Non-Invasive Geophysics for Active Mining Sites

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ABSTRACT: Non-invasive subsurface geophysical technologies are being applied within active mine sites in new and innovative ways to improve safety, aid production, and manage environmental challenges. The majority of contemporary subsurface investigative techniques rely on invasive and extensive drilling programs, which use point source information to infer the broader picture. Geophysical methods, on the other hand, offer a robust alternative that provides improved targeting options to enhance drilling programs. Geophysical methods can be applied over many stages of the mine lifecycle; including exploration, preconstruction investigations and characterization, heap characterization for permeability analysis in leaching operations, injection monitoring for enhanced recovery, and environmental characterization for seepage, acid rock drainage, and plume delineation. In addition, these surveys can provide a high-resolution, spatially-continuous study that when repeated in the same area using the same technique, presents a temporal component assessing subsurface changes over time. This paper gives an overview of geophysical applications applied specifically to solve problems associated with tailings and waste. We show how methods are applied to characterization, monitoring, conceptual site model development, siting of facilities, and how it could be used to monitor stabilization efforts.

1 INTRODUCTION

Historically, the primary role of geophysics in the mining industry was in the exploration for economically viable resources. As geophysics progressed, an expanding range of technologies and methods were developed and improved upon. Equally, as geophysical methods and purveyors of geophysical services became more prolific, applications for geophysical technologies began to develop. Currently, geophysical technologies are no longer limited to exploration and are now playing new and important roles within a diverse set of industries including mining. More importantly, geophysics can be applied throughout the entire mining life cycle. For example, in the production of metals such as copper, gold, and silver, geophysical methods are used to enhance the heap leaching process and improve metal recovery. A geophysical technology known as electrical resistivity tomography (ERT) can be used to assess adverse hydraulic processes in heaps such as pooling, preferential flow, and compaction (Rucker et al., 2009). Others have applied ERT to tailings facilities to investigate internal flow and transport within oil sands (Booterbaugh et al., 2015), acid mine drainage from metal mines (Placencia-Gómez et al., 2010; Benyassine et al., 2017), and to map underlying bedrock (Grangeia et al., 2011).

The fundamentals of ERT are based on the technology's ability to map contrasts in electrical resistivity (or its converse, conductivity) as is relates to the heterogeneity of soils, rocks, and the distribution of moisture and ionic solutions. Given the broad ability of ERT to easily characterize imposed fluids in the earth's subsurface, mining facilities are a perfect environment to apply geophysical studies for numerous subsurface site challenges. These studies can help understand the unique internal structure of tailings and waste rock and the influence that structure has on solution behavior within them. The ERT method affords a holistic approach, providing a means of spatially characterizing the subsurface to determine areas of potential leakage, weaknesses in dams, or plume mapping. Now, hydrological processes that were once invisible, unknown, and poorly understood can be mapped, thus allowing mining operators to target potential areas of concern for corrective actions.

In this paper, we give an overview of ERT and provide examples for usage on tailings facilities. These examples include tailings characterization, plume mapping, dam investigations, seepage characterization, and facility siting. We also discuss the potential for ERT to be used to monitor stabilization efforts for increasing structural support or for reduced permeability. We draw several of our examples from work on leach pads, which is another mining-based rock pile with hydraulic issues.

2 ELECTRICAL RESISTIVITY OVERVIEW

The relationship between the electrical resistivity, current and the electrical potential is governed by Ohm's law (Loke et al. 2013). To calculate the potential in a continuous medium, the form of Ohm's Law as given by Poisson's equation is normally used. The potential due to a point current source located at $\boldsymbol{x}$ is given by

$$\nabla \bullet \left[\frac{1}{\rho(x, y, z)} \nabla \phi(x, y, z) \right] = -\frac{\partial j_c}{\partial t} \delta(\mathbf{x}_s) \tag{1}$$

where ρ is the resistivity, ϕ is the potential and j_c is the charge density. The potential at any point on the surface or within the medium can be calculated if the resistivity distribution is known. This is the forward problem, and we specifically separate it from the inverse problem discussed below. Analytical methods can be used for simple structures such as a cylinder or sphere in a homogeneous medium. For modeling of field data, the finite-difference, finite-element, or finite volume methods are more commonly used. These methods discretize the subsurface into a large number of cells. By using a sufficiently fine mesh and the proper boundary conditions, an accurate solution for the potential over complex distributions of resistivity can be obtained.

