An Application of Electrical Resistivity Tomography to Investigate Heavy Metals Pathways

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ABSTRACT

The abandoned lead mine of Zeida is located at the center of the High Moulouya watershed between the Middle and the High Atlas Mountains of Morocco. Zeida has produced a total of 640,000 tons of concentrated lead during the 14 years of its activity (1972–1985). Three large tailings were left at the center of the mine on both sides of Moulouya River without any risk reduction measures or monitoring and there is a concern regarding heavy metal contamination of local groundwater. Samples taken from and around the tailings were found to contain average lead and zinc concentrations of 3,000 ppm and 140 ppm, respectively, primarily in the form of galena and barite. Prior studies have also found high concentrations of lead and zinc in both local wells near the town of Zeida and along the banks of Moulouya River. In this study, five electrical resistivity imaging surveys were performed to identify the risk of pollution and trace the pathways of mine-based contaminants to groundwater and to the Moulouya River. The analysis of electrical resistivity data has provided new insights showing: 1) an average tailings thickness of 15 m; 2) rounded structures with high resistivity values at the center and gradually decreasing toward their edges that are assumed to be granite, with fractures and a weathered zone; and 3) the potential pathways of heavy metal occur predominantly along these fractures and in the thick layers of the sandstone overlaying granitic bedrock.

Introduction

Exhausted mines usually leave behind potential hazards, especially if they are located near population center. These mines produce large amounts of residual waste, which have a negative impact on the surrounding environment. Acknowledging the risks from these sites, the government of Morocco has assigned financial support for scientific research to find solutions to these types of pollution. The research is aimed at establishing remedial actions for the hazardous mine wastes. It is clear in the legislation, Charters 11-12-13/2003 of the Moroccan mining code, that any exploitation of mineral reserves must be done with environmental protection consideration. Unfortunately, these laws are inadequate and sometimes vague.

The risk of abandoned mines resides in the presence of waste, *i.e.*, tailings with high concentrations of pollutants that can easily be eroded and transported either by wind or surface water. The abandoned mine of Zeida is a good example of tailings known to contain high levels of heavy metals. Seven heavy metals including Co, Cr, Cu, Cd, Ni, Zn and Pb were found at significantly high levels in 51 soil samples collected from various distances around the tailings (Laghlimi *et al.,* 2015). The average abundance of these metals were found in the following order Pb > Zn > Cr > Cu > Ni > Co > Cd. Zeida is located in the center of the high Moulouya watershed bounded by the Middle and High Atlas Mountains (Fig. 1). The area contains a large quantity of mining wastes, mainly from lead-based cerussite ($PbCO_3$) and galena (PbS) of supergene enrichment (Schmitt, 1976). The wastes are also rich with more inert minerals such as quartz, barite, orthoclase, and traces of illite, kaolinite, fluorite, bornite and wulfenite (Benyassine, 2015). These mining wastes were left on the surface or within large excavations as large abandoned tailing piles. Over time, the wastes were exposed to aeolian and water agents then eroded and dispersed further afield.

The mining activities in Zeida have left ten pits that are currently filled with water. Due to the climatic

