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ENVIRONMENTAL APPLICATIONS OF AIRBORNE GEOPHYSICS – GROUNDWATER AND CONTAMINATED SOIL IN FINLAND, GERMANY AND UNITED KINGDOM

by
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The use of airborne geophysical data for environmental studies started in GTK already in the 1970s, but came into common use only in the late1990s. In recent years airborne data have been used successfully especially in environmental studies related to old mines and old mining districts, groundwater and soil contamination. This paper presents five studies where GTK's airborne data have been successfully applied for environmental and groundwater investigation purposes.

In the section *"Airborne methods in groundwater studies in Finland"* Heikki Vanhala and Annina Mattsson discuss the use of airborne electromagnetic (AEM), magnetic and radiometric data for studying bedrock aquifers and groundwater areas related to glaciofluvial formations. Jouni Lerssi presents a case *"Mapping a waste-water pond – a case from Lievestuore, central Finland"*, in which AEM data were used for mapping and characterising a large wastewater (sodium lignosulphonate) pond and its surroundings. An example of site monitoring using airborne data is given by Mari Lahti. Her contribution *"Landfill monitoring at Ämmässuo, southern Finland"* is based on airborne measurements conducted in 1984, 1993, 1997 and 1999 over the Ämmässuo municipal landfill. The contribution related to abandoned mines "*Mapping the environmental risks of a wide contaminated site – results from a mining region in eastern Germany*", by Mari Lahti, discusses the use of airborne gamma-ray surveys in mapping an old uranium mining district and in monitoring radiation levels. She also presents a case of integrated use of radiometric and magnetic data in mapping an old black coal mining area and a case of the combined use of magnetic and ground resistivity data for mapping impacts of nickel mining and smelting. The last contribution *"Environmental applications of the GTK AEM data in the UK",* by David Beamish, is based on AEM data from four areas in the East Midlands, in the UK. Two sites, the area of the Thoresby coal mine, and municipal landfills in the Langar area, are discussed in detail.

Key words (GeoRef Thesaurus, AGI): geophysical methods, airborne methods, environmental geology, ground water, aquifers, waste lagoons, landfills, mining, soils, pollution, Finland, Germany, Great Britain

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INTRODUCTION

Airborne geophysics has a long record of success in mineral exploration in Finland, as discussed by Hyvönen et al. and Turunen et al. in this volume. Although the use of airborne data for non-mineral exploration activities started in the early 1970s, environmental applications came into common use only in the late 1990s. One of the early applications outside the mining industry was that of measuring snow-water equivalent by gamma-ray spectrometry (Peltoniemi et al. 1978, Peltoniemi & Kuittinen 1978). In the 1980s, within the nuclear waste disposal studies, airborne data were utilised in site selection studies (Kukkonen 1984, Saksa & Silvennoinen 1989), for estimating the thickness of peat lands (Vironmäki et al. 1989), and for soil classification (Hyvönen et al. 1991, Sutinen et al. 1994).

The first applications related to groundwater are from the early 1990s (Mattsson & Salmi, 1991). In the pilot study carried out in the Virttaankangas – Oripäänkangas groundwater area the radiometric and EM methods were particularly important in mapping the large esker area (Harittu et al. 1993). In the present paper, two cases of the use of airborne data for investigating glaciofluvial and bedrock aquifers are discussed, firstly an active pilot study from the Kempele groundwater area (Valjus et al. 2004) and then a new application where the AEM data have been used for mapping a "buried esker", i.e., clay and silt covered sand-gravel deposit (Vanhala et al. 2003, Lintinen et al. 2003).

The study over the Rovaniemi municipal landfill was the first case in Finland, where the airborne electromagnetic (AEM) data were used for mapping contaminated areas and contaminant leaks (Sutinen et al. 1994, Jokinen & Lanne 1996). The study started when a weak AEM anomaly was found southeast of the landfill (Fig. 1.). Ground EM and chemical data proved that the conductivity anomaly originated from the landfill leakage. EM modelling techniques and integrated use of airborne data along with ground geophysical and other available data sets, have strongly increased the usefulness of AEM data for studies of landfills and other contaminated sites (Lerssi et al. 1997; Jokinen & Lohva 1998; Lerssi et al. 1998; Lohva et al. 1999; Lahti 1999; Vanhala et al. 2000; Lohva et al. 2001). In this paper, two special cases, the Lievestuore waste-water pond, and the airborne monitoring of the Ämmässuo landfill, are discussed in detail. In an ongoing project, AEM interpretation and integrated use of ground and airborne data are developed for mapping extensive acid sulphate soil and sulphide clay areas in western Finland (Suppala et al. 2003, Vanhala et al. 2004). See also Fig.3.

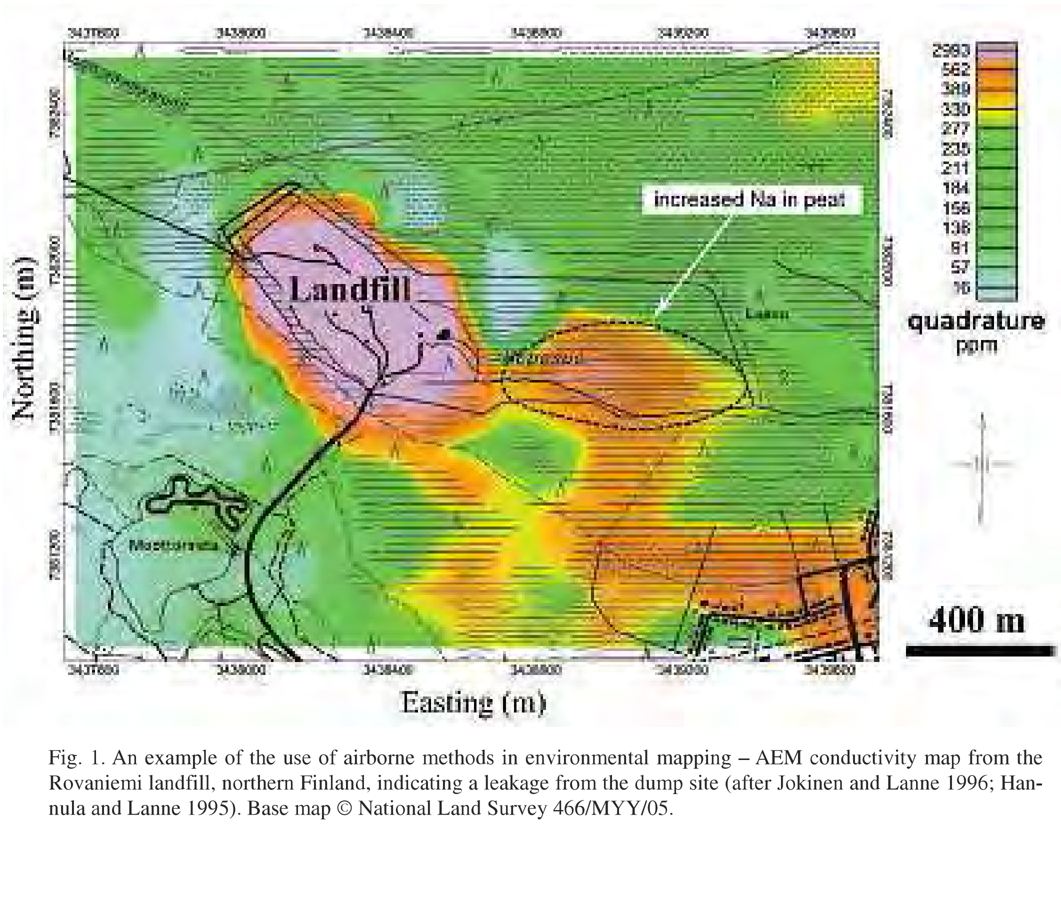

Fig. 1. An example of the use of airborne methods in environmental mapping – AEM conductivity map from the Rovaniemi landfill, northern Finland, indicating a leakage from the dump site (after Jokinen and Lanne 1996; Hannula and Lanne 1995). Base map © National Land Survey 466/MYY/05.

In recent years airborne data has been successfully applied to environmental impacts caused by mining. In these projects, carried out in various geological environments in Germany, England, Estonia and Finland, the importance of the multisensor system – i.e., simultaneous acquiring of EM, magnetic and radiometric data – has been emphasised. In Germany, the most striking results were related to radiometric data – a study over an earlier uranium mine area in Eastern Germany detected, not only the old mines and tailings ponds, but also leaks from mining areas and areas contaminated when transporting and processing the ore (Lahti & Vanhala 2000, Lahti et al. 2000a and 2000b, Lahti et al. 2001). In England, EM data has successfully been used for mapping subsurface pathways of acidic and conductive mine waters (Beamish and Kurimo 2000). In the latest project over the oil shale mining area of Estonia, both the magnetic and EM data were of great use (Vanhala et al. 2002). In this paper the German and English cases are discussed in detail.

AIRBORNE METHODS IN GROUNDWATER STUDIES IN FINLAND

Introduction

Today, practically all significant groundwater projects in Finland start with the interpretation of the airborne data – the major geological units, fractured bedrock zones and, for example, the distribution of clay-covered areas are mapped before the more detailed investigation plans are made. Glaciofluvial sand and gravel formations are the most important aquifer types in Finland. Although they are in most cases uniformly distributed, there are also regions in which they are absent. In these areas, the fractured bedrock aquifers can be important for household and municipal water supply.

The airborne magnetic data provide information especially about the fracturing of the crystalline bedrock (Lanne et al. 1998, 2002) but it is also utilised for mapping geological structures. For example, the presence of graphite and sulphide bearing schists and gneisses unsuitable for good-quality bedrock groundwater are routinely mapped by airborne magnetic and AEM data. The use of AEM data is today strongly increasing due to the improved means of interpretation, i.e., high-quality two-frequency data together with modern inversion and modelling techniques. Two cases are discussed here in detail – a present groundwater study from Kempele, western Finland, and a study from Ilmajoki where AEM techniques were used for mapping gravel-sand formations buried by conductive clay-silt sediments.