The purpose of the resistivity method is to calculate the electrical resistivity of the subsurface, which is an unknown quantity. The measurements for the resistivity survey are made by passing a current into the ground through two current electrodes (usually metal stakes), and measuring the difference in the resulting voltage at two potential electrodes. In its most basic form, the resistivity meter has a current source and voltage measuring circuitry that are connected by cables to a minimum of four electrodes. The basic data from a resistivity survey are the positions of the current and potential electrodes, the current *(I)* injected into the ground and the resulting voltage difference (ΔV) between the potential electrodes. The current and voltage measurements are then converted into an apparent resistivity (ρ_a) value by using the following formula

$$\rho_a = k \frac{\Delta V}{I}, \tag{2}$$

where k is the geometric factor that depends on the configuration of the current and potential electrodes (Loke et al., 2013). Different arrangements of the current and potential electrodes (or arrays) have been devised over the years (e.g., Cubbage et al., 2017).

Equation 2 represents the simplest form of the inverse problem and assumes that the earth is homogeneous for each combination of current and potential measurements. For more complicated problems, inversion relies on a methodology to back calculate the resistivity that gave rise to the measured potential measurements. Starting from a simple initial model (usually a homogeneous half-space), a non-linear optimization method is used to iteratively change the resistivity of the model cells to minimize the difference between the measured and calculated apparent resistivity values. The inversion problem is frequently ill-posed and ill-constrained due to incomplete, inconsistent and noisy data (Loke et al., 2013). Smoothness or other constraints are usually incorporated to stabilize the inversion procedure to avoid numerical artifacts. We call this type of calculation tomography, hence giving rise to the term ERT.

An example of an ERT section is provided in Figure 1, where low resistivity is typical of wet ore and high resistivity is indicative of drier conditions. The data were collected with a Schlumberger array and inverted using RES2DINV. The section shows coherency in both low and high resistivity targets, where both compacted and wet zones are identified (and summarily confirmed through drilling). Other interpretations were made based on hydrological principles, understanding stacking methodologies, and discussing the history of the facility with the mining superintendent.

