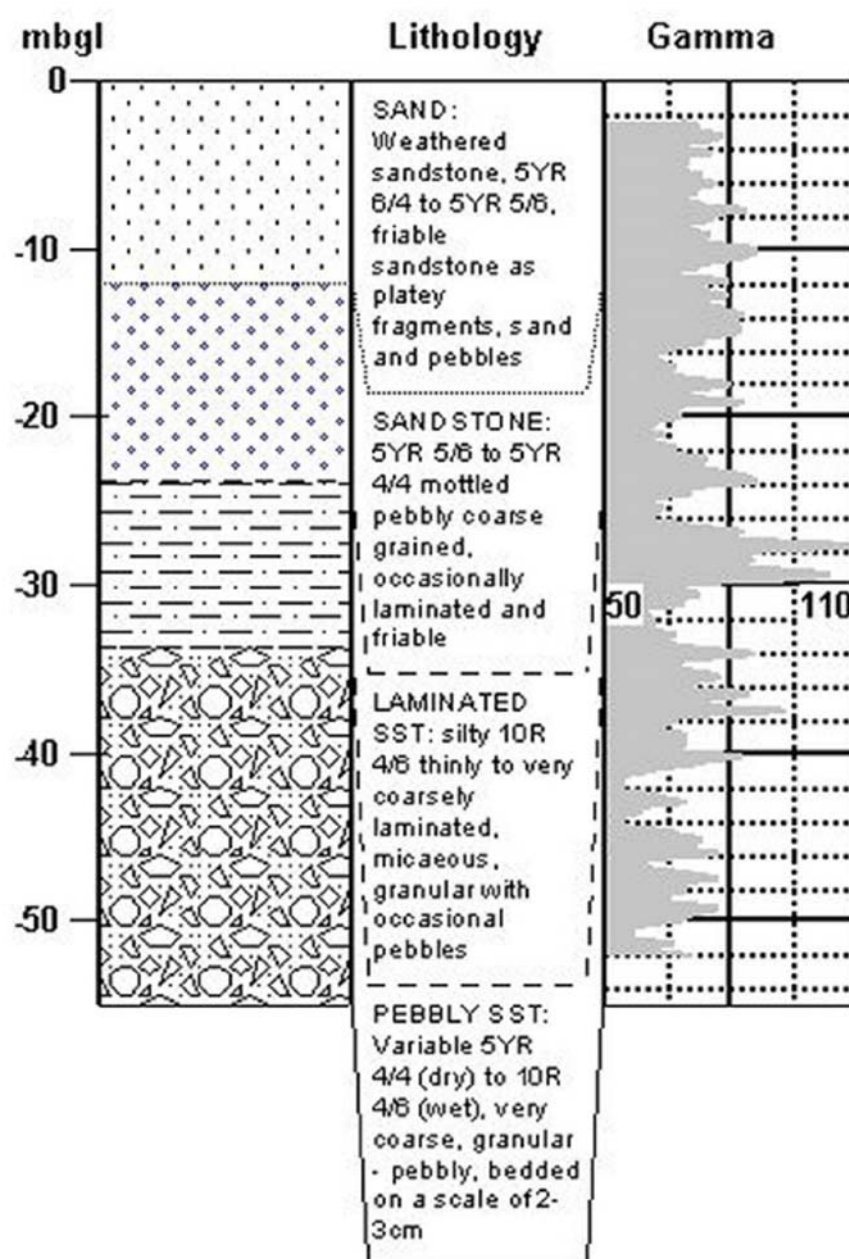


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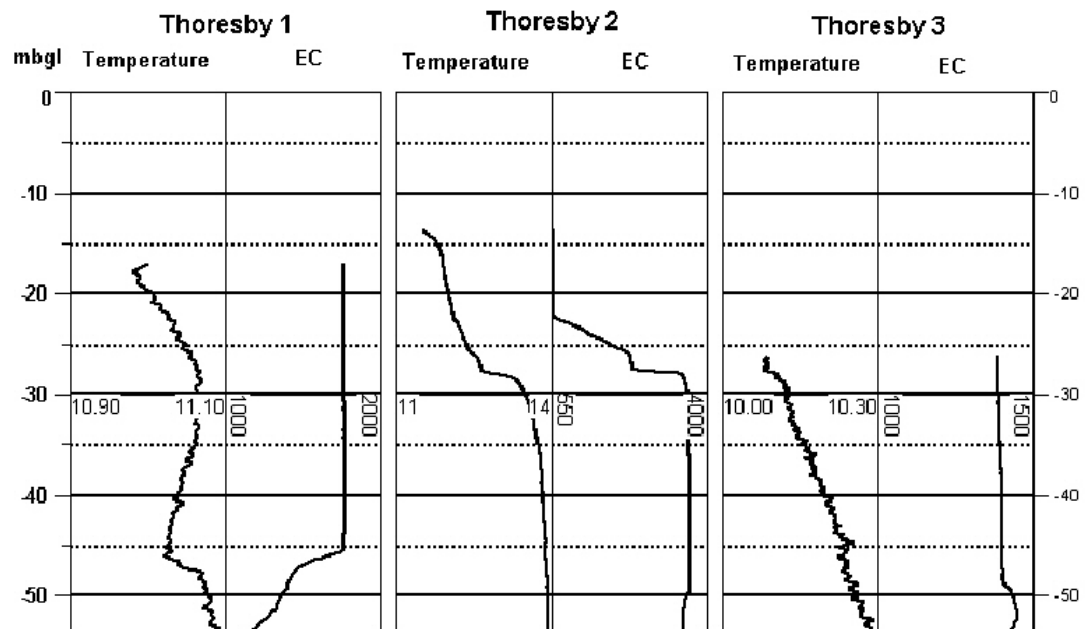


