Application of High-Resolution Airborne EM and Magnetic Data for Geotechnical Investigations of Tailings Facilities, Examples from Brazil.

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SUMMARY

We present an overview of an ambitious geophysical program undertaken by Vale to characterize both tailings storage facilities (TSF) properties around existing mine sites as well as an exploration program for iron ore. This resulted in 23 survey blocks being flown. There are a large number of mines in Minas Gerais where technical approaches and surviving records for TSF properties are not at the same standard as at modern mines. In some cases, there are no records regarding dam construction. Geophysics presents a non-invasive, cost-effective method of characterizing these dams. However, in places, ground geophysics is not permitted because of HSE concerns. Also, given the number of mine sites, ground geophysics would be an onerous endeavor.

Airborne geophysics is thus a compelling solution. There are two main reasons for airborne acquisition: (1) HSE for conducting ground surveys on top of the existing earth dams and tailing ponds and (2) speed of acquisition. To properly characterize the site, data must be collected in multiple lines over the dam, pond and the immediate surrounding area.

To characterize the dam, very near surface information is required. Frequency domain EM presents the best available near-surface sensitivity of airborne geophysical techniques. The Resolve system was used due to its wide frequency range of 400Hz to 140 kHz. In order to enhance sensitivity to magnetic material in the ground, Resolve was flown with a transverse horizontal magnetic gradiometer.

To ensure the correct interpretation of the complete earth response in these topographically complex settings, the data is being modelled with a 3D inversion program. A cooperative joint inversion is being conducted between the magnetics and the EM, and where available, surface, geotechnical and borehole information is being incorporated.

Key words: Airborne Geophysics, Airborne Electromagnetics, Tailings

INTRODUCTION

There are a large number of mines and associated tailings storage facilities (TSF) in Minas Gerais where technical approaches and surviving records for the TSF are not at the same standard as at modern mines. In some cases, there are no records regarding dam construction or the pre-TSF terrain. Geophysics presents a non-invasive, cost-effective method of characterizing these dams. However, in many places, ground geophysics is not permitted because of HSE concerns and given the number of mine sites, ground geophysics would be an onerous endeavor.

Airborne geophysics is thus a compelling solution. There are two main reasons for airborne acquisition: (1) HSE concerns for conducting ground surveys on top of the existing earth dams and tailing ponds and (2) speed of acquisition. To properly characterize the site, data must be collected in multiple lines over the dam, pond and the immediate surrounding area. Additionally, to characterize the dam, very near surface information is required. Frequency domain EM presents the best available near-surface sensitivity of airborne geophysical techniques, with the RESOLVE system being selected for this project due to its high operation frequency of 140 kHz. In order to enhance sensitivity to magnetic material in the ground, RESOLVE was flown with a transverse horizontal magnetic gradiometer.

The survey was flown over a number of tailings ponds. In some instances – particularly older TSFs inherited from other companies – it was not always possible to recover accurately recorded details about the TSF history. The geophysical surveys confirm existing records at many dam locations and in other areas provided very useful information about dam location and extent, and thickness of the tailings pond, as well as information about the surrounding geology.

To ensure the correct interpretation of the complete earth response in these topographically complex settings, the data is being modelled with a 3D inversion program. A cooperative joint inversion is being conducted between the magnetics and the EM, and where available, surface, geotechnical and borehole information is being incorporated.

