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Geophysical characterisation of a tailings lagoon at Frongoch Mine, Devil's Bridge, Ceredigion, Wales

Minerals and Waste Programme

Open Report OR/11/005

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Geophysical characterisation of a tailings lagoon at Frongoch Mine, Devil's Bridge, Ceredigion, Wales

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Keywords

Electrical resistivity tomography survey; mine tailings; environmental impact; Wales.

Front cover

View of Frongoch mine spoils.

Bibliographical reference

KURAS, O; BANKS, V; PALUMBO-ROE, B; KLINCK, B. 2011. Geophysical characterisation of a tailings lagoon at Frongoch Mine, Devil's Bridge, Ceredigion, Wales. *British Geological Survey Open Report*, OR/11/005. 28pp.

Keyworth, Nottingham British Geological Survey 2011

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Acknowledgements

The authors wish to thank the landowner of the Frongoch Mine area, Mr J. Bray, for his cooperation and for granting access to the study site.

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Summary

This report describes the results of a geophysical study undertaken in order to characterise mine tailings at the Frongoch Mine near Devil's Bridge, Ceredigion, Wales. This is part of ongoing research into the environmental impact of abandoned metalliferous mines in the Central Wales Orefield in the UK.

The site ranks highly in a list of abandoned mine sites, which were recognised by the Environment Agency for England and Wales as posing the greatest threat to surface waters (Environment Agency, 2002). Electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) surveys were carried out at Frongoch Mine in February 2008. A 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 was obtained. The resistivity data clearly show the highly conductive signature of the superficial tailings deposits and good correlation is observed with the outline of the lagoon recorded on historic maps. The depth extent of conductive material measured at the centre of the lagoon is of 12-13 m bgl and is found to exceed the suspected base of the lagoon. Intrusive investigation is required in order to corroborate the geophysical information. There is evidence to suggest that significant fine structure resolved in some of the shallow deposits corresponds to observations made in trial pits located in the vicinity of the geophysical profiles.

The wider context of this work relates to the increasingly stringent regulation of mine waste under EU environmental legislation, in particular the Water Framework Directive and the Mine Waste Directive. Both address the environmental impacts of abandoned mine sites, including mine spoils and tailings, which often represent a significant diffuse source of pollution. Geophysical techniques can provide helpful insight through non-invasive mapping of the extent and volume of mine tailings and any contamination associated with them.

1 Introduction

As part of ongoing BGS research into the environmental impact of abandoned mines in the Central Wales Orefield a geophysical study was undertaken in order to characterise metalliferous mine tailings at the Frongoch Mine near Devil's Bridge, Ceredigion (Figure 1).

A BGS team comprising members of staff of the Geophysicall Tomography and Minerals and Waste Teams carried out electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) surveys at the Frongoch site in late February 2008.

The aim of the geophysical 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 minewaste on the underlying bedrock and the surrounding environment. The geophysical characterisation of the site was intended as a precursor to potential future intrusive investigation.

The specific objectives were

- to define the boundaries of the lagoon,
- to estimate the thickness of the deposits in the lagoon,
- to facilitate the identification of potential locations for the drilling of boreholes, and
- to search for geophysical indicators for contamination of the bedrock and/or the surrounding area arising from the mine tailings.

1.1 FRONGOCH MINE

Frongoch Mine produced lead and zinc ore without interruption from 1834 until its closure in 1904 (Palumbo and Klinck, 2002). Since 1984, much of the site has been used inappropriately as an off-road driving course, while the northern section is currently being used as a wood yard/sawmill. Waste material from this operation is being dumped in the northern part of the open workings. At the centre of the Frongoch site is a shallow, flat-bottomed depression that appears to have been used as a tailings lagoon at the time when the mine was operational (Figure 2). In general, the spoil tips at Frongoch Mine are considered to be of national importance for their suite of secondary lead minerals.

The geological setting of the area is dominated by Silurian slates of the Devil's Bridge Formation.

1.2 THE TAILINGS LAGOON

The area that is thought to correspond to the former tailings lagoon lies in a shallow depression between the hills of Banc Lletysynod and Banc Penygwernydd and the road leading to Llyn Frongoch. With processing plant and water supply infrastructure (aqueducts) located at the northern end of the site on the slope leading up to Frongoch Cottage, it is likely that waste materials have been washed downhill towards the topographic low at the southern end of the site and deposited as tailings under gravity.

An indication of the historic extent of the lagoon can be found on historic maps (Figure 3), suggesting that at least at one point in time (around 1890) an area of approximately 180 m by 80 m was covered by the lagoon. However, no further information such as topographic maps prior to waste deposition or details on waste arisings is available.

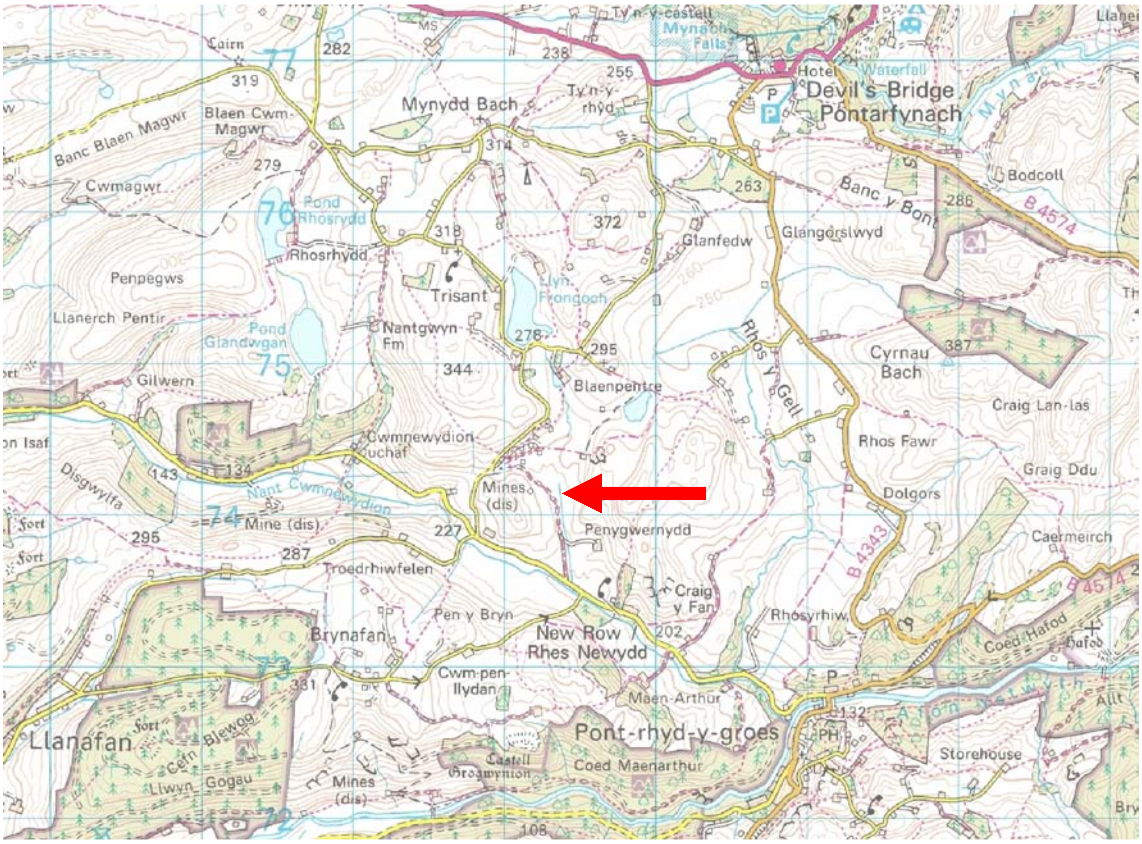


Figure 1: Location of Frongoch Mine.

Figure 2: View of the Frongoch Mine site looking south-east.

