# THE DETECTION AND TRACKING OF MINE-WATER POLLUTION FROM ABANDONED MINES USING ELECTRICAL TOMOGRAPHY

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## Abstract

Increasing emphasis is being placed on the environmental and societal impact of mining, particularly in the EU, where the environmental impacts of abandoned mine sites (spoil heaps and tailings) are now subject to the legally binding Water Framework and Mine Waste Directives.

Traditional sampling to monitor the impact of mining on surface waters and groundwater is laborious, expensive and often unrepresentative. In particular, sparse and infrequent borehole sampling may fail to capture the dynamic behaviour associated with important events such as flash flooding, mine-water break-out, and subsurface acid mine drainage. Current monitoring practice is therefore failing to provide the information needed to assess the socio-economic and environmental impact of mining on vulnerable eco-systems, or to give adequate early warning to allow preventative maintenance or containment. BGS has developed a tomographic imaging system known as ALERT ( Automated time-Lapse Electrical Resistivity Tomography) which allows the near real-time measurement of geoelectric properties "on demand", thereby giving early warning of potential threats to vulnerable water systems. Permanent *in-situ* geoelectric measurements are used to provide surrogate indicators of hydrochemical and hydrogeological properties. The ALERT survey concept uses electrode arrays, permanently buried in shallow trenches at the surface but these arrays could equally be deployed in mine entries or shafts or underground workings. This sensor network is then interrogated from the office by wireless telemetry (e.g: GSM, low-power radio, internet, and satellite) to provide volumetric images of the subsurface at regular intervals. Once installed, no manual intervention is required; data is transmitted automatically according to a pre-programmed schedule and for specific survey parameters, both of which may be varied remotely as conditions change (i.e: an adaptive sampling approach). The entire process from data capture to visualisation on the web-portal is seamless, with no manual intervention.

Examples are given where ALERT has been installed and used to remotely monitor (i) seawater intrusion in a coastal aquifer (ii) domestic landfills and contaminated land and (iii) vulnerable earth embankments. The full potential of the ALERT concept for monitoring mine-waste has yet to be demonstrated. However we have used manual electrical tomography surveys to characterise mine-waste pollution at an abandoned metalliferous mine in the Central Wales orefield in the UK. Hydrogeochemical sampling confirms that electrical tomography can provide a reliable surrogate for the mapping and long-term monitoring of mine-water pollution.

## INTRODUCTION

Time-lapse surveys are now routinely deployed in geophysics (Tsourlos *et al*, 2003, Grellier *et al* 2008, Versteeg and Johnson, 2008) but the cost of manual repeat surveys can be prohibitively expensive. To overcome these limitations, innovative ALERT technology has been designed which allows the near real-time measurement of geoelectric, hydrologic and other properties "*on demand*", thereby giving early warning of potential threats to vulnerable water systems. The ALERT survey concept uses electrode arrays, permanently buried in shallow trenches or attached to borehole casing (Kuras *et al* 2006, 2009, Ogilvy *et al*, 2008, 2009). This network is then interrogated from the office by wireless telemetry to provide volumetric images of the subsurface at regular intervals (Fig. 1). Once installed, no manual intervention is required; data is transmitted automatically according to a pre-programmed schedule and for specific survey parameters, both of which may be varied remotely as conditions change (i.e: an adaptive sampling approach). The entire process from data capture to visualisation on the web-portal is seamless, with no manual intervention. A similar, but less integrated, approach has been described by Daily *et al*, 2004, Versteeg *et al*., 2006. Some case histories are given where our ALERT technology has been successfully deployed to map surface-groundwater interaction and to assess the resilience of engineered earthworks. It is proposed that these examples could readily translate to the monitoring of acid mine drainage and to the use of ALERT for the early prediction of failure within hydraulic containment barriers (e.g: mine tailings dams).

