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Characterization of Abandoned Mine Tailings by means of Time- and Frequency-Domain Induced Polarization Imaging

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SUMMARY

Induced Polarization (IP) imaging datasets were collected in both time domain (TDIP) and frequency domain (FDIP) for the characterization of abandoned mine-tailings and in order to assess possible down-gradient transport of sulphide minerals. The study area is characterized by measurable iron and copper concentrations of fine-grained minerals (gain size < 1 mm), which are expected to cause a distinct IP response. This study aims at the evaluation of the applicability of TDIP and FDIP at the field scale, its capability to quantify metallic volumetric content and to discriminate between different metallic minerals. Furthermore, the analyses of water samples down gradient from the tailings have revealed significant concentrations of heavy metals, such as arsenic and mercury. Hence, imaging results of an extensive mapping campaign were used to delineate preferential flow paths of sulphides and the extensions of the contaminated volume.

Key words: frequency domain; time domain; field measurements; imaging; metallic minerals.

INTRODUCTION

There is a growing interest in the characterization of abandoned mine-tailings – on one hand, because of the possible economic value of metal-rich tailings, on the other hand, because of the need to evaluate the environmental impact due to the leaching and migration of heavy metals. Although the analysis of soil and groundwater samples provides direct information about the parameters of interest (e.g., chemical composition, concentration), such characterization is time consuming and does often not provide the required spatial resolution to evaluate the geometry and extension of mineral deposits or contaminated volumes. Furthermore, the relatively high costs of ex-situ characterization methods often render detailed site investigations prohibitively expensive. To overcome these limitations, recent studies (e.g., Jang M, 2009; Peinado et al., 2010) have suggested the use of portable X-Ray Fluorescence Spectrometry (XRFS) devices to determine *in-situ* concentrations of heavy metals and permit the assessment of extensive areas. Although promising, the XRFS technique has a limited investigation depth of a few millimetres.

Geophysical methods are well suited for collecting spatially continuous data. Given the strong induced polarization response observed in presence of electronic conductors (e.g., metallic minerals), the Induced Polarization (IP) method has been established as a standard tool for the exploration of metallic ores (e.g., Pelton et al., 1978). Recent studies have also demonstrated the capability of the IP method to assess changes in the chemical composition of groundwater (Flores Orozco 2011: 2013; Placencia-Gómez, 2014; 2015). Furthermore, petrophysical models have been suggested to quantify the grain size of metallic minerals based on the frequency dependence of the IP response (e.g. Wong, 1979).

In this study we present the application of the IP imaging method for the characterization of an abandoned mine tailing. Extensive field measurements were collected to delineate the geometry of the lithological contacts with high spatial resolution, identify zones at which metallic minerals accumulate and extend the interpretation of IP images towards the quantification of the metallic volumetric content. Measurements were collected in both frequency and time domain (FDIP and TDIP) in order to evaluate the applicability of existing petrophysical models to discriminate between metallic minerals, and to infer dominating grain sizes of the metallic minerals.

METHOD

Initial characterization of the site was done by means of frequency-domain measurements (FDIP). To minimize acquisition time and rapidly assess the main structures at the site, these measurements were collected at a single frequency (1 Hz). FDIP measurements were collected with a DAS-1 system (Multi-Phase Technologies, LLC). Based on the initial characterization, particular areas were selected for the collection of FDIP measurements over a broader frequency bandwidth (0.05 to 200 Hz). For comparison, the same profiles were re-collected in the time domain (TDIP) using a square wave form with 50% duty cycle, a pulse length of 2 s, and 35 linearly distributed IP windows. Selected TDIP profiles were also measured with a Syscal Pro (Iris Instruments) using a 2 s pulse length and 50% duty cycle, but sampling the entire wave form by means of voltage readings every 10 ms. The data were collected using multiple-gradient configurations, similar to those proposed by Dahlin and Zhou (2006). These configurations consist in potential measurements collected between electrodes located within the current dipole. In particular, we collected potential measurements using skip-0, skip-1, skip-2, skip-3 and skip-4 schemes (i.e., increasing the length of the potential dipole by increasing the number of skipped electrodes within the potential dipole). In order to use all eight channels of the DAS-1 equipment, the length of the current dipole was ten times the length of the potential dipole. For the evaluation of data error, selected profiles were also measured as normal-reciprocal pairs using a dipole-dipole configuration with dipole lengths varying from skip-0 to skip-6. Data error was quantified by means of the statistical analysis of normal-reciprocal readings as described by Flores Orozco et al. (2012a). The inversion of the data was performed with CRTomo, a smoothness-constraint algorithm by Kemna (2000). For the sake of comparability, the inversion of TDIP datasets was performed using a linear conversion of the measured integral chargeability to apparent phase values (at the fundamental frequency of 0.125 Hz), which assumes a constant-phase response (Kemna, 2000).