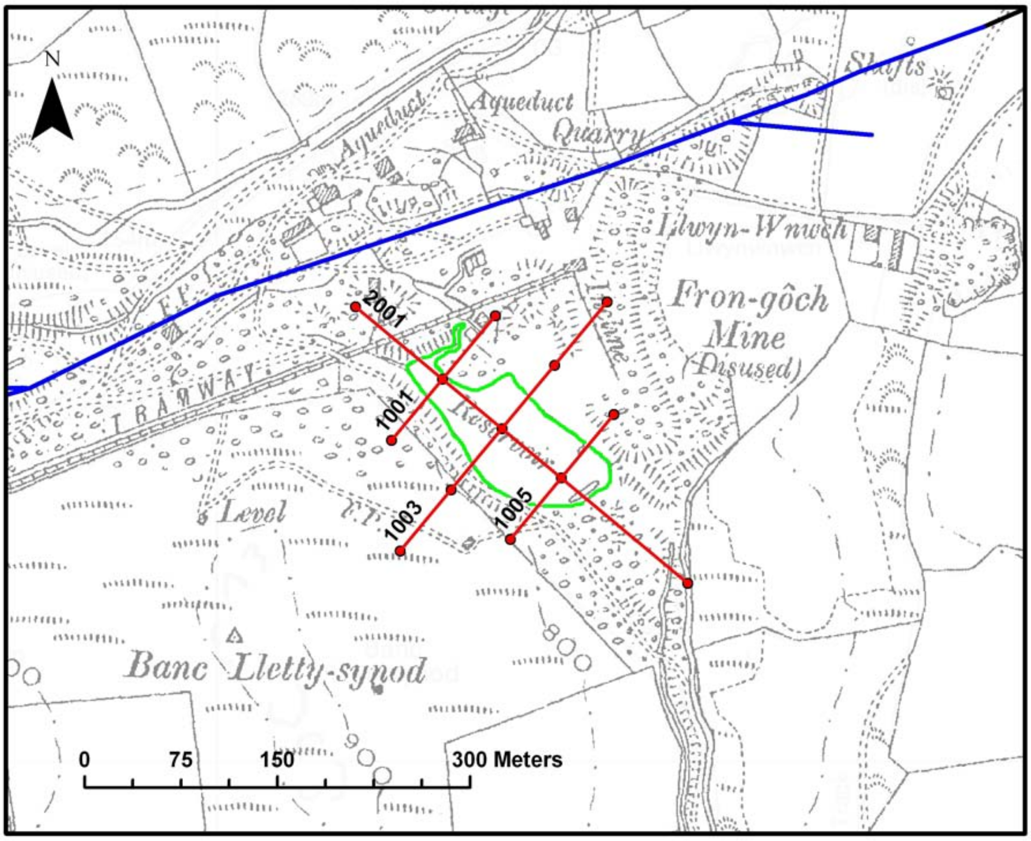


Figure 3: Historic map of Frongoch Mine showing the assumed outline of the tailings lagoon (green), a major fault line as indicated by the geological map (blue), and the geophysical profiles adopted for this survey (red).

2 Methodology

2.1 ELECTRICAL RESISTIVITY TOMOGRAPHY

2.1.1 Rationale

Electrical resistivity tomography (ERT) is a modern geophysical method that facilitates the generation of models of subsurface electrical property distributions, which often correlate with variations in subsurface structure and materials. In unconsolidated and partially saturated materials, such as mine tailings, general relationships exist between the following parameters and bulk resistivity:

- grain size/porosity
- water content
- solutes dissolved in the pore water, particularly ionic constituents.

As a consequence, ERT can be employed both qualitatively as a reconnaissance tool for variations in these parameters, but also quantitatively when material characteristics are well known and constrained by complementary data.

The principal benefit of ERT lies in its nature as a non-invasive method that can provide 3D spatial models of the subsurface at the site scale. This is in contrast to intrusive sampling methods, which typically provide information only at discrete locations.

2.1.2 Known limitations

ERT has a number of limitations that must be considered when designing surveys and interpreting resistivity models:

1. *Data quality*. The quality of the electrical measurements entirely determines the quality of any models derived from them. Measured data is subject to statistical and systematic errors from a variety of sources, including those introduced by the measurement device, poor electrode contact or electrode polarisation, and other indeterminate external effects.
2. *Non-uniqueness*. Field data can usually be explained by a whole range of theoretically equivalent models. The problem of non-uniqueness is exacerbated with increasing depth of investigation, or distance from an electrode array, as the model in these regions is less well constrained by the data.
3. *Three-dimensional character*. Resistivity variations on either side of 2D ERT lines will affect resistivity measurements even though these features may be offset from the survey line or outside the survey area. As a consequence, it may not be possible to accurately model 3D structures by 2D inversion.
4. *Static shift due to near-surface heterogeneity*. High-contrast heterogeneities in the subsurface that are small compared to the model discretisation cannot be accurately modelled, and thus may distort the resulting image or hinder convergence between measured data and the resistivity model during the inversion process.

2.1.3 Survey design

As geophysical fieldwork was limited to 2.5 days it was deemed appropriate to achieve coverage of the Frongoch site by 2D ERT. A total of four intersecting profiles were chosen on the basis of historical maps of the tailings lagoon (Figure 4). As the lagoon was thought to have an elongated shape, the greatest extent being in NW-SE direction, three of these profiles (1001, 1003, 1005) were positioned across the lagoon in SW-NE direction. One profile (2001) was chosen so that it crosses the entire length of the suspected lagoon in NW-SE direction, extending from NW of the former tramway to the stream by the track on the eastern edge of the site.

All profiles were occupied with a 64-electrode linear array connected by multicore cables. Standard BGS survey cables with 5 m takeouts were used. An electrode spacing of 2 m was used on profiles 1001 and 1005, 4 m was used on profile 2001, and profile 1003 was occupied both with a 2 m and a 4 m spacing. This was done in such a way that both arrays would have a common centre on the profile (here: electrode 32), thus enabling joint interpretation. A roll-along survey was carried out on profile 2001, using a single overlap on one 32-electrode cable segment. The properties and locations of all profiles are summarised in

All ERT measurements were carried out using an AGI SuperSting R8 resistivity meter, which has the capability to measure resistances on eight input channels simultaneously.

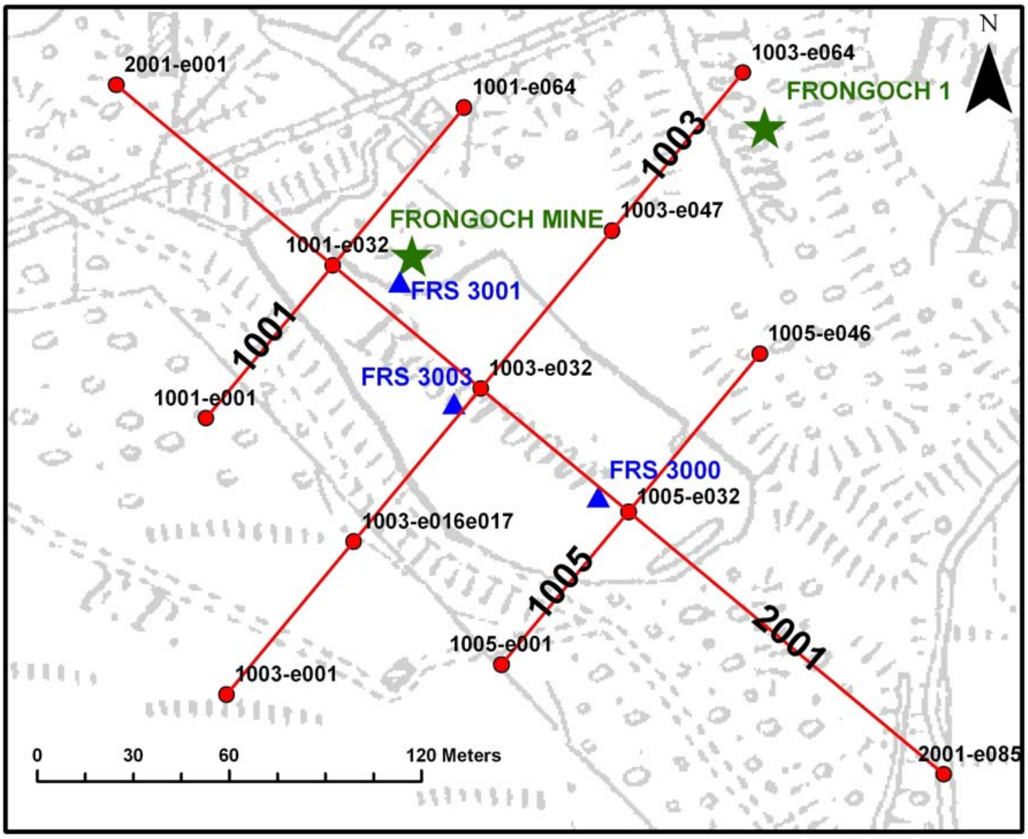


Figure 4: Survey basemap with locations of boreholes (green) and trial pits (blue).

Table 1: Properties and locations of ERT profiles.

Profile	Spacing	Number of electrodes	Total length	Start (BNG)	End (BNG)
1001	2 m	64	126 m	(272135.54, 274249.44)	(272216.13, 274346.30)
1003-2m	2 m	64	126 m	(272181.66, 274211.07)	(272262.25, 274307.93)
1003-4m	4 m	64	252 m	(272142.01, 274163.40)	(272303.18, 274357.13)
1005	2 m	64	126 m	(272227.79, 274172.69)	(272308.37, 274269.55)
2001	4 m	85	336 m	(272107.54, 274353.38)	(272365.84, 274138.49)

2.1.4 Array configurations

The nature of the study site demanded particular attention to the type of electrode array configurations used for ERT data acquisition. In view of the objectives set out in Section 1, it is clear that superior lateral resolving qualities were required in order to define the lateral boundaries of the lagoon. At the same time, the array had to have a superior depth of investigation and had to be able to resolve horizontal contrasts at depth with sufficient confidence in order to obtain information about the interface between tailings and bedrock. These requirements pointed towards a measurement scheme based on the dipole-dipole array.

On the other hand however, surface deposits on the Frongoch site are very heterogeneous and the site was found to produce extraordinarily high contact resistances due to the highly variable nature of the materials, as well as their porosity and moisture content. This demanded a robust array configuration that would be less affected by noise due to poor contact, surface heterogeneities and static shift. These requirements pointed towards a measurement scheme based on variations of the Wenner-Schlumberger array.