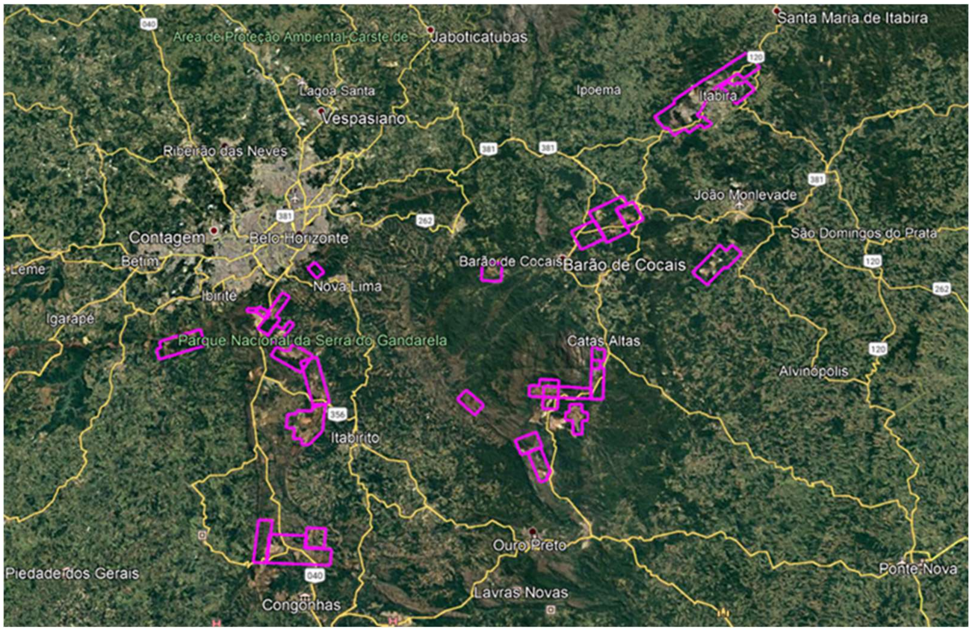


Figure 1. Diagram of ray-paths of phases *Ps* and *Ppps* to a receiver above a single layer. Solid and dashed lines denote *P*- and *S*-wave segments. Upper- and lower-case letters denote wave type in the half-space and layer respectively.

19,000 line-km of data were collected over 23 blocks in the Quadrilátero Ferrífero region, Minas Gerais and Carajas, Southern Para (see Figure 1). Line spacing ranges from 25m to characterize the dam sites with high resolution, to 100m over the exploration blocks. Extensive culture (buildings and power lines) caused the survey to be flown 30 m higher than typical surveys..

RESOLVE FDEM SYSTEM

Figure 2 shows a picture and schematic diagram of the RESOLVE frequency domain electromagnetic (FDEM) system as implemented for this survey. The 9m long “bird” houses transmitter and receiver coils and is towed by the helicopter at a nominal altitude of 30 m above the ground (or obstacles such as trees). RESOLVE has 6 transmitter coils (horizontal co-planar coils, most sensitive to flat-lying features, range in frequency from 400 Hz to 140,000 Hz; there is one vertical co-axial coil with best sensitivity to vertical features, operated at 3,300 Hz). Magnetometers were placed on each side of the tail to measure the transverse magnetic gradient. Additionally, the Resolve system is equipped with a laser altimeter to provide system height above ground and an inclinometer to correct for changes in coil attitude.

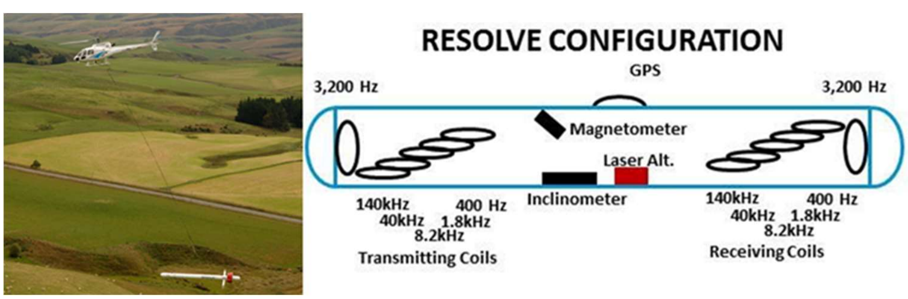
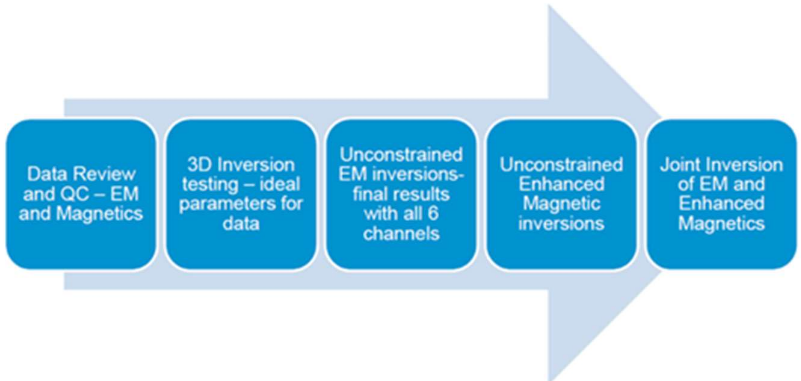


