Geophysical and Structural Survey in the Diagnosis of Leaks at a Fuel Station in a Uranium Mine in Decommissioning Phase (Poços de Caldas, Brazil)

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Abstract

Mining enterprises are in essence, landscape modifiers and sources of long-term environmental degradation. The development of activities within the mines requires a complex logistical system for better functioning. It is common to have gas stations in the vicinity of mining areas as a support for supplying vehicles and machines. Inadequate operation and the absence of monitoring, as well as a planned closure of the activities of these stations, may impose risks of contamination of the geological environment. This work presents the efficiency of using Electrical Resistivity Tomography to map aged hydrocarbon in subsurface in a former gas station area in a uranium mine. The presence and flow of hydrocarbons in the geological environment are also investigated through structural analysis of the area integrated with the geophysical results. The ERT results show a clear connection between the low resistivity anomalies contained in the subsoil with the presence of the rock mass. It was particularly interesting the ability of ERT results to model the fractures contained in the subsoil and that condition a certain flow orientation between porous and fractured systems. The integrated analysis of geophysical and structural survey proofed to be essential in cases of fracture aquifers contamination.

Introduction

Humanity has always sought for new sources of minerals to provide their needs. However, after the Industrial Revolution and the demand for metallic mineral inputs, theoretical knowledge was massively used in the creation of industrial production of equipment and processes. Since then, the demand for minerals has been growing significantly and accompanying social and technological changes and population growth (Chatterjee 2007; Richards 2009).

The discovery of mineral deposits is a high-risk economic activity due essentially to the complexity of the geological environment and the high scarcity of mineral accumulations of economic value. This initial phase is called Mineral Research, which aggregates activities such as geological mapping, geochemical and geophysical prospecting (Govett 2000; Moon et al. 2006; Dentith and Mudge 2014).

Mining is basically an economic activity on an industrial scale that involves the extraction of ores, processing and concentration of minerals or chemical compounds that are required by activities such as steel, metallurgy, chemical and pharmaceutical industries, energy sectors, civil construction, among others.

A mining enterprise is planned mainly based on variables such as resource and reserve size, extraction costs, supply and demand for products and variations in the sale price (Aalst 2016; Dhillon 2008). However, loading and transport equipment, beneficiation plant and tailings disposal areas are designed for decades of operation. Energy is the main operating cost in this type of industry, whether with diesel in charging and transport equipment or electricity in beneficiation plants (Hudson et al. 1999; Dhillon 2008).

Given the scale and time of operation, it is common in mining companies to have fuel filling stations, an operational support area often converted into an environmental liability, due to the lack of maintenance during its operation and abandonment during the decommissioning and closing phase (Hudson et al. 1999; Dhillon 2008). Factors such as depletion of the deposit, emergence or cheaper alternative materials, new technologies or industrial processes or excess supply for long periods, are factors that justify the closure of a mine on a temporary or permanent basis. This phase imply costs in a period in which profitability will be falling, in addition to environmental issues related to impacts related to mining areas, ore treatment and waste (Moon et al. 2006).

That final closing phase is called decommissioning and basically aims the sale of usable equipment or scrap of machinery or equipment, in addition to the geotechnical and environmental stabilization of mining areas, dams, tailings and waste dumps ((Dhillon 2008; Aalst 2016).

This work consists of a detailed geophysical study at a gasoline and diesel filling station, located in a complex for the extraction and processing of uranium in the decommissioning phase. The operational history reveals the potential for fuel leakage from buried tanks. The geological environment composed of little expressive soil layer and shallow rock indicates flow conditions in a porous and fractured system. Such conditions imply a real challenge to the environmental diagnosis, mainly, using direct techniques such as monitoring wells (Hudson et al. 1999; Knödel et al. 2007).

Study area

The site consists of a fuel filling station located at the Brazilian Nuclear Industries Mineral Processing Unit (INB), located in the municipality of Caldas, State of Minas Gerais, southeastern Brazil, with an area of 15 km² (Figure 1).

Figure 1 – *Location of study area with emphasis to the fuel station.*

This mining represents the first uranium concentrate production center in Brazil (Nascimento 1998). The main facilities of the complex include the mine pit, areas of waste piles and mine pickling material, physical processing plant, chemical processing plant for uranium extraction, tailings basin, abandoned fuel station and administrative and operational support buildings (Fernandes et al. 1996).