As a consequence, two different measurement schemes were prepared for use on site. Firstly, an extended dipole-dipole scheme was generated, which was optimised for the eight-channel SuperSting, using "*a*"-spacings from 1 to 5 and "*n*"-spacings up to 8. This scheme comprised full reciprocal configurations, thus allowing comprehensive assessment of measurement errors. Secondly, a customised scheme based on variations of the Wenner-Schlumberger array was created (known as "modified Wenner"), which was also optimised for eight-channel acquisition and supplemented by a small number of geometries designed to maximise the depth of investigation of this scheme. The nature of the "modified Wenner" scheme implies that only around 10% of measurements can be carried out in a reciprocal manner.

2.1.5 Field measurements

ERT measurements at Frongoch were carried out on 26 and 27 February 2008. On day one, four datasets were collected, namely 2 m data on profiles 1001, 1003 and 1005 and 4 m data on 1003. All data on day one were collected using the modified Wenner scheme. Each acquisition required installation of 64 stainless steel electrodes and the deployment of two 32-way survey cable segments. Contact resistance tests were carried out and the observed values ranged from approximately 500 Ω in wet and silty material to over 30 kΩ on dry, coarse and sandy material. Where necessary, galvanic coupling was improved by applying watery bentonite slurry to the electrodes. Each acquisition took approximately 60-80 min to complete. On day two, another four datasets were collected; this time 4 m data on profile 2001. One full segment at the start of the profile and one overlapping (roll-along) segment were occupied. Data were collected for both the modified Wenner and dipole-dipole array styles. A complete list of ERT datasets acquired during the Frongoch survey is shown in Table 2.

Table 2: List of ERT datasets acquired during the Frongoch survey.

Dataset	Array	Acquired on	Duration	Max. current
1003-MW-2	modWenn	26/02/08	70 min	100 mA
1001-MW-1	modWenn	26/02/08	70 min	100 mA
1003-MW-4	modWenn	26/02/08	65 min	50 mA
1005-MW-1	modWenn	26/02/08	65 min	50 mA
2001-MW-2	modWenn	27/02/08	55 min	50 mA
2001-DD-2	Dipole-dipole	27/02/08	75 min	250 mA
2001-MW-4	modWenn	27/02/08	35 min	50 mA
2001-DD-3	Dipole-dipole	27/02/08	40 min	250 mA

2.1.6 Data processing

Due to severe time restrictions, data processing was kept to an acceptable minimum. For this preliminary interpretation, only the modified Wenner data were fully processed as both array styles were found to give comparable results. However, the dipole-dipole data were found to be inherently noisier and thus will require further processing. For all datasets, raw data were screened for outliers and basic reciprocal analysis was carried out in order to obtain simple noise estimates. Surface topography was extracted from a preliminary digital terrain model (DTM) based on NextMap data. Elevations of individual electrodes were estimated based on their calculated positions on site. Processed datasets together with electrode elevation data were used to generate input files for resistivity inversion.

2.1.7 Data inversion

The generation of resistivity models (or tomographic images) from ERT field measurements requires data inversion; this is conveniently achieved by using regularised nonlinear least-squares algorithms (e.g., Loke and Barker, 1996). The aim of any geophysical inversion procedure is to calculate a model that satisfies observed data. A starting model is produced, in this case a homogeneous half-space, for which a synthetic response is calculated and compared to the measured field data. The starting model is then modified in such a way as to reduce the differences between the model response and the measured data within a suitable mathematical norm; the deviation is usually quantified as an RMS error value. This process continues iteratively until acceptable convergence between the calculated and measured data is achieved.

2.2 GROUND PENETRATING RADAR

2.2.1 Rationale

Ground penetrating radar (GPR) is a well-established geophysical technique that exploits the capability of geological materials to transmit electromagnetic waves and to reflect energy at interfaces exhibiting contrasts in dielectric properties.

GPR is often employed qualitatively for subsurface reconnaissance and is particularly useful for resolving near-surface spatial structure and for tracking interfaces and horizons.

2.2.2 Known limitations

The main limitation of GPR is the potential for energy loss in highly conductive media due to strong signal attenuation. This often precludes the use of GPR over clay and other conductive environments.

2.2.3 Survey design

With the main emphasis of this work being on the application of ERT, the use of GPR was limited to a feasibility study covering a subset of the ERT survey lines in order to obtain radargrams that could be compared to resulting 2D resistivity models. GPR surveys were attempted and good coverage achieved on ERT profiles 1001, 1003 and 2001.

The Noggin Plus 250, a monostatic GPR system manufactured by Sensors & Software Inc, was chosen for its simplicity and intuitive operation. The antenna of the Noggin system is mounted on a SmartCart, which also comprises a video console for controlling data acquisition and viewing incoming data in real-time. The centre frequency of 250 MHz was thought to be adequate to assess feasibility, although restrictions were to be expected with regard to depth of signal penetration. Lower-frequency GPR systems are available at BGS, however their operation is more complex and they require additional staff and more time for data acquisition.

2.2.4 Field measurements

Common-midpoint (CMP) datasets were acquired by starting the Noggin system at suitable locations along the respective ERT profile, pushing the SmartCart in positive x-direction and collecting data in a continuous fashion. Distance measurements were controlled by the built-in odometer, which resulted in a separation between GPR traces of approximately 0.025 m. As some areas of the Frongoch site were difficult to access with the SmartCart, data acquisition was stopped when obstacles were encountered. A complete list of GPR datasets obtained during the Frongoch survey is shown in Table 3.

Table 3: List of GPR datasets acquired during the Frongoch survey.

Dataset	ERT Profile	Start point on profile	End point on profile	Length
1	1001	62 m	98 m	36 m
2	1003	24 m	86 m	62 m
3	2001	12 m	100 m	86 m
4	2001	112 m	200 m	86 m
5	2001	200 m	300 m	100 m

Signal velocities at the Frongoch site were estimated by interactive hyperbola matching. A value of 0.05 m/ns was found to be representative for all survey profiles. With this velocity, trace lengths of nearly 120 ns resulted in a maximum depth of penetration of approximately 3 m.

2.2.5 Data processing

Due to time restrictions, only basic processing was applied to the GPR datasets. DC shifts were removed and static corrections and a dewow filter applied. A linear gain function, starting at a traveltime of 50 ns, was then applied in order to improve the definition of the radargram at greater depths.

3 Results and discussion

3.1 RESISTIVITY MODELS

ERT results are presented in Figure 5 to Figure 7. Each Figure shows inverted 2D models (i.e. tomographic images) of bulk subsurface resistivity for a particular profile. The colour scale is logarithmic and uniform across all images, ranging from dark blue (highly conductive, ρ<25 Ωm) to dark red (highly resistive, ρ≥6,584 Ωm). This range of values was found to cover all materials likely to be present on site, including metalliferous tailings with varying content in moisture and fines, soils and made ground, and bedrock at various stages of weathering and fracturing.

Figure 5 shows the resulting image for the profile crossing the lagoon in the NW part of the site (Line 1001) using the modified Wenner array style. Figure 5a contains the smooth (contoured) representation, Figure 5b the blocky representation of the model. The SW end of the line (profile distance 0 to 44 m) is located on the northern slope of Banc Lletysynod and is dominated by very high resistivities (ρ>>2,000 Ωm), which most likely reflect slate bedrock on that hill, covered by a thin soil layer and subject to varying degrees of weathering and fracturing. The centre of this line shows a highly conductive feature (ρ≤100 Ωm) extending to the surface at a profile distance of approximately 55 m. The edges of this conductive zone appear to correlate very well with the mapped extent of the reservoir indicated on the historic map, thus supporting an interpretation of this material as conductive tailings. The reservoir boundaries are marked as “RB” on the images. The SW marker coincides roughly with the 708 Ωm contour line. The shallow subsurface (down to approximately 2.5-3 m) in the NE half of the line is dominated by increasingly resistive material (≈400 –3,000 Ωm), which correlates well with a protruding feature near the reservoir inflow on the historic map and may reflect the remnants of ruined buildings encountered in the vicinity of this section of the profile. The highly conductive feature associated with the tailings is found to extend laterally underneath this resistive surface material up to a distance of approximately 88 m. The conductive zone appears reasonably well defined by the 160 Ωm contour line, however its depth extent is not overly well constrained. Nevertheless, contours appear to be flattening out at around 10 m below ground level (bgl). High resistivities that one might associate with bedrock are not resolved at the base of Line 1001, except for a faint signature at 48 m. A conductive feature underlying the slope at the beginning of the line has no obvious explanation. A potential connection with the tailings at the surface is speculative, but cannot be ruled out. There is also a possibility that this feature may be associated with fracturing/faulting, given that a major fault line with ENE strike is thought to traverse the Frongoch site (Figure 3).