## ALERT SURVEY METHODOLOGY

### Monitoring seawater intrusion in a coastal aquifer

Our ALERT prototype was first deployed in the bed of the River Andarax, Almeria, Spain, to monitor seawater intrusion and transient recharge events such as flash floods which often occur in the autumn and winter. The electrode array was buried in a trench about 1 m deep and nearly 1.6 km in length, extending upstream from a point about 300 m from the shoreline (Fig. 2). The subsurface array, which is still transmitting data 3 years after its installation, has electrode take-outs at 10 m intervals, all of which are addressable so any electrode array may be selected (e.g: Wenner, Dipole-Dipole or an optimised user-specified configuration). The array gave a maximum depth of investigation of ~160 m. For control purposes 3 deep boreholes were drilled through the Quaternary aquifer sediments into the relatively impermeable Pliocene marls at a depth of ~100 m. These boreholes were spaced about 500 m apart on the line of the ALERT array to provide ground-truth and to assist image calibration. Electrode arrays of 50 m length with take-outs at 1 m spacing were attached to the outer PVC casing of two of the boreholes to facilitate surface-to-hole measurements (see Fig 3).

The ALERT instrumentation (see Fig. 4) is located about 300 m from the river in secure housing, within a water treatment plant. The instrument is connected to a high capacity battery pack, battery charging source and a data communications link. It comprises a central processor that co-ordinates and controls all the major functions: data collection, storage, and transmission. Subsurface cable conduits link the instrument to the array in the riverbed.

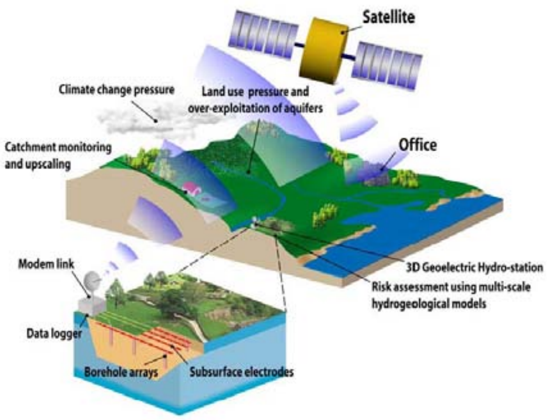


Fig 1 Schematic ALERT concept showing buried ERT arrays and remote data transmission

Fig 2 Excavation of the ALERT trench and drilling

Fig 3. Attaching downhole electrodes to borehole

Fig 4 Fully integrated ALERT prototype casing during drilling

The instrument is remotely configurable through customised software which can be run on a standard PC anywhere in the world. In this specific installation, it is linked to a BGS server via a PSTN modem interface – this being the cheapest of the available options. Other links are possible including satellite, GSM (GPRS, 3G) via a router, or by direct internet link. Once installed the system has been designed to operate around a measurement schedule linked to specific command files which contain information on both the geoelectric measurement (Resistivity, Induced Polarisation, Self-Potential), electrode selections and data acquisition parameters. In addition the command files contain unique identifiers which allow resultant measurement data to be uploaded and automatically handled by the data management system (DMS). The system is serially based but has been configured to operate through TCP/IP protocols. The data is automatically captured, processed, stored in the relational database, modelled and then displayed on a web-portal for future analysis. Data has been collected using a Wenner-Schlumberger surface array and a Dipole-Dipole borehole electrode array. The ALERT instrument is fully integrated in a single, field-hardened, water-proof sealed box, designed to withstand extreme conditions in remote localities. No PC is needed in the field. It is novel in the sense that one can install the system and literally "walk away". The technology has been shown to be robust and highly reliable for several years in a moderately hostile environment.

## DATA MANAGEMENT

The anticipated frequency of data acquisition and the unprecedented amount of raw data collected demanded a systematic approach to data processing and management. A fundamental component of the ALERT concept is the DMS, which is based upon a relational database and implements a comprehensive relational data model for time-lapse ERT data. The DMS uses a Java-based architecture for web applications with a database backend. The current deployment uses Open Source products for the relational database (MySQL) and the J2EE application server (JBoss). The use of Open Source solutions contributes to the cost-effectiveness and portability of the ALERT data management concept.

