A Trial of 4D Cross-Borehole Electrical Resistivity Tomography (ERT) for Detecting and Monitoring Subsurface Leakage and Contaminant Transport, Supporting the Decommissioning of Legacy Silos at the Sellafield Site, UK – 14161

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ABSTRACT

A full-scale field trial of electrical resistivity tomography (ERT) technology has been undertaken in a controlled experiment at the Magnox Swarf Storage Silos (MSSS), part of the legacy ponds and silos at the Sellafield Site in Cumbria, UK. The trial constitutes the first application of ERT monitoring at a UK nuclear licensed site. Full 4D ERT processing provided images of resistivity changes occurring since a baseline date, which have revealed likely pathways of silo liquor simulant flow in the vadose zone and upper groundwater system. These pathways were found to be compatible with historic contamination detected in sediment cores retrieved from the trial boreholes. The ERT results have enhanced our conceptualization of likely leak behavior and contaminant transport in the shallow subsurface at the MSSS.

INTRODUCTION

A strategic priority for the UK's Nuclear Decommissioning Authority (NDA) is the reduction of risk and hazard across its estate of nuclear facilities. Legacy ponds and silos at the Sellafield Site in Cumbria, UK, pose the most significant technical challenges in this context. The safe emptying and decommissioning of the MSSS is one of the flagship projects that Sellafield Ltd (SL) is currently undertaking on behalf of the NDA. The uniqueness of the MSSS facility and its location in a complex industrial environment require the use of innovative decommissioning and monitoring technologies both to prepare and to execute the retrievals. The current strategy is for Silo Emptying Plant machines to be installed within the MSSS, which will then be used to retrieve wastes from the silo compartments, thus enabling safe transfer, immobilization and long-term intermediate storage in a modern containment facility.

Leakage of radioactive liquor from the MSSS to ground occurred during the 1970s. While none has been measured since, there is an increased risk that new leakage from the MSSS may occur during waste retrievals. To demonstrate control of silo liquor under normal and abnormal conditions the Ground Environment Management Scheme (GEMS) study was instigated by SL [1]. A key component of GEMS is environmental monitoring to assess the impact (groundwater contamination and risk to offsite receptors) of contaminants that are thought to have leaked to ground in the past and those that could potentially leak to ground during retrievals operations, thus ensuring regulatory compliance.

Scoping studies [2, 3] have identified ERT as the best available technology (BAT) for in-ground detection and volumetric monitoring of potential leakage from the silo foundations within the

GEMS remit. However, ERT had never been used for leak detection at a nuclear licensed site in the UK before, and the complexity of the Sellafield site and its geological setting gave cause for skepticism about the likelihood of a successful application of the method. In January 2012 the British Geological Survey (BGS) was therefore commissioned by SL to undertake a full-scale field trial of ERT technology in a controlled experiment at the MSSS facility in order to establish the suitability of the method for the intended purpose and to determine Technology Readiness for future permanent deployment at the building perimeter. An earlier ERT desk study [4] had demonstrated the feasibility of the approach in principle, based upon numerical simulations of trial scenarios.

This paper summarizes the results of the ERT monitoring field trial after the end of an active period, during which simulated silo liquor was injected at a location and depth commensurate with those that might be expected of a real leak. These results form the basis for designing and planning the deployment of a permanent ERT monitoring system at MSSS.

BACKGROUND

Site history

The Sellafield nuclear facility began operations in the mid-1940s as a military plutonium production plant, using the site of a former wartime munitions factory in Cumbria. In the 1950s the first Magnox civil power stations came into service and the magnesium alloy clad fuel from these reactors was reprocessed through existing facilities at Sellafield. Following a significant increase in nuclear generating capacity within the UK in the late 1950s, a Magnox reactor building program commenced and enhanced waste management facilities were brought into service at Sellafield in the early 1960s. The fuel cladding and other solid intermediate wastes were stored in water-filled silos, this function being fulfilled by MSSS [5]. The Silos were built in 1964, and over their 25-year operational life received Magnox swarf from nuclear sites across the UK. The facility initially comprised a limited number of compartments, but three extensions were constructed over a period of 20 years, with progressively improving build standards. Whilst the inventory of the waste is broadly known, its condition varies between compartments and sampling is only indicative.

During the 1970s, silo liquor is known to have leaked out of the building foundations, entering into the ground below and creating a plume of contamination. The leak was discovered when routine monitoring of the silos revealed a fall in the water level. Liquor balances have since been closely monitored and measurable leakage is thought to have occurred until 1980/81, when the estimated rate of liquor loss fell to the approximate levels expected for evaporation only. A rate of 3 m^3/day has generally been used as a maximum rate of leakage in liquor balance models; however 10.8 m^3/day is also sometimes used as a more pessimistic scenario. A rate of 0.2 m^3/day (5 m^3/month) is the modern investigation trigger.

Hydrogeology

The shallow bedrock beneath the Sellafield site comprises the two uppermost units of the Triassic Sherwood Sandstone Group. Sandstone bedrock below MSSS is encountered at depths of ~40-45 m below ground level (bgl); the comparatively greater thickness of the superficials at this location is due to the suspected presence of a buried valley beneath the Sellafield Separation Area. The superficial geology comprises a variable thickness of Quaternary deposits. On site a layer of made ground extends to depths of up to 5 m. The surviving Quaternary sediments can be attributed to the last major glaciation that affected West Cumbria (26,000 years BP), and comprise a complex sequence of glacial and postglacial deposits including tills, alluvial sands and lacustrine sediments. The superficial deposits are the principal medium through which contaminant transport occurs in the ground [6].