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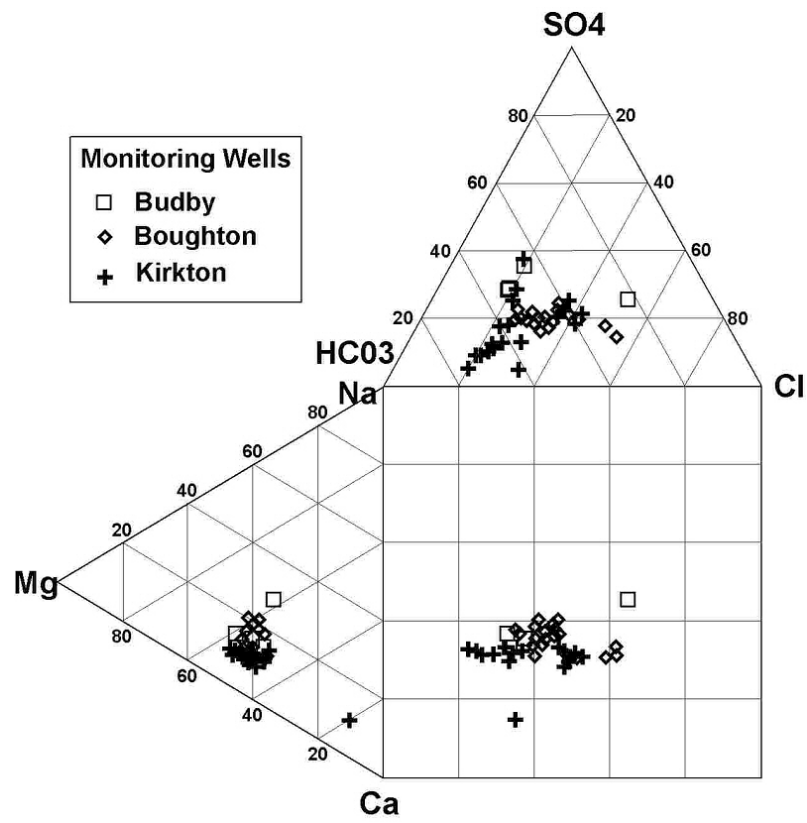


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