 DOI: #10.2113/JEEG22.4.315

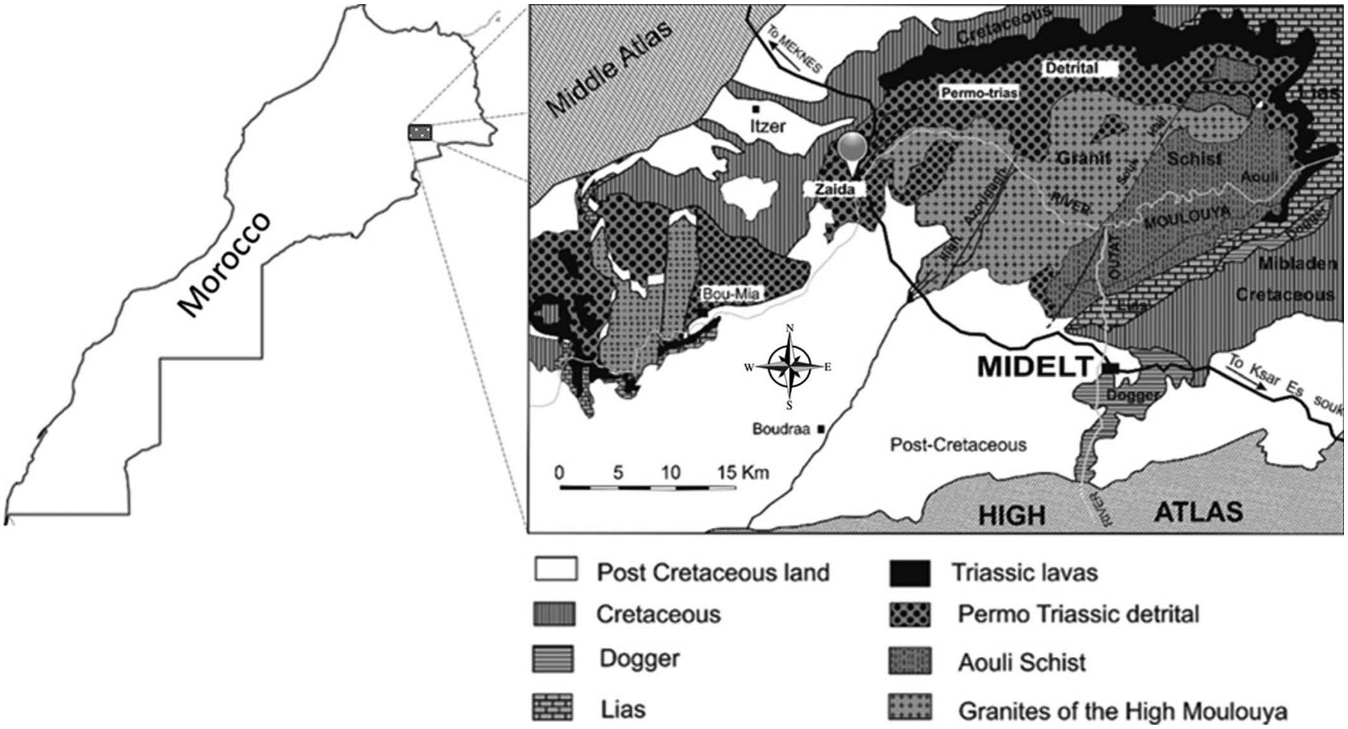

Figure 1. Site Location and local geological map.

conditions and the lack of water in the region, the water in these pit lakes is used as a source of drinking water for livestock and for irrigation. The lake water has been analyzed and found to be highly contaminated by the heavy metals (Benyassine *et al*., 2013). This contamination is triggered by mining residues through a direct effect of wind or from run-off through a network of connecting systems that link the tailings to the lakes. Two of the studied tailings, located next to Moulouya River were subjected to mass erosion and caused heavy metal contamination as far as the Mediterranean Sea (Bouabdli *et al*., 2005; Baghdad *et al*., 2009).

Geophysical exploration by the electrical method has been used by many to identify the pathways of leachate taking place in the tailings and within the sublayers carrying contaminants to nearby water bodies (Rucker *et al*., 2009; Bortnikova *et al*., 2013; Lghoul, 2014; Martínez *et al*., 2016 and 2014; Crespo *et al*., 2015; Nejeschlebová *et al*., 2015; Zarroca *et al*., 2015; El Amari *et al*., 2014; Olenchenko *et al*., 2016). Geophysical investigation methods are preferred due to their non-invasiveness and cost-effectiveness compared to other techniques such as drilling. The application of electrical resistivity tomography (ERT) to mine tailings in Kattara, near Marrakech, Morocco, and Brunita and San Cristobal in Murcia, Spain have shown to be effective with positive results regarding the assessment of mobility of heavy metals via preferential flow.

The study herein focuses on the use of ERT to detect the pathways taken by heavy metals in contaminated water from the tailings at the Zeida mine to the underlying granitic bedrock. Three large tailings have been surveyed with five electrical resistivity profiles. In addition to mapping the thickness of the tailings and their potential hydraulic connections to the granite, ERT has successfully helped identify the existence of relatively permeable areas within the uppermost layer of granite. The data were partially validated by the existence of intense fractures observed in some of the granite outcrops in this area.

Study Area

The abandoned mine of Zeida is located 26 km northwest of the town of Midelt (Fig. 1) in the center of high Moulouya watershed which extends over an area of 4,500 km^2 between the Middle and the High Atlas Mountains (Emberger, 1965). Its climate is semi-arid with an annual precipitation of 300 mm/yr and a temperature ranging between 12 and 32°C (Derrar, 1996). The mine of Zeida, which was once active between 1972 and 1985, is now a site of large tailings piles exposed to weathering. The tailings piles are in very close proximity to the Moulouya River and the village of Zeida. The village has a population of 5,000 people, according the 2014 census. In addition to the risk to the local inhabitants, the river plays a major role in mobilizing heavy metals further downstream (Boualbdali *et al*., 2005; Makhoukh *et al*., 2011). Over a period of 14 years of mining, this exploitation left behind large quantities of mining waste, represented by three large tailings having more than 10 metric tonnes (Mt) and heights exceeding 10 m (Wadjinny, 1998). These tailings are continuously discharging contaminants by means of precipitation and wind factors. Heavy metals were found in the Moulouya River and in local ponds with concentrations exceeding standard limits (El Hachimi *et al*., 2005, Bouabdli *et al*., 2005, Baghdad *et al*., 2009). Groundwater samples taken from nearby domestic wells were also found to be critically contaminated with concentration reaching 1,500 μg/L for lead and up to 1,000 μg/L for zinc (Baghdad *et al*., 2009). Soil surrounding the tailings and on the banks of the Moulouya River, where important agricultural activities are taking place, were also found to contain heavy metals (Iavazzo, 2009, 2012; El Hachimi *et al*., 2014; Benyassine, 2015).