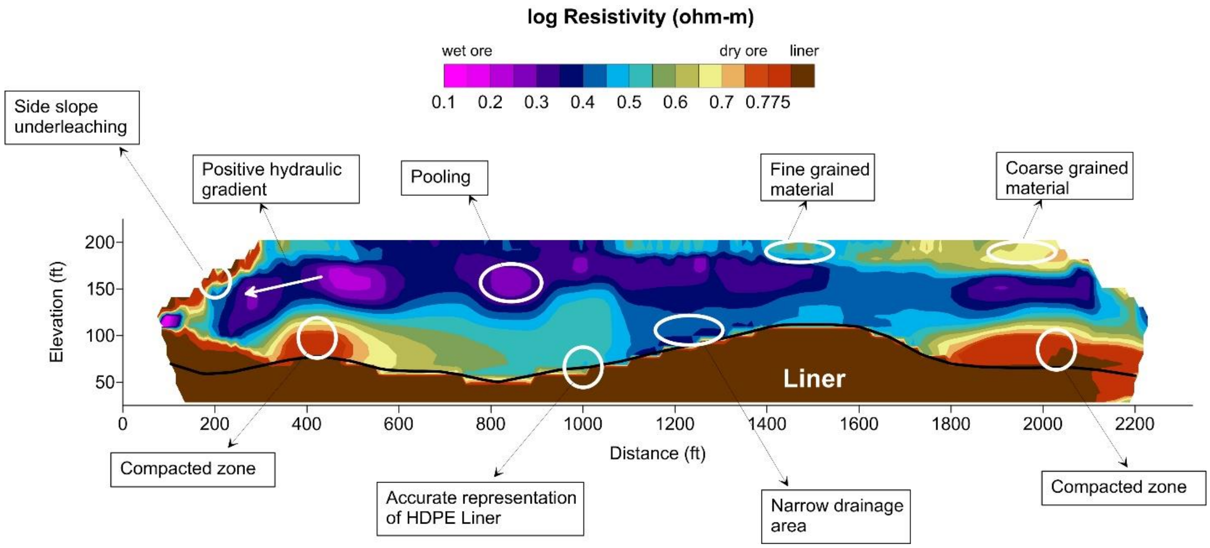

Figure 1. Example of ERT applied to a rock pile with an underliner.

3 TAILINGS CHARACTERIZATION

Tailings and waste rock piles are extremely heterogeneous systems, comprising various features at different scales. Characteristics of these piles can vary greatly with respect to rubblized and processed content, grain and rock size, rock type, large-scale structural design, and stacking strategies. In every case, no two tailings piles are the same and will differ in mineralogy, morphology, and chemical characteristics. To understand the influence of these factors, it is critical to characterize the structure and the relevant material distribution within tailings piles (Dawood et al., 2009).

Electrical resistivity affords a dynamic approach to tailings characterization and understanding of the properties that dictate solution movement by providing a means of spatially characterizing their unique structure. For instance, mapping the permeability of tailings piles can expose areas of high moisture which may be a consequence of preferential flow or perched aquifers within the structure. Whereas dry resistive areas may be the result of compacted areas or zones that no longer allow water to drain effectively.

An example of these types of conductive and resistive targets can again be seen in Figure 2. We used electrical resistivity to discover large conductive anomalies that are responsible for creating seeps on the margins of a waste rock pile. The conductive anomalies represent saturated material as dark blue and purple targets while a more resistive, less saturated zone sits below the upper conductive areas at the center of the profile, represented by variations of olive green.

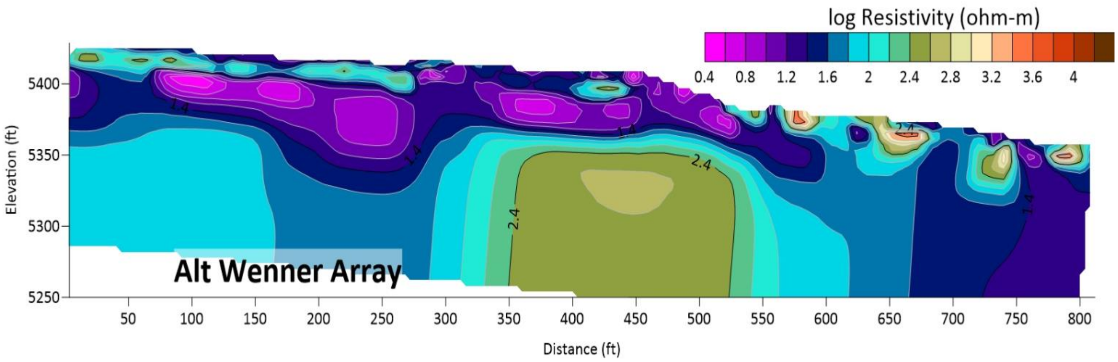

Figure 2. Example of electrical resistivity across a waste rock pile with seepage issues.

4 STRUCTURAL MAPPING AND FACILITIES SITING

As the flow of both surface and groundwater domains provides the main pathways of mine pollutants to the environment, it is essential that the geological materials that control them are well understood (Howett et al., 2015). Towards this end, mapping the subsurface becomes an important step in siting new facilities to minimize damage. Several have used surface geophysics and ERT to help site these facilities and establish background conditions prior to construction (Bauman et al., 2014; Pettifer et al., 2017).