The gas station under study consists of one of the environmental liabilities abandoned due to the definitive cessation of mining and processing activities in 1994. The structure installed during the construction phase in 1971 remains intact, represented by two sets of buried pumps and diesel and gasoline tanks.

Method

The analysis of the operational history and the geological / hydrogeological context served to plan a detailed geophysical study using the Electrical Resistivity Tomography method, in 10 lines parallel profiles oriented in the E/W direction (Figure 2). Nine lines were positioned on the area of influence of the filling station and an additional line for resistivity in clean soil, called Reference line, was 12m away from line 1 and positioned upstream of the terrain. It was adopted 2m spacing between metal electrodes, 3m spacing between lines 1-2, 2-3 and 3-4, and 4m spacing between lines 4-5, 5-6, 6-7, 7-8 and 8 -9. Each line was limited to 40m in length, through which electrical resistivity measurements were made.

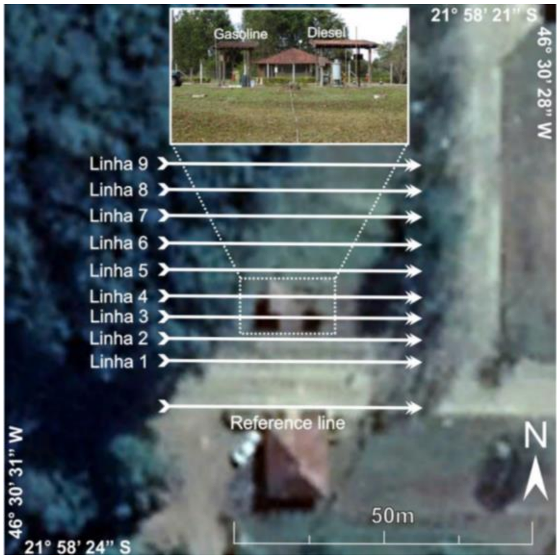

Figure 2 - *Arrangement of ERT lines in the study area.*

The resistivity meter used was an ABEM Terrameter LS, which consists in automatic and programmable single transmission/reception module of the 250W with the capacity to acquire Spontaneous Potential (SP), DC resistivity (ER) and Induced Polarization (IP) field data (Figure 3).

Figure 3 - *Scheme for preparing the geophysical survey. A) Demarcation of the lines, B) Fixation of the metal electrodes. C) Assembly of the reference line (upstream), D) Acquisition lines in front of the supply pumps, E) Acquisition lines downstream of the filling station, F) Equipment with previous result.*

The survey acquisition parameters were: injected current = 200mA; injection time = 2s, with the adoption of a ceiling of 3% of maximum standard deviation in relation to the average of measured values. These parameters were fixed after preliminary tests in the field, for verification and analysis of disturbances as power lines, telluric noise, EM coupling, among other. The Schlumberger array was chosen due to its sensibility to identify horizontal and vertical structures and its high sampling density (Milson 2003; Mussett e Khan 2000).

Res2Dinv Software 3.53 version (Geomotosoft, 2014) was used for data processing, considering topographic variations. The software interpolates and invert field data according to the mathematical model of ordinary least squares (OLS) in order to smooth extreme values (Loke & Barker 1996; Loke 2010; Bania & Cwiklik 2013). Then, provides inversion models that are represented as 2D colored sections with a chromatic logarithmic scale range. Finally, 3D models were produced using the Oasis Montaj Platform (Geomotosoft, 2014), where data sheets from the inversion models were uploaded and interpolated based on the kriging and minimum curvature methods in order to smooth the extreme values and to reduce differences between the measured and modeled parameters. The 3D models provided conditions for a better understanding of geological structures and complex hydrogeological systems, like spreading patterns of contamination plumes and geometry of ore deposits (Aizebeokhai et al. 2011; Moreira et al. 2016; Casagrande et al. 2018; Helene et al. 2020; Moreira et al. 2020).

Structural analysis was divided into two steps, according to Targa et al. (2019). The first one consisted of extraction of structural features at regional scale from aerial images of Google Earth Pro, which were digitalized by ArcGis 10.3 software (2014). This product allowed the identification of regional discontinuity trends and a possible correlation with local structural setting. In a second moment, a geological recognition was performed to describe materials in the mine pit, with emphasis on controlling structures by fractures in soil, saprolite and rock.

Results

The interpretation of geophysical data in environmental studies must consider the history of the area, the characteristics of the environment and the behavior of hydrocarbons in the shallow geological environment.