The geology of Zeida is well known and has been widely discussed in several scientific publications (Amade, 1965; Emberger, 1965, 1968; Schmitt, 1976; Hoepffner, 1987; Dagallier, and Charoy, 1991; El Kochri *et al*., 1992; Oukemeni and Bourne, 1993;; Saadi, 1996; Filali, 1996; El Jaouani, 2001; Igmoullan, 2003; Naji, 2004). Geological descriptions of geotechnical rock cores show granite bedrock from the Hercynian belt, overlaid by arkoses, sandstones, clays, and marls of the Mesozoic Triassic period. These geological formations are fractured by faults caused by different tectonic phases and are oriented in the directions of N0° to N40°, N120° to N150°, N10° to N30°, N40° to N60°, N90° (Meju, 2000; Pagan *et al*., 2011). The mineralization of lead is observed in the form of $PbCO_3$, PbS and barite ($BaSO_4$), and found in the Triassic arkoses (Amade, 1965; Emberger, 1965). Traces of mineralization were also found within veins of other geological formations.

Electrical Resistivity Tomography

ERT was used to explore the internal structure of the tailings and the preferential pathways. It was thought that the preferential flow paths allow leachate, laden with dissolved heavy metals, to contaminate the aquifer. The ERT method has been used successfully in many cases of abandoned mines (Martínez *et al*., 2014; Martín-Crespo *et al.,* 2011; Martínez-Pagán *et al.,* 2011; Grangeia *et al.,* 2011; Martínez *et al.,* 2012; Martín-Crespo *et al.,* 2012) and tailings (*e.g*., Booterbaugh *et al*., 2015). In this study, all ERT surveys were implemented with the ABEM SAS 4000. A 64 electrode spread was used with a Wenner-Schlumberger array and either 5 or 10 m electrode spacing. Information regarding automated data acquisition can be found in Dahlin (2001).

The inversion and interpretation of the electrical resistivity profiles were aided by EarthImager (Advance Geosciences, Inc., Austin, TX), similar to that of Woodbury *et al*. (2016). The inversion program is based on the mathematical method of least squares optimization enforced by a Quasi-Newton method (Artola and Dell, 1994). The objective of the optimization is to minimize the difference between modeled and measured apparent resistivity, subject to certain constraints. This difference is captured in the root mean square (RMS) error difference between the two datasets, usually presented as a percentage. The inversion method creates a model estimate of the true resistivity of the subsurface using rectangular prisms to determine resistivity values between every two successive measurement points (Loke and Barker, 1996; Loke and Dahlin, 2002). For this work, all ERT profiles were completed with an RMS error between 2.79% and 3.72%.

Five ERT profiles (P1 through P5) were taken over the three tailings. All survey lines, with the exception of P4 were oriented NW–SE. P4 was taken orthogonally to P3 over Tailings 2 (Fig. 2(a)). Figure 2(b) is a photo of the highwall taken from the north side of Tailings 1, with position of camera cartooned in Fig 2(a). P3 and P5 were later concatenated into a single profile to include both Tailings 2 and 3 and the area in between. The concatenated profile was oriented NW–SE and covered a distance of 1,270 m. The details of the line orientation and acquisition for each tailings is presented below.

Tailings 1

Tailings 1, located west of Moulouya River, has an elliptical shape with 700 m along it major axis, 550 m along its minor axis and a height of approximately 15 m. The pile contains about 8 million Mt of waste (Wadjinny, 1998). The P1 profile was taken over a length of 640 m using 10 m electrode spacing. This profile extended from the NW side of a small decant pond located at the center of the tailings to a point located across the river on the SE. The second profile P2 was completed on the top of the tailings covering a distance of 320 m long with a 5 m spacing to acquire more internal detail regarding the tailings material.