In our work, we have used ERT extensively to map structure beneath potential locations for tailings facilities. In Figure 3, we present two sections that were acquired within a mile of each other to investigate subsurface conditions. The top section (Line 1) was acquired across a single sedimentary rock formation and the resistivity is shown to be fairly uniform at high values. Given that moisture would dramatically reduce the resistivity, it is likely that the formation is fairly competent with low fracture-based porosity to hold moisture. In Line 2, the ERT line crosses several formations of varying sedimentary, igneous, and metamorphic complexes. These data show that geological boundaries can extend deeply into the subsurface, thus allowing a means for contaminants to transport more easily to groundwater. Formation 2, in particular, is rather conductive, hinting at the fact that it could be fractured and holding some moisture. These fractures too could act as conduits. Therefore, we would recommend further exploration near Line 1 and abandon the consideration of siting the facility at Line 2.

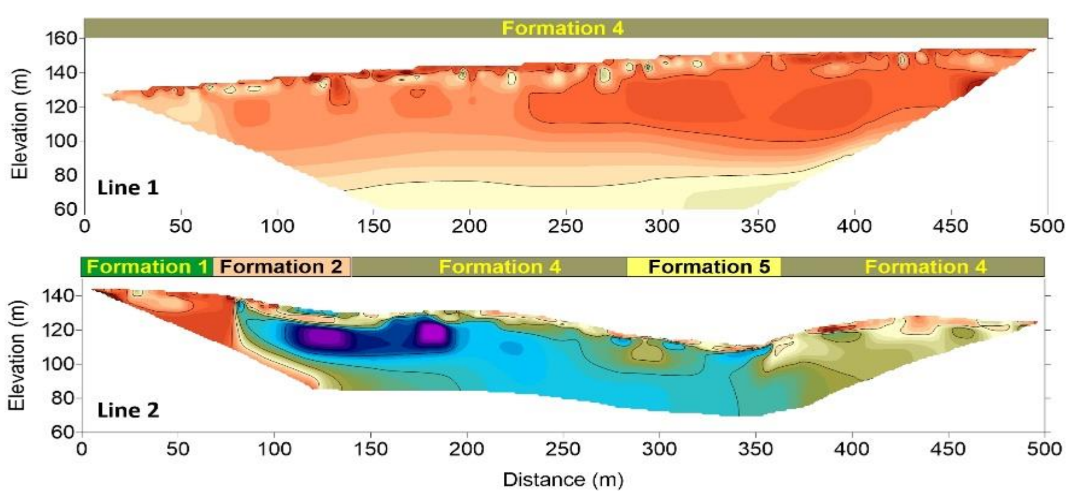

Figure 3. Example of ERT applied to structural mapping for siting facilities

5 LEAKAGE AND SEEPAGE CHARACTERIZATION

While it is valuable to understand properties that dictate solution movement and the distribution of solution within tailings piles, it is equally important to understand where that solution may go beyond the impoundments boundaries. Thus, the long term stability and environmental performance of these structures is critical to their long-term management and cost. The primary impact on these structures is atmospheric water or ground water that intrudes into tailings piles leading to the formation of acid creating the problem of acid rock drainage (ARD). Fundamentally, ARD challenges are related to the flow of water through tailings and it becomes critically important to be able to evaluate water movement and distribution in these piles (Dawood et al., 2009).

These structures are uniquely constructed and are commonly placed in areas where the geology forms natural depressions or boundaries to contain the large quantities of waste. However, the very geological and environmental conditions pursued to build tailings structures can also lead to the development of subsurface seepage pathways that progress beyond the impoundments confines. This is because geological depressions and valleys are commonly associated with faults and other related geological structures that can carry tailings solutions off site through natural subsurface pathways. Locating these pathways can prove exceedingly difficult and costly, especially when using invasive measures such as drilling and potholing.

While ERT serves as a valuable characterization application to understand the internal hydrodynamic structure of tailings piles, it can also be used to track and delineate the extent of seepage pathways beyond impoundment boundaries. Both applications have the distinct advantages of imaging through the entire tailings pile, tailings dam or impoundment and its contact with basement geology to understand fluid movement. When tracking seepage, ERT arrays are arranged perpendicular to suspected subsurface solution pathways and moved outward from the source toward known 'outfalls', creating a linear series of 2D profiles mapping fluid infiltration through natural geologic conduits. This methodology is used to determine both the direction and depth of seepage pathways. Figure 4 shows a series of ERT arrays used to track solution emanating from a tailings pile.