The Kempele study

Figure 2 (after Valjus et al. 2004) is an example from a pilot study carried out at the Kempele groundwater area. Kempele is situated near Oulu in western Finland. The study area differs from the typical Finnish geology by being a part of the Muhos formation (Fig. 2). The Muhos formation is up to one-kilometre deep graben-like structure filled with Vendian – Jotnian (0.6–1.2 Ga) sedimentary clay- and siltstones. The surrounding bedrock consists of Precambrian crystalline rocks. The sedimentary rocks of the Muhos formation are covered by 10–100 m thick layer of Quaternary glacial sediments such as till, gravel, sand and postglacial clays, silts and sulphide bearing sediments. Due to isostatic land uplift the study area rose above the sea level 800 – 2000 years ago and the older sediments were covered by littoral sands and fine sands.

The objective of the survey was to provide information on the structure and distribution of the glacial sediments and on the topography and fracturing of the underlying crystalline bedrock for the water supply of the Kempele settlement. Airborne EM and magnetic data were used to map the major lithological units. The aeromagnetic data was useful by giving invaluable information about the fracture system of the crystalline bedrock near the contact of the

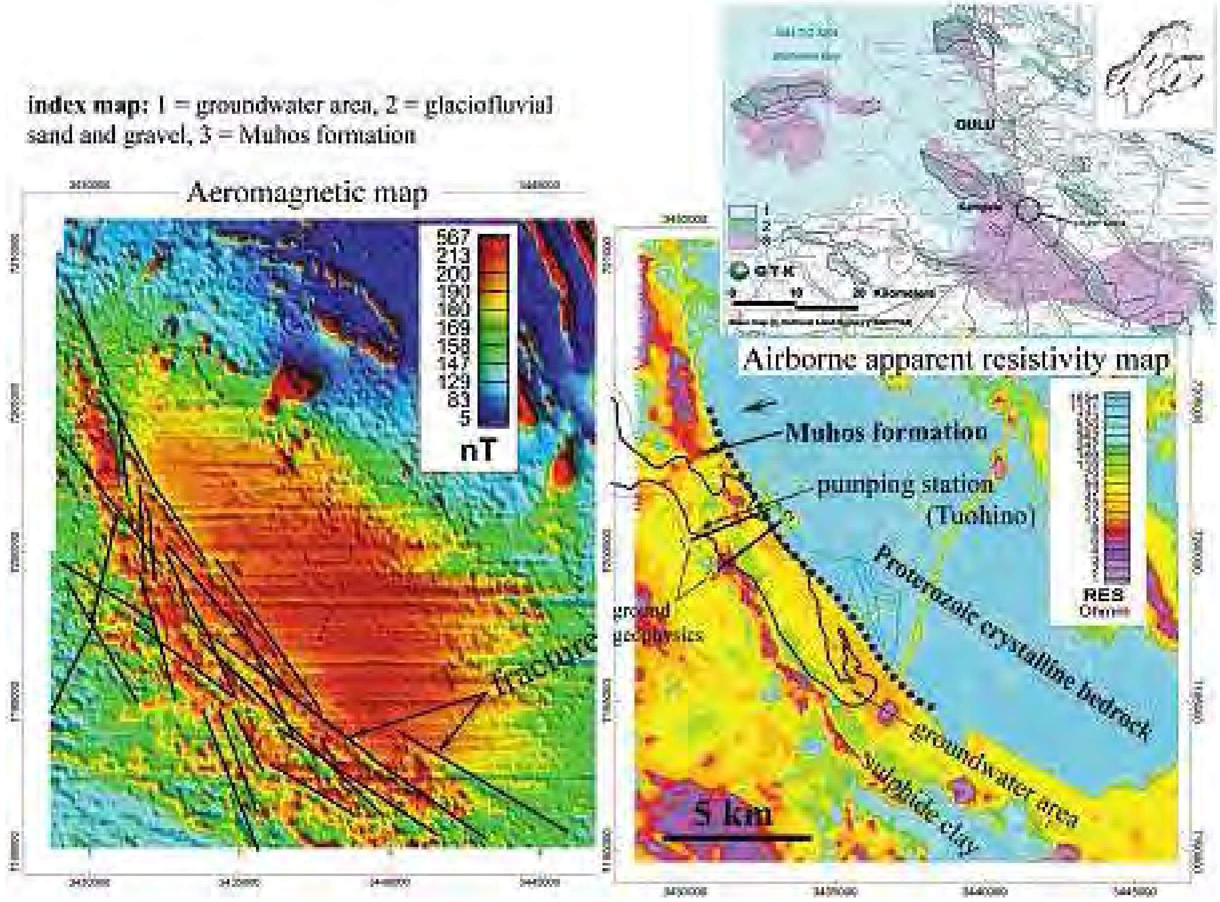

Fig. 2. Airborne magnetic and apparent resistivity maps from the Kempele groundwater area, western Finland (after Valjus et al. 2004). The fracturing of bedrock appears as linear minima in the aeromagnetic map. Base map © National Land Survey 466/MYY/05.

Muhos formation, while the AEM data was used for mapping the distribution of the low-resistivity clays and silts. The circular aeromagnetic anomaly in Figure 2 originates from a weakly magnetized granitic rock partly underlying the non-magnetic Muhos formation shales. The fracturing of the bedrock, as well as contact between granite and the Muhos formation, is clearly visible as linear magnetic minima in the magnetic map. The contact of the Muhos formation is also visible on the AEM map because of the conductivity contrast between the claystone and the granite (20–50 Ohmm and thousands of ohmimeters, respectively (Valjus et al. 2004). The highest conductivities in Figure 2 originate from shallow-depth marine sulphide clays.

The study strongly emphasised the importance of integrated use of different geophysical techniques in mapping thick Quaternary deposits. The role of the airborne data was extremely important by providing regional scale information on the crystalline and sedimentary bedrock structures as well as on the glacial deposits.

Ilmajoki “buried esker”

Glaciofluvial deposits are relatively uniformly distributed in Finland but there are also regions where they are absent. These regions are typically situated in low-lying coastal regions. There, lacustrine and glaciolackustrine deposits, up to several tens of metres in thickness, cover the glaciofluvial deposits.

An airborne survey, to test the applicability of AEM data for mapping buried ice-marginal deposits, was carried out in the Kyrönjoki river valley between Ilmajoki and Seinäjoki (Fig. 3) in southern Finland in 2002 (see Lintinen et al. 2003). The size of the flight area was 8x12 km^2. The landscape of the study area is typical for Southern Ostrobothnia having low-lying river valleys filled by lacustrine and glaciolackustrine sediments. Bedrock outcrops delineate the river valleys (see the geological map in Fig. 3). A few glaciofluvial deposits are found in the flight area. A small esker, running from northwest to southeast, is situated northwest of the Kyrönjoki river (Fig. 3). A sand deposit, about 0.15 x 1.1 km^2 in size (called Aavala by Kurkinen et al. 1992) outcrops through the water-laid sediments in the central part of the river valley. Based on the drilling data and seismic soundings, Kurkinen et al. (1992) have shown that the Aavala deposit is more extensive than the outcropped sand area (in Fig. 3 the Aavala sand-gravel deposit is close to line L-1). The true lateral extent of the Aavala sand deposit is, however, not known.

The idea of mapping buried glaciofluvial deposits by AEM measurements arises from the fact that the electrical resistivity of clay and other fine grained sediments is lower than the resistivity of sand and gravel deposits. The model calculations made by Huotari (Huotari 2002, Vanhala et al. 2002) suggest that GTK's AEM system is sensitive to detecting buried valley type deposits, i.e., high-resistivity bodies situated in low-resistivity ground. The size of the Ilmajoki flight area was 96 km^2 and the line spacing 100 metres (in total 903 line kilometres were measured). The nominal flight altitude was 30 m (median