All functionality is provided by two central servers at BGS. A Dell PowerEdge 2850 hosts the database and web application server. This machine also acts as a communications server by running customised control software, which automatically contacts the ALERT field system and controls the upload of measurement schedules and the download of measured data. A Dell PowerEdge 850 acts as a dedicated inversion server, running the numerical inversion code and accepting automated job submissions from the data management system.

After the field system has been set up to make scheduled measurements, it is polled at predefined intervals by the communications control software, using a telemetric link as appropriate. Once the workflow is optimised for a specific site, the process from data capture to image visualisation on the screen is seamless and automated for all further time-lapse datasets. Manual intervention is only required if automated quality checks fail or visual inspection shows large errors or dynamic changes in the image that would warrant a change in acquisition parameters (e.g: a change in sampling rate, or electrode configuration to better resolve a specific feature). Figure 5 shows a 2D ALERT image superimposed on an aerial photograph of the delta region. The image shows the influence of deep conductive saline water (dark blue), unsaturated surficial sediments (red) and a freshwater-saltwater mixing zone (green). The white dots denote buried electrode locations. The results show an increase in the depth of the saline interface inland, as expected. Further developments are on-going to optimise image reconstruction (Wilkinson *et al.*, 2006a, 2006b) and to program the ALERT system for adaptive sampling based on predefined scenarios (trigger thresholds). Similar thresholds could be coded into the software to automatically alert asset managers to potential threats such as impending mine-water break-out.

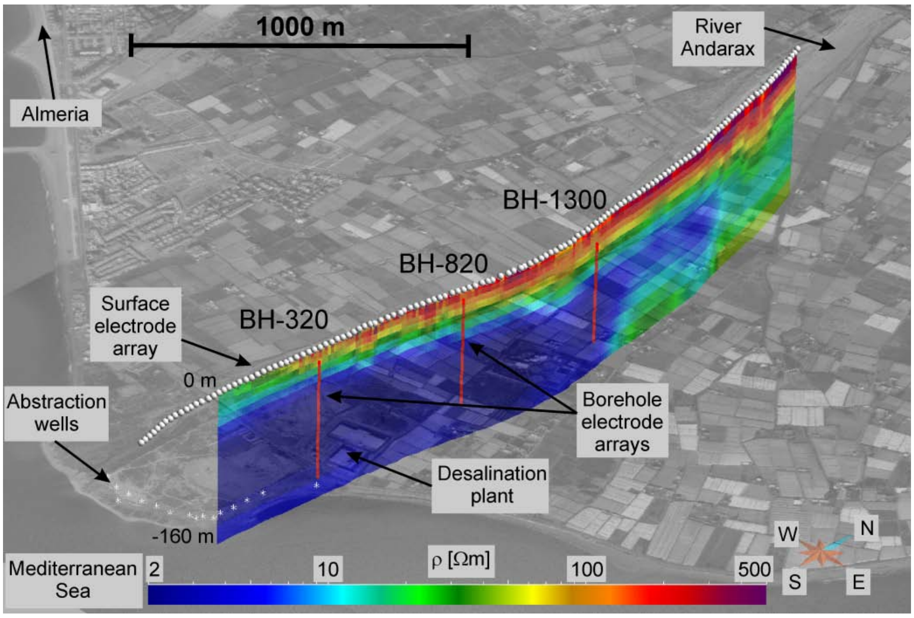


Fig 5 Aerial photograph with 2D ALERT image overlay. Visualisation of the subsurface aquifer showing conductive saline water (blue), resistive freshwater (red) and a mixing zone (green).