Figure 2 – A picture of the RESOLVE system in flight (left) and a schematic diagram of the RESOLVE frequency domain EM system.

METHOD & CASE STUDY – AREA 1

We provide an example of the workflow by reviewing the data and inversion results for one of the survey areas. The workflow is summarized as follows:



The Area 1 survey block contains 5 TSF, with structural reports available for only three of these. We will show examples from Block 1 of Area 1 where the geology consists of various metamorphic rocks. RESOLVE FDEM and magnetic gradient data were acquired. In-phase and quadrature EM components were processed and preliminary interpretation products generated. These include apparent resistivity calculations and Differential Resistivity, a rapid conductivity depth algorithm.

For 3D inversion, cultural noise was first removed. Because of the tuned coils of RESOLVE, power line signal has a very different response in each of the frequency channels. Figure 3 shows the measured response in the vicinity of a strong power line. The highest frequencies (140 and 40 kHz) show very little response from the power line. The 8200 Hz shows some power line response, but the data is still very much interpretable. The lowest frequencies are swamped by power line noise, similar to what would be seen by a time domain electromagnetic system.

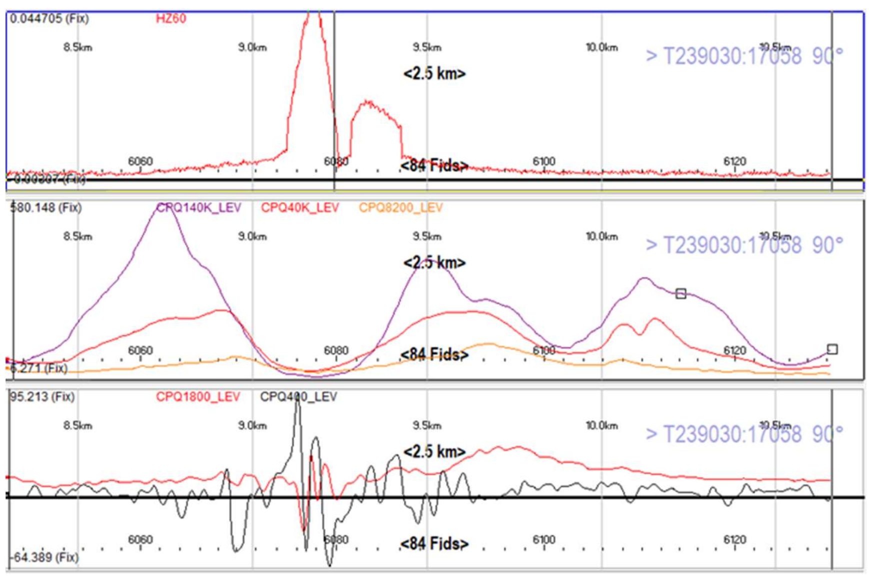


Figure 3 - Power line monitor (top), 140, 40 and 8.2 kHz quadrature (middle) and lower freq. signal (1800, 400 Hz, bottom).