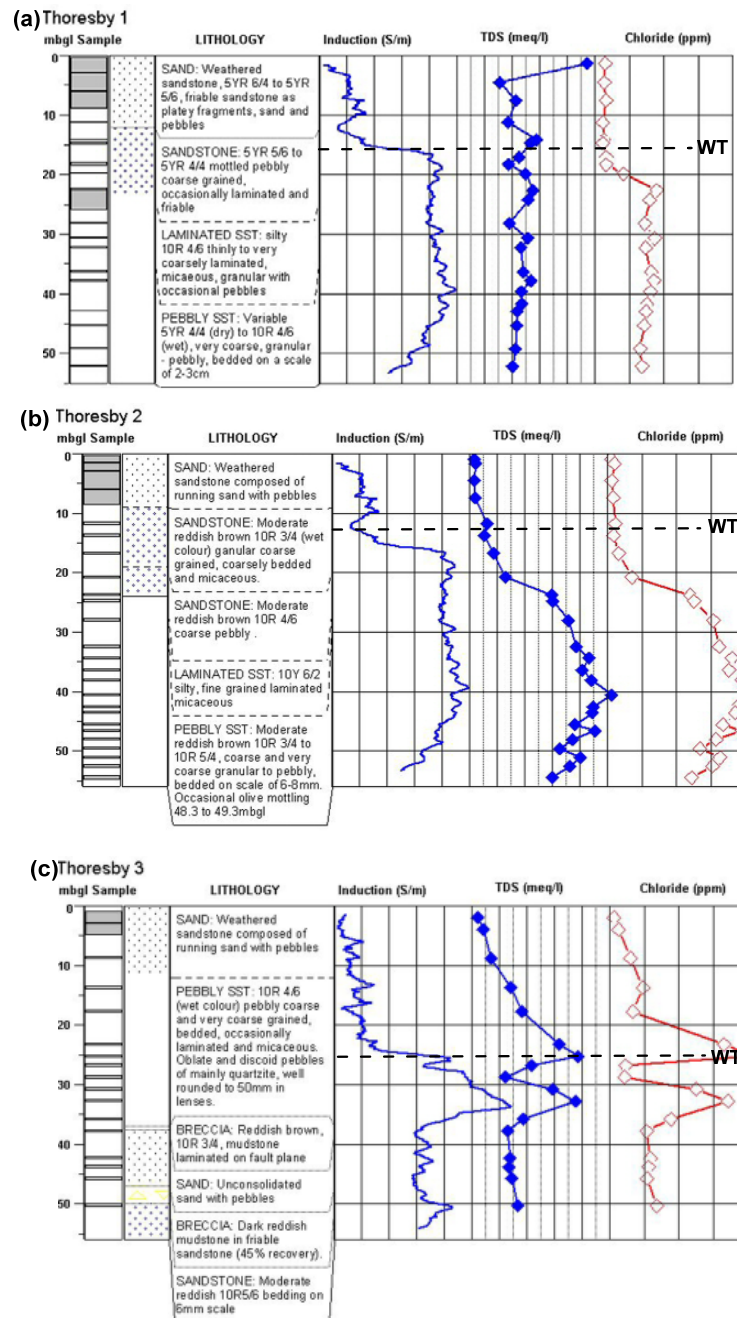


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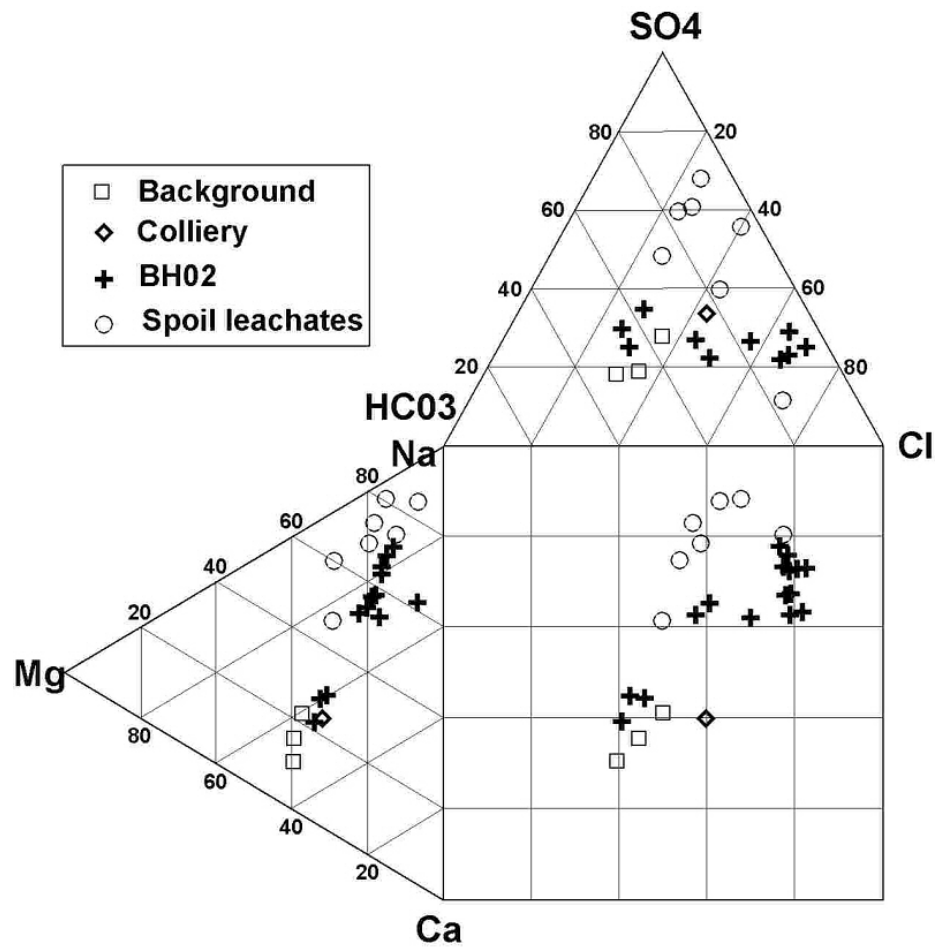


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