## MONITORING CONTAMINATED LAND SITES

We have also used ALERT system to monitor the in-situ remediation of contaminate land. In this case, we installed an ALERT array at a former gasworks site in a built environment. Our electrode network comprised 14 boreholes, situated along two of the site boundaries. Each of the borehole arrays comprised 16 electrodes spaced at 0.5 m depth intervals. This arrangement was designed to monitor potential residual contaminant plumes in a minor sand and gravel aquifer situated 5-6 m below ground level (bgl). After a year of monitoring no contaminant migration was detected. A saline tracer test was undertaken to determine the direction and speed of the groundwater flow and to demonstrate the ability of ALERT to monitor natural attenuation processes such as dilution and dispersion in near real-time. In this case, volumetric time lapse monitoring was used to visualise the evolution of the tracer in 3D with high spatial and temporal resolution. Resistivity data were collected between pairs of adjacent boreholes (“panels”) with measurements made with current flow and potential differences imposed and measured across the panel (i.e. in crosshole configurations). Only horizontal current and potential bipoles were used, and reciprocal measurements were made to assess noise levels only prior to the tracer injection. These measures enabled a complete set of data to be collected on every panel in two hours. Allowing a further two hours for battery recharge permitted six complete sets to be recorded per day. This high temporal resolution was desirable to prevent smearing of the images caused by changes in the tracer distribution during data acquisition. The measured piezometric levels in three nearby monitoring wells suggested that the groundwater velocity would be ~0.5 m/day. In the inverted images, the model cell is cubic with a side-length of 0.25 m, so tracer movement during measurement would have been typically ~15% of the dimensions of a cell.

A strong saline tracer (1000 litres, at a concentration of 40 g/l) was released into the aquifer via a groundwater monitoring well immediately adjacent to the borehole arrays. Despite the high concentration of the tracer, gravitational sinking was not expected to occur since the aquifer was confined by underlying bedrock and overlying alluvium. The inversion produced models with low mean misfit errors of ~3%. The time-lapse images of the tracer are shown Figure 6. The images are shown normalised to the baseline model, hence the conductive tracer exhibits resistivity ratios < 1. The isosurfaces are plotted at a ratio of 0.79 at times *t* days after tracer release. There are no conductivity increases above 5 m bgl, implying that there was little upwards migration of tracer through fissures in the alluvium, and that the aquifer is well confined. There were also no apparent tracer losses from the electrode array boreholes, confirming that no pollution pathways were created during the array installations. The tracer speed can be estimated directly from the images giving an average of $v = 0.49 \pm 0.07$ m/day, in excellent agreement with the value derived from the measured piezometric levels and estimated material parameters. This result suggests that geoelectrical monitoring has accurately mapped the dispersal of the tracer.

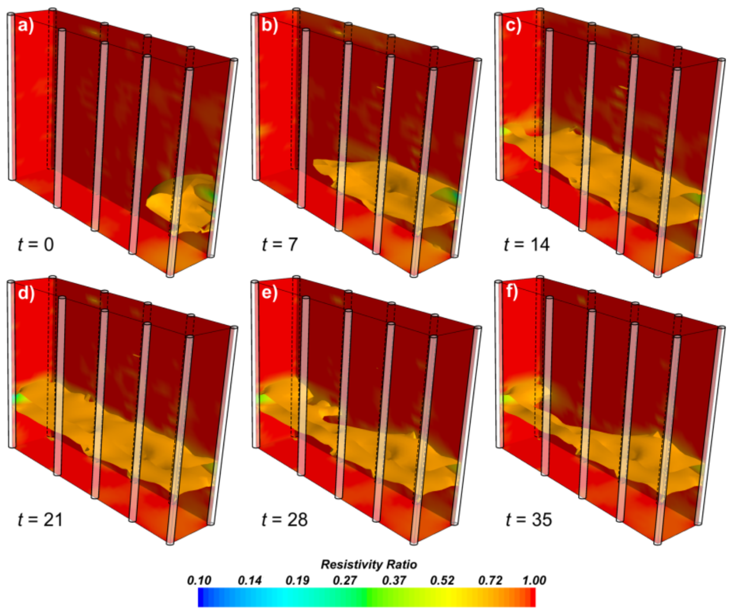


Fig 6 Controlled injection of a conductive saline tracer in a confined aquifer enabled the direction, dispersal, and velocity of groundwater flow to be determined directly from the ALERT real-time images.