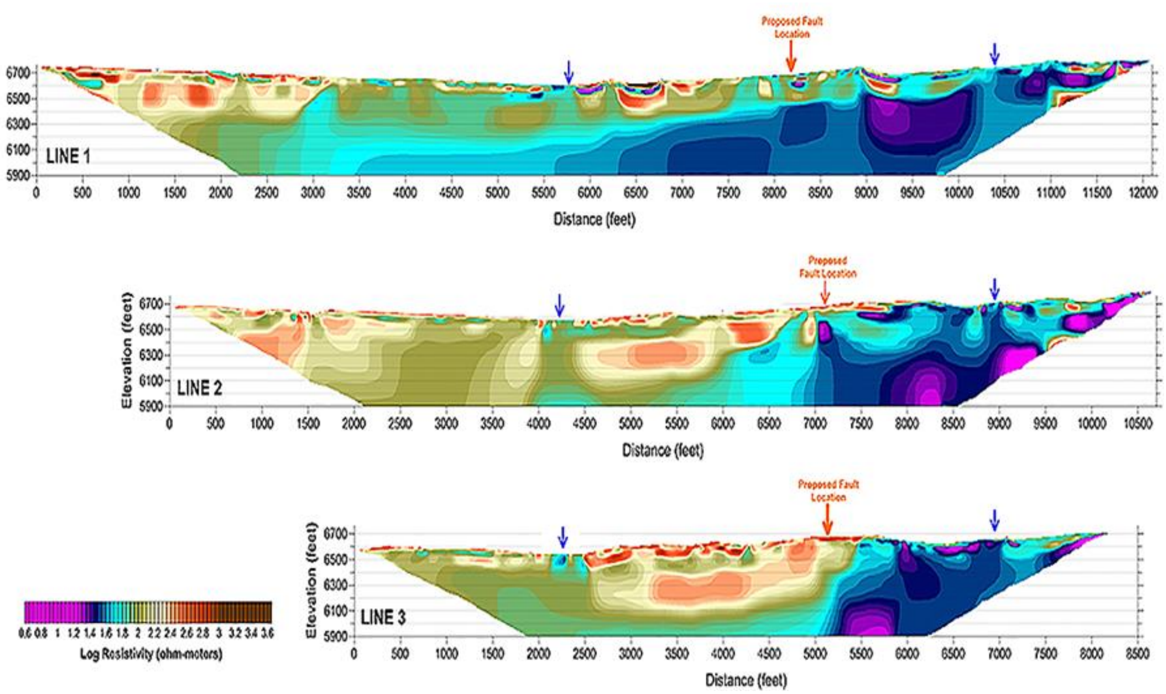

Figure 4. Example of ERT arrays down gradient of a tailings dam.

Additionally, ERT can be used to track leaking or flowing water into tailings and waste rock through covers. Tailings piles are always under the influence of seasonal and diurnal cycles that affect internal temperature, moisture, and solution movement. When combined with natural atmospheric precipitation and groundwater fluctuations, understanding water infiltration can be challenging without the use of more holistic measure such as ERT. Covers are designed to absorb some precipitation and allow the rest to run off in an effort to keep the contaminant material beneath dry and reduce future impacts to the environment. In Figure 5, a series of ERT arrays were used to understand seasonal changes occurring in waste rock and the integrity of an earthen cover over a pile.

In the Figure 5 example, the operator monitoring the mine waste was unsure whether the cover was effective based on long-term treatment of drain down waters and atypical water level fluctuations. The ERT survey revealed limited weak spots where the cover was compromised. The weak areas appear as low resistivity anomalies punctuating the resistive cover, whereas the waste is significantly more conductive when compared to the resistive cover and weak areas. This example demonstrates that potential seep migration pathways into the waste are not likely coming through the cover and, in fact, the cover is intact and working as designed. The source of water entering the pile is likely groundwater and not surface rainfall.