The 140 kHz apparent resistivity is shown in Figure 4. The tailing ponds are conductive in comparison with dams, in terms of intermediate conductivity when compared with the country rocks of higher resistivity. The apparent resistivity plot provides a check on the inversion process, identifying the main resistivity structures.

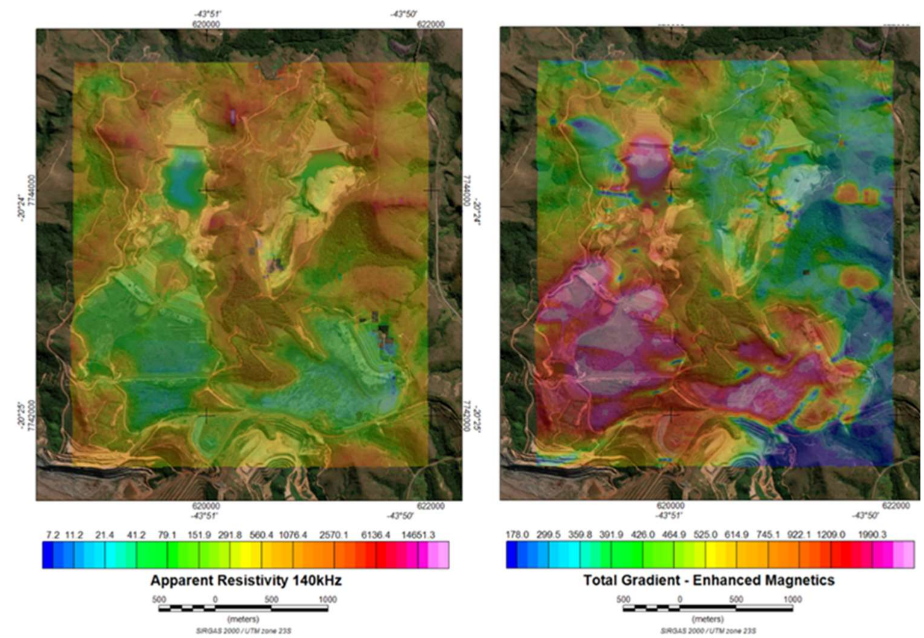


Figure 4 – Apparent resistivity,140 kHz channel (left); Magnetic susceptibility inversion; depth slice at 5 m below surface (right)

Several tests were performed using both the magnetic and airborne EM data in direct joint and cooperative inversions. An important consideration in performing these joint inversions is the relative depth of penetration of the two techniques involved. The airborne EM data is expected to provide inversion results to approximately 100m depth. The magnetic data is sensitive to the magnetically susceptible material from the surface to depths of many km's. In order to get meaningful results, the cooperative joint inversion approach was selected, where the magnetics is inverted using the EM resistivity result as structural constraint (Scholl et al., 2017).

An example of cooperative joint inversion is shown in Figure 5. The lower panel shows a slice through the unconstrained 3D magnetic inversion. The upper panel uses the EM structure in a joint cooperative inversion to better distribute the higher magnetic susceptibly material. As shown in Figure 4, high magnetic susceptibilities were correlated with the locations of some of the ponds, suggesting the pond fill contained minerals with magnetic susceptibility. The ponds were also more conductive than the surrounding geology. The cooperative joint inversion placed more susceptible material within the pond tailings, and the rest of the highly susceptible material was modeled as coming from the deeper geology.