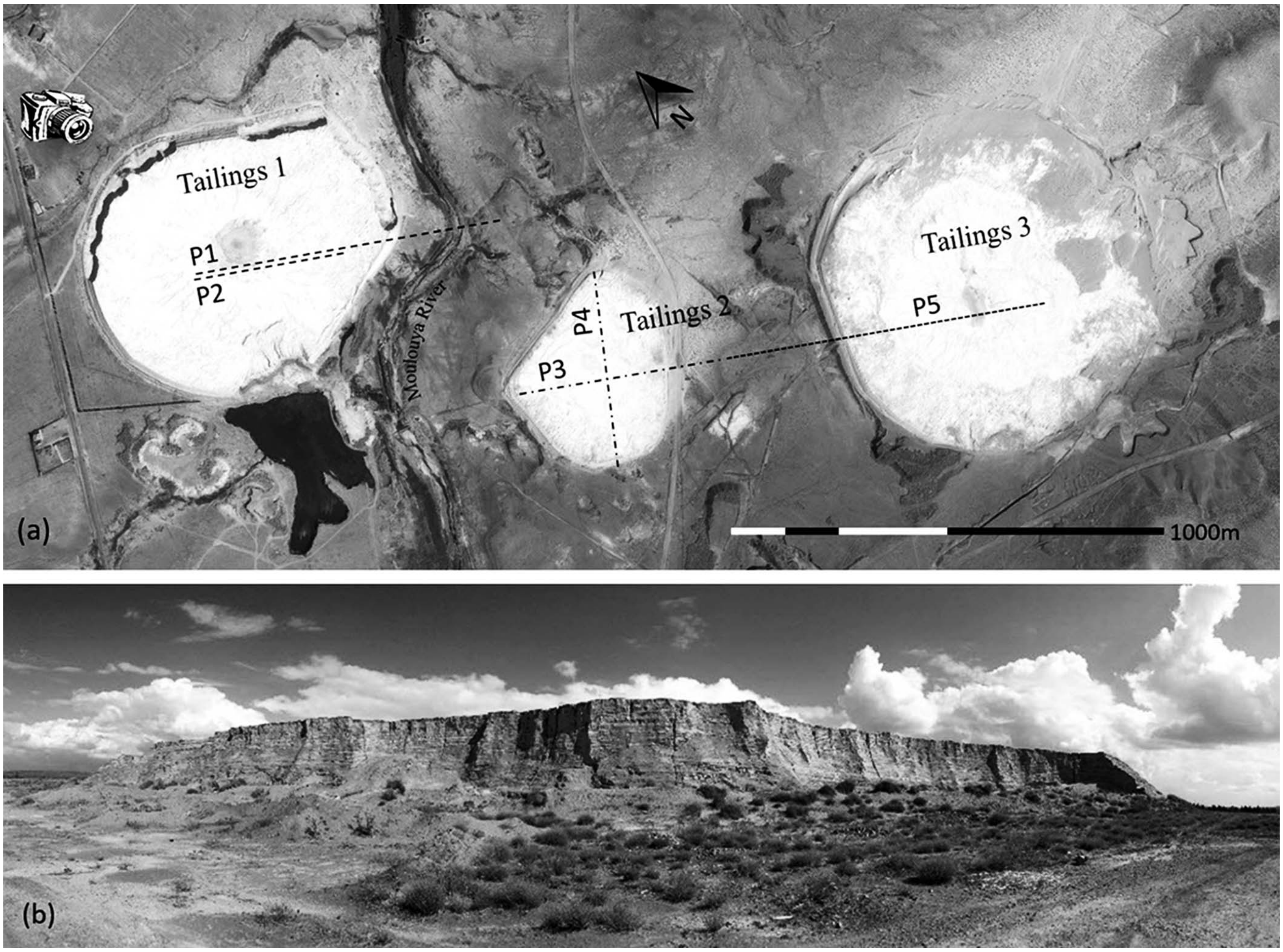

Figure 2. a) Tailings locations and layout of the five ERT surveys and b) photo of the highwall taken from the north side of Tailings 1 (with position of camera cartooned in Fig. 2(a)).

Tailings 2

Tailings 2 with an estimated waste load of 4 million Mt (Wadjinny, 1998) is located on the east shore at 250 m from Moulouya River. Geometrically, it has a rectangular shape with approximately 470 m long by 460 m wide and 8 m height. Two survey lines were taken over this tailings, P3 was taken along the NW–SE over 790 m using a roll-along method where the first segment of the multi-core cable was moved from the NW side to the SE. Line P4 was taken diagonally across P3 over a distance of 640 m along the NE–SW.

Tailings 3

Tailings 3 is located 1km to the east of Moulouya River. It has a rounded shape of 750 m in diameter and about 10 m deep. It is spread over an area of 50 ha and has an estimated load of 10 million Mt. Line P5 was taken along the NW–SE extending P3 to greater range. The two profiles P3 and P5 were concatenated to create a 1,270 m survey line comprising Tailings 2 and 3 and the native area between the tailings (Fig. 2a).

Results

From the five ERT profiles, we obtained information about the depth of the tailings, their relationship to the granitic bedrock, and how fractures are taking part in moving contamination from the tailings to the groundwater and eventually to the river. All ERT profiles showed low resistivity values in areas corresponding to the tailings and the fracture zones. Fractures found in this area were either closely joined or filled with grinding materials. Historically geophysical investigations by the Bureau of Research and Mining Participations (BRPM) in 1988 have shown that fractures are likely filled with surficial material originating from