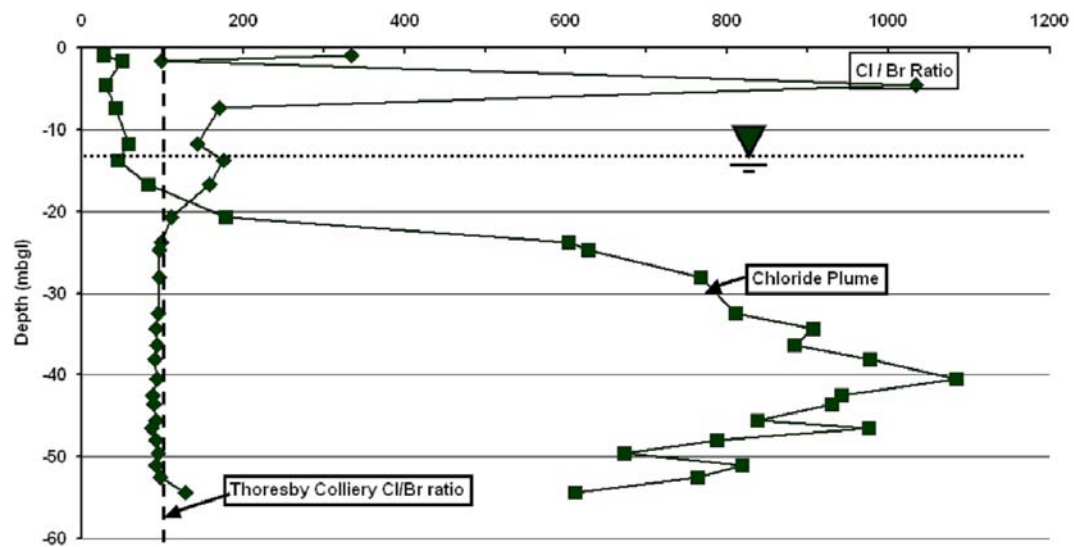


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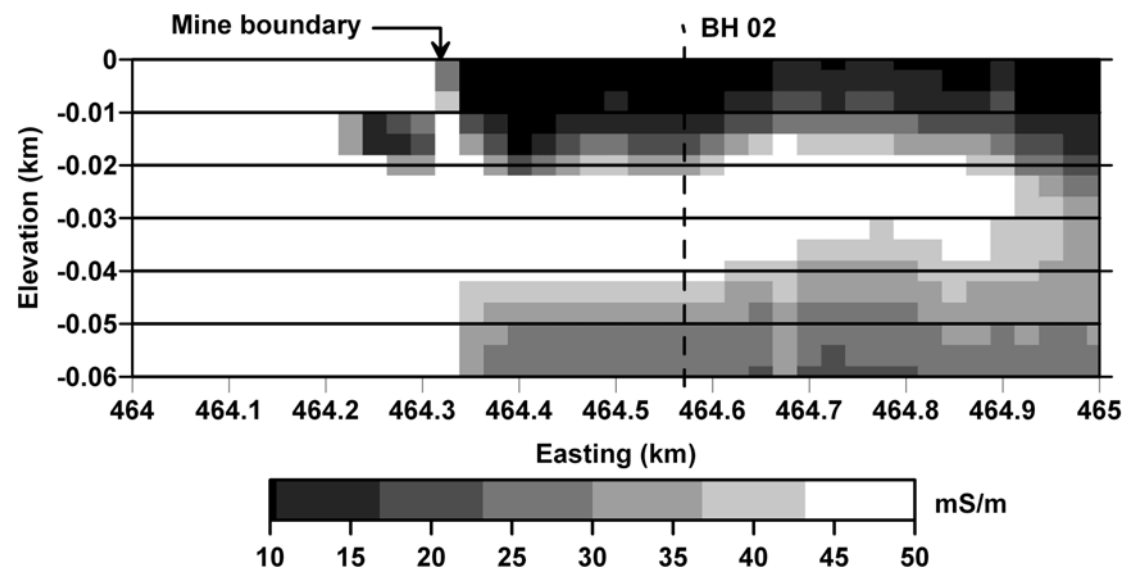