Images for the profile crossing the lagoon in the centre of the site are shown in Figure 6 (Line 1003, modified Wenner). Similar to Line 1001, the SW end of Line 1003 is located on a slope and is dominated by very high resistivities (ρ>>2,000 Ωm, profile distance 0 to 26 m), which most likely reflect bedrock. The entire centre of this profile is then governed by a vast conductive zone, extending from the surface to a depth of at least 15 m bgl, if the 160 Ωm contour is again regarded as indicative. Again, good correlation is observed between the edges of this conductive zone and the “RB” markers. The SW marker once more coincides roughly with the 708 Ωm contour line, whereas the same contour is not observed until approximately 4 m beyond the NE marker. Interestingly, the NE marker nearly coincides with a more resistive subsurface feature protruding vertically from the base of the model (x≈92 m). The NE end of the profile shows intermediate resistivities, with some high-resistivity surface expressions of stone building foundations that are crossed by the line in that area. As with Line 1001, it is not obvious that bedrock has been resolved at the base of Line 1003. Greater depths of investigation and hence larger array separations are required, hence it was anticipated that this information would be contained in the 4 m data. However, the most striking result found in these images is the fine structure resolved within the central conductive zone. A more resistive "layer" is clearly observed at the centre of the lagoon, extending laterally at least between 60 m≤x≤85 m, and vertically between 2.5 m≤z≤6 m bgl, taking the 111 Ωm contour as indicative. Resistivities both in the shallow surface layer (0 m≤z≤2.5 m bgl) and at depth (z≈10 m bgl) reach extremely low values of 50 Ωm and less. This observation fits in well with log data obtained in Trial Pit 3 (FRS3003), which is located around 3.5 m off the ERT profile (Figure 4). FRS3003 showed a peat layer at 1.15 m≤z≤2.40 m bgl, underlain by silty clay (Table 4). The latter was found to become wet at z=2.50 m bgl, with subsequent occurrence of much fragmented slate. A possible interpretation might be to assume that tailings were deposited on a natural surface in a topographic depression, which may have been a peat bog prior to the commencement of mining activities. The base of the peat could therefore be interpreted as a notional base of the lagoon (Figure 6a).

Table 4: Log of Trial Pit 3 (FRS3003, SN 72213 74254, obtained on 09/08/06).

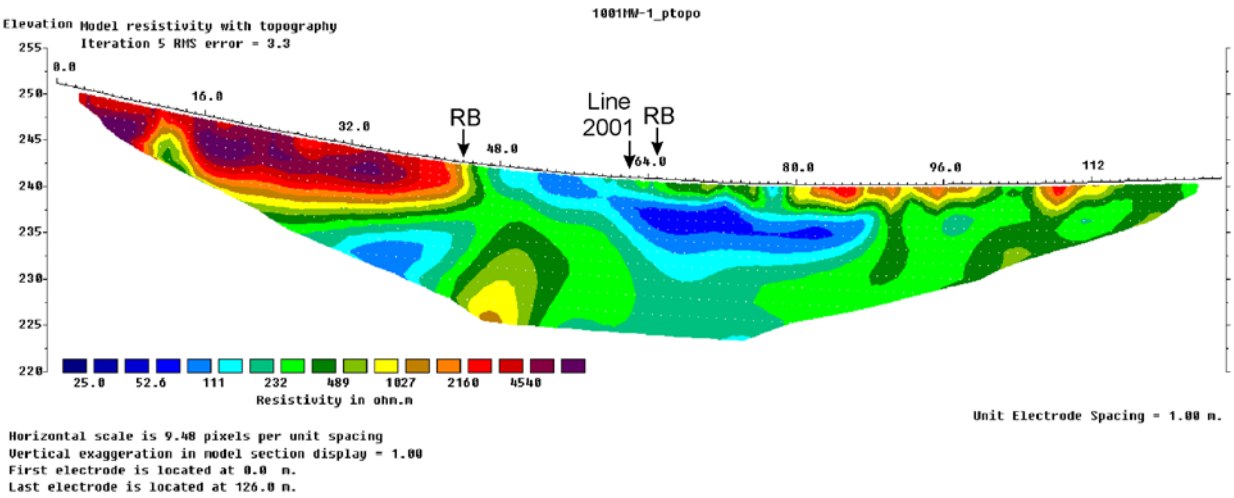
Depth (m)	Description	Notes
0.00 - 0.18	Slightly yellowish brown (5Y 4/4 and 5/4) silty fine to coarse SAND with occasional clay laminae	Sampling: 2 No. paper envelopes
0.18 - 0.28	Laminated dark grey and light brown (10YR 3/1 and 5/2) fine clayey SILT	
0.28 - 0.87	Dark grey (GLEY 3/1) slightly silty, sandy fine GRAVEL	
0.87 - 1.15	Dark brownish grey to black (5Y 2.5/1) finely laminated silty CLAY tailings	Groundwater standing at 1.10m depth. Groundwater: eH 199 mV; pH 4.84; Electrolytic Conductivity 702 μS; Temperature 21.3 C and Alkalinity 0 mg/kg
1.15 - 2.40	Firm brown amorphous and fibrous (particularly on partings) PEAT, becoming darker in colour below 1.70m depth	Additional plastic bag sample of peat. Pit sides starting to fail, necessary to lengthen pit to achieve depth of excavation
2.40 - 3.35m	Soft to firm grey silty CLAY, becoming wet with much fragmented slate at 2.50m	Sample at 3.25m plastic bag. Second groundwater strike at 3.35m depth: eH 183 mV; pH 4.88; Electrolytic Conductivity 653 μS; Temperature 13.6 C and Alkalinity 0 mg/kgPit dimensions approximately 1.0 x 3.00m, orientated approximately east-west and backfilled with arisings upon completion.

The 4 m data for Line 1003 confirm the above observations (Figure 7). In addition, bedrock now appears to be resolved below the SW part of the assumed lagoon, albeit at depths greater than 10 m bgl, where it is difficult to constrain the ERT model with sufficient confidence, given the limited profile length. In analogy to Line 1001, significantly lower resistivities are observed at depth below the NE end of the profile. Furthermore, a conductive zone is found below the high-resistivity zone on the slope at the SW end of the profile, with a possible connection to the assumed lagoon. This mirrors a tendency observed on Line 1001, where a similar feature could be distinguished. Due to the longer line length, the 4 m data on Line 1003 extend past the suspected location of a borehole known as "Frongoch 1", although its exact position is known only to within an accuracy of 10 m. This small-diameter borehole was drilled in late 1971 for mineral exploration and recorded "made ground" down to a depth of approximately 24 ft (≈7.3 m), before encountering competent "medium-grey mudstone with frequent graded sandstone beds" (Figure 7a). A minor horizontal fault was detected at approximately 47 m depth.

Figure 8 shows the images for the profile crossing the lagoon in the SE part of the site (Line 1005, modified Wenner). Once more, the SW end of Line 1005 is located on a slope and is dominated by very high resistivities (profile distance 0 to 38 m). The centre of this profile is again widely governed by conductive material, although a condensed zone of low resistivities can now be distinguished at the surface in the northern part of the line, offset from the centre of the assumed lagoon (65 m≤x≤89 m). Its depth extent is clearly limited to approximately 2.5 m to 3 m, with highly resistive material (bedrock?) being resolved beneath it and extending down to the base of the model. Correlation between the edges of conductive material at the surface and the "RB" markers is not as strong as on the neighbouring profiles, with the 708 Ωm contour observed roughly 4 m from either marker towards the inside of the assumed lagoon. A segment of the profile between x=38 m and 65 m shows intermediate resistivities, with decreased values near the surface. This zone extends to the base of the model and appears to be dipping below the high-resistivity zone seen on the slope at the SW end of the profile, thus mirroring the trend observed on Line 1001, where a similar feature could be distinguished. Trial Pit 0 (FRS3000) falls in this zone, but it only reached a depth of 1.65 m and is located around 10 m off the ERT profile (Figure 4). The NE end of Line 1005 is governed by intermediate resistivities with highly resistive surface features, likely to be associated with the rough topography encountered in this area of the site, where small heaps of coarse, sandy tailings are interrupted by sharp cuttings and deep channels created by surface runoff.

Results for the profile traversing the lagoon on its long axis are shown in Figure 6 (Line 2001, modified Wenner). The start of this profile is on slightly higher ground near the former processing facilities; it continues across the topographic depression forming the centre of the lagoon, before gently rising again onto a shallow embankment comprising coarser waste material. On the other side of this embankment, the profile continues downslope into a gentle valley across a track and a small stream. The images clearly show the conductive zone already captured by the perpendicular lines 1001, 1003 and 1005. The NW edge of this zone at the surface correlates reasonably well with the "RB" marker at 63.5 m, with the 708 Ωm contour located around 56 m. In contrast, the SW edge falls well short of the "RB" marker at 234 m, with the 708 Ωm contour placed around 204 m. A possible explanation might be an elongated, isolated feature depicted on the historical map near the SE shore of the lagoon, although the significance of this "island" remains unclear. In the centre of the assumed lagoon, the highly conductive zone has significant thickness, with the 160 Ωm observed at depths of up to 12–13 m bgl. Bedrock appears to be resolved everywhere at the base of the model below the assumed lagoon. Highly resistive features at the surface near the NW end of the profile correspond to large heaps of coarse, dry reddish sand. However, their detailed topography is not reflected in the NextMap DTM. Interestingly, a strongly conductive zone is resolved immediately below the high-resistivity material, and the images suggest a connection to the main conductive body. This area is thought to be near the inflow to the lagoon. The SE end of profile 2001 is dominated by a highly resistive surface layer (ρ >>2,000 Ωm), thought to correspond to the drier and coarser material on the shallow embankment. Intermediate resistivities are observed at the very end of the profile ($x \geq 320$ m), where the line crosses a stream at the valley bottom. Finally, a conspicuous, highly conductive feature is observed at depth below the resistive surface layer near the SE shore of the assumed lagoon ($x \approx 230$ m). The sharp gradient and near-vertical shape raise suspicion that this feature might be an artefact and not related to real geological structure. Due to the inherent assumption of a two-dimensional earth model, 2D ERT is not immune to image bias from strong anomalies offset laterally from the profile. For example, a conductive surface feature at some distance from the actual survey line may produce a deceptive signature at depth in the resulting 2D image. Line 2001 is perpendicular to the structural grain, which is dominated by eastnortheast to westsouthwest trending fault sets, which suggests a possibility that the conductive feature reflects a dominant fissure zone, or unmapped fault.