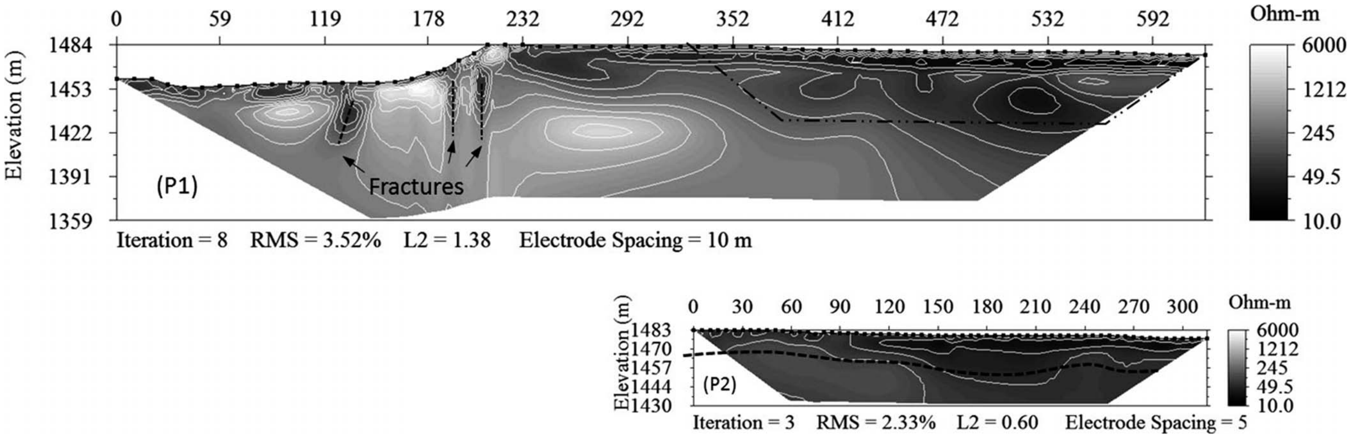

Figure 3. Electrical Resistivity Tomography of transect P1 (top) and P2 (bottom) taken over Tailings 1.

arkoses, sandstone, and clay above or found in the vicinity of these fractures. It is through these joints, filled with erosion materials, that water laden with heavy metals percolates to reach the aquifer. In general, the ERT showed low resistivity areas extending downward beyond the tailings-bedrock interface which almost certainly represent the fractures buried beneath the tailings.

Tailings 1

Figure 3 shows low resistivity material, generally lower than 180 ohm-m, toward the NW side of P1, which is the left side of the plot. This low resistivity material corresponds to the mine waste deposit with a depth reaching 20 m. The existence of very low resistivity areas (less than 50 ohm-m) in P1 and P2 indicate a strong infiltration of low resistivity leachate origination from the mine waste. The low resistivity leachate is symptomatic of ionic constituents in the water, resulting in high total dissolved solids. In certain areas, these low resistivity zones can extend downward to 50 m below the ground surface. Line P1 showed a clear boundary between the mine waste and the basal surface of the tailings. Below this section, the granite formation is recognized by its relatively high resistivity values (resistivity greater than 1,000 ohm-m). Between the Moulouya River and the tailings, the high resistivity granite was marked by multiple discontinuities, separated by sub-vertical structure features that possibly represent fractures in the rock; the fractures are noticeable by their low resistivity values. These areas, marked by changes of low to high resistivity values, were likely caused by the weathering of granite and the filling of the vertical fractures.

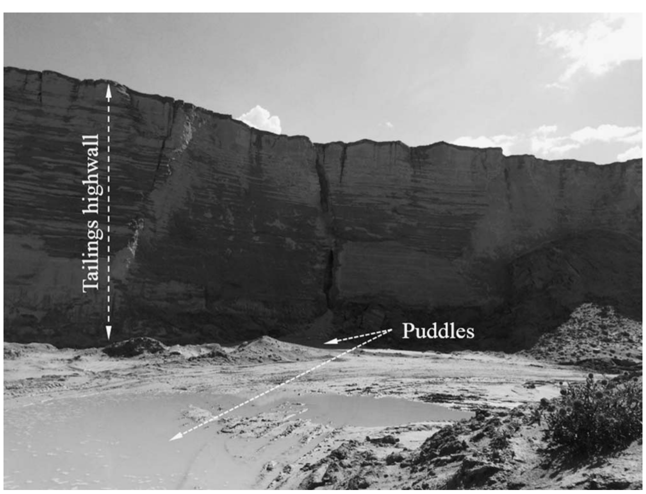

Figure 4. A photo of the highwall of the north side of Tailings 1 (with position of camera cartooned in Fig. 2(a)).

For a better understanding of the upper part of P1, a second ERT profile was acquired over a 320 m distance with 5 m electrode spacing. The aim of P2 was to acquire more details on the internal structure of P1, with an overlap starting around 312 m and extending to the northwestern end of the P1 line. This profile acquired data below the tailings-bedrock interface and showed low resistivity values that ranged between 23 and 185 ohm-m. There appears to be a dip in the resistivity structure, towards the northwest, that we hypothesize to control flow of leachate in that direction. The existence of multiple puddles along the north boundary of this tailings pile is evidence of the flow taking place within and along the base of the tailings. The photo in Fig. 4 shows the tailings highwall on the northwest side of Tailings 1, with puddles at the base. The puddles become more prevalent during precipitation events as more run-off and additional recharge through the tailing occurs.