Both the superficials and the sandstone bedrock are of hydrogeological significance [7], with the former being classified as a minor aquifer and the latter as a major aquifer. The aquifer system has been divided into seven hydrostratigraphic units, summarized in TABLE I. The water table below MSSS is located at around 9-10 m bgl; this shows only a moderate seasonal variation (typically ± ~1 m). Partially saturated conditions prevail in the vadose zone above the water table, which is likely to be the primary entry zone for any liquor leaking from the building.

The Quaternary deposits in particular are highly variable and not laterally continuous and it is generally difficult to predict hydraulic properties and resulting flow regimes in the shallow subsurface at the scale of an individual building. Assessing the performance of a leak detection system based upon subsurface property estimates derived from geophysical measurements therefore necessarily included an in-situ trial. Besides proving the technology, one of the wider goals of the ERT trial was to enhance our conceptualization of the hydrogeology at MSSS and improve our understanding of contaminant transport and likely plume behavior in the shallow subsurface.

TABLE I. Relationship between aquifers, hydrostratigraphic units and lithological units at Sellafield.

Aquifer	**Hydrostratigraphic Unit**	**Lithological Unit**
Quaternary aquifer	Made Ground Perched Unit	Made Ground upper Post Glacial Formation and Oscillation Till Formation
	Post Glacial Formation Unit (PGF)	Post Glacial Formation
	Upper Oscillation Till Unit (OTF)	Oscillation Till Formation above Brown clayey diamicton/Red clayey diamicton
	Clayey Diamictons Unit (CDU)	Brown clayey diamicton and Red clayey diamicton
	Lower Oscillation Till Unit (LOU)	Oscillation Till Formation below Brown clayey diamicton/Red clayey diamicton
	GlacioFluvial Unit (GFU)	GlacioFluvial Formation, Oscillation Till Formation and Lower Till Formation
Sandstone aquifer	Sherwood Sandstone	Bedrock

ERT technology

ERT relies upon multiple and repeated measurements of bulk electrical resistance of the soil and subsurface deposits in the area of interest; these are carried out with a buried array of ERT electrodes ("sensors") that must cover (as a minimum) the perimeter of the volume of ground to be monitored. Through inverse geophysical modeling, ERT then transforms these measurements into images of ground resistivity in the region being monitored. Since resistivity is strongly dependent on saturation and dissolved contamination, changes in resistivity can potentially be used as a proxy to track the evolution of leakage plumes.

METHODOLOGY

Trial design and staged process

The trial was designed to provide sufficient underpinning data to allow the achievement of a Technology Readiness Level (TRL) of 6 for ERT. Controlled injections into the vadose zone of environmentally benign conductive simulants (saline tracer solution) were to be carried out and monitored by automated ERT measurements at regular intervals. The simulants were developed to replicate the range of measured conductivities of measured silo liquors. Guided by the U.S. Environmental Protection Agency's (EPA) Data Quality Objectives (DQO) framework, a trial procedure was implemented covering six key practical steps:

1. The production of boreholes and the installation of the ERT equipment;
2. Baseline ERT monitoring to assess the ambient noise conditions at the site;
3. Injection of a conductive simulant into the outermost injection borehole (BH5, Fig. 1) for up to one month, or until sufficient data has been collected to demonstrate functionality;
4. ERT monitoring to study the decay of the plume from step (3), and to re-baseline the system;
5. Simulant injection into the innermost injection borehole (BH4), with any remnant plume from step (3) remaining in the ground;
6. Injection to the outermost borehole increased to a high flow for up to four days;
7. Extended ERT baseline monitoring to capture decay of injected simulants and assess seasonal variation of trial parameters (noise, sensor health, hydrology).

The details of the trial stages are summarized in TABLE II.

TABLE II. ERT trial stages.

Trial stage	**Indicative duration**	**Injection rate (simulated leak)**	**Simulant electrical conductivity**	**Injection borehole**	**Indicative simulant volume**
Baseline noise assessment	1 month				
Injection of simulant to form a plume ("Stage 1 injection")	1 month	0.7 m^3/day	850 μS/cm	BH5	22 m^3
Monitor decay and re-baseline	1 month				
Injection of simulant at a second location, with existing plume present ("Stage 2 injection")	3 months	0.7 m^3/day	550 μS/cm	BH4	64 m^3
Outer bound scenario ("Stage 3 injection")	3 days	10.8 m^3/day	1,500 μS/cm	BH5	34 m^3
Extended Baseline Noise Assessment	1 year				
			Total injected volume		120 m^3

ERT array design

Leak detection and monitoring at MSSS requires a focus on regions at or below the base of the building foundations, and ideally a capability to detect and characterize potential leakage plumes beneath the building itself. Only a cross-borehole configuration of ERT fulfills these criteria, where the sensors are located in boreholes situated on both sides of the building. At the same time, the sensitivity and resolution for crosshole ERT imaging are closely linked to and constrained by the separation between the boreholes. Previous studies have shown that the aspect ratio for a crosshole panel (separation between boreholes divided by length of electrode string in each borehole) should not exceed 0.75 in order to provide sufficient image resolution [8]. Imaging is likely to be most successful for ratios below 0.5 [9]. The limiting distance for deployment at MSSS is the width of the building, which is typically around 18 m. Boreholes cannot be installed within ~2 m of the silo walls, so that a minimum borehole separation of 22 m must be considered.