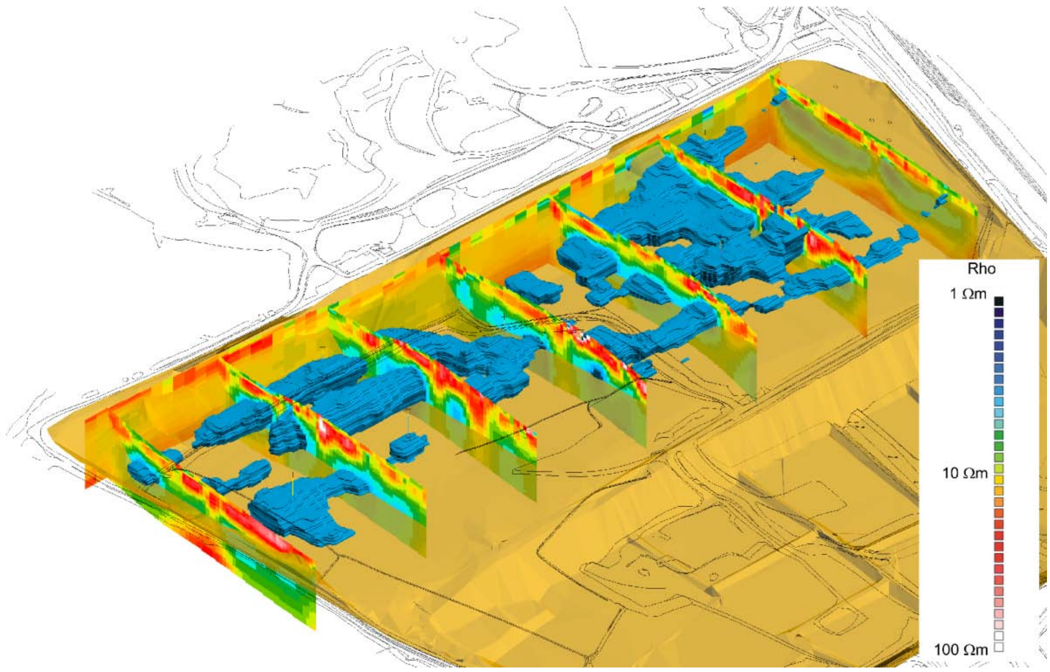


Fig. 7 3D ERT model of a domestic landfill showing how volumetric resistivity isosurfaces can be used to infer the leachate distribution.

## MONITORING DOMESTIC LANDFILLS

The advantages of volumetric, and non-invasive, 3D ERT imaging are well illustrated when applied to leachate mapping within commercial landfills. The inferred resistivity model can be combined with other relevant information such as well data and pit base topography to create an integrated 3D spatial model of the landfill, as shown in Fig. 7. Detailed waste logs from gas monitoring wells are needed to calibrate the resistivity model and set an appropriate iso-resistivity level for the leachate distribution, but the number of wells (and hence costs) is significantly reduced compared to conventional methods.

The use of ERT helped to unravel previously unresolved questions arising from the monitoring of landfill leachate by manual measurement of the liquid level in a borehole. Discrepancies between liquid levels obtained by dipping the gas wells and the leachate distribution inferred from the 3D resistivity model were explained by the fact that liquid levels in the wells are affected by atmospheric pressure and/or the pressure used in the gas extraction system and hence give a much higher leachate level in the waste mass than is actually the case. In contrast to the dipped levels, the leachate strike observed in waste logs from calibration wells corresponded extremely well with the resistivity model distribution. We concluded therefore that isolated dipped liquid levels were not an accurate representation of the true leachate distribution. By analogy, this finding may have implications for assessing the true water levels within mine workings where intrusive drives, shafts and drilling can disturb the natural hydrogeological balance.