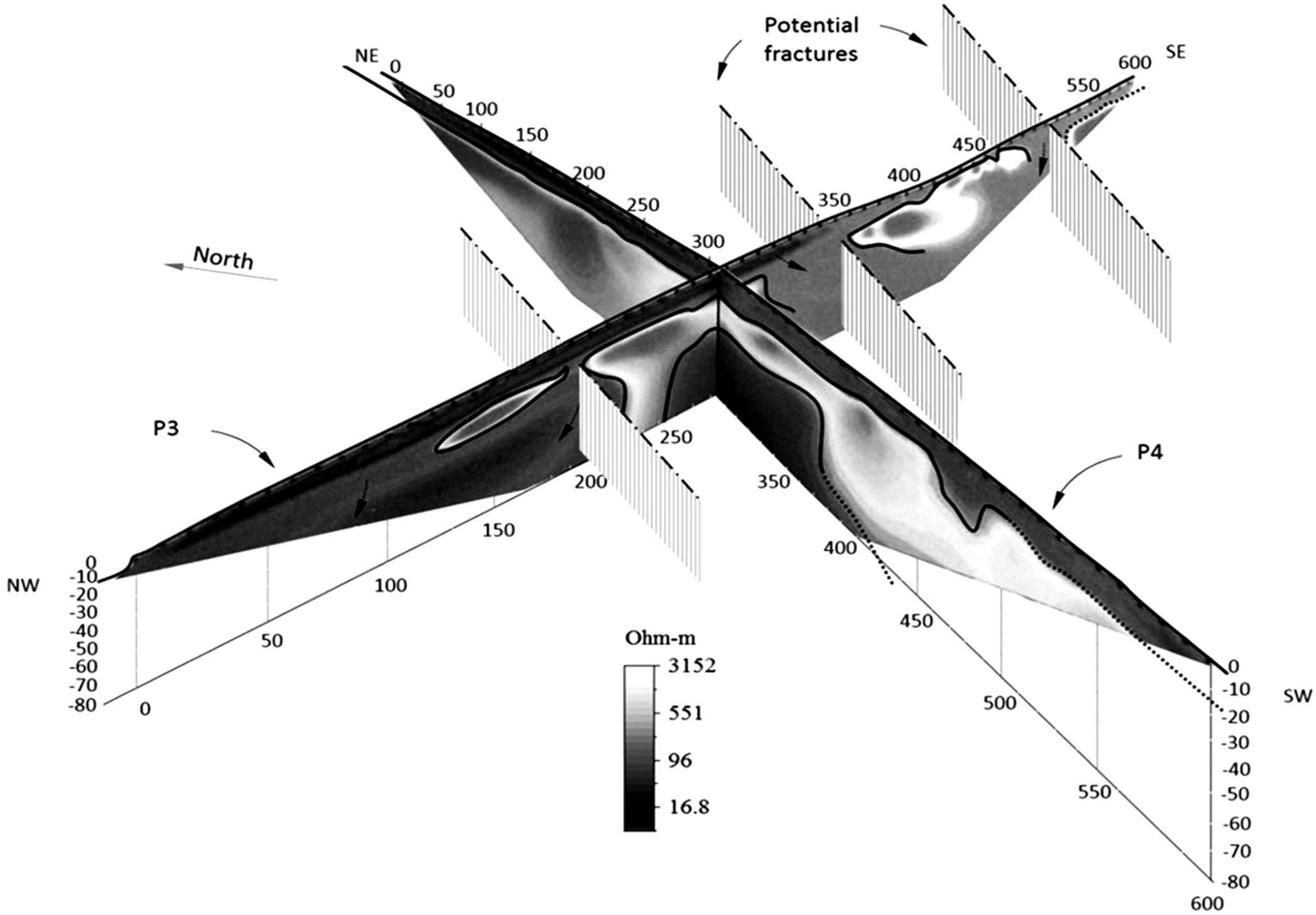

Figure 5. Fence diagram illustrating the results of P3 and P4 taken orthogonally over Tailings 2. Potential fractures are shown, based on the geological interpretations of nearby outcrops.

Tailings 2

Two ERT profiles P3 and P4 were acquired near the center of Tailings 2. The lines were taken orthogonally to each other with their intersecting point at the mid-point of the two survey lines. Figure 5 shows the ERT results as a fence diagram, which helps to display the continuity of features in both lines. The fence diagram shows that the tailings have been deposited on a relatively flat surface and the infiltration was potentially caused by the existence of fractures with a strike perpendicular to P3. In several places, these fractures outcrop at the surface in the vicinity of the three tailings, which allow us to estimate their orientation at N30°, N40°, and N60°.