Below the older sections of MSSS, which tend to cause greater concern in terms of their potential for leakage, the building foundations extend to approximately 6 m bgl. Monitoring of changes in saturation levels and fluid flow between this depth and the water table below the building is of particular interest for leak characterization. It is however unclear how quickly and how deep any potential contaminant plume would eventually sink, and the fate of historic contamination is also unknown. For the purposes of the ERT trial it therefore seemed reasonable to include the entire sequence of superficials in the initial monitoring strategy, hence the boreholes were extended down to bedrock~40 m bgl, which also satisfies the above geometric condition for imaging (aspect ratio ~0.55).

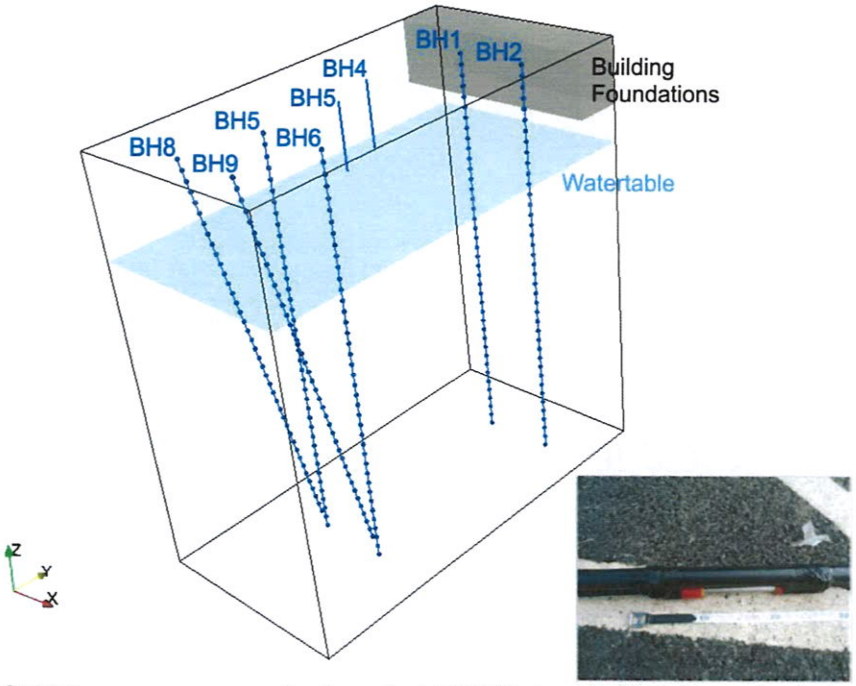

Fig. 1. Geometry of ERT sensor arrays deployed at MSSS. Inset: Stainless steel electrodes used for the trial installation.

Downhole ERT sensor arrays in six boreholes south of the MSSS structure were arranged in an approximately rectangular fashion, simulating deployment on opposite sides of the building (Fig. 1). Four of the boreholes were vertical and represented the fundamental ERT imaging cell. Two further boreholes were inclined to test deployment in areas with limited surface access to the building. These, together with the two vertical boreholes adjacent to the Silo formed a separate "inclined cell", for which the imaging geometry was slightly less favorable. Each sensor array comprised 40 stainless steel (316L) electrodes (Fig. 1), spaced at 1 m separations, resulting in a total of 240 sensors buried in the trial area. Two shallow boreholes for tracer injection (depth of 6 m), simulating possible leak locations at the base of the silo foundations, were placed near the center of the area bounded by the four vertical boreholes.

Borehole and ERT system installation

The six ERT boreholes together with the two shallow injection boreholes were installed by a sonic drilling method between August and October 2012 (Fig. 2). In each borehole, temporary steel casing was initially deployed. ERT sensor cables were then mounted onto flexible PVC tubing that served as a carrier, before the assembly was lowered into the open borehole. The casing was then gradually withdrawn, whilst backfilling the borehole annulus with bentonite clay pellets; this process resulted in sensor emplacement that was mechanically stable and provided good electrical contact between electrodes and the surrounding formation. Only three electrodes out of the 240 installed had to be excluded later from active measurements due to poor contact.

Fig. 2. ERT borehole installation at MSSS.

Once the boreholes were completed, the sensor arrays were connected to BGS-designed ALERT instrumentation [9-11], which allows autonomous scheduled collection of large amounts of electrical resistance data. A telemetric link to the BGS offices in Nottingham, UK, enables fully remote operation of the ERT system, upload of command schedules and regular download of datasets via broadband internet.