## MONITORING VULNERABLE EARTH EMBANKMENTS

ERT has been used by BGS to investigate and monitor aging railway earthworks. Earth structures, such as embankments, require ongoing monitoring and maintenance to identify potential failure zones and to compensate for the effects of settlement. Extreme weather events leading to prolonged periods of desiccation or saturation are becoming more frequent and threaten embankment stability due to shrink/swell effects associated with clay minerals, the mobilization and precipitation of soluble constituents, and changes in strength caused by varying water content. The advantage of applying time-lapse ERT for earthwork monitoring is that spatial changes in moisture content can be mapped to identify zones of potential weakness prior to failure (Chambers et al., 2007 and 2008). We anticipate that a similar approach could be adopted by the mining industry to remotely monitor the physical integrity of tailings dams.

In the case of the railway earth embankment, permanent ERT electrodes were installed as a series of linear 2D arrays, both parallel and perpendicular to the long-axis of the embankment. The resulting ERT images, when calibrated using intrusive sampling methods, revealed the spatial variability of the embankment soils and also helped to identify major discontinuities between material types at locations associated with differential settlement and poor track geometry. Subsequently, we used time-lapse ERT images to monitor moisture content changes in the embankment; these images revealed both the spatial extent and magnitude of water content variations (Figure 8). In particular, these images showed the development of seasonal wetting and drying fronts in the embankment, and the effect of an extreme rainfall event during the summer of 2007.

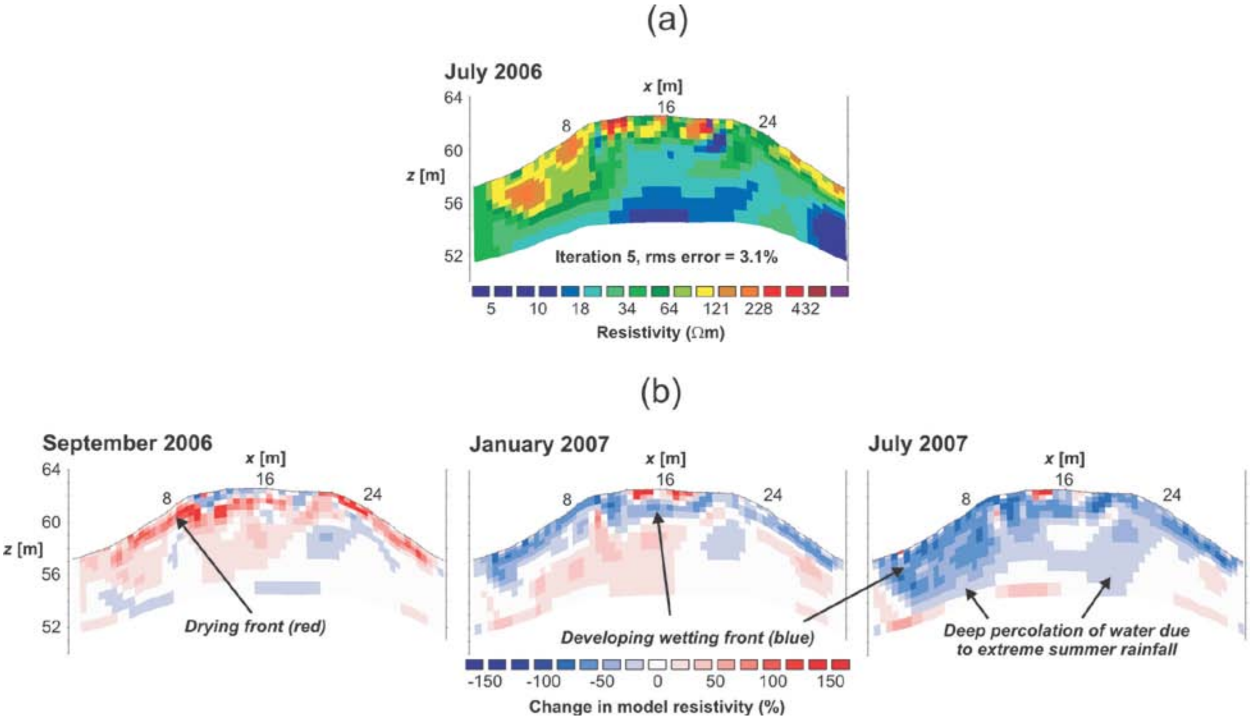


Fig. 8. (a) ERT earth embankment reference image and (b) differential resistivity images showing percentage changes in resistivities from the baseline model (July 2006).