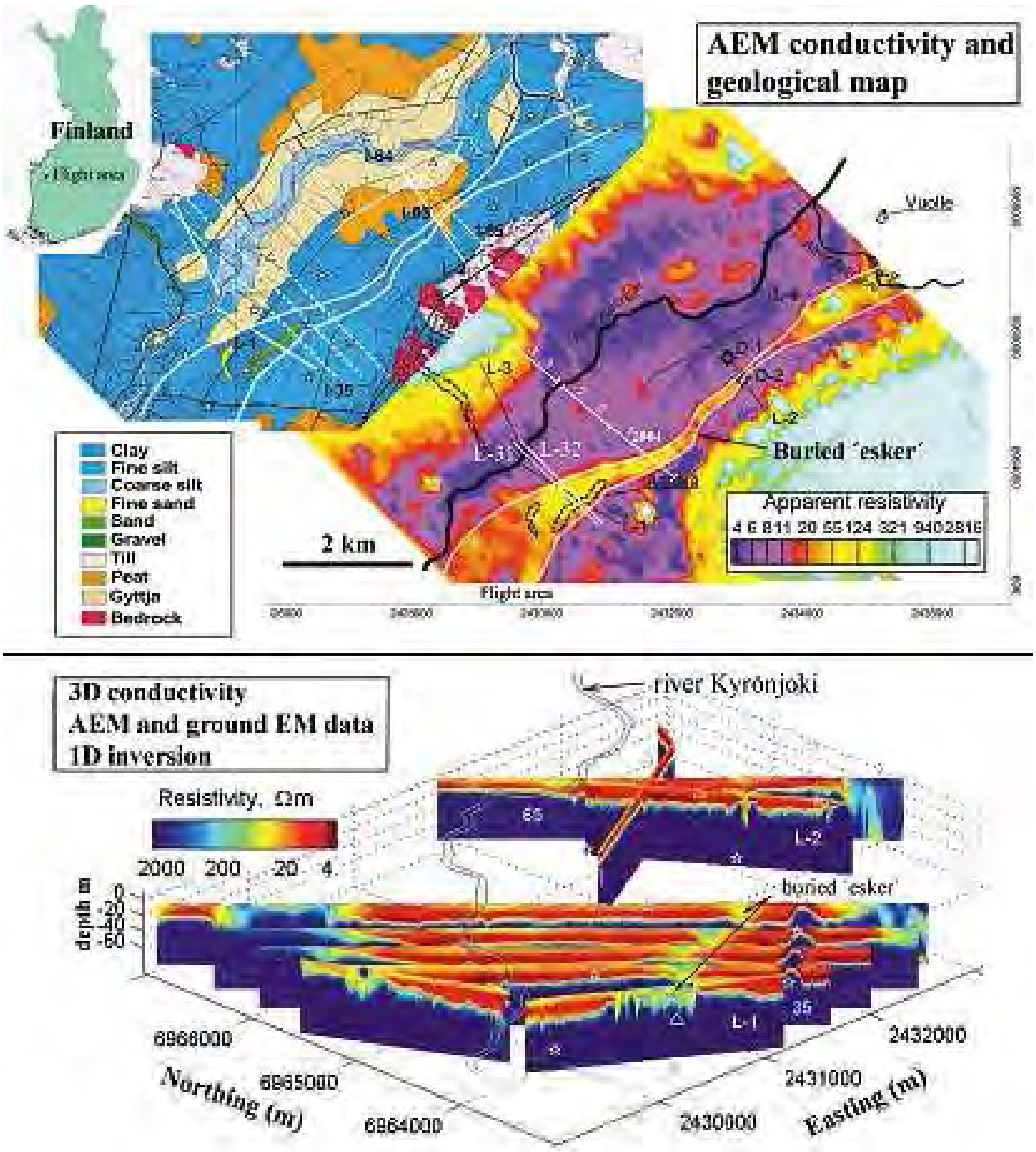

Fig. 3. Airborne apparent resistivity map (3.1 kHz) from the Kyrönjoki river valley, near Ilmajoki, southern Finland and the geological map of the site (upper). 3D conductivity map based on 1D inversion of AEM and ground EM data (lower) (Suppala et al. 2003). Base map © National Land Survey 466/MYY/05.

flight altitude was 32.5 m). Ground EM, gravity, electrical and refraction seismic measurements were made for calibration and verification of the AEM interpretation. Sampling and laboratory measurements of core samples were also made.

In the apparent resistivity map in Figure 3 the river-valley covered by lacustrine or glaciolackustrine sediments shows a very low resistivity, 4–20 Ohmm. As presumed, a distinct high-resistivity anomaly can be seen at the location of the known part of the ice-marginal deposit (Aavala). In addition to that there also exists a several kilometres long NW-SE trending resistivity anomaly over the clay-covered part of the map area, predicting a buried esker from Aavala to the NW. The anomaly was verified by modelling the airborne and ground EM data and by drilling. At the drilling site D2 (see Fig. 3) stratified sand and silt were met under an 11 m thick clay-silt cover. The depth to the bedrock was 25 m and the lowermost 7 metre thick layer composed of till. The final result support the conclusions of Kurkinen et al. (1992), that the buried ice-marginal deposit is far more extensive than the outcropping glaciofluvial deposits show in the study area. The airborne EM results suggest that the ice-marginal deposit continues laterally at least 10 km.

The interpretation of the AEM data, seen in the lower part in Figure 3, was based on layered-earth interpretation (model norm-based inversion). The 1D responses and sensitivity matrices were calculated by the Airbeo –program (Chen and Raiche 1998). The minimisation of objective function (*data misfit* + βx *model norm*) was carried out with the damped Gauss-Newton algorithm of Haber (1997). The inversion provided us with the thickness of the clay layer and with the conductivity distribution inside it. The estimation of the thickness and conductivity of the sediment material lying under the clay (till, for example) is a more complicated task and it is essential to use reference material, such as gravity or seismic data when interpreting the thickness of the coarse-grained sediment beds under clay.

MAPPING A WASTE-WATER POND – A CASE FROM LIEVESTUORE, CENTRAL FINLAND

Background to research

Lievestuore pulp mill generated waste effluent during 1935–1967. The waste was pumped to the nearby Koivusensuo mire, where the Lipeälampi waste pond was formed. Pulp mill effluent is very acidic (ph = 2–3) and rich in sodium lignosulphonate (NaLS), which is not usually present in natural waters (Mäkelä 1986). Because it contains hydrogen ions and dissolved solids, the effluent has good electric conductivity that correlates directly with high NaLS concentrations. The spread of the effluent into the pond's environment has enhanced soil conductivity, which can be detected by airborne electromagnetic mapping complemented by conductivity logging in the field (Puranen et al. 1997). The AEM anomalies indicate that the most heavily polluted mire area extends north- and southwards from the pond. Logging and seismic results were also used as reference material in the interpretation and modelling of bedrock topography and effluent plume migration (Lerssi et al. 1997)

Aerogeophysical survey

The aerogeophysical measurements were done at an altitude of 30–50 m with 100 m line spacing, and 12.5 m point spacing covering about 12 km^2 using configurations described in Peltoniemi et al. (1986) and Poikonen et al. (1998). The results were compiled on the maps of the Lipeälampi locality. The AEM map shows a strongly anomalous area, which is clearly better conducting than the glacial till environment that dominates the area. The anomalous area extends for over 200 m, from the pond's northern side to Koivusensuo mire, and for over 100 m to a depression zone on the pond's southeastern side (Fig. 4). The anomaly becomes weaker and continues towards the southeast, to the lower-lying Lake Koivujärvi area. Thus, between the pond and the lake, there is a zone in the till and sand formations, which is better conducting than its environment. From modelling studies (layer, 2-D and 3-D) performed on the two-frequency AEM-results, it was concluded that the anomaly in the central part of Koivujärvi is caused by a depression filled with lake sediments. Lineaments within the research area were

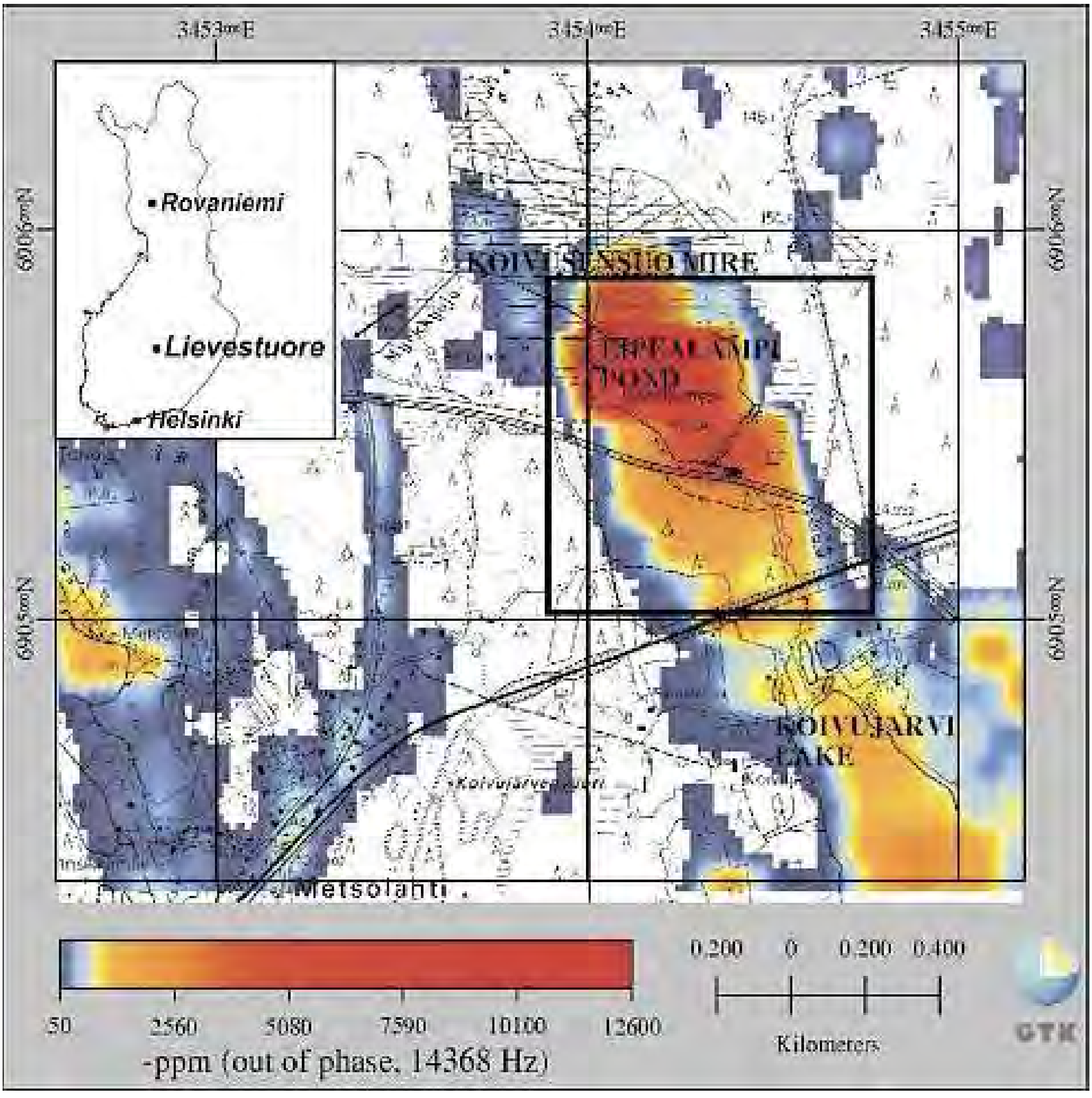

Fig. 4. The location of the Lipeälampi area, topography and the AEM imaginary (out-of-phase) component anomaly map (measurement frequency is 14 368 Hz).

interpreted from magnetic results, complemented by seismic profiling and a digital elevation model, and these revealed and verified fracture zones in the bedrock interpreted from AEM-results. As a result possible routes of pollutant migration in bedrock were determined (Fig. 5).