Baseline measurements

Testing and commissioning the ERT system involved an initial period of system optimization measurements. As was expected in the complex industrial environment at MSSS, spurious electrical potentials were found to affect the measured data to varying degrees at different times. These potentials were suspected to be a combination of spontaneous potential (SP; electrical fields unrelated to the ERT system) and induced polarization (IP; ground charging phenomenon) effects. Countermeasures included reorganizing our measurement scheme to reduce such effects and to exclude specific electrodes from further measurements (2 for vertical/inclined cells and 2 further for inclined only).

After commissioning, a 6-week period of quiescent baseline measurements was undertaken, during which no further changes to the system setup were made. For all measurements, data acquisition on vertical and inclined cells was scheduled separately on alternating days. A comprehensive sequence of bipole-bipole measurements was programmed for each cell, resulting in a total number of four-point resistance measurements per dataset of ~53,100. These contained reciprocal configurations (where current and potential electrodes are swapped [12]), which allowed the calculation of ~13,400 averaged reciprocal measurements per dataset. The measurement duration per cell was approximately 22.5 hrs, while data retrieval and transmission to the BGS servers took around 25 min; therefore a routine 24-hour measurement cycle could be achieved.

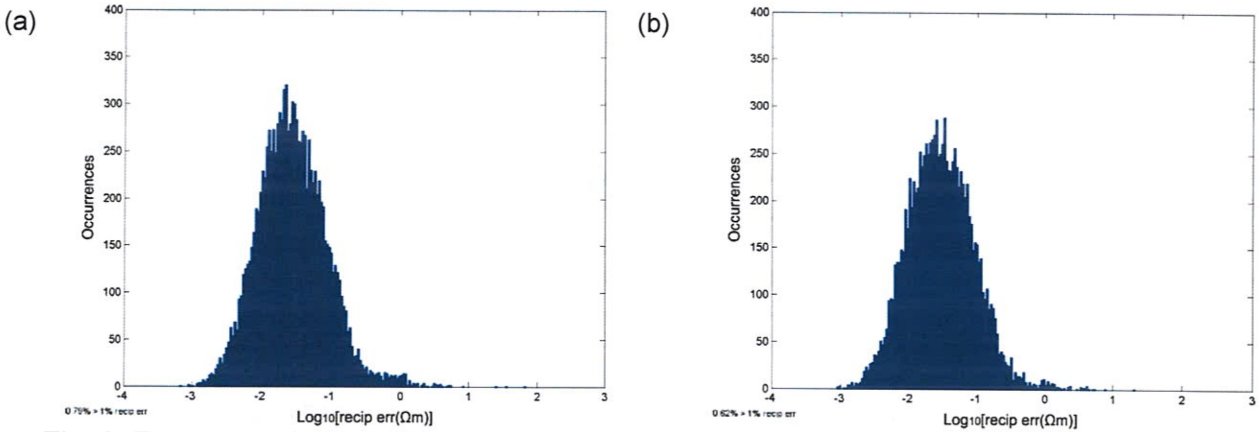

Fig. 3. Examples of distributions of the reciprocal error for (a) vertical and (b) inclined ERT datasets during baseline acquisition, providing a measure for short-term variability in the MSSS data.

Error estimates from reciprocal measurements (timescale ~several hours, Fig. 3) were compared with apparent resistivity variations in the data over the baseline measurement period (timescale ~several weeks, Fig. 4), in order to understand short-term and long-term variability at the site under baseline ("no leak") conditions. Short term variability was found to be very low, with reciprocal error distributions peaking below 0.1% (Fig. 3). Longer term variability of resistivities was found to be significantly greater, but still acceptable compared with the levels of change caused by simulated leaks that were forecast by desk study numerical models [4]. A one-week period of the quiescent baseline, in which no significant variations were observed, was later used as the "reference baseline" against which statistical variations in the ERT data were subsequently assessed.

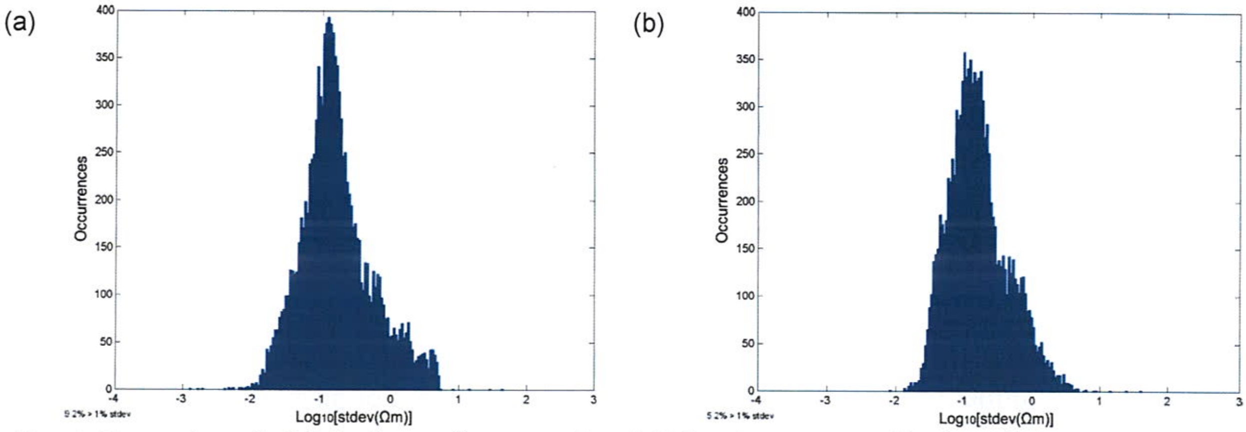

Fig. 4. Examples of distributions of apparent resistivity change over the baseline measurement period, providing a measure for longer-term variability in the MSSS data. (a) Vertical, (b) inclined cell.