## CHARACTERISING MINE WASTE

As part of ongoing BGS research into the environmental impact of abandoned metalliferous mines in the Central Wales Orefield in the UK, electrical resistivity tomography (ERT) surveys were carried out to characterise mine tailings at the Frongoch Mine near Devil's Bridge, Ceredigion. The mine produced lead and zinc ore from 1798 until its closure in 1904, when the site fell into disuse (Palumbo and Klinck, 2002). The site ranks highly in a list of abandoned UK mine sites, which were recognised by the Environment Agency for England and Wales as posing the greatest threat to surface waters (Environment Agency, 2002). The aim of the study was to obtain a more detailed understanding of the lateral extent of the historic tailings lagoon, the thickness of the tailings and any potential impact of the mine waste on the underlying bedrock and the surrounding environment. The geophysical characterisation of the site was intended as a precursor to future intrusive investigation and potential permanent monitoring with ALERT.

The tailings lagoon at the site occupies a shallow depression. The tailings were considered an environmental hazard due to erosion by water and wind and their high susceptibility to leaching of lead and zinc. They are a chemically active environment, with acidic conditions being prevalent in the near surface. Groundwater sampled in trial pits showed pH values between 3.9 and 6.2 and fluid conductivities (EC) of 650–700 μS/cm within the top 2 m. Concentrations of Pb from 0.1 to 12.7 wt% and of Zn from 1.1 to 11.2 wt% have been observed in the tailings.