P3 showed very similar features as in Tailings 1. The upper material within P3 was characterized by low resistivity values corresponding to the mining waste, with resistivity values generally lower than 300 ohm-m. The geological formations below the tailings pile comprise of conglomerates, reds beds, marl, and arkoses above altered granite bedrock and were characterized by higher resistivity values greater than ohm-m. Below these formations, the ERT profile showed intermittent areas of low resistivity (<80 ohm-m) extending downward into the granite most likely due to heavily fractured rock that allowed contaminants to reach groundwater. The black arrows within P3 represent these sub-vertical fractures that can sometimes exceed 50 m in depth. Within the geophysical section, it appears that the fractures create blocks characterized by high resistivity values separated by low resistivity zones where polluted water can flow into the aquifer (Martinez *et al.*, 2012). P4 also shows a surface layer of low resistivity (<100 ohm-m) which represents the tailings material. The deeper portion of P4 is shown to have higher resistivity values without the discrete blocks observed in other lines. The absence of clear fracturing in P4 is likely due to the line being parallel to the fracture planes.

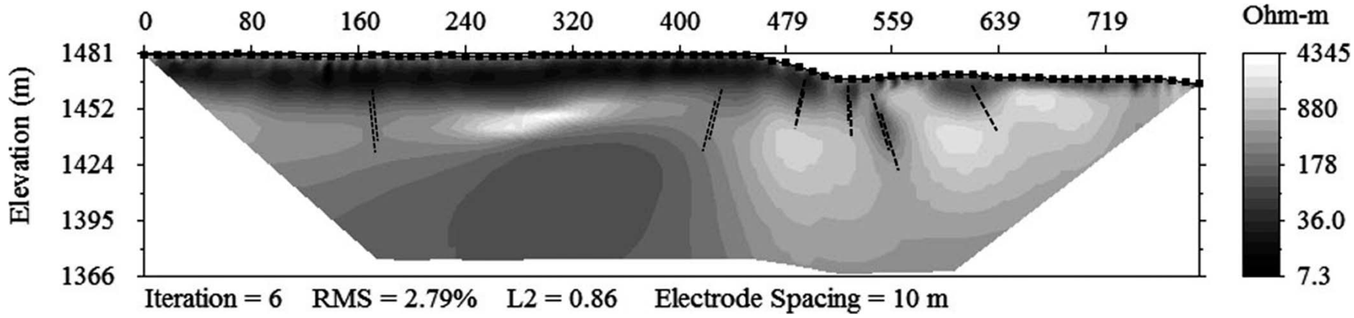

Figure 6. Electrical Resistivity Tomography of P5 taken over part of Tailings 3 and extension towards the northwest.

Tailings 3

Two approaches of explorations were performed in this area: 1) P5 survey extending over 790 m was taken from the center of Tailings 3 to a point halfway between Tailings 2 and 3, and 2) a concatenation of P3 and P5 into a single profile crossing both Tailings 2 and 3 and the area in between. The concatenated profile was oriented NW-SE and extends over 1,270 m.

In addition to the information on the geometry of the tailings, P5 showed the existence of semicircular lobes separated by contracted low resistivity area (dashed lines in Figs. 6 and 7). This alternating pattern