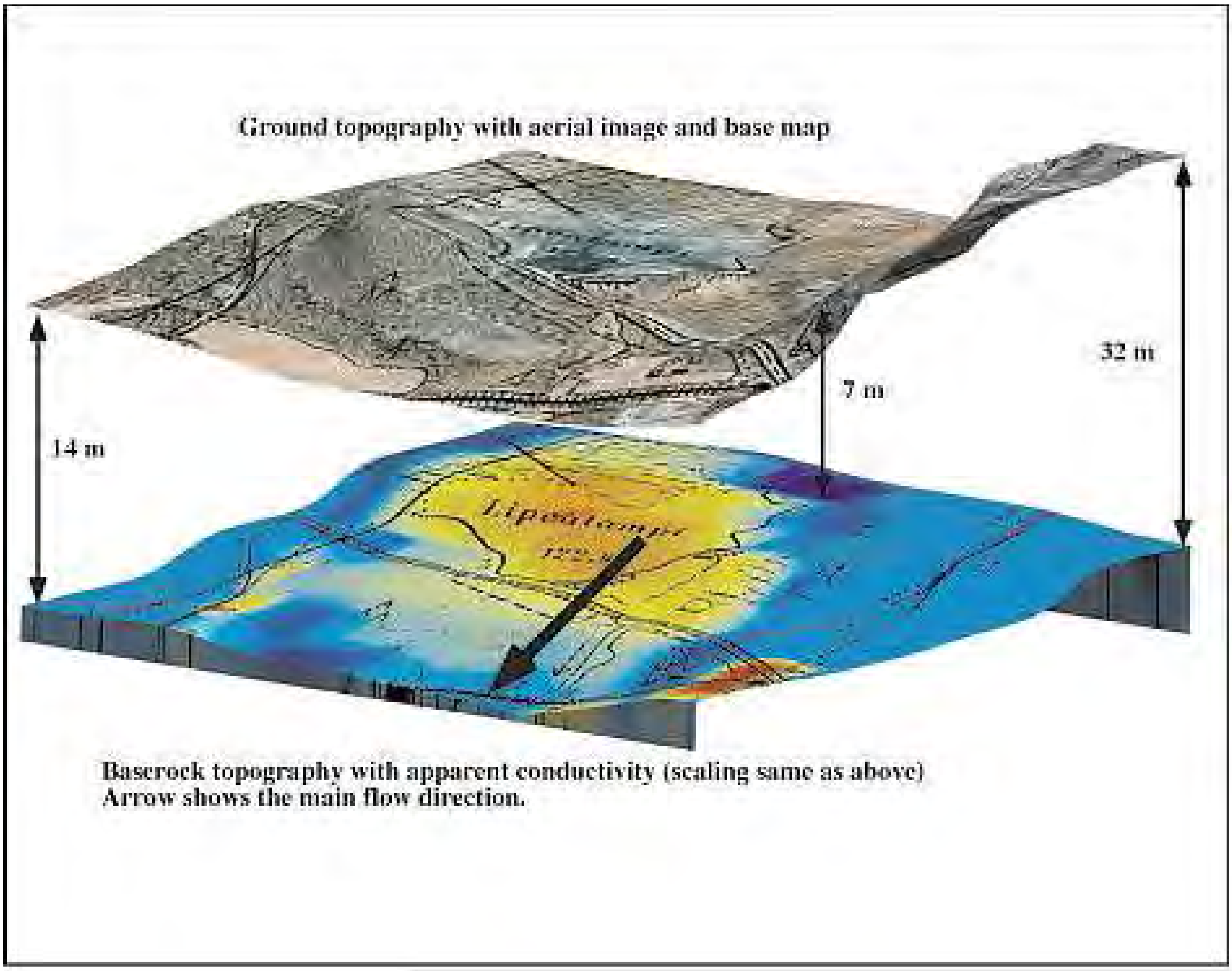

Fig. 5. 3D view of surface and bedrock topography of the Lipeälampi area. Base map © National Land Survey 466/MYY/05.

Summary

Information on the areal and vertical extent of polluted soils was obtained quickly by airborne measurements and field logging. By comparing the results of the airborne and ground surveys, it could be further concluded that there is clearly more of the pollutant below the bottom of the pond than below the mire depression. Pollutants with high conductivity in a low-conductivity environment represent optimal targets for electric methods, but the methods described can also be used to map even weaker conductivity contrasts.

LANDFILL MONITORING AT ÄMMÄSSUO, SOUTHERN FINLAND

Introduction

The possibilities of using the GTK's AEM method in monitoring landfill environments have been studied in several projects in Finland (i.e. Jokinen & Lanne 1996; Lohva et al. 1999), in the UK (Beamish et al. 2000) and in Germany (Lahti et al. 2000). The advantages of the AEM method are the effective mapping of the soil and groundwater contamination covering extensive areas surrounding the landfill. The ideal monitoring system of a modern, substantial landfill would consist of easily and quickly repeatable AEM measurements to cover extensive areas, carefully located geophysical ground monitoring lines and scattered groundwater monitoring wells only in the most important points.

The systematic airborne surveys conducted in Finland provide excellent material for preliminary land use planning and environmental projects like landfill monitoring. The Ämmässuo landfill is the principal municipal landfill in the Helsinki region located in western Espoo, approximately 30 km from the city of Helsinki. The results of the systematic airborne measurements over the Ämmässuo area during 1984 and later targeted airborne surveys carried out in 1993, 1997 and 1999 provide a very comprehensive compilation of airborne geophysical multisensor data. Ground geophysical measurements have been carried out to verify the airborne anomalies, as well as to study the accuracy of the geophysical methods detecting landfill contamination.

The AEM results

The first airborne survey in the Ämmässuo area was conducted as part of the systematic mapping program. The results illustrate the natural state of the site before the landfill was established. The AEM map outlines the wet marshlands from the generally resistive environment of thin Quaternary layers on the top of homogenous granite bedrock (Fig. 6). Prior to the next survey, in 1993, the landfill had been

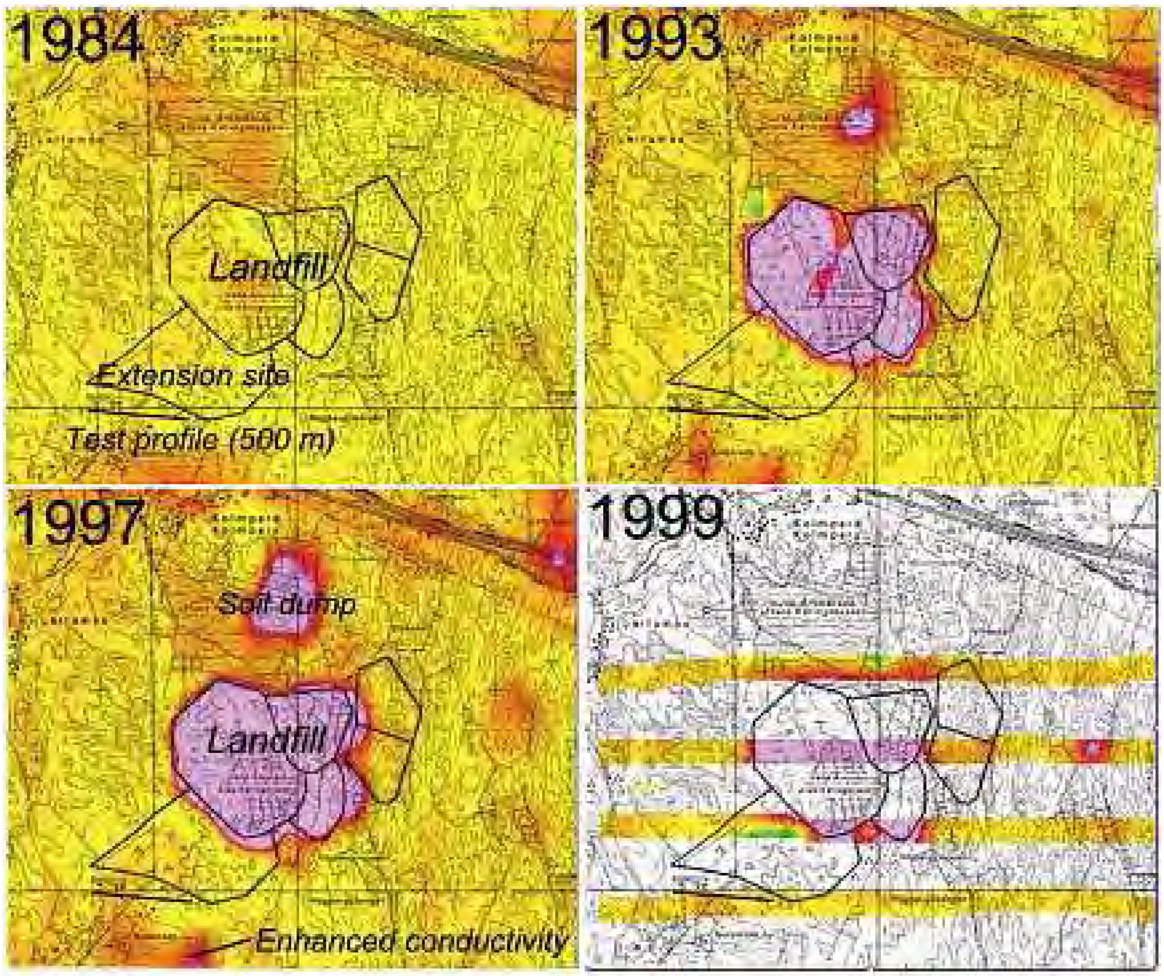

Fig. 6. The AEM maps from the Ämmässuo landfill covering the history of the landfill activity. The 1984 results are from a time before the landfill was established, the 1993 results represent the situation after 5 years of activity, and the 1997 results as well as the 1999 results after more than 10 activity years. The landfill impacts during the years are mainly discernible as a strong conductivity anomaly over the waste deposit (purple colour). The conductivity anomaly north of the landfill that has been increased from 1993 to 1997 is a separate soil dump site. The conductivity changes that could reflect the landfill impacts are located southwest of the landfill. Base map © National Land Survey 466/MYY/05.

active for 7 years and the general view of this survey's AEM results is completely different. The heap of the domestic waste appears as a highly conductive anomaly. The situation is quite similar to the results from 1997. The amplitude of the landfill anomaly is stronger than in 1993 and, in particular, the in-phase/out-of-phase index is reversed indicating dimensional expansion or increase in the electrical conductivity of thewaste. Naturally, the volume of the waste increased from 1993 to 1997 but also the waste layer had become denser and probably electrically more conductive. The flight survey conducted in 1999 was conducted with a relatively coarse configuration but shows similar features to the earlier results.