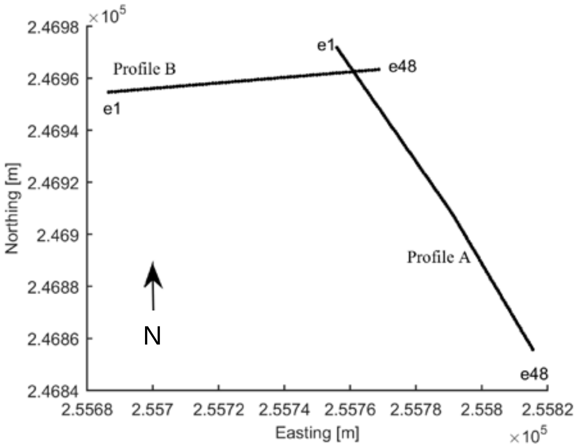

Figure 1. Orientation of the electrical profiles A and B. The position of the first (e1) and last electrode (e48) is indicated for each profile.

Here, we are presenting imaging results obtained for FDIP data collected along two transects: 1) Profile A, which starts 20 m outside of the tailings and crosses the study area from North to South. Measurements were collected with 48 electrodes with a separation of 3 m; and 2) Profile B, which is located down-gradient of the tailings, perpendicular to Profile A (from West to East), using 48 electrodes with a separation of 2 m. A schematic representation with the orientation of profiles A and B is presented in Figure 1.

RESULTS

Imaging results for FDIP data collected at 1 Hz along profile A (Figure 2) reveal three main units. 1) at the beginning of the profile, generally low resistivities (ρ) and phase shifts (ϕ) prevail; 2) between 30 and 60 m along the profile, an anomaly characterized by high resistivities (> 10^4 Ωm) and low phase shifts can be observed; and 3) an anomaly characterized by low resistivity values (< 1000 Ωm) and high polarization response ($-\phi$ > 15 mrad) appears approximately between 60 and 120 m along the profile. The electrical images presented in Figure 2 were intriguing, particularly the anomaly characterized by the extremely high electrical resistivity values. Excavations at the location of the resistive anomaly between 30 and 60 m along the profile revealed a construction waste dump that mainly consists of large rocks and bricks. This was an important finding of the exploratory campaign, as this dump is not described in any of the records of the mine and might have a strong impact on the hydrogeology of the site. However, the shallow anomaly observed between 80 and 120 m, which is also characterized by high resistivity values (~1000 Ωm), is not related to construction waste, but to fine grained sand. Collection of samples at the site revealed the presence of fine-grained metallic minerals at depth (~ 1.5 - 3 m below the surface), which explains the high polarization response ($-\phi$> 15 mrad). XRFS measurements on the sediment cores recovered from drillings at this location reported values between 2000 and 3000 ppm copper. The anomaly observed at the beginning of the profile A, characterized by low resistivity values (<100 Ωm) is likely related to the accumulation of metallic sulphides which are transported down gradient the mine tailing.

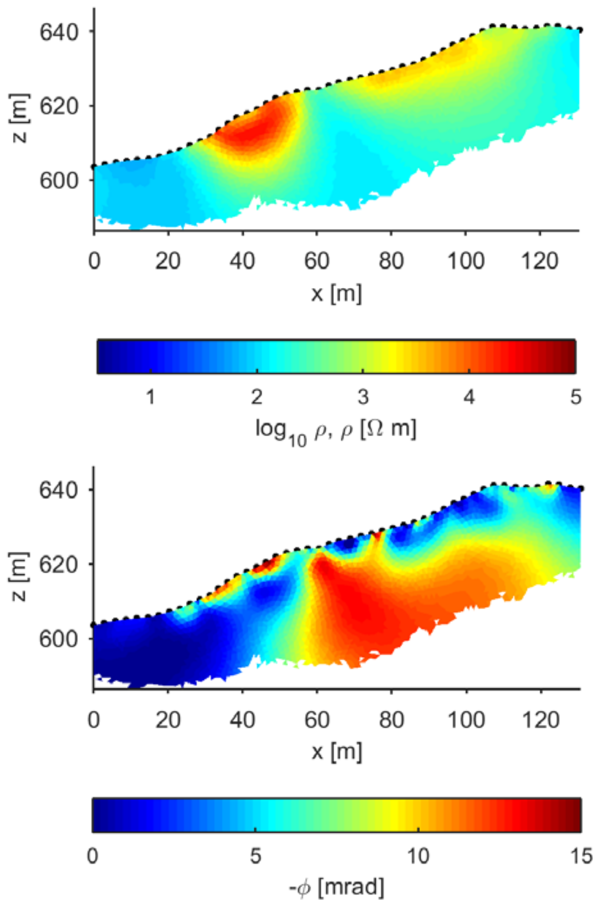

Figure 2. Electrical imaging results for FDIP data collected at 1 Hz along profile A. The complex electrical resistivity is expressed in terms of electrical resistivity (top) and phase shift (bottom). The positions of the electrodes are indicated by black dots.