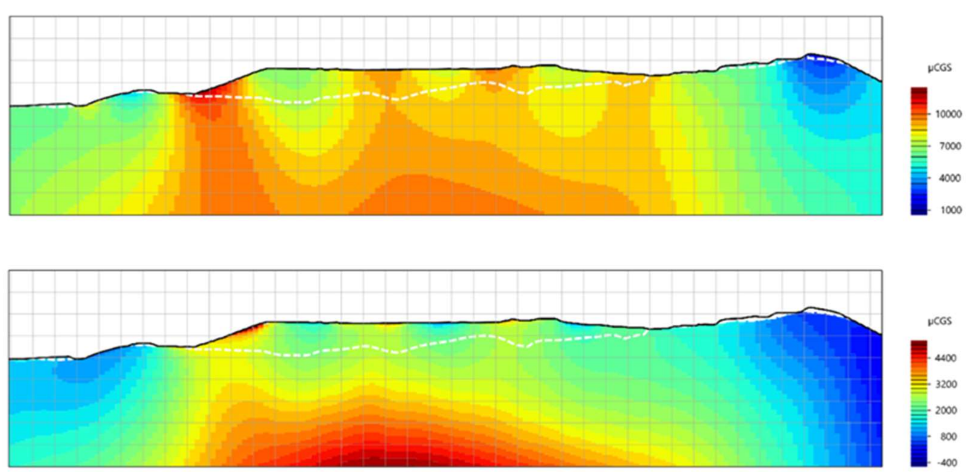


Figure 5 – Comparison of the magnetic inversion using co-operative joint inversion with the FDEM data (top) and unconstrained magnetic inversion (bottom) for one of the dam sites. The white dashed line indicates the estimated bottom of the tailings pond.

Ground DC resistivity data was collected over a few of the dams in 2019, and inversion modeled before the current study. Figure 6 shows inverted resistivity for a series of ground DC lines over one of the dams. The tailings material appears as only slightly less resistive (~2,000 ohm-m) in absolute sense but still distinct from the highly resistive host rock (~10,000 ohm-m).

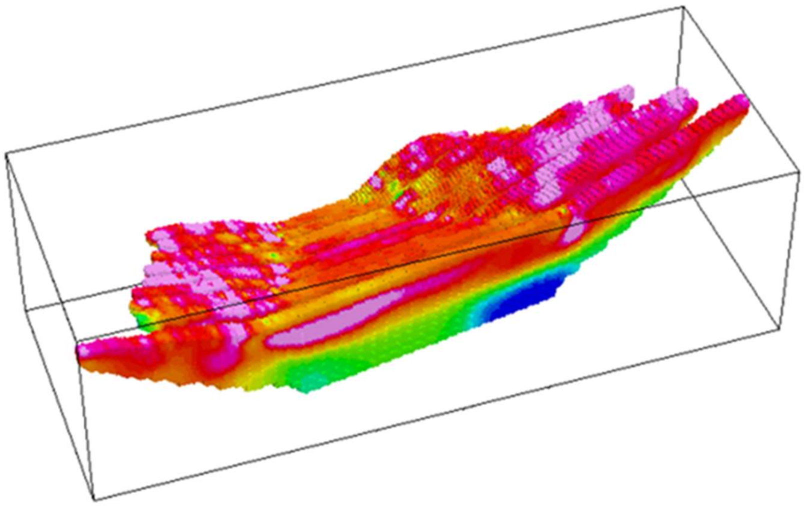


Figure 6 – Legacy inversion result from ground DC resistivity over dam #5.