The landfill anomaly follows quite precisely the boundaries of the filling area and the spatial accuracy mainly depends on the point interval (typically 13 m). The waste material is characterised by a very low resistivity, typically 5–10 Ohm-m and even lower. Considering the impact of the strong electromagnetic response caused by the waste, reliable data characterising the soil properties outside the landfill can be acquired roughly at 50–100 m distance from the perimeter of the landfill. Whether the contamination-derived increase in the electrical conductivity of the soil is detectable with the AEM measurements depends strongly on the geology, the extent of the contamination and the survey parameters. Tentative numerical modelling shows that it is theoretically possible to detect even a change from 20 Ohm-m (representing clay in natural state) to 10 Ohm-m (representing contaminated clay) in a 20 m thick surface layer (Lahti 1999). The contamination impact would be prominent especially in the low frequency (3.1 kHz) and high frequency (14.4 kHz) out-of-phase component.

The environment surrounding the Ämmässuo landfill is naturally resistive, having a thin overburden cover mainly comprising moraine with predominant outcrops of granitic bedrock. The AEM anomalies outside the landfill illustrate the wet marshlands and occasional small clay deposits. The extent and the amplitude of some of those AEM anomalies were enhanced during the landfill activity from 1993 to 1997. The groundwater quality was at the same time actively monitored by sampling and laboratory analyses, and no significant contamination was reported. The increased electrical conductivities detected with the AEM monitoring might have been caused by the sequential changes in the soil water content.

The monitoring possibilities

The monitoring possibilities of the AEM method to detect landfill derived soil and groundwater contamination should not be considered adequate by themselves. However, together with appropriate ground geophysical and sampling data, an AEM survey greatly improves the integrity of the otherwise scattered data. For the purpose of studying the monitoring possibilities of geophysical data GTK introduced a geophysical test line located outside the landfill in a possible direction of contamination transport (Fig. 6.). The test line has been surveyed with several geophysical methods to create a precise geological model of the site. The 500-m long line is covered with three groundwater wells, which monitor the actual groundwater chemistry. The geophysical measurements have been repeated to define the noise level and reliability of each method. The Ämmässuo landfill will remain active for several decades and therefore the test line provides a great opportunity to study the monitoring capabilities of AEM and other geophysical methods.

MAPPING THE ENVIRONMENTAL RISKS OF AN EXTENSIVE CONTAMINATED SITE – RESULTS FROM A MINING REGION IN EASTERN GERMANY

The AERA project (Assessment of Environmental Risks by Airborne Geophysical Techniques Validated by Geophysical Field Measurements) is a pioneer survey applying airborne multisensor measurements combined with various ground geophysical surveys aimed especially at studying environmental risks of a relatively wide contaminated site (Gaál et al. 2001). The airborne measurements of the 1100 km^2 wide area in Saxony, southeast Germany were carried out within three weeks during August-September 1999 using GTK's three-method system. The ground surveys were conducted during May 2000 by GTK and several European partner companies.

The project site was selected because of the versatile environmental risks recognised inside the area. The area surrounding the city of Zwickau has been an important uranium-mining region as well as being densely industrialised. The soil and the groundwater are potentially endangered by waste from the mining and chemical industry, as well as by settlements and agriculture. The airborne survey was a preliminary study to define the regional scale of the contamination and to collect geological information. The airborne measurements enabled follow-up ground surveys to be targeted in relation to the most significant anomalies.

The GTK three-method airborne survey produced a relevant regional dataset that can also be used in more detailed studies. The airborne geophysical data revealed the integrity of several geological and man-made features and detected many interesting small-scale anomalies. The gamma ray survey yielded the most significant results illustrating effectively the long-term environmental impacts of uranium mining. The radiometric results can be used for mapping the dispersion of radioactive material as well as assessing the radiation dose levels. The magnetic data discriminates mainly geology and cultural noise, while at the same time locating several landfills containing scrap metal and mine tailings containing magnetic minerals. For locating old buried domestic waste deposits the airborne magnetic mapping would be a superior method. The AEM results were influenced by cultural noise and the naturally highly conductive soil. Yet the AEM data reveal many interesting anomalies related to landfills and mine tailings. To interpret whether the anomalies reflect soil or groundwater contamination or a natural increase of conductivity would require more information on the soil and groundwater properties.

Results of the gamma-ray survey – Mapping of the uranium mining impacts

The test area in Germany is ideal for mapping the dispersion of radioactive materials from uranium mining. The background radiation levels are naturally low and all the detected anomalies except a couple of geological features are manmade. Also the area has been an important producer of uranium ore, leaving behind two closed mines and yellow cake process plants as well as large amount of mining and processing waste inside the test site.

The most interesting anomalies detected with airborne radiometric measurements are the transport of radioactive contaminants along the local river system and the high radiation levels above large uranium mining tailing ponds. In both cases the environmental risks are previously known and documented. The advantage of the airborne gamma-ray survey is to show the integrity of contaminated features producing spatially precise maps over the whole area.

Contamination of the Zwickauer Mulde riverside. The transport of contaminants along the river system originates from an accident at a so-called yellow cake process plant during the 1960s. The river system can be traced in the total radiation and uranium maps throughout the test site (Fig.7a, b). Two sites along the river located 7.5 km and 10 km downstream from the process plant were selected for the topsoil sampling. The samples were collected from the riverbeds and from the bottom of a dry flood canal. The uranium concentrations of all the samples showed increased values compared to background levels. The concentrations were from 7 to 66 ppm. The airborne uranium data range from the same area is 10–18 ppm. The airborne measurements apparently underestimated the highest uranium peaks. The difference in the ground sample data and in the airborne data is partly explained by the airborne system calibration and in the different averages involved in the two measurements. The spatial coverage of the flight lines (100 m spacing) provides a large scale average measurement of near-surface values.

Tailings ponds. The tailings of the yellow cake process plants were deposited in abandoned open pits or valleys closed off by a dam. The uranium content of the tailings after the acidic and alkaline processing remains high. This is visible in the airborne gamma-ray data as strong anomalies over the tailings (Fig. 7b). The tailings are isolated from the environment by covering them with water or soil. It was surprising that the water covered ponds showed strong radioactive anomalies. Normally, a metre thick water layer absorbs the gamma radiation totally. In this case, the water covering the tailings is deeper, from several metres up to 20 metres. The ex-