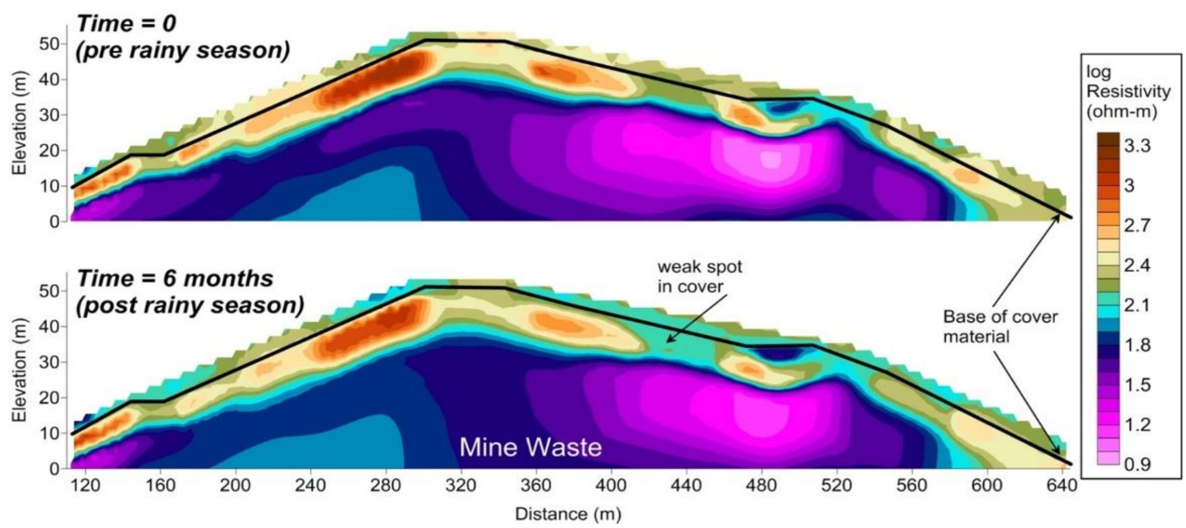

Figure 5. Example of two ERT surveys acquired 6 months apart over a covered tailings pile.

6 PLUME MAPPING

Geophysical methods have increasingly demonstrated their potential to delineate areas contaminated with potentially harmful elements and compounds and acidic seepage from mine waste sites (Placencia-Gómez et al., 2010). ERT is a highly promising tool for investigating the internal structure of mine wastes that are controlled by water and oxygen fluxes responsible for sulfide oxidation and possible generation of acid rock drainage (ARD) (Chouteau et al. 2005). ARD is comprised of highly ionic porewater, providing a strong target for ERT relative to the typical resistive host rock. Vanhala et al. (2004) provides more proof of the power of ERT to map ARD.

In our example, provided in Figure 6, an ERT line was placed adjacent to a tailings facility to investigate the extent of contamination to the subsurface. Line C shows a strong conductive anomaly of around 10 ohm-m, with a center of mass around 33ft below ground surface. This would seem to be an extreme environmental hazard, but fortunately, the plume was truncated as shown in Lines A and B, placed at incremental distances from Line C. These sections become more resistive owing to the decreased mine impacted waters flowing from the tailings facility. The ERT data were then used to site an environmental monitoring well and a pumping well for reducing contamination and tracking the progress.