To better understand the response down gradient the mine tailing and to characterize possible transport and accumulation of metallic sulphides at the foot of the mountain, extensive measurements were collected down gradient the tailings. Figure 3 shows the imaging results for data collected along profile B located in this area revealing low electrical conductivity values, which are likely related to the increase of the metallic content. XRFS measurements on recovered sediments (down to 3 m depth) revealed values varying between 1400 and 10,000 ppm copper and 2.2 ppm mercury. However, such concentrations are a consequence of the down-gradient transport of metallic sulphides. Besides the occurrence of metallic minerals in the subsurface, the low electrical resistivity values are also a consequence of the high clay content observed in collected sediments. Nonetheless, the resistivity image (Figure 3, top panel) exhibits an anomaly characterized by slightly higher resistivity values (~ 100 Ωm), which is related to sandy materials. At both edges of this resistive anomaly we also observe two anomalies characterized by high phase-shift values ($-\phi > 15$ mrad), which are correlated with an increase of the metallic content reported by XRFS measurements. Plots in Figure 3 also reveal an increase in the IP response for measurements collected at the lowest frequencies (0.25 Hz), with negligible values observed at higher frequencies (not shown here for brevity). We hypothesize that the increase of the phase shift at the lower frequencies corresponds to the presence of larger grain sizes as predicted by the model of Wong (1979).

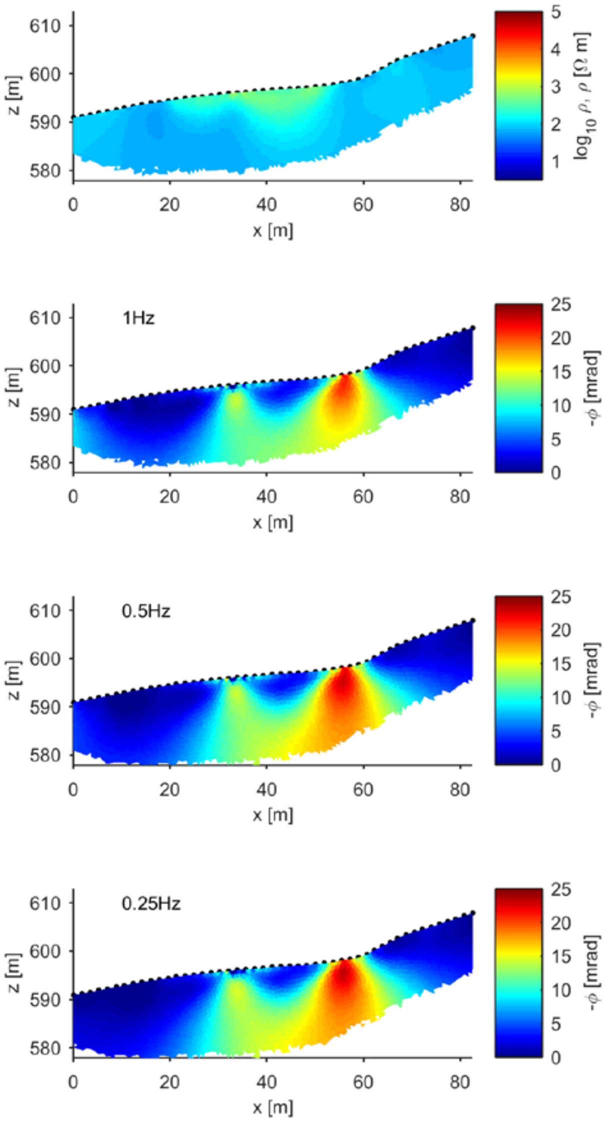

Figure 3. Electrical imaging results for FDIP data collected along profile B (located down gradient the mine tailing). The complex electrical resistivity is expressed in terms of the electrical resistivity (top) and the phase shift (the last 3 rows) for data collected at three different frequencies (1, 0.5 and 0.25 Hz). The electrode separation for the collection of the data was 2 m.

Although not presented here, the electrical images for FDIP and TDIP datasets reveal consistent results, demonstrating the robustness of the IP technique, independent from the measuring technique. Ongoing work focusses on the quantification of spectral parameters (e.g., Cole-Cole parameters) to describe the frequency dependence of the observed IP responses. We believe that maps representing the distribution of spectral parameters at the study area, and their correlation with XRFS data, will permit an improved characterization regarding the changes in the composition and grain size of the metallic minerals. Furthermore, we are planning the inversion of the extensive datasets using a full-wave form approach (e.g., Fiandaca et al., 2012) in order to extract spectral parameters also from TDIP measurements.

CONCLUSIONS

Our results confirm the potential of the IP method to characterize the occurrence of metallic minerals in the subsurface, even if the size and concentration of such minerals in mine tailings is much lower than those observed in mining exploration. However, results presented here reveal the large degree of heterogeneity typically observed on mine tailings. Although not a primary objective of the study, IP images permitted the identification of a secondary deposit associated to construction waste, linked to high electrical resistivity values. The characterization of such heterogeneities is critical to fully understand the fate and transport of metallic sulphides. For data collected at 1 Hz, the sediments at the mine tailing presented only a modest polarization response ($-\phi \sim 15$ mrad); whereas down gradient, the polarization response was larger ($-\phi > 20$ mrad), with a stronger response observed at lower frequencies (<1 Hz). This indicates transport and accumulation of metallic sulphides down gradient the mine tailings.

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