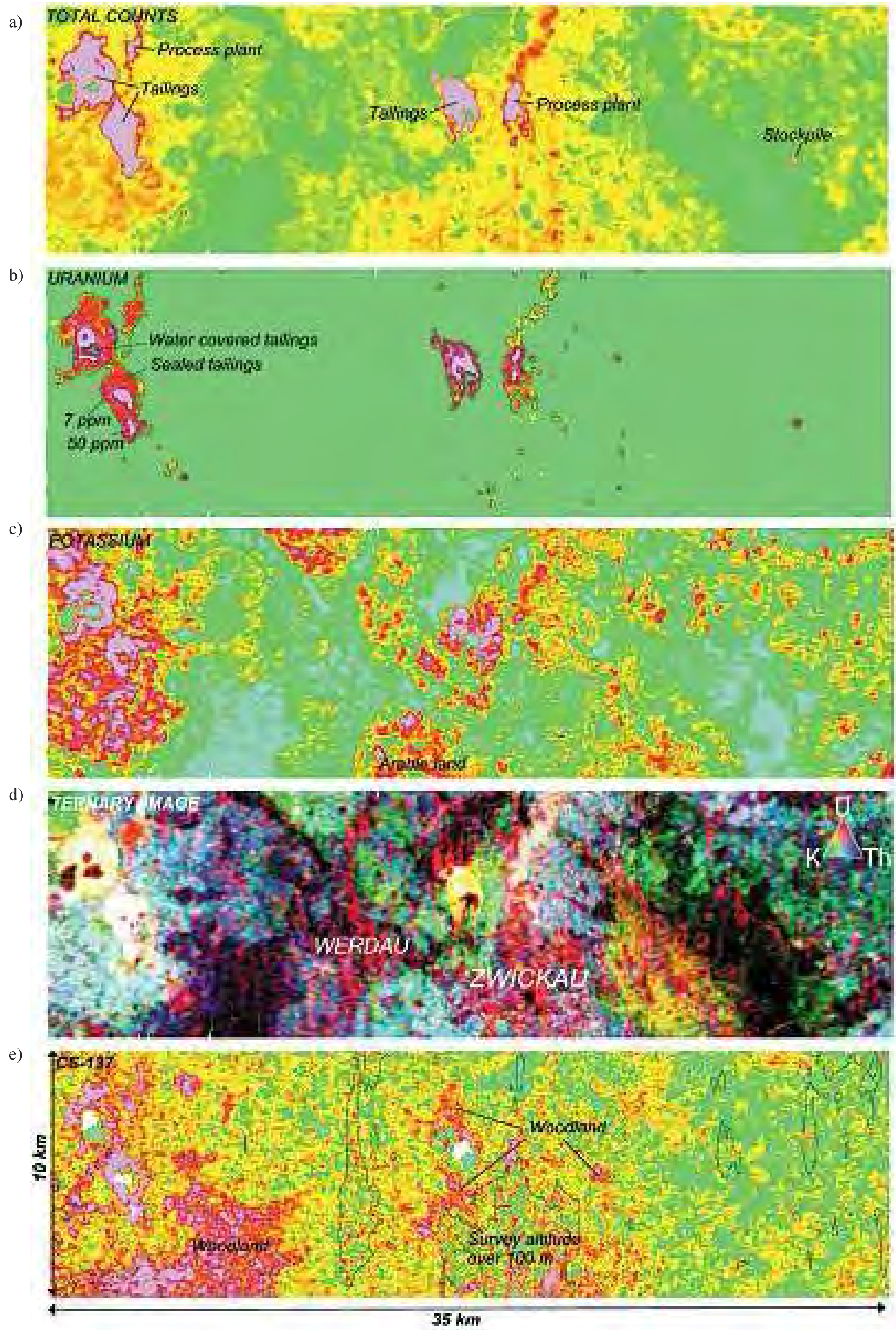

Fig. 7a). Airborne radiometric maps from the study area in Germany. The total radiation (a), equivalent uranium (b), equivalent potassium (c), ternary U-Th-K (d) and caesium (e) maps cover a 35 km´10 km area in the Zwickau region, southeast Germany.
b) Uranium map enhances the high uranium anomalies over the tailing ponds, stockpiles and process plants. The background (less than 5 ppm) is illustrated in green. The contours define areas having equivalent uranium concentrations over 7 ppm (orange and red colour) and over 50 ppm (purple colour).
c) Potassuim map, as well as the ternary image (d), enhance the geological features and topsoil properties. Some increase in the potassium concentration is detected over arable land indicating extensive use of fertilisers.
d) The city of Zwickau is discernible in the ternary image by enhanced uranium concentration (red colour) probably due to rock material used for construction.
e) Cs-137 map has the area with flight altitude over 100 m outlined showing the high noise pattern related to the high survey altitude over cities of Zwickau and Werdau. Woodlands have enhanced caesium levels compared to the arable land.

planation for the high radiation levels could be detection by the spectrometer of the daughter product of uranium, the radon gas which is transported through the water. The soil-covered parts of the tailings clearly show lower radiation levels indicating effective isolation from the environment.

Monitoring radiation levels. Ground measurements and systematic soil sampling over extensive areas are slow and expensive methods. Especially the identification of scattered contamination over large areas can be very costly. Airborne gamma-ray surveys provide a quick, effective and reliable method for surveying radioactive elements. The survey can also be repeated easily and precisely with modern positioning systems. The measured total counts can be used for estimating radiation dose rates over abandoned mining sites.

The comparison between the airborne gamma ray data measured within the AERA project area and data collected during the mid 1980s using German helicopter equipment shows a good correlation. The two surveys implemented technically different systems but the results are still comparable. The two sets of results, over a 15-year period, show a decrease in radiation level at many sites that have had their uranium mining waste recently cleaned. However, the results show that is possible to detect very small concentrations of radioactive materials. Even some roads that have been used for the transport of the tailings are visible on the uranium maps. The resolution of the gamma-ray method depends naturally on the survey configuration, e.g. flight altitude, speed and line separation. The survey parameters implemented in this case (50–60 m altitude, 50 m point interval, 100–200 m line spacing) worked quite effectively in the detail studies, although the design was more of a regional survey.

Caesium analysis. Gamma-ray spectrometry allows the analysis of additional radioactive elements apart from the conventional uranium, thorium and potassium. One such interesting radioactive element is caesium (^{137}Cs). Our experience from the Chernobyl accident and the fallout from nuclear weapon tests shows that it could be expected that ^{137}Cs exists inside the test area also. The Caesium data were analysed by Grasty (2001) utilising noise adjusted singular value decomposition (NASVD) method (Hovgaard 1997).

The ^{137}Cs map of the German test site enhances the woodlands compared to the agricultural fields (Fig. 7e). The undisturbed forest topsoils apparently contain higher concentration of ^{137}Cs than the ploughed fields where the radioactive particles have migrated deeper. The Caesium data also showed high ^{137}Cs values over high uranium anomalies. However, due to the methodology these anomalies are quite certainly apparent and caused by the very high uranium peaks. Moreover, the noisy pattern of the Caesium maps over the built up areas is probably due to the high survey altitude over the settlements with the noise being amplified by the height correction.

Combining radiometric and magnetic data – Black coal mining

Coal mining in the region has a long history starting from the medieval times. The village of Oelsnitz is today characterised by abandoned collieries and stockpiles that cause land subsidence and groundwater problems. The waste rock from the mines contains magnetic minerals and therefore the stockpiles around the village show a positive magnetic anomaly in the airborne magnetic maps (Fig. 8a). Also one of the stockpiles shows a relatively strong radiation anomaly (Fig. 8b). It is documented that the waste rock in that particular stockpile is originally from mines outside the region where the host rock is uranium bearing.

The analyses of the rock samples taken from the stockpiles support the interpretation of the airborne data. The rock material from the stockpiles associated with the magnetic anomaly were analysed and found to have magnetic susceptibilities from 0.0027 to 0.032 SI. This is due to the presence of monoclinic pyrrhotite in the stockpile material. The high magnetic susceptibilities and the high remanent magnetization values explain the airborne anomalies.

The topsoil samples from the stockpile with a strong radiation anomaly showed uranium concentrations from 76 to 168 ppm. The corresponding airborne results indicate a range of 17–51 ppm. Reference samples were also collected from another stockpile displaying background radiation levels in the airborne data. These samples showed uranium concentrations of 3–4 ppm. The corresponding airborne results indicate a range of 2–4 ppm. Thus the accuracy of the airborne measurements appears very good for the low uranium values but at high levels the airborne results are apparently underestimated due the methodological issues.

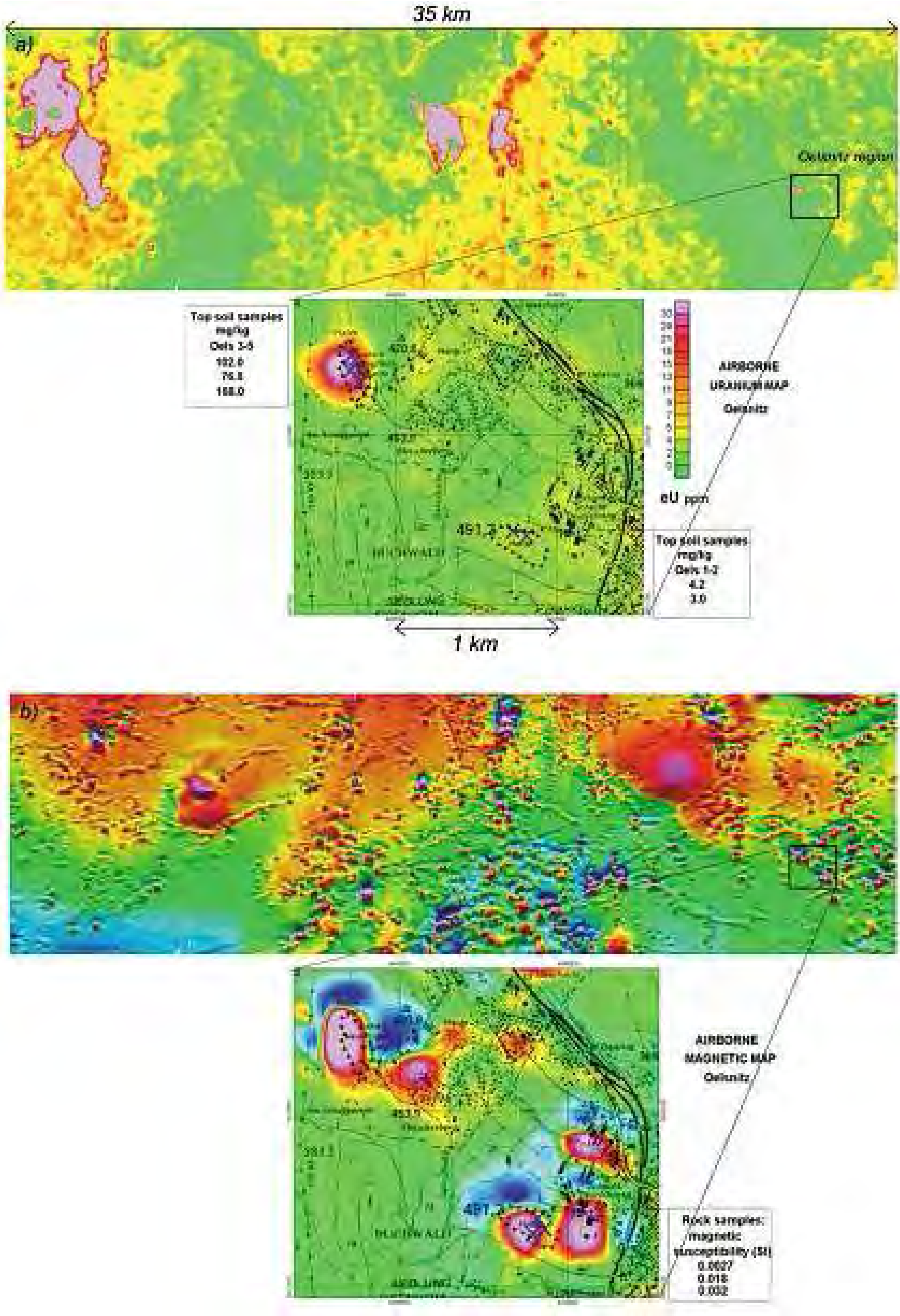

Fig. 8. Airborne radiation (a) and magnetic (b) maps of the Oelsnitz coal mining region.
a) Uranium map highlighting one particular stockpile having a strong radiation anomaly. The soil sample analyses of that stockpile and another showing background radiation levels demonstrate the significant difference in the uranium concentrations.
b) Stockpiles containing waste rock from the coalmines are visible on the magnetic map as positive anomalies having a side minimum on the northern side due to the shallow location of the anomaly source. The sample analyses show that the waste rock has a relatively high magnetic susceptibility, which explains the anomalies.