(a) Line 1001, mW, 2m, smooth



(b) Line 1001, mW, 2m, blocky

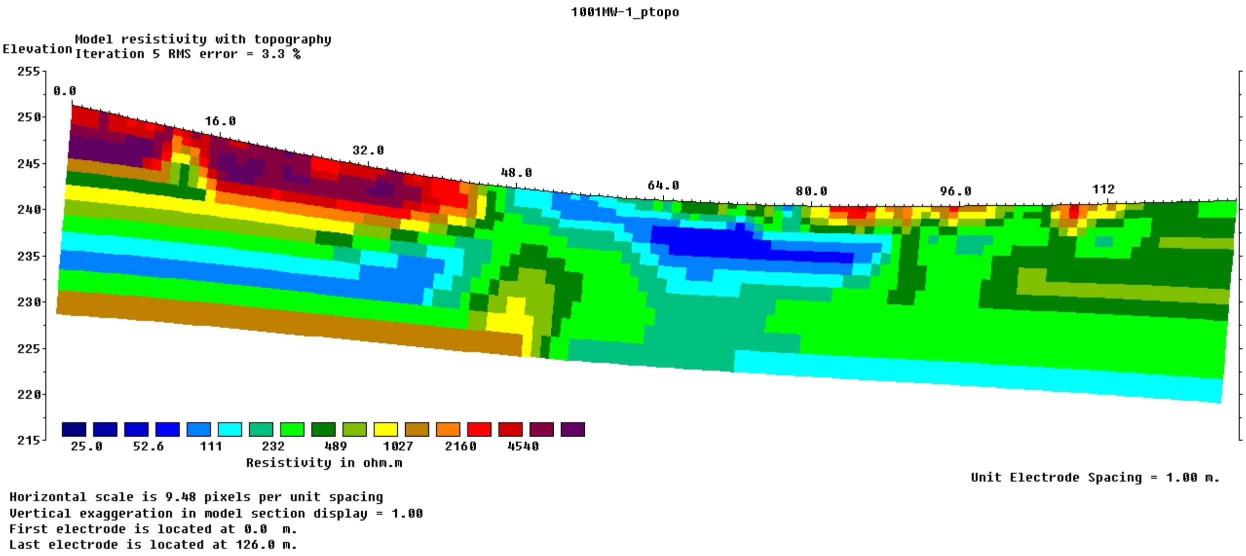
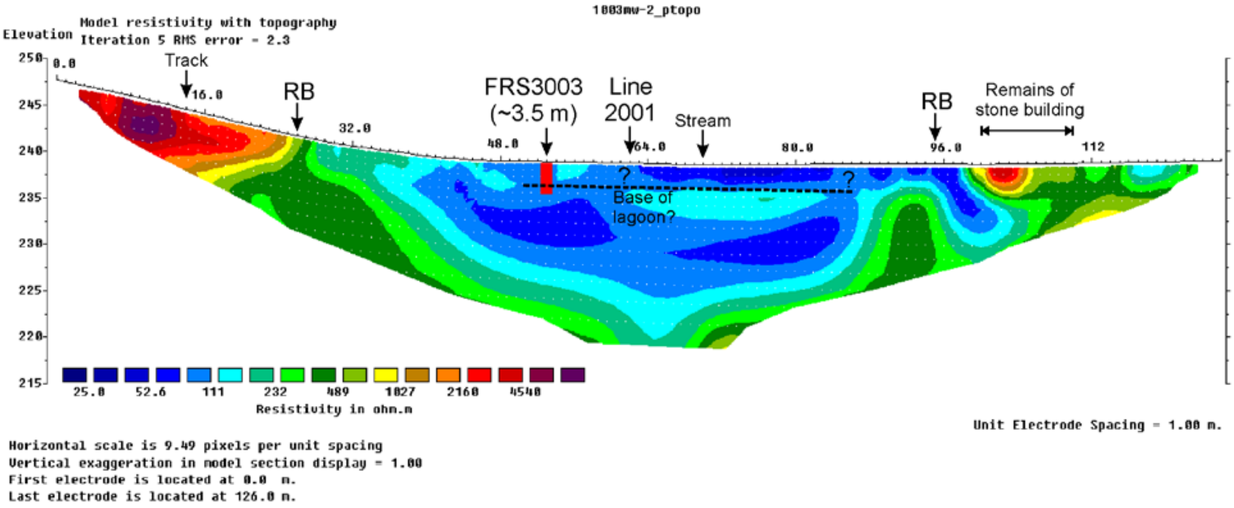


Figure 5: Inverted resistivity images for Line 1001, modified Wenner array, 2 m electrode spacing. (a) Smooth representation with annotations showing known or interpreted features (RB – reservoir boundaries as shown on the historical map). (b) Blocky representation.

(a) Line 1003, mW, 2m, smooth



(b) Line 1003, mW, 2m, blocky

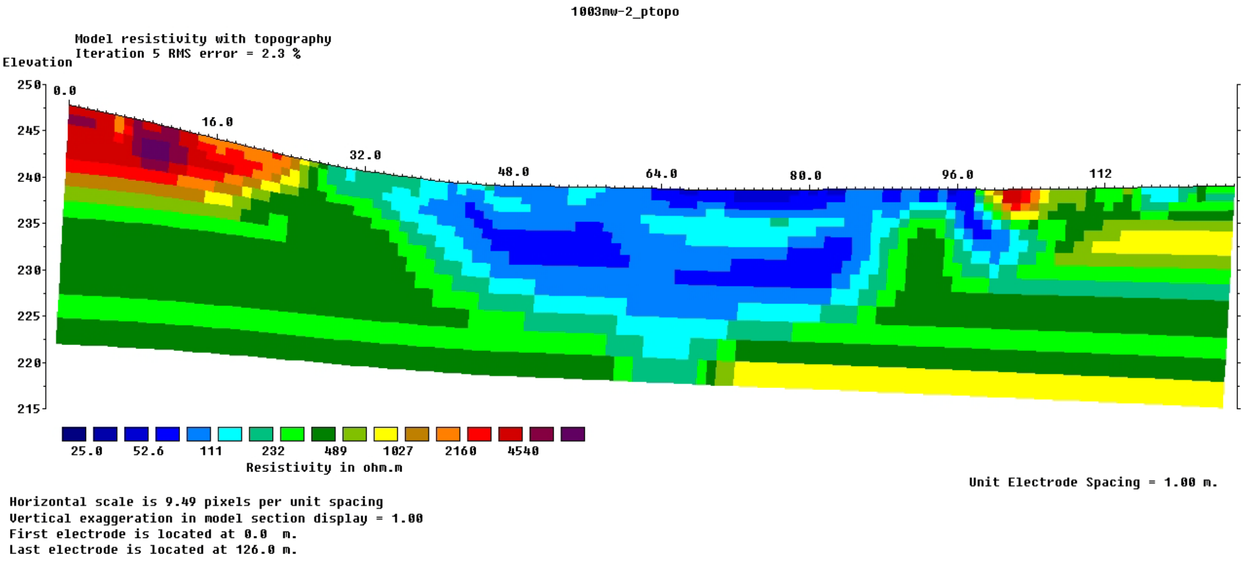
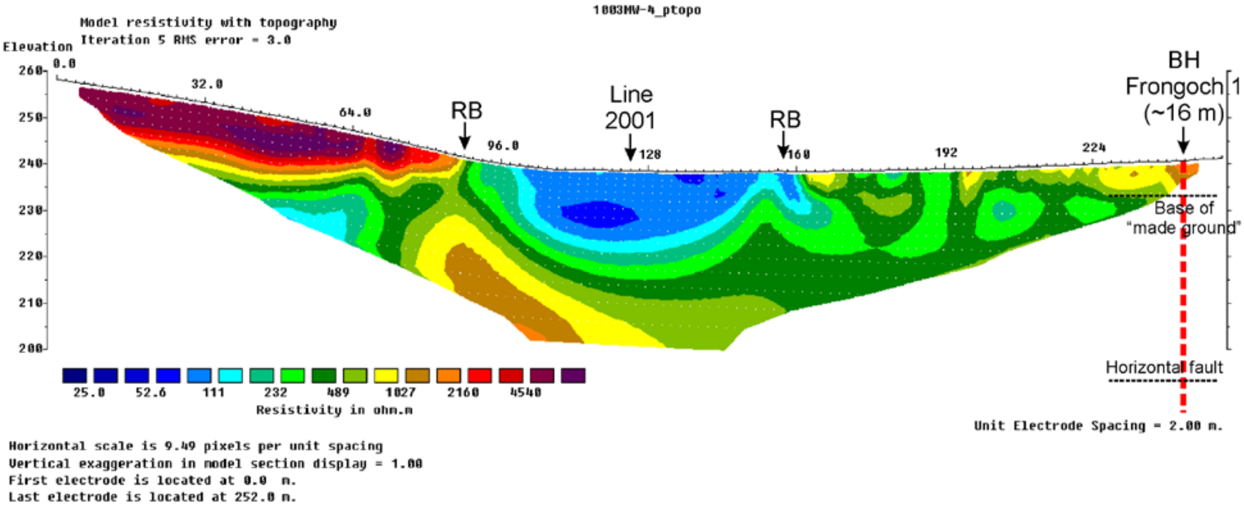


Figure 6: Inverted resistivity images for Line 1003, modified Wenner array, 2 m electrode spacing. (a) Smooth representation with annotations showing known or interpreted features (RB – reservoir boundaries as shown on the historical map). (b) Blocky representation.

