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Shooting lines and finding mines: A case study of geophysics to locate and characterize mine water thermal resources

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INTRODUCTION

Electrical Resistivity Tomography (ERT) is a well-established geophysical technique used for a wide range of purposes including resource exploration and geotechnical investigation. ERT uses electrodes to measure the spatial distribution of electrical resistivity in the subsurface. This is achieved by sending a current through a substrate via current electrodes and measuring the voltage of the substrate using potential electrodes. The output of an ERT survey is therefore the relationship between injected current and measured potential.

There are many published examples of ERT being used to detect both natural and engineered buried void spaces (Rahimi *et al*., 2024; Ungureanu *et al.*, 2017) including buried mine infrastructure (Banham and Pringle, 2011; Wilkinson *et al*., 2005). However, there are no published examples of ERT being used to de-risk drilling programs aiming to access mine water resources.

This research aims to assess the suitability of ERT for the purpose of mine water thermal resources. To achieve this aim, sites across the Midland Valley of Scotland were selected to test the capability of ERT in detecting mine infrastructure and voids at varying depths. Sites were selected based on their differing surface, subsurface, resource characteristics and data availability to assess the suitability of ERT for the purpose of mine infrastructure detection in a variety of environments.

The works discussed in this extended abstract focus on one of these case studies, the Dalquharran Estate in South Ayrshire, Scotland. The site is underlain by a series of abandoned mine workings including excavated mine seams and roadways. This site is undergoing mine water resource assessment for low-carbon heat supply to agricultural operations. Confirmation of flooded mine void location and the de-risking of drilling campaigns to access the potential resource was the primary focus of this study. ERT surveys were part of a larger research program, including ongoing water and gas sampling and monitoring, which are not discussed in the present paper.

1 METHODS

1.1 Desk study

An initial desk study was carried out to understand the subsurface characteristics of the Dalquharran site and inform geophysical survey parameters. Coal seams beneath the site were mapped using data acquired from the UK Mining Remediation Authority under a non-commercial license. A georeferenced GIS was used used to create a series of cross sections showing depths of mined coal seams, and therefore, target void spaces for prospective heat extraction.

The mine workings themselves target the coal seams of the Limestone Coal Formation (Smith and Monoghan, 2013). The Upper Limestone Formation is logged in a nearby shallow borehole (BGS ref. NS20SE44) as being dominantly siltstone, mudstone and sandstone. The Upper Limestone Formation conformably overlies the Limestone Coal Formation. Both solid formations were deposited in the Carboniferous. Rock head is logged in a local borehole (BGS Ref NS20SE41) at approximately 16 m. The same borehole describes the diamicton that is mapped as covering the site, consisting of clay with sandstone boulders.

An initial ERT survey line (**Figure 1**) was centered over the primary target for drilling, an area where the deepest packet of workings could be targeted. According to a cross section produced along the intended survey position, these deeper workings started at a depth of c. 71 m below ground level (m bgl). A secondary goal was to image as many other known workings as possible. However, due to spatial deployment constraints and based on

mapped locations and depths of workings it was deemed that this would prove unlikely for this particular line due to: (i) the eastern section of the survey transect not being located above any mapped coal seams: (ii) a general northward dip of 3˚ in mine seams, meaning that the shallower packet of mine workings would below imaging depth in the western section of the transect.