Magnetic and resistivity data – Nickel mining and smelting

The abandoned nickel mines in the test site are mainly back-filled or water-filled open pits having very small environmental impacts. The former nickel smelter in St. Egidien, however, still forms a significant environmental risk due to heavy metal residuals of the nickel processing deposited in a nearby filled valley that is closed by a dam. The nickel tailings pond shows a magnetic and conductivity anomaly in the airborne mapping (Fig. 9). The anomalies continue outside the pond revealing a dispersion of contamination from the tailings pond into the nearby environment. Based on the magnetic and AEM results, the site was selected for validating ground geophysical measurements implementing electrical, IP, EM, magnetic and neutron well logging methods. The ground measurements outside the pond show structures with increased electrical conductivities indicating possible heavy metal contamination. The measurements conducted inside the pond proved that the tailings are both highly magnetic and electrically conductive, and that the tailings layer is approximately 15–20 metres thick.

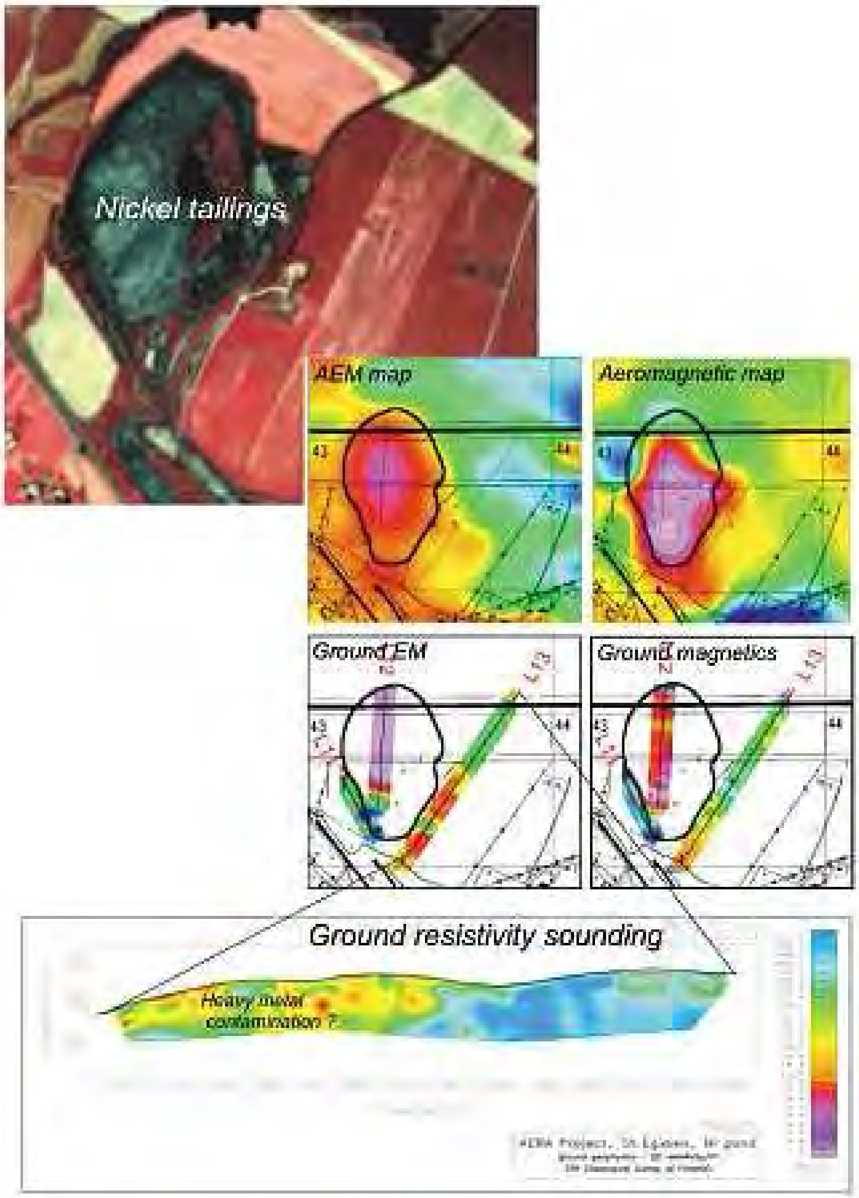

Fig. 9. Tailings pond containing slag from a nickel smelter holding an anomaly on the AEM and AM maps. The airborne results were checked with ground HLEM (slingram), magnetic and resistivity measurements both inside and outside the pond. The ground surveys enhance the similar features to the airborne measurements. The resistivity line measured outside the pond in an arable field illustrates a conductivity contrast in the middle of the line. The low resistivity values (10–50 Ohm-m) possibly characterise heavy metal contamination compared to background (100–500 Ohm-m).

ENVIRONMENTAL APPLICATIONS OF GTK AEM DATA IN THE UK

Introduction

In 1999, the GTK Twin-Otter AEM system was used in a series of trials to acquire detailed EM data sets in addition to magnetic gradiometer and radiometric information. The purpose of the trials was, in part, to assess the case for the inclusion of AEM in future airborne geophysical surveying in the UK context. The limited data acquired (3324 line km in 5 days of flying) constitute the first high resolution AEM survey information to address specific environmental issues in the UK.

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. 30 and 90 m) and flight line spacing (50 and 200 m) to be investigated. Some data sets were repeated at different elevations. In practice, data obtained from elevations up to 120 m were found to be fit-for-purpose although signal/noise levels were aided by the relatively conductive geology encountered in the trial areas.

The trial data were used to develop a modelling/inversion strategy to achieve reliable and consistent results. The conductivity estimates shown here are half-space inversions of the data at each of the two frequencies. Data from only two of the trial areas (to the north and east of Nottingham, respectively) are used to illustrate general relevance to environmental applications.

Although used for over a decade for environmental assessments in the hard-rock environment of Finland, only recently have AEM techniques been applied to similar problems in the UK. The initial AEM data sets obtained across small portions of "average" UK geology have proved revealing. Work, to further understand the data and provide firmer interpretations using ground truth studies, continues.

The Shirebrook survey

Investigations into detectable environmental effects across the Permo-Triassic sandstone aquifer were conducted in northern Nottinghamshire. This sandstone unit is the second most important groundwater resource in the UK after the Chalk. The 13 x 9 km^2 Shirebrook survey was performed using 200 m E-W flight lines at a nominal elevation of 40 m. Subsequently, 50 m infill flight lines were flown to provide higher resolution data in two sub-areas.

The geology of the area is highly uniform (the Sherwood Sandstone with a typical thickness > 100 m) and the survey area contains a swathe of closed and active collieries. Representative background information was established using data from an area free of anomalies. According to these data, background conductivities range from values of 4 to 10 mS/m at high frequency (14 kHz) and from 2 to 8 mS/m at low frequency (3 kHz). During the course of the background study, differences between agricultural and historically forested zones (the former Sherwood Forest) were detected.

The sandstone provided the least conductive environment of the four trial areas surveyed; the geology is also relatively simple. These factors meant that environmental influences were observable to considerable depths (e.g. 40 m at high frequency and towards 70 m at low frequency) and that a simple conductivity "level" (e.g. values > 15 mS/m) could be used to identify anomalous zones.

The survey area contains two active and three former colliery sites. The at-surface coal spoil and processing areas, associated with the mine sites, all provided high amplitude conductivity anomalies in excess of 100 mS/m. The only other feature to provide this level of conductivity was an isolated, closed landfill. Away from the immediate vicinity of the mine sites, less conductive anomalies with a plume-like quality were observed, some extending several kilometres in length.

High resolution results obtained across a 3 x 2 km^2 area, centred on the working Thoresby mine are

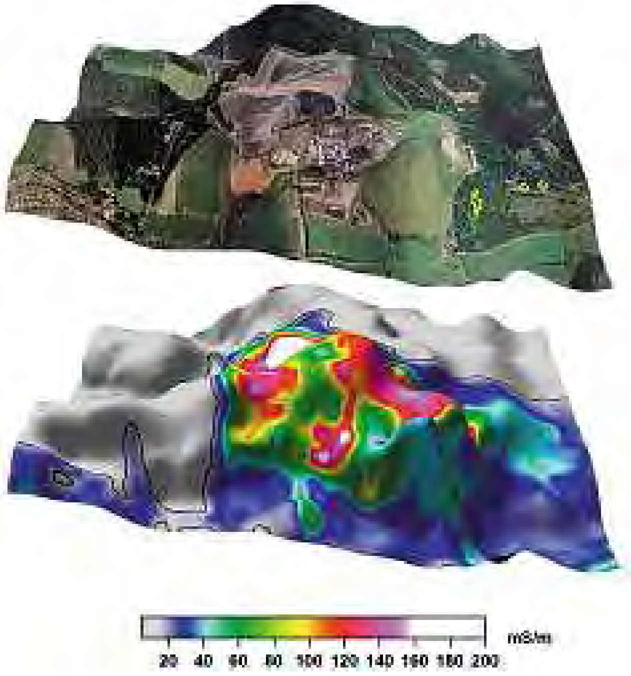

Fig. 10. 3x2 km^2 area centred on Thoresby mine, looking North. Upper frame: aerial photograph draped on exaggerated topography. Symbols denote VES soundings. Lower frame: Draped high frequency conductivity results

shown in Figure 10. 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 southeast, topographic highs indicate landscaped spoil zones. The conductivity distribution is selectively contoured and shown in the lower frame. The grey area denotes conductivity values < 15 mS/m and 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 to values in excess of 150 mS/m. 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. This apparent eastward migration may be a regional scale effect associated with the main stratigraphic dip of the sandstone.