(a) Line 1003, mW, 4m, smooth



(a) Line 1003, mW, 4m, blocky

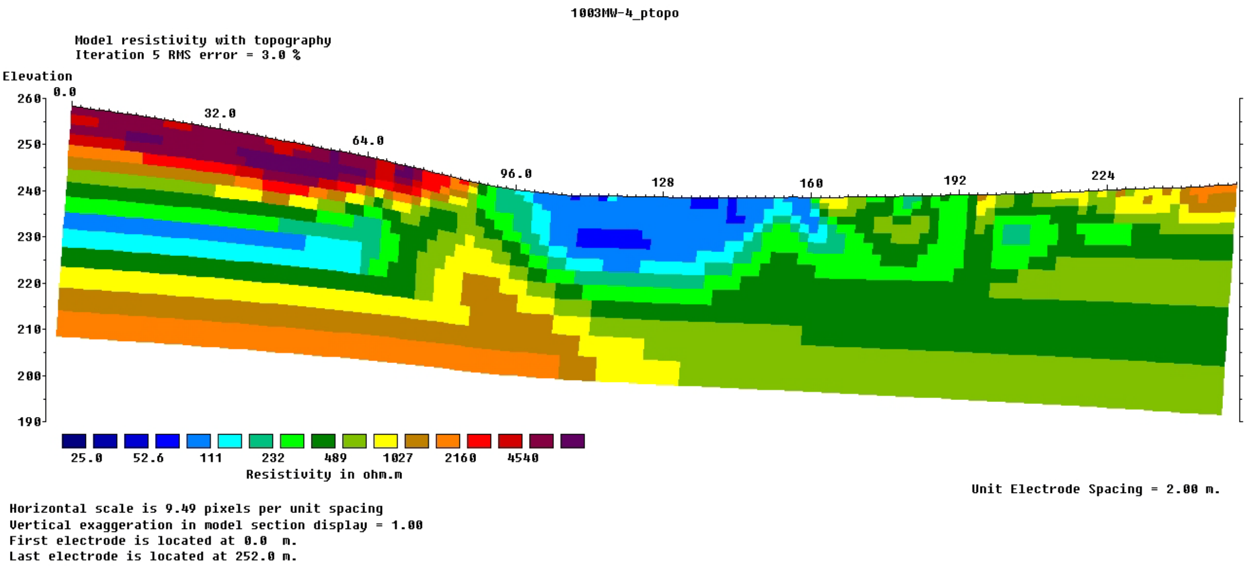
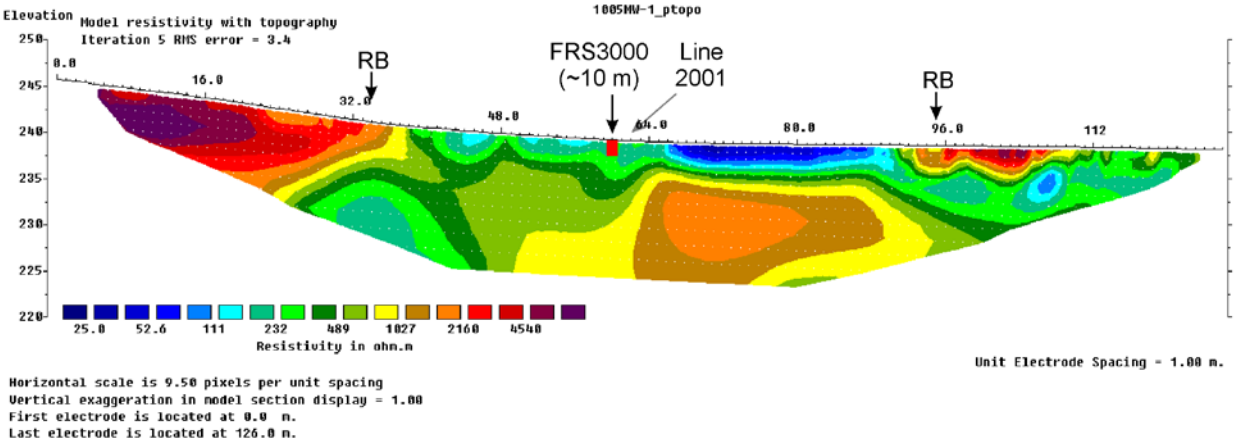


Figure 7: Inverted resistivity images for Line 1003, modified Wenner array, 4 m electrode spacing. (a) Smooth representation with annotations showing known or interpreted features (RB – reservoir boundaries as shown on the historical map). (b) Blocky representation.

(a) Line 1005, mW, 2m, smooth



(a) Line 1005, mW, 2m, blocky

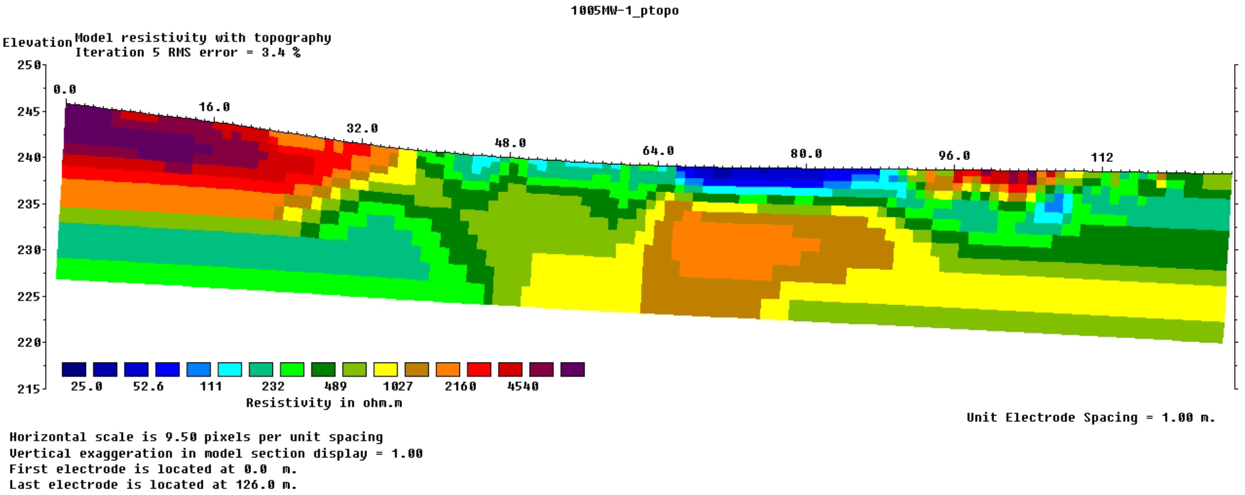
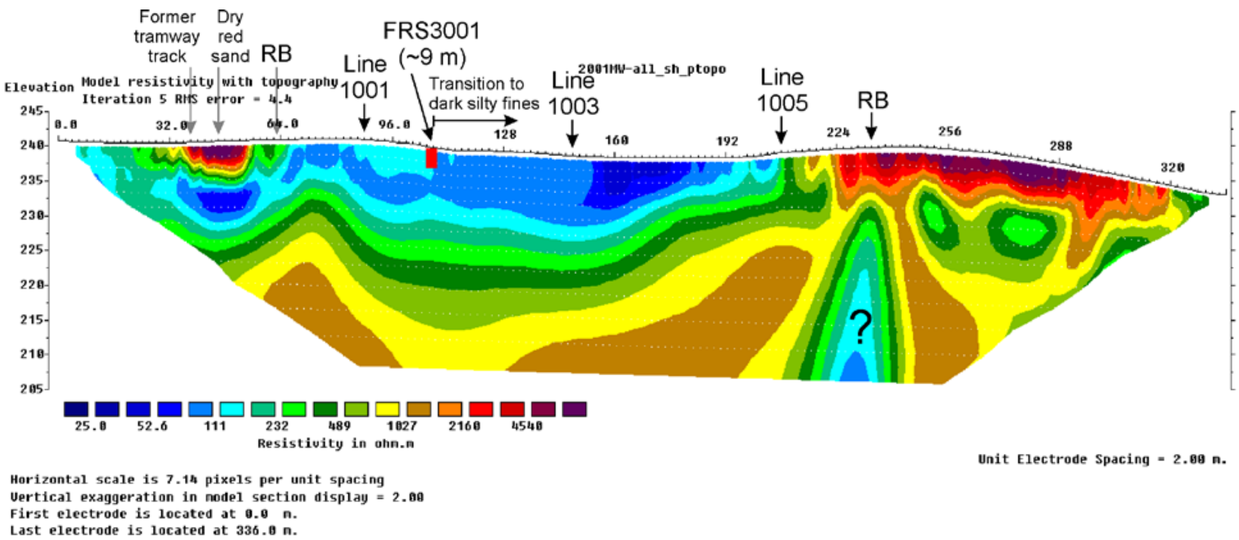


Figure 8: Inverted resistivity images for Line 1005, modified Wenner array, 2 m electrode spacing. (a) Smooth representation with annotations showing known or interpreted features (RB – reservoir boundaries as shown on the historical map). (b) Blocky representation.