Simulant injection

Once baseline measurements were complete, controlled injections of saline tracer solution into the shallow injection boreholes were carried out from a pump/tank skid deployed next to the trial area. The simulant comprised process water dosed with NaCl and NaBr to required specific conductivities of 850 µS/cm, 550 µS/cm and 1,500 µS/cm at 25°C. A target molar ratio of Cl:Br of 10:1 (mass ratio of 4.4 : 1) was used in order to make the solution sufficiently distinct from the known Sellafield groundwater chemistry. Injection timings, indicative duration and simulant properties are described in TABLE II. Stage 1 and 2 injections were performed "blind", i.e. the ERT monitoring team did not know the start date and time of the injections.

Repeated ERT cross-borehole measurements using the vertical and inclined cells were made before, during and after the injections in order to assess the information content of the ERT data with respect to the occurrence of the simulated leak and the fate of the resulting plume.

ERT data processing

The complexity of the geology at MSSS and the presence of clay-rich sediments, combined with the relatively small contrasts in electrical properties that the silo liquor was thought to exhibit against the groundwater and the site geology had cast initial doubts over the likelihood of success for ERT at MSSS, particularly when compared with previous applications of ERT to nuclear waste leak detection reported in the literature under more favorable conditions, for example at Hanford [13]. Moreover, leak detection based on ERT is challenging in any circumstance as competing (but unrelated) processes are known to affect resistivity, including soil temperature variations, precipitation and recharge, and electrical noise from plant operation and natural sources. Indeed, early attempts to perform leak detection based upon the raw resistance data statistics alone were deemed inadequate, and as a result we carried out full 3D time-lapse inversion (4D ERT inversion) to generate resistivity images of the subsurface in the trial area for further analysis. A 4D resistivity inversion algorithm implementing the method proposed in [14, 15] was used.

RESULTS AND DISCUSSION

Absolute images of resistivity obtained during the baseline period reflected the complex geological setting at the MSSS site (Fig. 5). These were found to correlate well with stratigraphic logs obtained from the inspection of sediment cores from ERT boreholes.

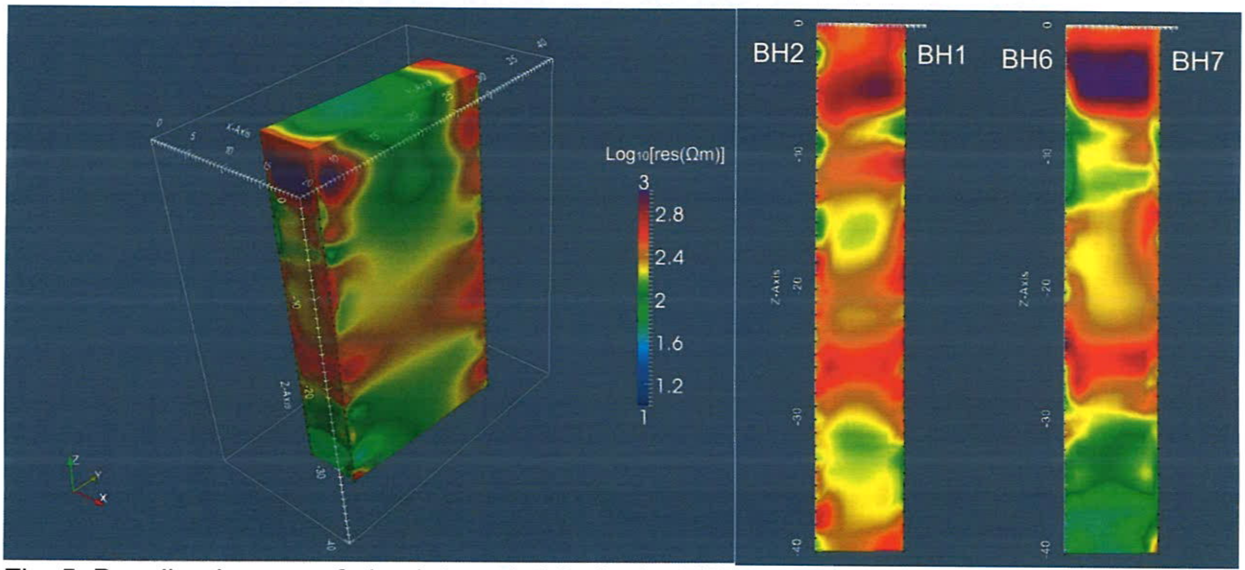

Fig. 5. Baseline images of absolute resistivity in the ERT Trial area, reflecting the complexity of the superficial deposits at Sellafield. Left: 3D image within the vertical cell; Right: 2D crosshole panels.