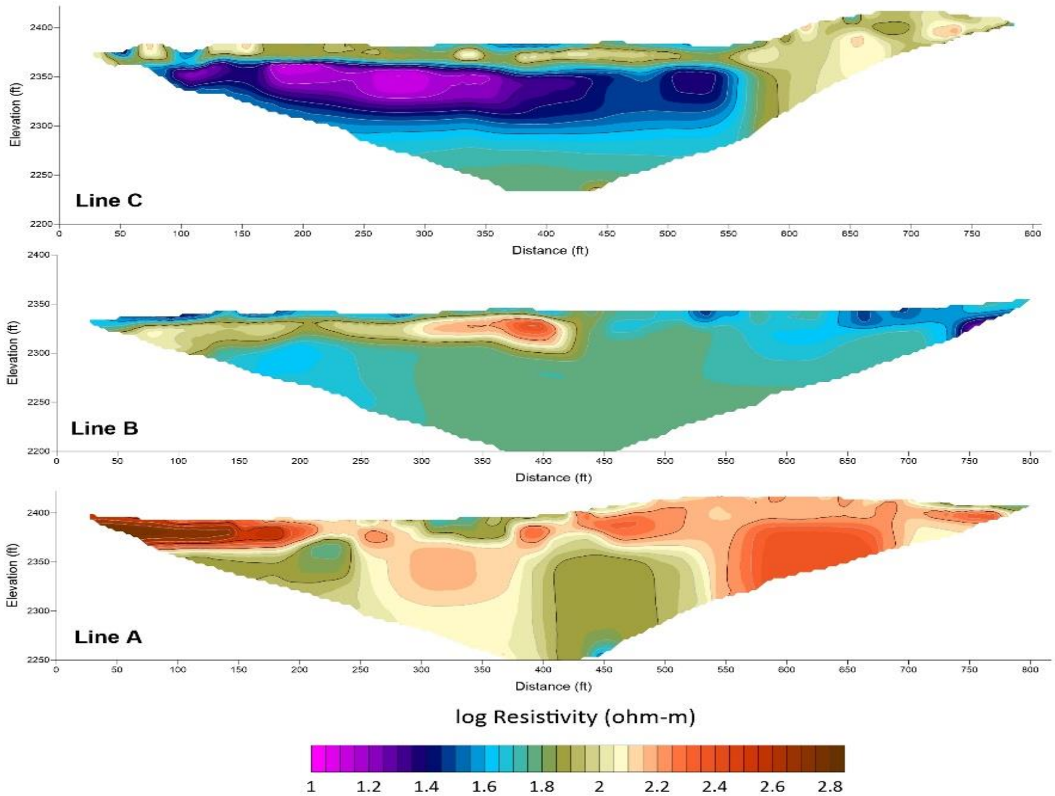

Figure 6. Example of ERT applied to mapping ARD plumes adjacent to a tailings facility.

7 STABILIZATION MONITORING

Under certain scenarios, it is necessary to stabilize a tailings facility, as Cline et al. (2016) showed with the use of grout injection. In their work, the grout was used to strengthen the zone of overbank deposits, on which their tailings were built, thus it was a critical element to improving the geomechanical stability of the facility. The overbank deposits have low shear strength and could liquefy during a seismic event. In other work, Kim et al. (2003) used iron as a reducing agent to geochemically stabilize tailings from arsenic contamination. Mohamed et al. (2003) used a fly ash based cement with aluminum to hydro-mechanically stabilize tailings, which reduced permeability and increased strength.

In each of these examples, the stabilizer needs to mix with existing material. An efficient means of mixing could be through injection, which would ensure depth penetration of the stabilizer. To optimize delivery of the stabilizer, one would need information on penetration and ERT can be an excellent tool for monitoring events in time. The ERT would be collected over a series of snapshots, with the data being compared to a baseline event prior to injection. In our work (Rucker, 2014; Rucker et al., 2014; Rucker et al., 2015) we have used ERT extensively to track injections into rockpiles and heaps to understand fluid propagation and movement. The data are then used to develop upscaled well fields and ensure adequate coverage.

An example of injection monitoring is shown in Figure 7. In this example, we placed electrodes for the ERT monitoring survey on the surface of the rockpile as well as within boreholes to increase resolution. We then acquired ERT data on 168 electrodes with a pole-pole array, taking a snapshot every 25 minutes. The data show the injected solution to be nearly symmetric about the injection well extending out to a radius of about 58ft. Having this information allows placement of other injection wells at optimized distances to ensure complete coverage of the injected solution.