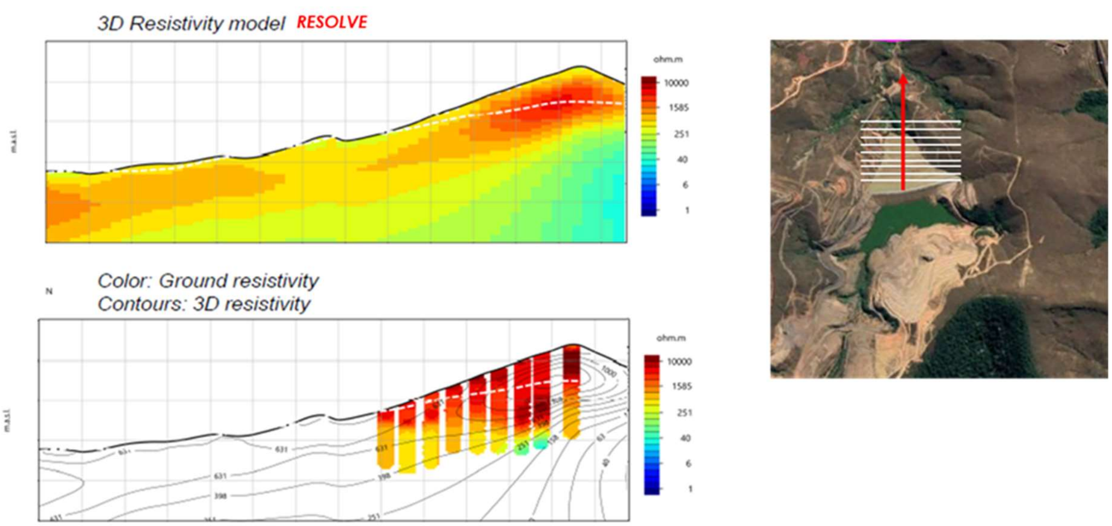


Figure 7 – 3D FDEM inverted resistivity (top). Below, DC resistivity (colour) and 3D inverted resistivity (contours). Section on map with ground lines in white and airborne line in red (right).

The DC resistivity lines were acquired across the dams, while the airborne lines were flown at approximately 90 degrees to this. Figure 7 provides a comparison the inverted FDEM 3D resistivity with ground DC resistivity models conducted prior to this study. The airborne FDEM does not image the very resistive material at surface, likely because the skin depth in this resistor is very large so there is poor sensitivity. The FDEM shows a resistive wedge dipping to the north with approximately the same thickness as the DC resistivity. The FDEM inversion also shows a large conductor that is the tailings pond. Note that ground DC resistivity surveys, naturally, cannot be conducted over the pond itself and while the airborne data is not as sensitive as the ground data, it provides full coverage of the area.

FURTHER EXAMPLES

Area 2

In Area 2 we focus on a dam that has DC resistivity lines over the rim, and in Figure 8 compare the DC inversion results with the 3D FDEM inversion. While the DC resistivity shows higher absolute values of resistivity, the trend shown within the dam is similar between the two methods. Both show elevated resistivity values at the back of the dam at the front of the dam, curving away from the front face to the back of the dam towards the eastern extent. The central part of the dam shows a higher conductivity from both techniques.

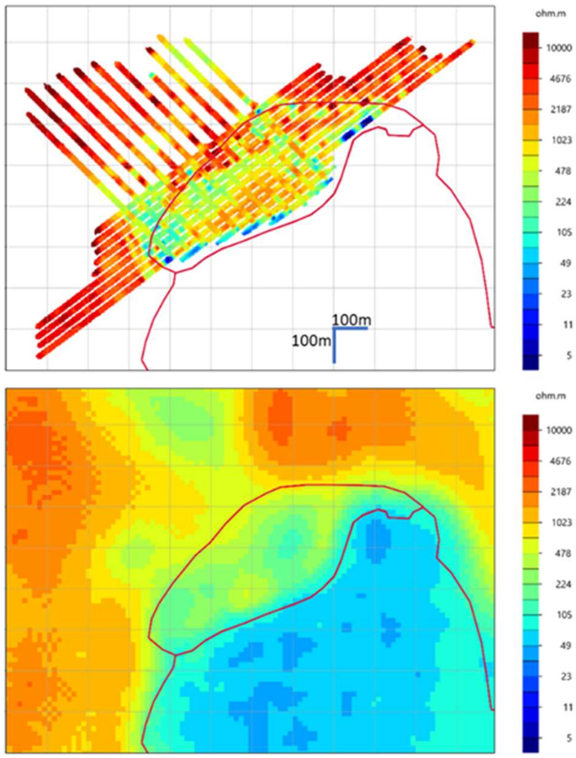


Figure 8 – Comparison of ground DC resistivity (top) and 3D FDEM resistivity (bottom) at 20m below ground level.