Stage 1 injection

The Stage 1 injection introduced simulant with an intermediate conductivity contrast via BH5, but at a relatively low leak rate. The statistics of conductive changes in the raw ERT data relative to the baseline were found to be insufficiently distinct to be attributed unambiguously to the injection. Instead, stronger correlation was observed with unrelated (but clearly relevant) processes such as heavy rainfall and subsequent infiltration into the vadose zone, surface runoff and infiltration of dissolved road de-icing salt following snowfall, and variations in ground temperature. However, a more consistent picture emerged after ~4 weeks of continued injection, when conductive anomalies developing in the time-lapse resistivity images, plotted as ratios relative to a baseline resistivity image (inverted resistivity at time *t* divided by inverted resistivity at baseline time), were found to have strengthened in contrast (Fig. 6).

Their locations in the vadose and upper saturated zones were consistent with the known injection point and the suspected behavior of gravitational sinking under the influence of small lateral hydraulic gradients. The strongest features of conductive change in the upper saturated zone appeared in the immediate vicinity of ERT boreholes 1, 2 and 7 within narrow depth windows that were consistent with zones of historic contamination, which had been detected in core recovered from the boreholes. This led us to infer the presence of a preferred contaminant flow path that appears to have been active in the past, and to have been subsequently re-occupied by the Stage 1 simulant. No significant decay of the conductive plume signature was observed over the space of ~10 weeks of routine monitoring following the end of the Stage 1 injection.

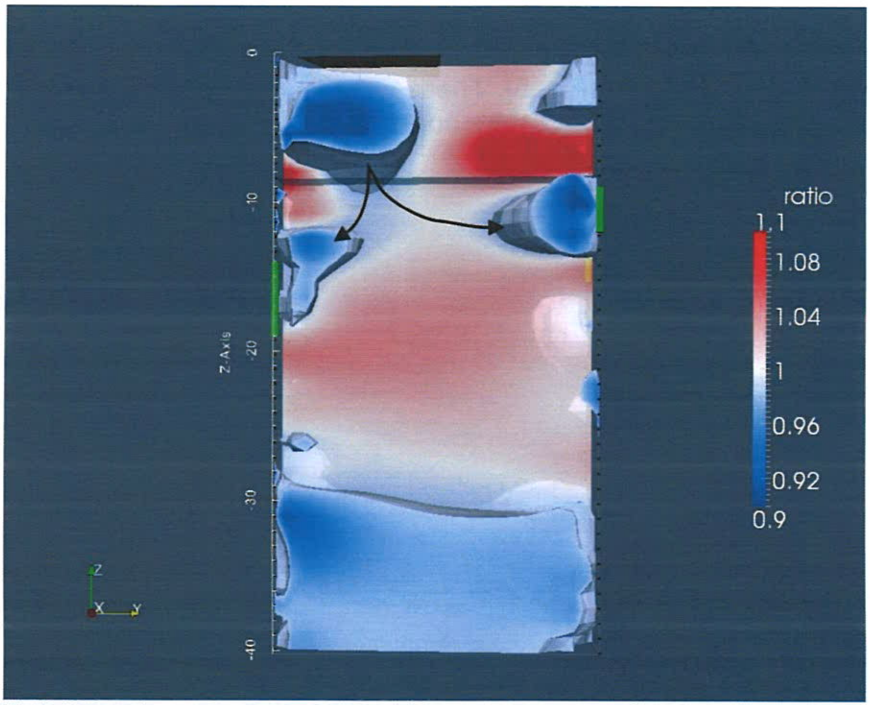

Fig. 6. 3D resistivity ratio image showing results of Stage 1 injection. Warmer colors indicate increases relative to baseline resistivity, while cooler colors reflect decreases. Black arrows indicate inferred pathway; green bars show regions of historic contamination found in ERT boreholes.

Stage 2 injection

For the Stage 2 injection, simulant with a lower conductivity contrast was injected into BH4 at the same low leak rate as in Stage 1 in order to investigate whether ERT could help distinguish separate events in a "leak-on-leak" scenario. However, expectations were modest as the Stage 2 plume behavior was likely to be complex, and a leak-on-leak scenario had not been simulated prior to the experiment. Once again, due to the low target contrast and low leak rate, no appreciable response was noted for at least ~4 weeks. Sporadic conductive changes in the vadose zone appeared to be dominated by further surface infiltration, as some correlation with rainfall data could again be observed. Further negative changes occurred eventually, which, compared with Stage 1, had increased in strength and appeared in new regions.

More detailed analysis, examining the spatial moments of resistivity changes in specific subvolumes, allowed us to separate two apparently distinct sets of changes for Stage 2 (Fig. 7). Some are consistent with the pathway already identified in Stage 1 (green ellipse), suggesting that the same pathway was re-occupied despite the injection location being offset. Other changes appear at greater depth (below 20 m; purple ellipse) and could potentially indicate a vertical connection to the lower groundwater system. However, at the time of writing independent ground truth confirmation had yet to be obtained, for example from routine groundwater sampling in the vicinity of MSSS.

The Stage 2 analysis relied again on resistivity ratio images recovered from 4D inversion; in contrast to Stage 1 however, datasets acquired at different times were now used as references for comparison and the calculation of ratios. The impact on the analysis of the change in reference datasets is demonstrated in Fig. 7, which shows the same resistivity inversion towards the end of Stage 2; new features in the image that have occurred as a result of Stage 2 injection are enhanced when the image is referenced to the end of Stage 1, rather than to the baseline at the beginning of the experiment.