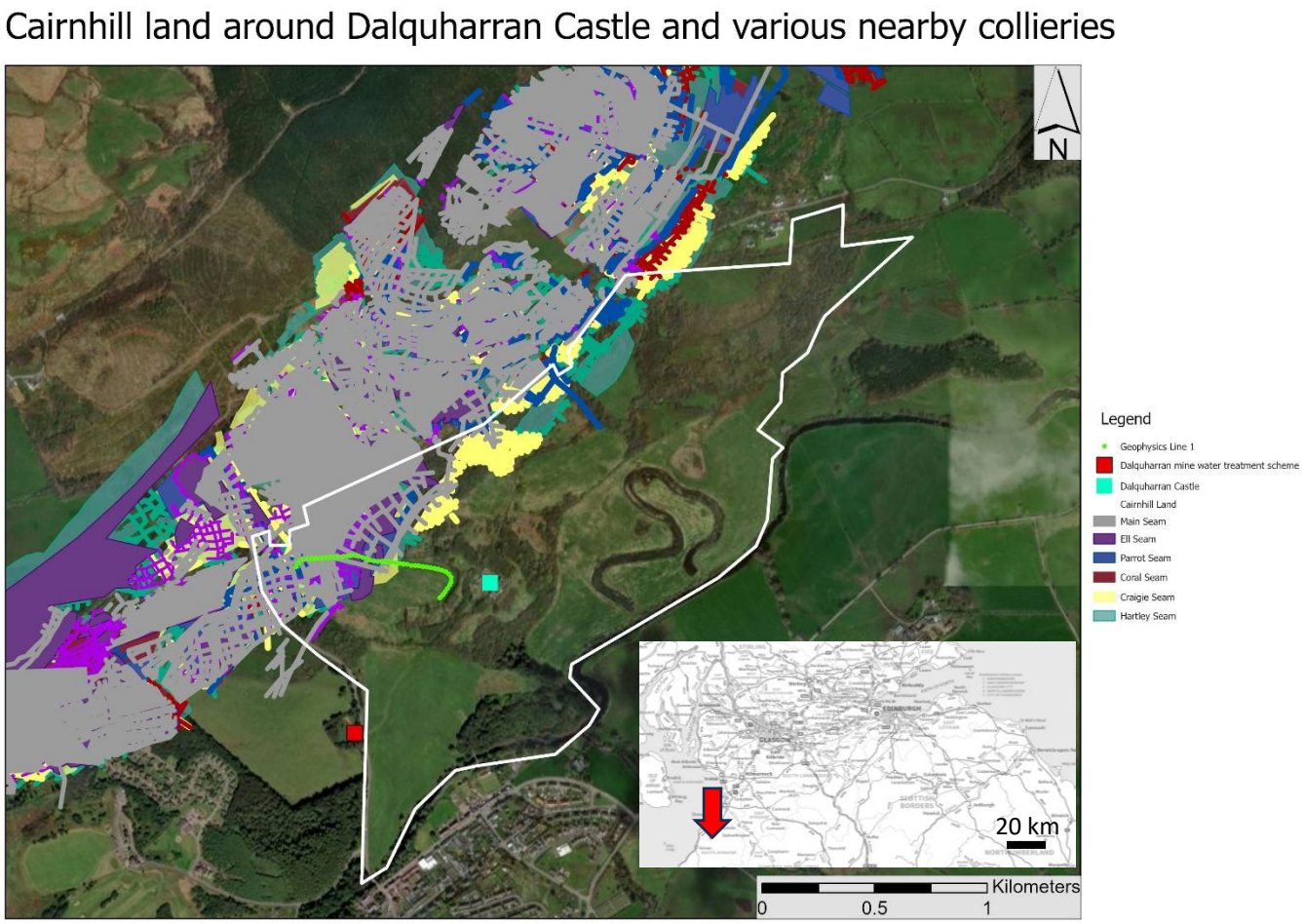


Figure 1. Site outline, mine workings (colour coded to worked seam) and ERT section mapped onto an aerial photograph of the site. Mine plan data © the Mining Remediation Authority.

1.2 Fieldwork

ERT data was acquired in the field with an ARES I Automatic Resistivity and IP system (**Figure 2a; 2b**) using a dipole-dipole configuration. This configuration was chosen to maximize vertical extent of the survey while also being sensitive to lateral changes in resistivity (Martorana *et al.*, 2017). Electrodes were spaced at 10m in a series length totaling 480m.

The transect was entirely located on agricultural land used for growing crops. To limit disturbance to these crops and for ease of deployment, the transect followed pre-existing tramlines where possible (**Figure 2c**). The transect followed the curve of walls and fences at the eastern and western extremities of the line with under 2 m variation in elevation. The areas outside the main wheat field were not safely accessible due to steep slopes and thick vegetation cover.

Deployment of the ERT line on site took approximately three hours. The cable itself was unspooled manually. Once the cable was laid out, electrodes were hammered into the ground and connected to the cable at 10 m intervals with crocodile clips. Once deployed, using the ARES I, each electrode connection was tested to identify loose connections. After all connections were confirmed to be secure, the section took approximately an hour to capture.



Figure 2. Photographs taken during field work. A) kit used to acquire ERT data including ARES 1 Automatic Resistivity and IP system. B) Deployment of ARES 1 at site. C) Deployment of two 240 m cables with 10 m spaced electrode connections in pre-existing tramlines on site.