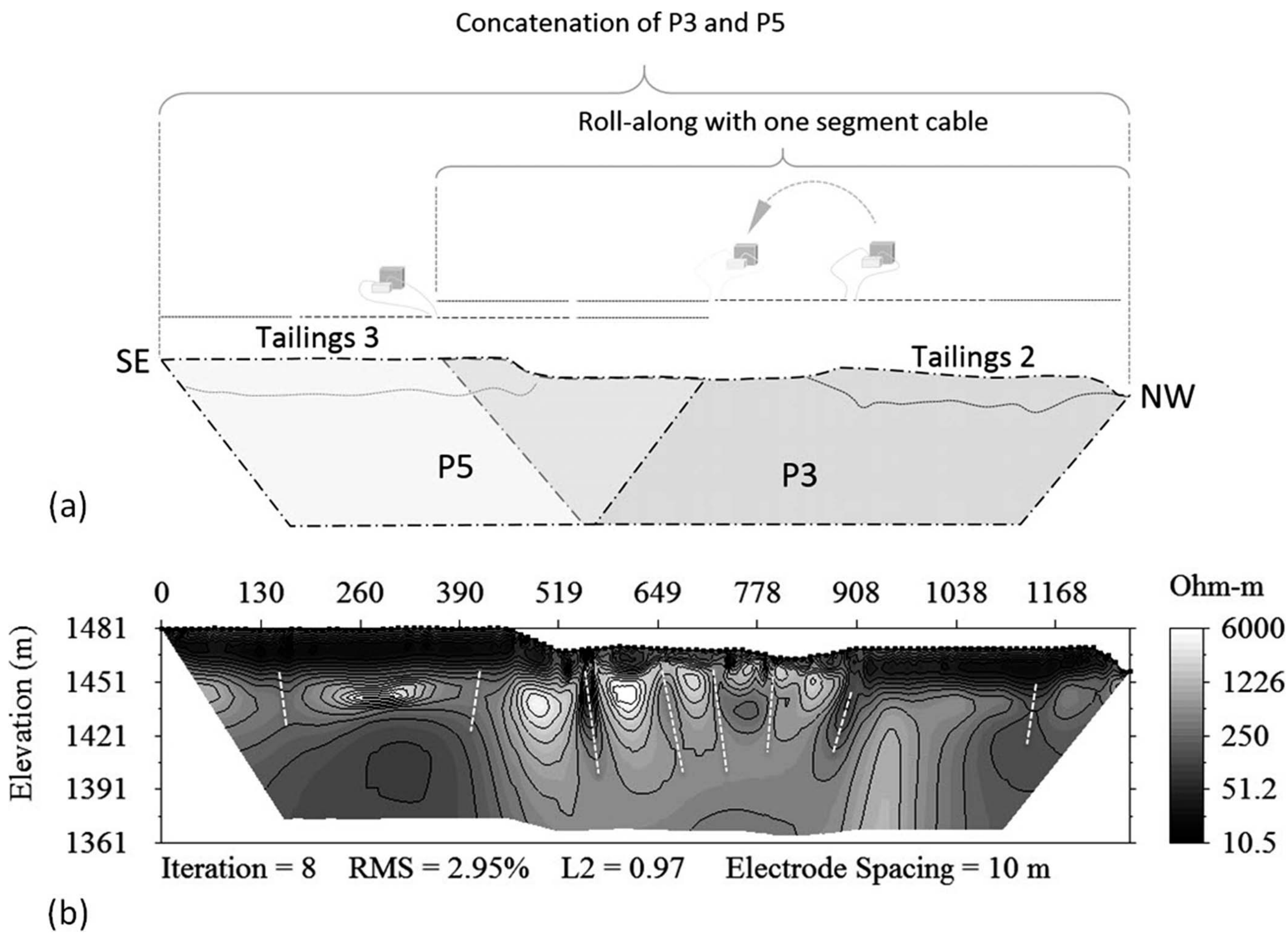

Figure 7. Electrical Resistivity Tomography profile based on the concatenation of lines P3 and P5 taken over Tailings 2 and 3 and the area in between: a) schematic of how the data were concatenated, b) results of the 1,270 m line oriented from southeast to northwest.

in resistivity values was clearly visible along the section between 470 m and 650 m of P5. These fractures are most probably serving as pathways of water laden with dissolved heavy metals to contaminate groundwater. Based on the records, Tailings 3 were deposited in an excavated pit making the contamination take place perhaps at faster rate due to the direct contact of the tailings on the granite.

Water ponds seeing over the tailings, forms after rain events and often persist over an extended period of time provide continuous seepage keeping the tailings saturated. As a result, the identification of fractures directly below the tailings can be hindered when using the electrical resistivity method due to the existence of highly saturated zone, especially at the base of the tailings. Fractures are much easier depicted in P5 between 480 m and 790 m due to the absence of tailing's deposit, while directly beneath the tailings the fractures seem to be missing due to the highly conductive tailing's material.

The P3–P5 profile was obtained by concatenating P3 and P5 to cover a 1,270 m transect to better visualize the existence of fractures along this survey line (Fig. 7). This profile showed that the electrical resistivity has easily identified the presence of fractures beneath the unaltered area between the two tailings yet seemed challenging directly below the conductive tailings material. It has been shown that when a large low resistivity body exists near the surface, it tends to create a shadow zone, where the meaning of resistivity profiles becomes difficult (Loke, 1999). P3–P5 was successful in showing the fractures in the area between the two tailings, yet difficult to identify the fractures directly below the tailings.

Conclusion

Five ERT profiles were acquired over a set of three tailings piles in northeastern Morocco. The ERT profiles showed that all tailings were characterized by low resistivity, typically less than 90 ohm-m, and have a thickness varying between 10 and 20 m. Additionally, all ERT profiles showed that the granite blocks were either adjacent to or separated from the tailing by a Triassic formation. The low resistivity is caused by the presence of water in these tailings. The persistence of moisture in the tailings over an extended period of time is caused by the low hydraulic conductivity of the sublayers and the existence of ponds supplying water gradually beyond the rain events. It is this saturation that makes the identification of what is directly beneath the tailings challenging. While it was difficult for the ERT to reveal the existence of fractures directly beneath the tailings, it has clearly identified them between the two tailings. These fractures range between 30 to 60 m in depth from one location to another. The ERT profiles also showed that fractures (identified as low resistivity areas) serve as funnels, allowing contaminants to preferentially flow towards groundwater and eventually to Moulouya River. Earlier studies have shown the existence of high concentrations of lead and zinc in local wells and in water samples from Moulouya River (Bouabdli *et al*., 2005; Baghdad *et al*., 2009). The ERT provided a mechanism to bridge the information gap in establishing a path from tailings to river

Acknowledgment

We would like to thank the National Center for Scientific Research and Techniques (CNRST-Rabat, Morocco) for funding this research project.

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