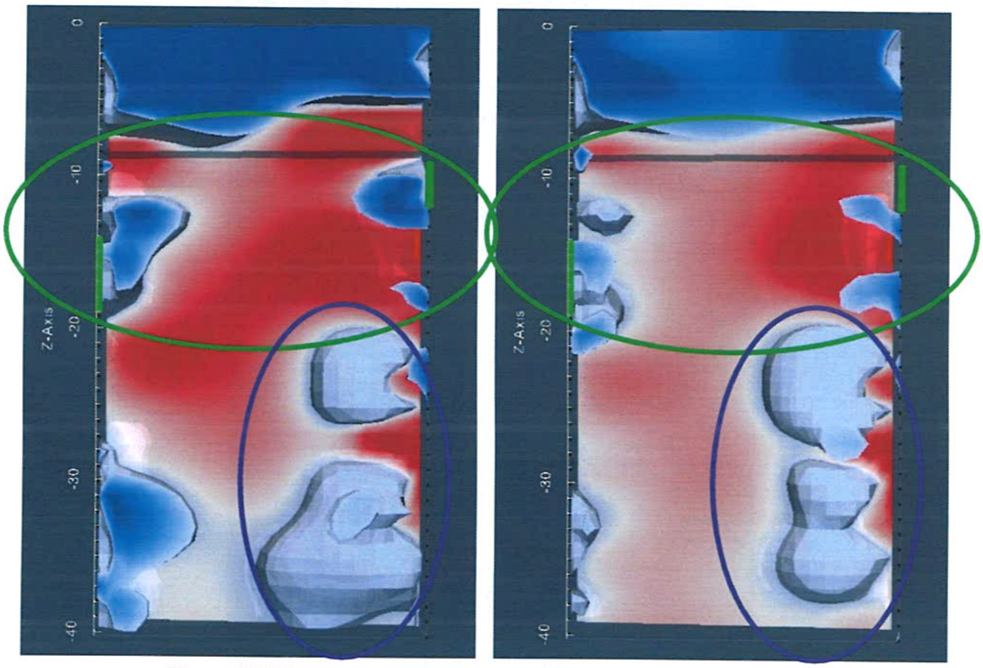

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Fig. 7. 3D resistivity ratio images showing results of Stage 2 injection (color scale identical to Fig. 6). Left: image referenced to baseline period at the start of the experiment; Right: image referenced to the end of the Stage 1 injection. The green ellipse highlights further changes in the pathway already identified in Stage 1; the purple ellipse indicates changes that appear at greater depth (below 20 m).

Stage 3 injection

The Stage 3 injection involved the introduction of simulant with a significantly higher conductivity, and at a high leak rate reflecting the most pessimistic scenario. This was done in an effort to corroborate the results of the previous two Stages, as it was expected that the existing flow paths would be occupied once more and that the cumulative effect of the more conductive simulant would overcome the limitations of the low-sensitivity cross-borehole geometry, by consistently highlighting flow paths throughout the 3D ERT model. The Stage 3 injection lasted three days, during which approximately 34 m^3 of simulant were introduced into the vadose zone via BH5. Resistivity ratio images for Stage 3 responded very soon (~1 week) after the injection event, and the change evolution over the subsequent 1.5 months showed that the Stage 1 flow path was indeed occupied once again. However, this time the resistivity ratio isosurface plots were spatially coherent across the model (Fig. 8) and provided an intuitive visual representation of inferred fluid flow in the shallow subsurface beneath the Trial area.

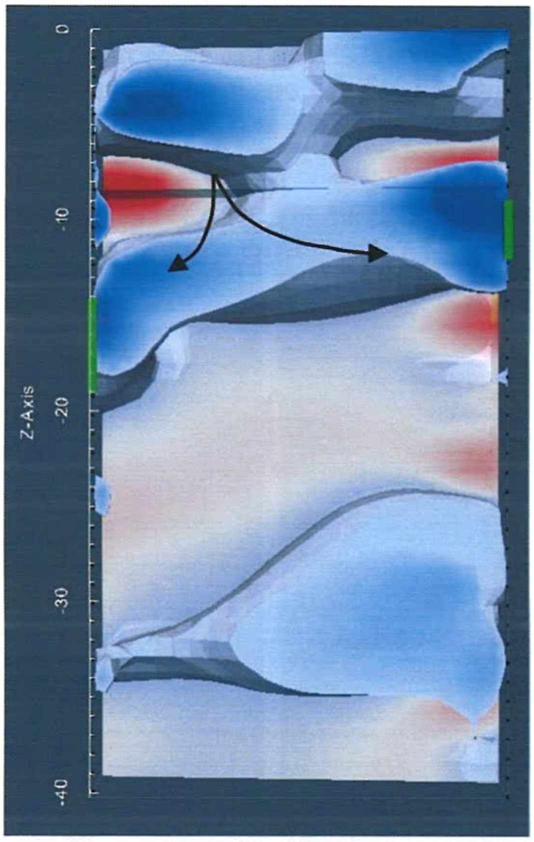

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Fig. 8. 3D resistivity ratio image showing results of Stage 3 injection (color scale identical to Fig. 6).