1.2 Data processing

RES2DINV software was used for data processing and inversion of ERT data. Outliers and noise were removed from the dataset. Five iterations were set and a logarithmic pseudosection was generated with a Root Mean Square error of 8.1%. The resulting ERT output reached a survey depth of 89.7m in the middle section of the survey transect (195 - 275 m) (**Figure 3**).

2 RESULTS

In the pseudosection, there is a laterally continuous horizon of lower resistivity values in **Figure 3**, ranging between 26 and 79.1 Ωm at a depth of 10 to 20 m. This range of depths corresponds to the depths at which rock head was mapped in cross sections from borehole data. This horizon has therefore been interpreted as saturated overburden. It is likely that the area highlighted in box 1 is also a perched aquifer due to its depth.

A continuous zone of high resistivity was identified (reddish purple colour corresponding to over 716 Ωm). Published datasets (Malliol *et al*., 1999; Das *et al.*, 2017; Bharti *et al*., 2022) indicate that regions of resistivity over 700 Ωm can be indicative of solid, intact rock. Which was how this feature was interpreted.

Between 120- 210 m on the ERT line and depths ranging from 42-89 m, resistivity was measured at 79 Ωm decreasing to under 0.32 Ωm at the edge of the captured section (zone 1 in **Figure 3**). The depth and lateral position of this zone of anomalously low resistivity corresponds to the depths at which mine workings have been mapped in cross sections. Comparison to published ERT sections (Sun *et al*., 2025) of flooded mine infrastructure suggests that water filled cavities have similar resistivity values to those seen in this region of **Figure 3.**

The area highlighted in box 2 also fits the description of water filled voids given by Sun *et al.* (2025). The shape of this feature makes this zone of particular interest, as it extends vertically down beyond expected rock head and is laterally constrained by features in the section interpreted as solid rock. When compared to cross sections, the depth of this feature (c.50 m) corresponds to the mapped depth of workings associated with the Parrot seam. This feature is also within 20 m of the mapped location of these workings.

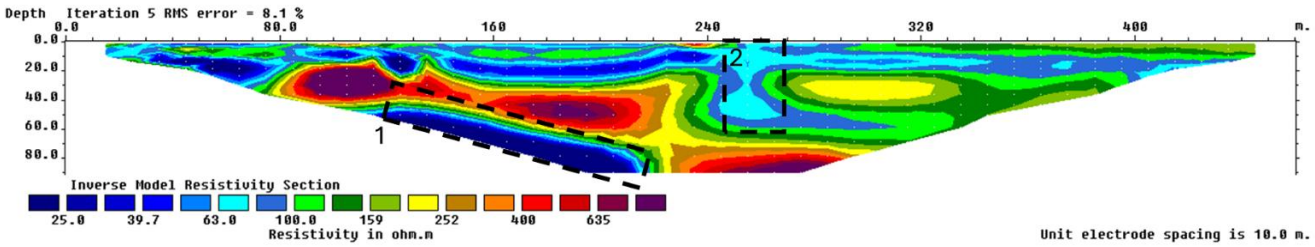


Figure 3. Apparent resistivity pseudosection generated of the subsurface at Dalquharran site. Two areas of interest are highlighted by black boxes and numbered.

To the south and to the east, two additional surveys were undertaken at Dalquharran to further assess the capabilities of ERT and the subsurface characteristics of the site, in addition to confirming the findings of this initial survey. The methodology for conducting these surveys was the same as presented here.

3 CONCLUSIONS

At Dalquharran Estate, an initial ERT survey was carried out to evidence presence and location of flooded mine workings under investigation for low-carbon heat supply. A larger region with resistivity values an order of magnitude lower than surrounding material was found in the section and labelled as zone 1. Zone 2 presents a more laterally constrained feature fitting this description, located at 245 to 270 m along the section. This zone could indicate the presence of flooded mine workings due to the position of this region corresponding with the location and depth of mapped mine workings, and similarity in resistivity characteristics to flooded subsurface voids presented by previously published research. Zone 2 is therefore recommended for further investigation as a mine water thermal resource.

A continuous zone of high resistivity between 238 and 716 Ωm has been interpreted as being a continuous unit of intact rock.

Through this work, Electrical Resistivity Tomography has shown promise as a technique to de-risk drilling operations to exploit geothermal resources within mine infrastructure at depths of up to 90 m by allowing for the interpretation of flooded mine workings and solid bedrock at this site through variations in resistivity characteristics.

Additional ERT surveys were conducted to the south and south east of this section to further investigate the subsurface characteristics of buried mine infrastructure and to verify the findings of this experiment.

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