The characterization of the natural environment occurred by a reference ERT line, upstream of the station, which presents the natural conditions of electrical resistivity for the location (Figure 4). In this sense, values below the natural minimum (77.6 Ω.m) are considered as places affected by the presence of hydrocarbons or by-products of their degradation.

In lines 1, 2 and 3, located near the fuel station, the vertical variation of resistivity defines the layer of dry to partially saturated soil (between elevations 1334m and 1331m) and the underlying geological material (Figure 4). Resistivity zones below the natural minimum indicate the possible presence of hydrocarbons in an advanced stage of degradation present in the most superficial portion of the soil. Specifically, on line 3, in the position of the gas tank, between 8m and 16m, the areas of low resistivity reach greater depths (1329m) and greater coverage. In line 4, the low resistivity values are restricted to the position of the diesel tank, apparently dissolved in water, in continuity with line 3. From the resistivity pattern of line 5, located further downstream, the high resistivity of the rock in depth it is no longer visible, assuming low resistivity values, which seems to represent a migration of hydrocarbon downstream.

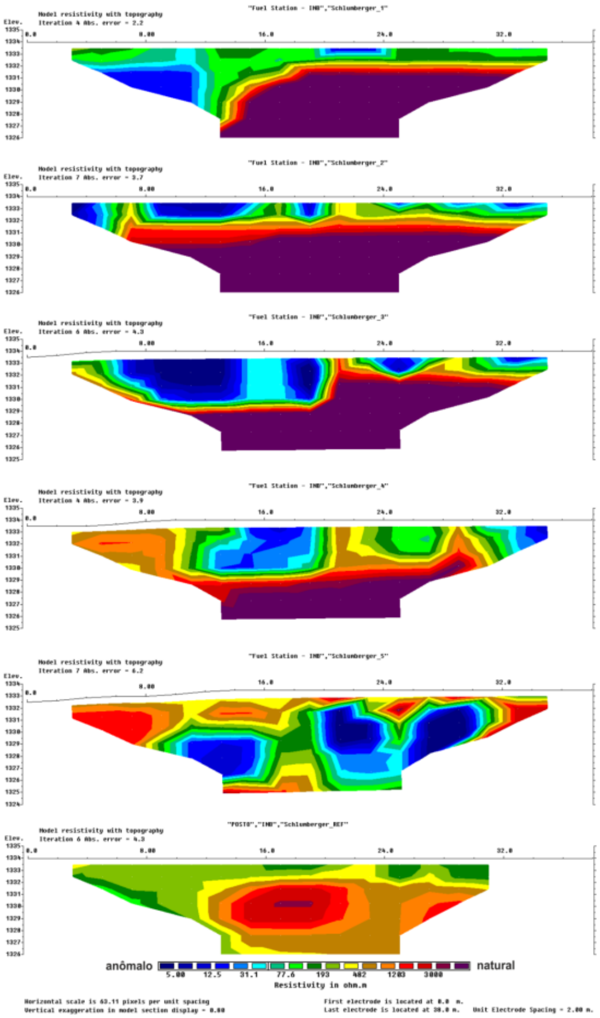

Figure 4 – *2D inversion model of resistivity for lines 1 to 5 and reference.*

Line 6 contains a wide zone of low resistivity in depth and in connection with the low resistivity zone of line 5. The apparent flow downstream is less visible in lines 7, 8 and 9, with resistivity values are close to natural (Figure 5).

To understand the infiltration and flow paths of hydrocarbons in the geological environment, the 3D visualization model is analyzed in perspectives and integrated with the position of the gas station and buried gas tank. It was modelled a volume of geological material with electrical resistivity lower than the natural pattern of the study area (30Ω.m), which possibly describes a material saturated with hydrocarbons in an advanced state of degradation (Figure 6).

The gasoline and diesel tanks are positioned exactly on the largest volume modeled of low resistivity. In contrast, the various volumes of low resistivity positioned close to the surface are located immediately below the filling station. Apparently, these two structures contributed to the percolation of hydrocarbons in the geological substrate.