In order to understand better the airborne data, three vertical electric soundings (VES) were made to the east of the mine (the sounding centres are indicated in the upper frame). Below a depth of about 15 m, the VES results display a ramp-like increase in conductivity through the unsaturated zone to reach maximum values (35 to 50 mS/m) within the aquifer at depths of about 50 m. The variation in the maximum amplitudes reflect variations also observed in the airborne results. The most important conclusion is, however, that the airborne data, at both frequencies, are mapping enhanced conductivities primarily within the aquifer.

Although the colliery sites provided the highest amplitude anomalies, many other types of land-use were found to provide smaller amplitude but detectable effects. Figure 11 is an illustration of the high frequency conductivity distribution around two closed landfills (hatched polygons) across a 1.5 x 1.5 km^2 area. The southernmost landfill is located within a former quarry and operated between 1976 and 1989. The conductive features connected with the former landfills are most apparent at the higher frequency and centroid depths are less than 12 m. The airborne results have been confirmed by a limited ground geophysical study across the southern landfill. The quasi-continuous conductive feature associated with the road traversing the small ridge appears at both frequencies. The road is a major service route and carries a cast-iron water pipeline together with an 11 keV power cable (above and below ground).

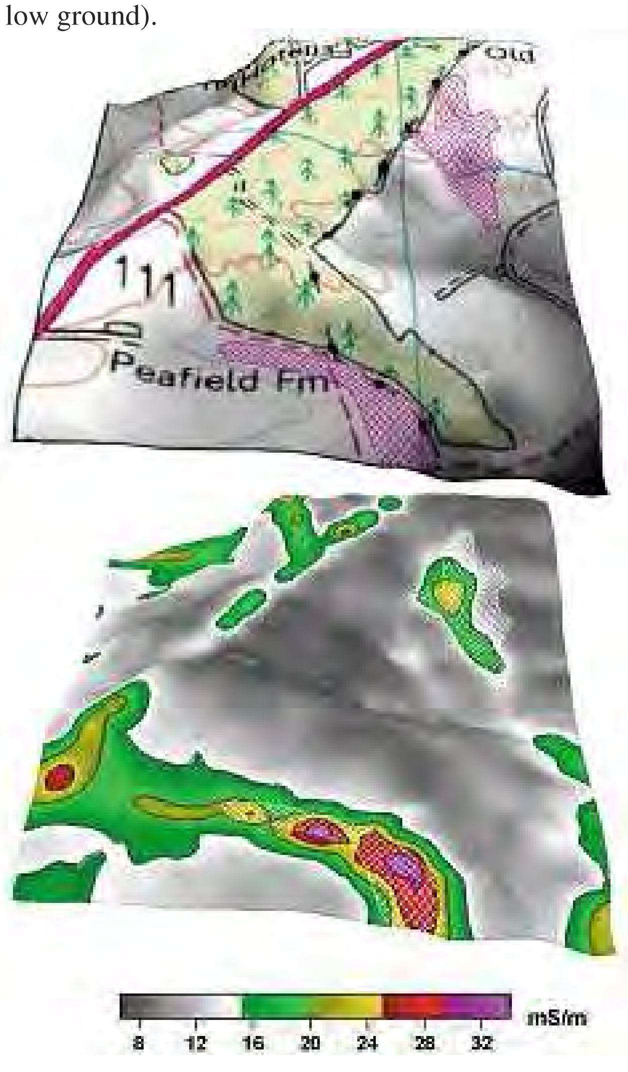

Fig. 11. 1.5x1.5 km^2 area, looking North. Cross-hatch polygons denote former landfills. Upper frame: OS map (© Crown copyright. All rights reserved.) draped on exaggerated topography. Lower frame: Draped high frequency conductivity results.

The Langar survey

The conductivity results obtained in a second trial area provide a contrast to those of the previous area. The smaller Langar survey (4 x 1.5 km^2, Fig. 12) was flown using 50 m E-W flight lines at a nominal elevation of 40 m. Here, depths of investigation are generally less than 20 m. The two “targets” were municipal landfills for Nottingham (L1 closed in 1971 and L2 is operational and expanding); both are former quarry sites. The geological setting (Fig. 12b) comprises the Mercia Mudstone Group (MMG) with a thin partial cover of alluvium. The main contact with the Lower Lias Barnstone Member occurs along a major break in slope (C1, Fig. 12b). The Barnstone Member provides a contact with the clay-rich Barnby Member along a further break in slope (C2, Fig. 12b). The three units are all crudely represented by different “levels” of conductivity in the lower frequency results (Fig. 12c).

Even within this highly conductive environment, the two target landfills (L1 and L2, Fig. 12) are resolved since their peak conductivities exceed 300 mS/m. As with all the other trial areas, additional anomalies were detected. Two major conductive features are associated with works areas (e.g. cement production) where maximum values exceed 1000 mS/m. Across the highly conductive “trough” within the Barnby member, small scale anomalies associated with a farm and aerodrome runways are also resolved.

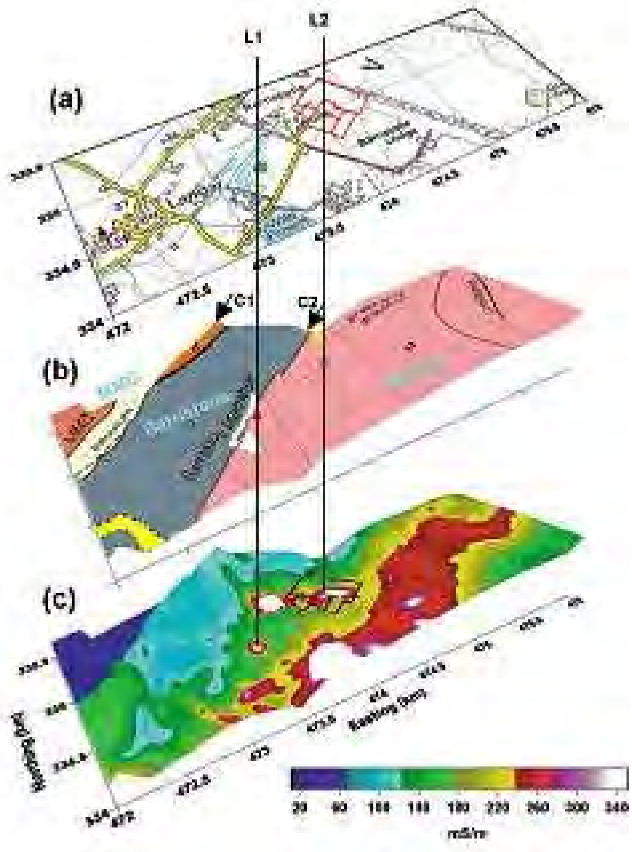

Fig. 12. 4.5x1.5 km^2 Langar survey area. L1 and L2 denote target landfills. (a) OS map (© Crown copyright. All rights reserved.). (b) Simplified geological map draped on exaggerated topography. (c) Draped low frequency conductivity results.

DISCUSSION AND CONCLUSIONS

The environmental applications of airborne geophysical measurements comprise a wide selection of investigations from groundwater prospecting to soil contamination mapping. The possible targets in mapping of contaminations include for example mining industry (tailings), chemical industry (waste-water ponds) and municipalities (landfills). Other applications comprehend geological and geotechnical investigations e.g. soil classification and land use planning.

The applicability of different geophysical methods depends on the nature of the contamination or target under investigation. The airborne electromagnetic (AEM) method has the most considerable potential for the environmental studies as for example where the contaminants increase the electrical conductivity of the soil. The gamma-ray spectrometry has several interesting applications related to mapping the concentrations of the radioactive elements in the topsoil and the absorption of the radiation into water-bearing soil. The magnetic measurements have its applications in the geological mapping of fractured zones and locating buried magnetized targets e.g. domestic wastes, tailings, ammunition etc.

The airborne mapping provides information of the horizontal extension of the contamination although ground surveys and sampling are still essential for validating the type and vertical extension of the contamination. The mapping of contaminants using the AEM method is based on detecting conductivity contrasts. The AEM method has been successfully applied in the resistive environments in Finland but the surveys in the UK and in Germany proved that the method works even better in geologically conductive environments.

The survey configuration (e.g. flight altitude, line spacing) influences significantly the resolution and interpretation of the data. Authorities are regulating the flight altitude and it can be difficult to get permission to fly low altitude (35–50 m) surveys over areas with settlements and cattle farms. Still, data collected in Germany (using 50–60 m altitude) and in the UK (using altitudes up to 120 m) were proved to be useful for the environmental investigations. The cost-effective line spacing for environmental applications would probably be 100 m, although it depends on the size of the target. For high-resolution surveys a line spacing of 50–75 m would be recommended.

In the surveys presented here, the GTK three-method airborne survey produced an integral regional dataset that can be utilised also in detail studies due to the small grid size of the resulting maps and accurate GPS positioning. The combination of simultaneously measured three geophysical methods is being proved to be highly useful for environmental applications. The different methods support each other's interpretation and give beneficial geological information.

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