CONCLUSIONS

Automated ERT monitoring has been applied at a UK nuclear licensed site for the first time and a full-scale field trial of the technology at MSSS in Sellafield has shown success. Whilst the use of raw data statistics alone did not allow us to discriminate simulated leaks from unrelated processes, full 4D ERT processing has proved sufficiently sensitive and images of resistivity changes relative to a baseline date have revealed likely pathways of simulant flow in the vadose zone and upper groundwater system. These pathways were found to be compatible with historic contamination detected in sediment cores retrieved from the trial boreholes. The ERT results have enhanced our conceptualization of likely leak behavior and contaminant transport in the shallow subsurface at MSSS. The remainder of the trial comprises a year-long extended baseline measurement to capture the seasonal variability within the ERT data. Further analysis of trial data will attempt to characterize the sensitivity of ERT to different leak rates and simulant conductivities.

Future plans include the installation and routine operation of a permanent ERT monitoring system at MSSS in order to support the scheduled decommissioning of the Silos over the coming decades. The permanent system will cover much of the building, and require about an order-of-magnitude more boreholes and ERT sensors, and a proportionally higher effort in terms of data collection and processing.

REFERENCES

1. Dewey, G., N. Atherton, T. Ball, O. Kuras, P. Wilkinson, and P. Meldrum. *The Ground Environment Management Scheme (GEMS): Development of technologies for detecting and monitoring subsurface leakage and contaminant transport, supporting the decommissioning of legacy silos at the Sellafield Site, UK.* Waste Management (WM) Conference, WM Symposia, 2014. Phoenix, AZ.
2. Cummings, R.L.K., *Options for Leak Management from Nuclear Legacy Facilities during Decommissioning*, 2012, Royal Holloway University of London. p. 91.
3. Emptage, M., S. Hepworth, V. Winspear-Roberts, and R. Cummings. *The leak management hierarchy.* Decommissioning Challenges: An Industrial Reality and Prospects, Société Française d'Energie Nucléaire, 2013. Avignon, France.
4. Kuras, O., P.B. Wilkinson, J.C. White, J.E. Chambers, P.I. Meldrum, and R.D. Ogilvy, *MSSS Leak Mitigation - Leak Detection Phase 3: Desk Study for ERT Technology.* Commissioned Report CR/11/053, British Geological Survey, 2011.
5. Baldwin, N.D. *Remediating Sellafield - A New Focus for the Site.* Waste Management (WM) Conference, WM Symposia, 2003. Tucson, AZ.
6. Smith, N. and S. Cooper, *SCLS Phase 1 - Sellafield Geological Conceptual Model.* Nuclear Sciences and Technology Services, NSTS 4866, BNFL, 2004.
7. El-Ghonemey, H., *SCLS Groundwater Conceptual Model.* Nuclear Sciences and Technology Services, NSTS 4443, BNFL, 2004.
8. LaBrecque, D.J., A.L. Ramirez, W.D. Daily, A.M. Binley, and S.A. Schima, *ERT monitoring on environmental remediation processes.* Measurement Science & Technology, 1996. **7**(3): p. 375-383.
9. Wilkinson, P.B., P.I. Meldrum, O. Kuras, J.E. Chambers, S.J. Holyoake, and R.D. Ogilvy, *High-resolution Electrical Resistivity Tomography monitoring of a tracer test in a confined aquifer.* Journal of Applied Geophysics, 2010. **70**(4): p. 268-276.
10. Kuras, O., J.D. Pritchard, P.I. Meldrum, J.E. Chambers, P.B. Wilkinson, R.D. Ogilvy, and G.P. Wealthall, *Monitoring hydraulic processes with automated time-lapse electrical resistivity tomography (ALERT).* Comptes Rendus Geoscience, 2009. **341**(10-11): p. 868-885.
11. Ogilvy, R.D., P.I. Meldrum, O. Kuras, P.B. Wilkinson, J.E. Chambers, M. Sen, A. Pulido-Bosch, J. Gisbert, S. Jorreto, I. Frances, and P. Tsourlos, *Automated monitoring of coastal aquifers with electrical resistivity tomography.* Near Surface Geophysics, 2009. **7**(5-6): p. 367-375.
12. LaBrecque, D.J., M. Miletto, W. Daily, A. Ramirez, and E. Owen, *The effects of noise on Occam's inversion of resistivity tomography data.* Geophysics, 1996. **61**(2): p. 538-548.
13. Daily, W., A. Ramirez, and A. Binley, *Remote monitoring of leaks in storage tanks using electrical resistance tomography: application at the Hanford Site.* Journal of Environmental and Engineering Geophysics, 2004. **9**(1): p. 11-24.
14. Kim, J.H., M.J. Yi, S.G. Park, and J.G. Kim, *4-D inversion of DC resistivity monitoring data acquired over a dynamically changing earth model.* Journal of Applied Geophysics, 2009. **68**(4): p. 522-532.
15. Loke, M.H., T. Dahlin, and D.F. Rucker, *Smoothness-constrained time-lapse inversion of data from 3D resistivity surveys.* Near Surface Geophysics, 2013: p. DOI: 10.3997/1873-0604.2013025.

ACKNOWLEDGEMENTS

This paper is published with the permission of the Executive Director of the British Geological Survey (NERC).