Figure 9 shows a resistivity section through the dam and over the tailings pond. The tailings pond appears as a conductor, while the dam is a relative resistor. The basement here is very resistive. The 3D FDEM inversion is doing an excellent job mapping the thickness of the pond material. When combined with SRTM elevation data from before the TSF was built, as well as geotechnical drill holes, the FDEM data now provides an estimated pond depth that can now be confidently used in baseline studies of the TSF.

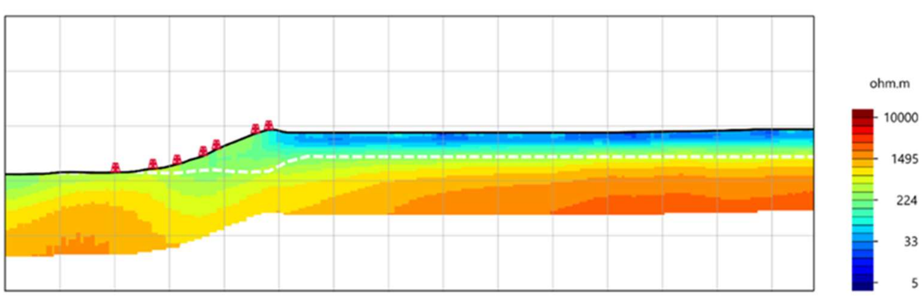


Figure 9 – Section view of the Area 2 dam and pond. White line shows inferred pond depth from pre-dam construction SRTM data. Red symbols show locations of geotechnical drill holes.

Area 3

Area 3 is a large pond separated by an auxiliary dam in the middle of the pond. Figure 10 shows the inverted FDEM resistivity at depths of 5 m, 20 m and 40 m. As is expected, the tailings pond is conductive compared to the surrounding resistive geology causing a physical property contrast that can be mapped to infer the thickness of the pond. The FDEM inversion result is thus able to show variations in the thickness of the pond, which is deepest in the central part of the northern pond close to the central dam, and exceeds 40 m. The both dams are imaged as resistors.

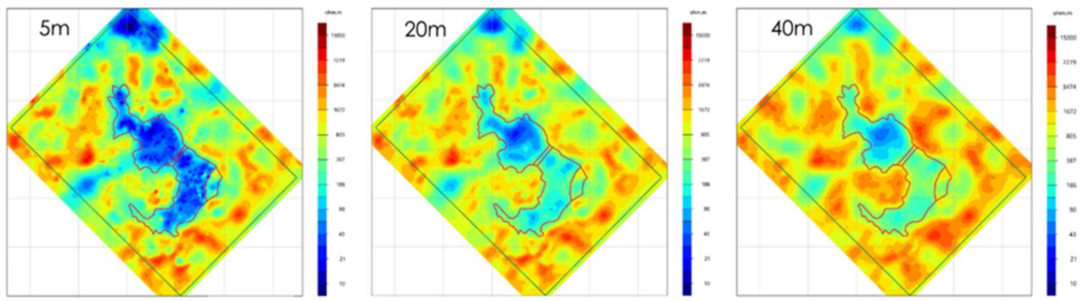


Figure 10 – Inverted resistivity from FDEM data for depth slices at 5, 20 and 40m below surface.

CONCLUSIONS

Vale is employing a pioneering, proactive strategy to manage historical mine sites. The results from a high resolution airborne frequency domain electromagnetic system and gradient magnetometer, inversion modeled in 3D, show that it's possible to efficiently image the subsurface, reliably. The resulting physical property models are being interpreted to better understand the geotechnical environment and history of dams and tailings ponds. The Resolve FDEM data, in general, agrees with ground DC resistivity but provides valuable advantages through spatially consistent and complete data coverage over the entire dams, tailings ponds and host rock system. The geophysical data has helped to confirm subsurface hypotheses at different locations and has provided additional information to further interrogate the existing geotechnical model.

ACKNOWLEDGMENTS

We would like to thank Vale for insight into the data and geology and for permission to publish. We would like to thank CGG for their support in writing this paper

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