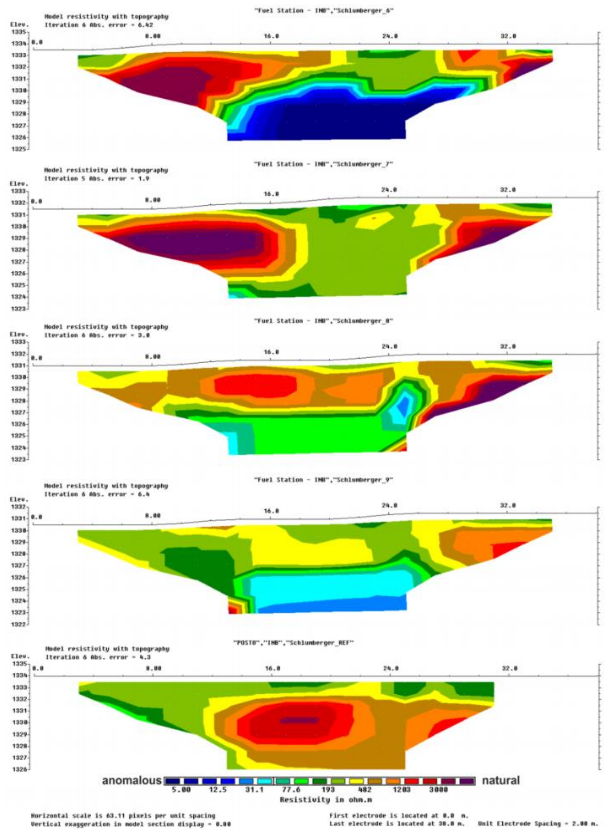

Figure 5 – *2D inversion model of resistivity for lines 6 to 9 and reference.*

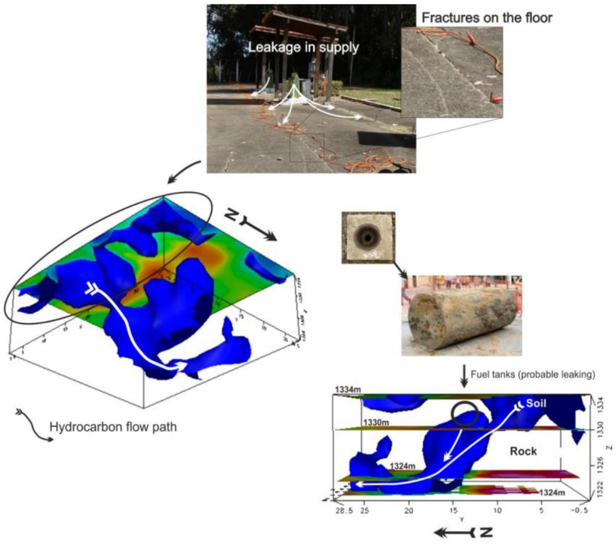

Figure 6 – *A) Fractures on the floor indication infiltration zones; B) Direction of contaminant flow in soil 350 and rock; C) Point of leakage in depth.*

Accidents related to carelessness during refueling often result in small spills. The supply system of the area under study does not have automatic disarming by a full tank detection sensor, that is, the pump was turned off manually by visual recognition. It is possible that small volumes spilled recurrently in more than 20 years of operation have infiltrated through the fractures in the pavement and reached the local soil.

The base of the underground tanks was positioned at the maximum depth that could be excavated by backhoe, limited to the interface between soil and rock, recognized in the 2D inversion models of lines 3 and 4 at a depth of 4m. Thus, any fuel leaked from the buried tanks could flow through the interior of the fractured rock mass in vertical flow by the action of gravity. The finding of the presence of diesel in one of the tanks, in addition to the strong oxidation at the end of the supply well and absence of fuel in the other tank, are elements that indicate that the leaked hydrocarbon is probably gasoline (Figure 2).

The oxygen renewal was of great significance to accelerate the natural attenuation processes. In this sense, the advanced degree of degradation provides greater generation of by-products (ions), with a consequent drop in the values of electrical resistivity in relation to natural values. However, in the absence of chemical analysis of soil or groundwater, the geophysical evidence clearly suggests the existence of hydrocarbons in the residual phase and possibly in an advanced state of degradation.

The support of geological descriptions and previous structural survey described in Targa et al. (2019) were fundamental in understanding the spatial distribution of hydrocarbons in the geological environment. The local geological substrate has up to 4m of soil above a fractured rock, both recognized in the pit of the mine, once there are no exposures in the vicinity of the filling station. The strong structural control in the drainage system in the Poços de Caldas alkaline complex is also expressed in a local context (Figure 7).