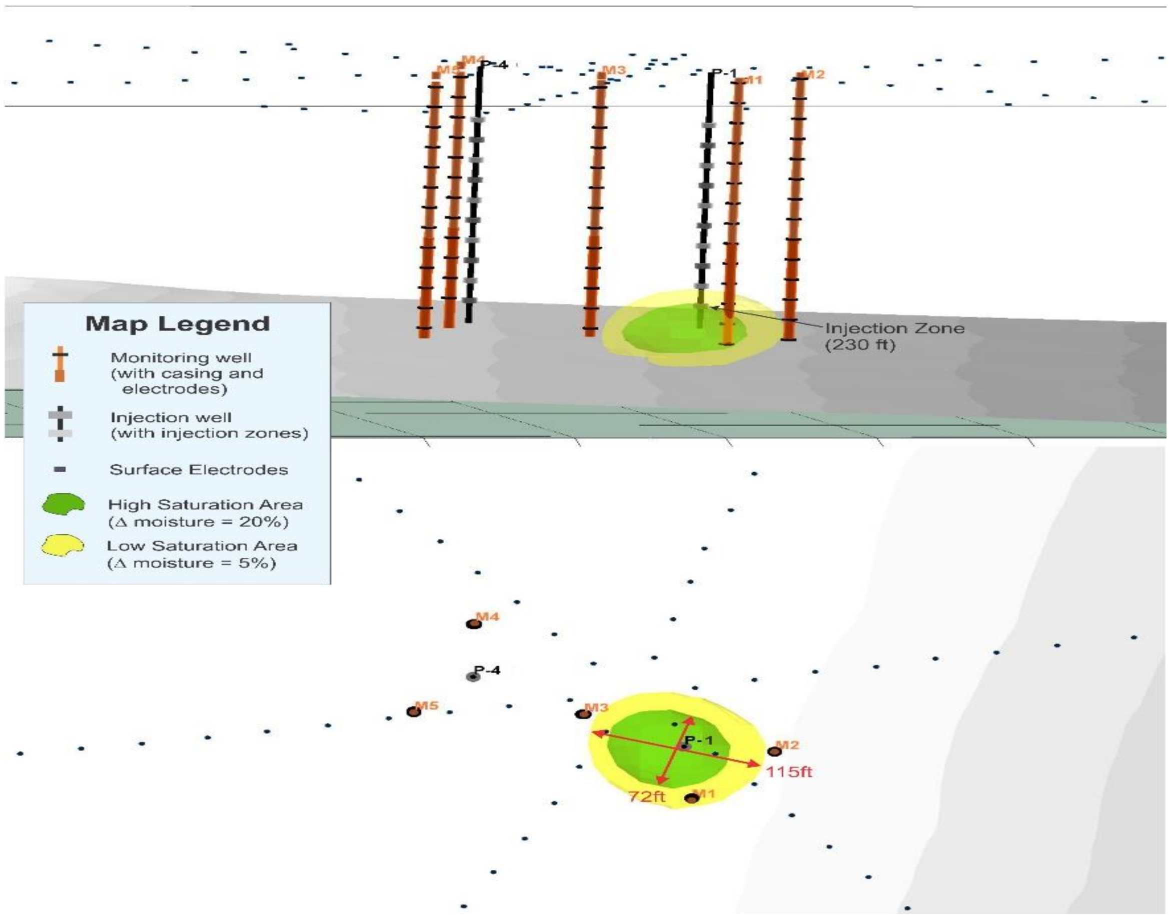

Figure 7. Example of time lapse ERT applied to injection monitoring.

8 CONCLUSION

Electrical resistivity methods afford a dynamic approach to tailings characterization and understanding of the properties that dictate solution movement, providing a means of spatially characterizing their unique substructure. ERT methods have been successfully used to map the subsurface of tailings piles for spatial distribution of pore water content, monitoring fluid infiltration through geologic materials, delineating preferential groundwater flow pathways, and determining structural integrity. These innovations have allowed broader assessment of large-scale hydraulic processes, helping tailings managers gain holistic information to highlight areas where potential challenges may exist. This allows for proactive mitigation of tailings managements challenges.

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