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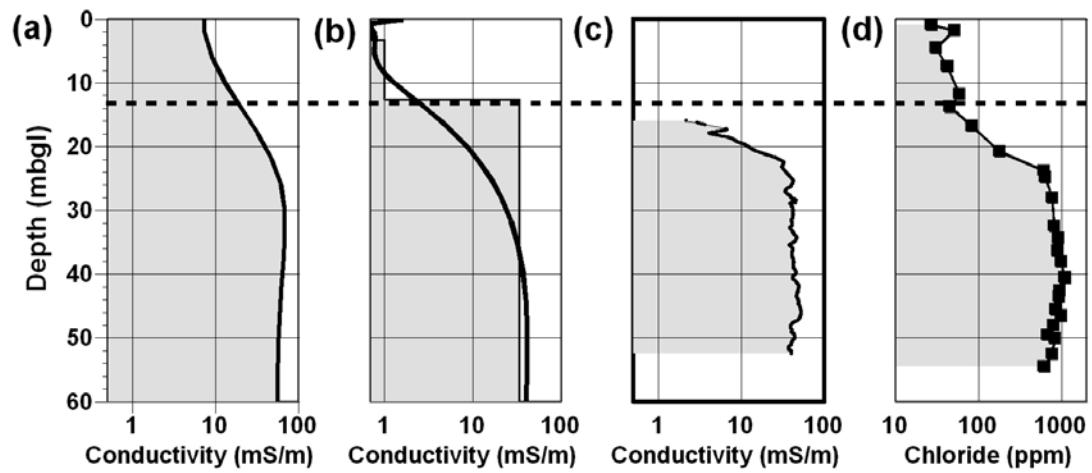


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