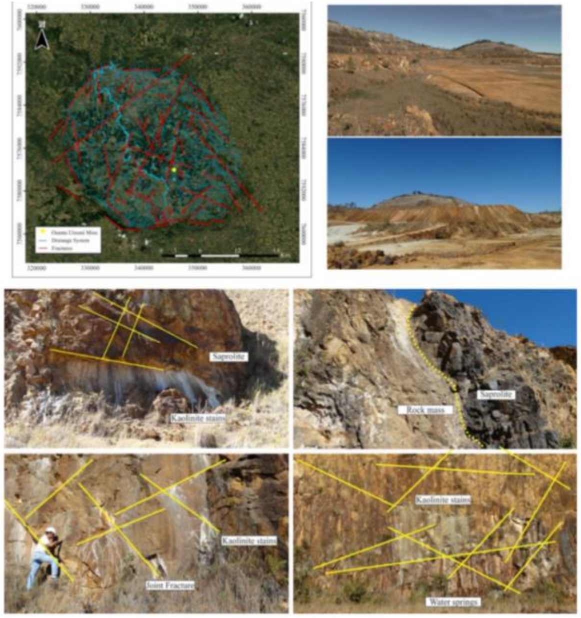

Figure 7 – *Regional structural context from satellite image, panoramic view of the mine pit and geological detail on mining fronts.*

The low resistivity volumes modeled in a fractured system as well as the connection between porous (soil) and fractured (rock) systems are clearly aligned and possibly controlled by pre-existing fracture systems when installing the filling station (Figure 8). The geological and structural recognition revealed that the soil and saprolite resulting from processes of alteration of the rock mass, preserve structures such as faults and fractures. The different perspectives of visualization of the 3D model reveal an oriented connection between the areas of low resistivity contained in the ground with the area of the interior of the rock mass. It is quite likely that there is some flow in relic fractures contained in the soil and that condition a certain flow orientation between porous and fractured systems.

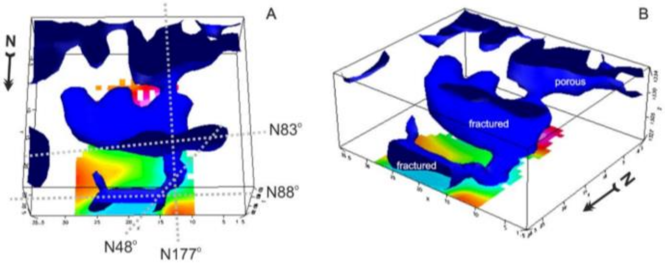

Figure 8 – *A) Structural orientation of preferred hydrocarbon flow paths. B) Scheme of local aquifer systems.*

Conclusions

The results demonstrate the versatility of detailed geophysical studies in the preliminary diagnosis of areas with suspected hydrocarbon leakage to the geological environment. This type of investigation must be preceded by a history of occupation of the area and the chemical compounds involved, fundamental information for programming the level of detail and selection of the recommended geophysical method. The types of hydrocarbons involved, and the age of the project are indications of the advanced state of alteration of products eventually leaked to the geological environment. Several studies reveal the great contrast of electrical properties between the natural environment and areas with degraded hydrocarbons, information that justified the use of the DC resistivity method. A fuel supply installation with metallic storage tanks buried in 1971, in a country with a tropical climate like Brazil, is hardly able to maintain the tightness and integrity of the system for more than 20 years. The fuel level inspection revealed strong oxidation in the access pit to the gas tank, in addition to the surprising existence of diesel in its respective tank. Previous studies related to the hydrogeological flow in the mine pit revealed that the region has soil limited to a few meters in thickness and a complex network of fractures, with significant continuity and great importance in maintaining flow in the local and regional drainage network.

In view of the clear possibility of the flow of hydrocarbons eventually leaked, to positions below the soil layer and inside fractured systems, a highly detailed network in electrical tomography lines was proposed. This decision was quite assertive and enabled a robust set of electrical resistivity measures that provided the development of 3D visualization models and a sense of architectural areas with a probable presence of leaking hydrocarbons. The 3D modeling analyzed together with technical information on the operation of the station, construction of the pavement and the position of the buried tanks, made it possible to trace the hydrocarbon infiltration routes. Both the surface supply and the buried gas tank were potential sources for the modeled low resistivity volume and associated with the existence of hydrocarbons and an advanced state of degradation. The identification of totally different flow systems (porous and fractured) in a relatively small area and in a shallow position, coupled with the modeling of areas with a high potential for the presence of hydrocarbons, allow planning of verification actions through soil samples and groundwater directly and objectively. This set of information should also support the planning of extraction systems or in situ consumption of hydrocarbons, in view of the need for remediation of the area in the context of decommissioning of the mining complex.

Acknowledgments

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