(a) Line 2001, mW, 4m, smooth



(b) Line 2001, mW, 4m, blocky

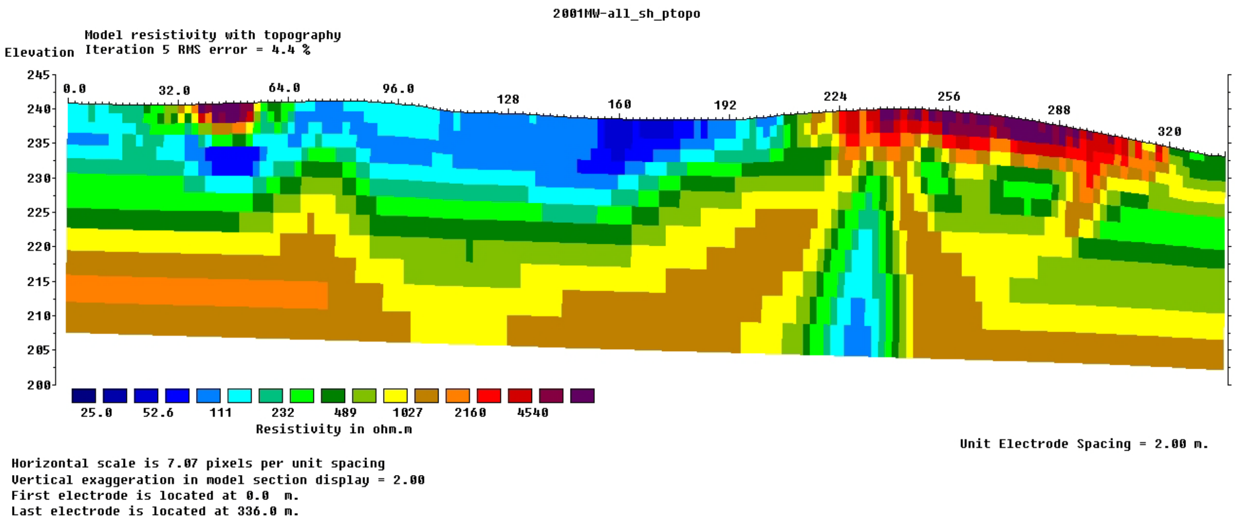


Figure 9: Inverted resistivity images for Line 2001, modified Wenner array, 4 m electrode spacing. (a) Smooth representation with annotations showing known or interpreted features (RB – reservoir boundaries as shown on the historical map). (b) Blocky representation.

3.2 RADARGRAMS

GPR results are presented in Figure 10 to Figure 14. Each figure shows a radargram corresponding to the five datasets acquired (Table 3). The horizontal distance scale at the top of the images relates to the distance measured along the respective ERT profile. The vertical scale on the left shows two-way travel times (in ns), while on the vertical scale on the right the travel times have been converted to depth using a uniform velocity model of v=0.05 m/ns. The recorded length of each GPR trace is 120 ns, hence the maximum depth shown is 3 m bgl.

All radargrams show strong reflectors and relatively coherent reflection patterns near the surface. However, strong signal attenuation tends to set in at a certain depth that varies within each profile, and below this critical depth the GPR response weakens dramatically, with only faint reflections from stronger contrasts remaining visible above noise. Typically, the critical depth appears to be at around 1 m bgl for areas that lie within the suspected lagoon. At the maximum depth of 3 m, the signal has decayed completely almost everywhere. This behaviour was expected with a 250 MHz GPR system – greater depth of penetration would require a lower frequency antenna.

GPR data on Line 1001 (Figure 10) cover only a short section near the centre of the ERT profile. Between 62 m and 70 m, strong reflectors are visible up to 2 m depth. A weak reflector is detected at approximately 2.5 m bgl at the beginning of the GPR line; however this reflector dips away and disappears at around 70 m. No structure is visible at depth beyond a distance of 70 m.

On Line 1003, GPR data are available over a greater distance, and this time the profile covers the suspected boundary of the lagoon (26 m) already identified on the ERT images (Figure 11). At that point, a weak reflector similar to the one observed on Line 1001 emerges at around 1.3 m bgl, dips to a maximum depth of around 3 m at 44 m distance, before rising again to shallower depths of around 1.5 m at 70 m distance. This reflector defines a layer of strong attenuation, whose top boundary lies at around 1 m bgl. These findings can be compared to the observations made in Trial Pit 3 (Table 4), where a peat layer was identified at 1.15 m bgl. This layer extended to 2.4 m bgl, where clay with fragmented slate was encountered. Subject to the positional uncertainty, it therefore is reasonable to hypothesize that the attenuating zone seen in the GPR data is associated with peat.

The radargrams for Line 2001 (Figure 12, Figure 13 and Figure 14) are less conclusive. Some evidence of a weak reflector at depth can be found in the former two, while the latter is dominated by stronger, incoherent reflections likely to be associated with the coarser waste material encountered on the shallow embankment beyond a distance of 200 m.

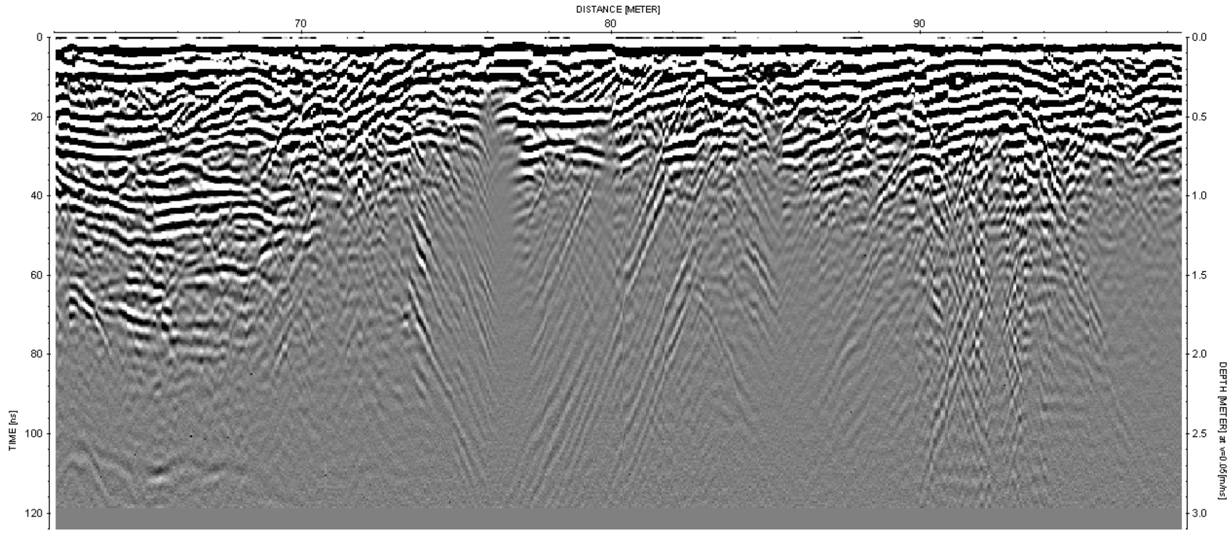


Figure 10: Radargram for dataset 1 (Line 1001).

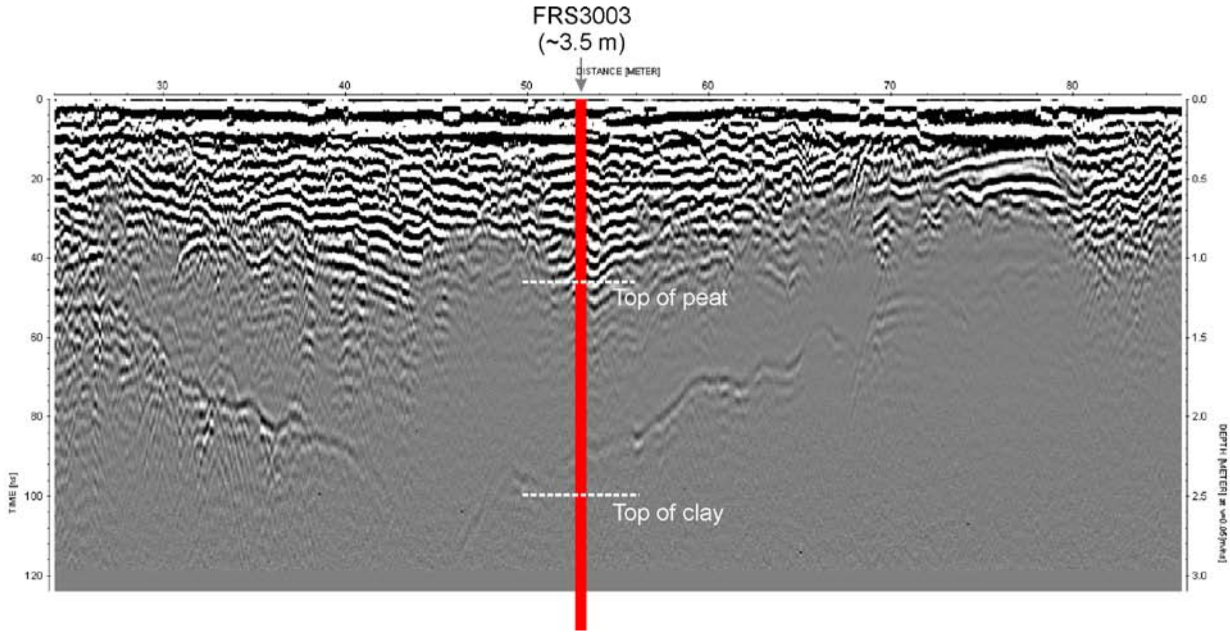


Figure 11: Radargram for dataset 2 (Line 1003).