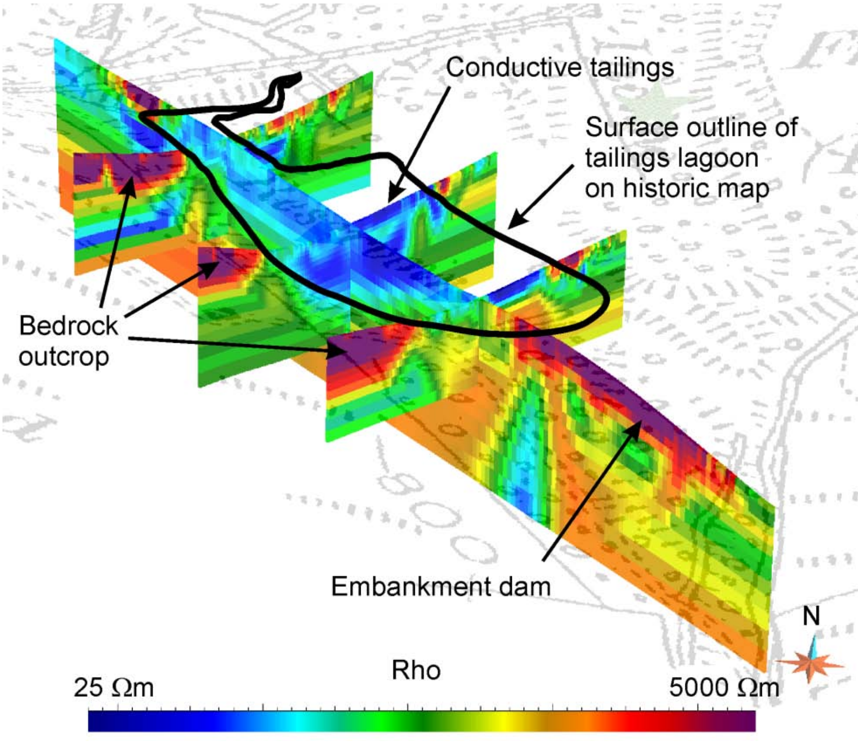


Fig. 9. 2D ERT image sections across the abandoned tailings lagoon

### ERT survey and results.

Results of the ERT survey are shown in the form of a fence diagram (Fig. 9), showing inverted 2D models of bulk subsurface resistivity for four intersecting profiles. The wide range of values reflects the variety of materials present on site, which include metalliferous tailings with varying content in moisture and fines, soils and made ground, peat and tills, and slate bedrock at various stages of weathering and fracturing. The observed resistivity distribution is in accordance with the previous extent of the lagoon indicated on historical maps. Fluid conductivities of groundwater samples obtained in trial pits correspond to pore water resistivities of around 15 ohm.m, which is in good agreement with the bulk resistivities observed for the tailings. A key finding is that low resistivities are found to extend to significant depths (up to 14 m bgl) and also laterally underneath resistive surface material on some profiles. As possible geological explanations are limited, potential contamination of the underlying bedrock due to downward leaching from the tailings is therefore being considered for the purpose of future site investigation and remediation measures.

### Implications for permanent monitoring

ERT surveys over a tailings lagoon have revealed the extent of the tailings deposits as well as the presence of underlying strata, including peat and glacial till. The geophysical data were used to site new boreholes in the lagoon area. The study has highlighted the potential of manual ERT surveys as a rapid and cost-effective tool in the context of the appraisal and environmental impact assessment of mine waste. However, much greater benefit can be expected from the installation of permanent ERT monitoring in form of ALERT technology. This would enable time-lapse studies of the evolution of resistivities in tailings lagoons and dams, which would allow decoupling of the process (fate of contaminated mine waters) from the static background (complexities of underlying geology and engineered structures within the mine). Analyses of the resistivity changes of mine waste with time are expected to provide new operational data for mine owners as well as vital input for mine waste science, such as reactive transport modelling.

## PLANNED WORK

A comprehensive test of ALERT for monitoring the environmental impacts of mine-waters in South Africa will commence in 2010. This research will be funded by the European Commission FP7 programme and will be undertaken by a consortium of academic and industrial partners, including the Council for Geoscience (CGS); formerly the South African Geological Survey, the Mineral Industry Research Organisation (MIRO), Anglo American plc and Anglo Operation Ltd. It is likely that we will instrument an abandoned open-cast mine in the Witbank Coalfield.

The project known as EO-MINERS will study the environmental impacts of mine waste, and acid mine drainage on surface waters, groundwaters and vulnerable ecosystems. Although satellite imagery (hyperspectral imaging, SAR) can provide high spatial resolution over large areas, it has a penetration depth of only a few centimetres and is unlikely therefore to detect deeper processes. ALERT tomography should provide a better characterisation of the spatial and temporal hydraulic behaviour of mine-waters at depth, especially beneath low permeability backfill in abandoned open cast mines. It will be important to relate this behaviour to anthropogenic or climatic forcings and to known changes in ecosystems. Once installed, the ALERT system will notify mine managers or Health & Safety authorities of potential threats by cellphone text message, visual alarms on the web-portal, or by email. To-date, none of these planned applications have been tested or demonstrated in areas impacted by mining. A project website will be set up in due course and we would welcome interaction with the wider mining community.

## CONCLUSIONS

The advantages of the ALERT monitoring concept have been clearly demonstrated for a range of dynamic surface-groundwater scenarios, including pollution mapping. It provides the basis for an early warning system to detect potentially catastrophic impacts or processes at an early stage before any visible manifestation. In the context of landfills or contaminated land, it is shown that subsurface conductive leachate plumes can be detected and remotely tracked in real-time using wireless telemetry. It is proposed that this technology might be similarly used to detect and monitor acid mine drainage from abandoned mines or tailings lagoons or to monitor the physical integrity of tailings dams. ALERT should not only permit a more sustainable approach to mine-water management (both quantity and quality), but will provide temporal and spatial sampling at a rate which has not previously been possible. ALERT should greatly assist our understanding of the hydrologic processes that occur in abandoned mines, particularly at depth where remote satellite imagery is not applicable. By imaging the migration of mine-waters in near real-time, the asset managers and local regulatory authorities could more readily assess the environmental impact of mining operations during and post-closure at minimal cost. The technology should effectively remove, or at least minimizes, the need for the manual sampling of water samples and time-consuming laboratory analysis.

## ACKNOWLEDGEMENTS

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