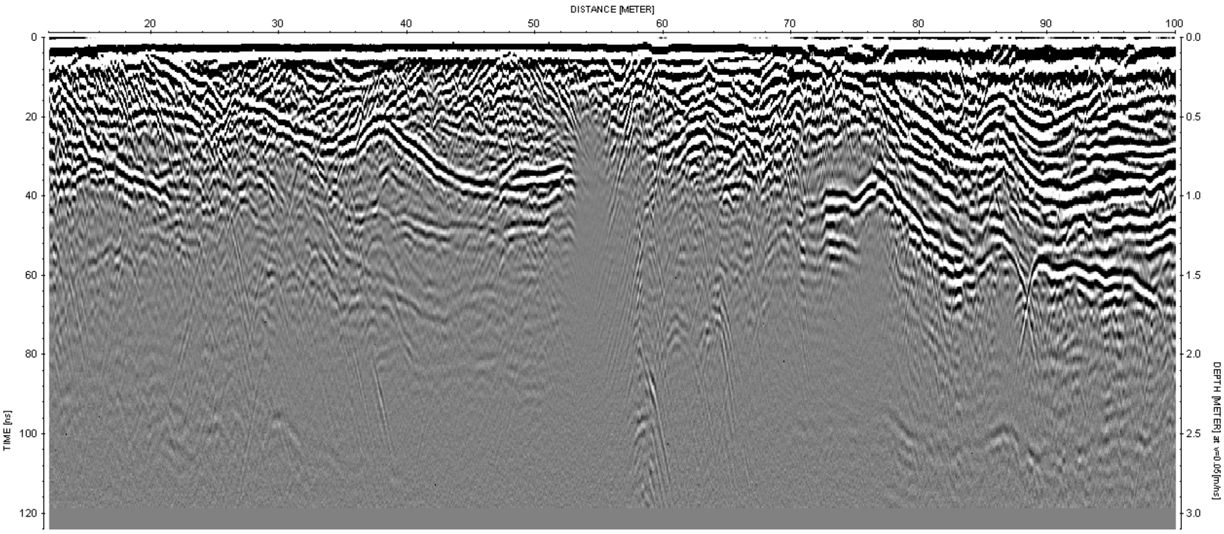


Figure 12: Radargram for dataset 3 (Line 2001 Part 1).

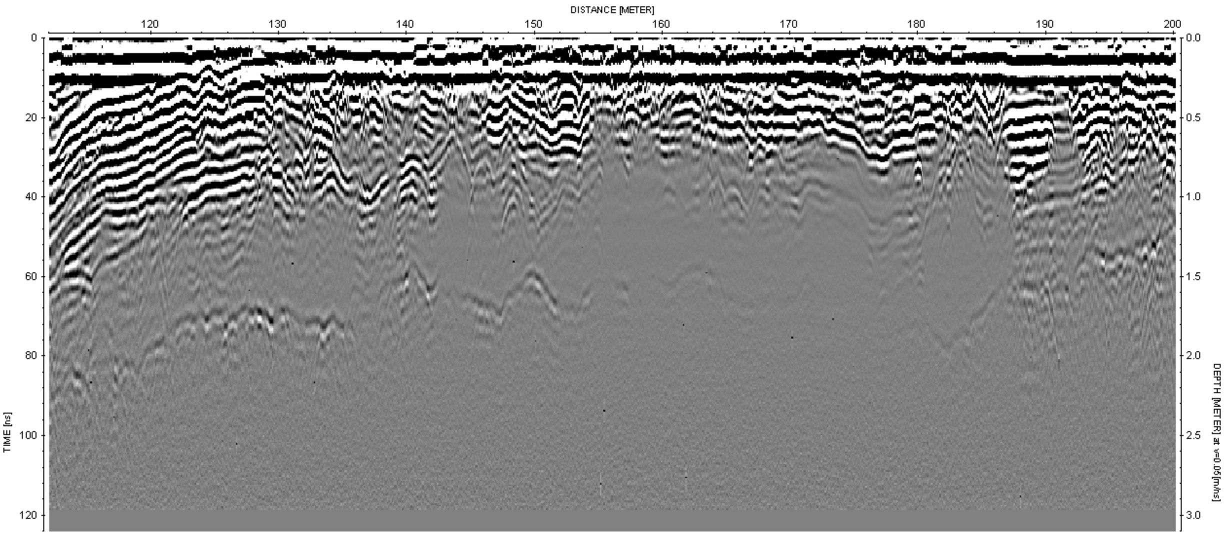


Figure 13: Radargram for dataset 4 (Line 2001 Part 2).

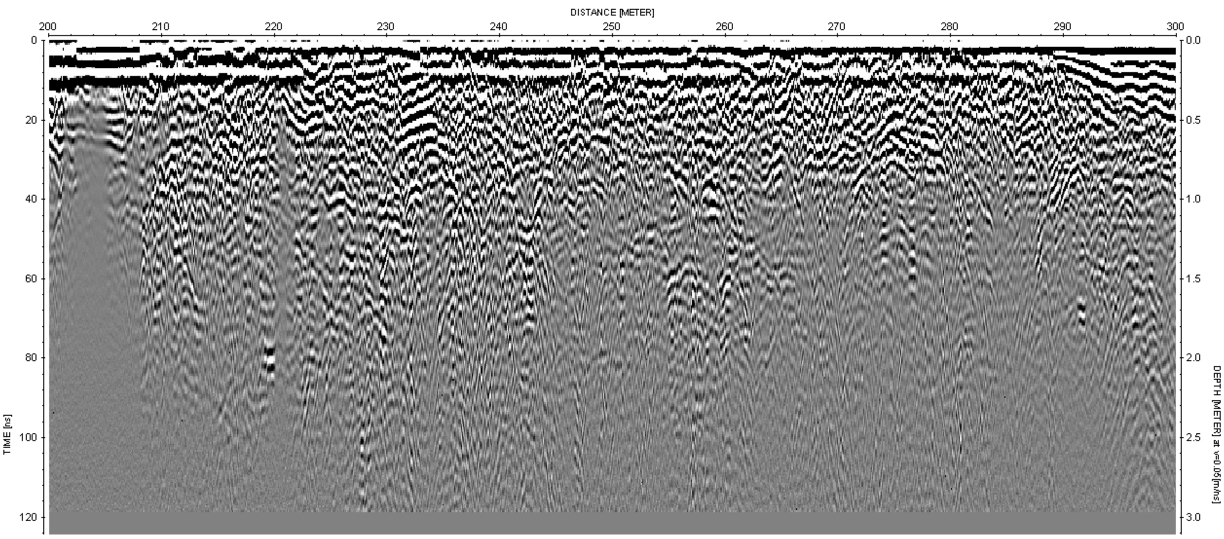


Figure 14: Radargram for dataset 5 (Line 2001 Part 3).

4 Conclusions

A non-invasive geophysical study using electrical resistivity and ground penetrating radar has provided subsurface information with the aim of characterising a former tailings lagoon at Frongoch Mine. ERT and GPR data were successfully collected on four intersecting profiles across the historic reservoir and 2D resistivity models and radargrams were obtained.

The resistivity data clearly show the highly conductive signature of the superficial tailings deposits and good correlation is observed with the outline of the lagoon recorded on historic maps. The depth extent of conductive material is found to exceed the suspected base of the lagoon, but intrusive investigation is required in order to corroborate the geophysical information. There is evidence to suggest that significant fine structure resolved in some of the shallow deposits corresponds to observations made in trial pits located in the vicinity of the geophysical profiles.

Despite strong signal attenuation in the conductive tailings, the GPR data were found to be valid and useful and several radargrams are thought to reveal spatial characteristics of the stratigraphy observed in the trial pits. A repeat investigation using a lower frequency GPR system is recommended in order to achieve greater depth of signal penetration.

The geophysical data obtained will allow the siting of boreholes and other relevant intrusive sampling in the future.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

Loke, M.H. and Barker, R.D. 1996. Rapid least-squares inversion of apparent resistivity pseudosections. Geophysical Prospecting, 44 (1), 131-152.

Palumbo, B. and Klinck, B., 2002. The environmental impact of abandoned lead mining in mid-Wales. Internal Report IR/02/123, British Geological Survey.