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Geophysical investigation using the GPR method: a case study on the contamination of lead in the Santo Amaro town, Bahia, Brazil

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Abstract

In Brazil, until the 1970s, industrial and urban waste was directly disposed of in the soil, as it was believed that the soil was an unlimited receptor for disposable and noxious substances. However, this capability was overestimated, causing irreparable damage to the environment. Geophysics has been shown to be effective in identifying areas contaminated by waste disposal, contributing to the greater efficiency of soundings programs and the installation of monitoring wells. In this work we have evaluated the potential of the Ground Penetrating Radar (GPR) method in the characterization of a hazardous waste site generated by the lead ore processing, where the slag resulting from this process was used to pave streets and backyard residences in the town of Santo Amaro, state of Bahia, situated on the domain of the massapê soil. The used method enabled the identification of geophysical anomalies, which characterized the presence of contamination from slag material. It was also possible to define the interface between the paving and the soil-slag, as well as the interface between the soil-slag and the massapê soil. Chemical analysis of the soil confirmed the contamination, with high concentrations of lead found in at least three drill holes. The geophysical method used in the investigation provided an excellent tool for environmental characterization of the area, and could be applied in the study of similar areas elsewhere.

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1. Introduction

The town of Santo Amaro, in the state of Bahia, Brazil, presents a history of contamination, mainly by lead (Pb), originating from the intense activity of metallurgical extraction by the mining company “Plumbum-Mineração e Metalurgia Ltda.” between the years of 1956 and 1993. It should be noted that the lead slag was deposited carelessly in the factory area, creating a huge hazardous waste site. Subsequently, the problem increased when this slag was used as the basis for the paving of city streets, gardens and school yards due to its granular characteristic and good support capacity. However, the ongoing need to remove the street paving for work on the water and sewage networks requires the exposure of the slag, making it a source of active contamination.

The “Companhia de Tecnologia de Saneamento Ambiental de São Paulo - CETESB” recommends geophysical surveys for the diagnosis of the contaminated areas. The purpose is to identify the ground contamination as well as to define geological and hydrogeological features of the investigated site (CETESB 2001). The use of non-invasive geophysical methods avoids infiltration of the contaminated to non-contaminated layers and does not impact the environment. In addition, geophysical methods can investigate larger areas with lower costs as compared to direct investigation methods.

Geophysical methods show excellent results in environmental studies and are widely reported in the technical-scientific literature (Davis and Annan 1989; Benson 1995; Dehaine 2001; Castro and Castelo Branco 2003; Lago et al. 2006; Borges et al. 2006; Lago et al. 2008; Moreira 2009; Bahia et al. 2011; Mello et al. 2014; Park et al. 2016).

In this context, in the study of contamination by lead slag in the town of Santo Amaro, the Ground Penetrating Radar (GPR) method was used as a tool to support and guide the evaluation of the existence of anomalous areas associated with the source of local contamination (slag) under the paving.

2. Soil and slag characterization

The characteristic soil of the region of the town of Santo Amaro is known as massapê, which is a “vertissolo”, originating from greenish shale interleaved with the limestone of the Santo Amaro Group. This “vertissolo” is characterized as clayey to very clayey soil with a clay content similar to

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the montmorillonite group, which presents characteristics of contraction and expansion as a function of its humidity content, moderately drained to poorly drained and with low permeability (Anjos 1998). Due to its low permeability and high metal retention capacity, the massapê soil is advantageous in this region in case of contamination because it makes it difficult to percolate the water and, consequently, reduces the contamination front.

The slag is a by-product of the lead-making process, and is granular, gray, and classified as Class I hazardous waste (CONAMA 2012). The geophysical signature using the GPR method at the interface between the slag and the massapê soil is detectable, mainly due to the high contrast in the resistivity of the two materials, where the wet and dry slag presents values of resistivity between 200 and 1200 Ωm, respectively; while the massapê soil presents resistivity values of approximately 5 Ωm (Machado et al. 2004).

3. Methodology

3.1. Acquisition and processing of geophysical data

The Ground Penetrating Radar (GPR) is a geophysical method that uses electromagnetic (EM) waves in frequencies from 15 to 2,000 MHz to locate shallow structures and geological features (Davis and Annan 1989; Annan 1992).

This method consists of the emission and reception of reflected EM waves from the boundaries of the medium, resulting in a high resolution image of the subsurface. The GPR signal is controlled by the frequency and velocity of the EM wave in the medium, the reflection coefficient (the contrast of dielectric permittivity inside the medium) and the medium's attenuation of the waves. The wave attenuation is proportional to the electrical conductivity of the medium so that the higher the conductivity, the higher the attenuation of the EM wave (Annan 1992).

The conventional techniques used for data acquisition are the common offset and velocity sounding. The technique used most often is the common offset, where a pair of antennas (transmitter and receiver) are moved at the same time along a profile. The most common velocity soundings are CMP (Common Mid Point) and WARR (Wide Angle Reflection and Refraction). In the CMP technique, the spacing between the antennas (transmitter and receiver) is increased in opposite directions from a fixed central point. In the WARR technique, one of the antennas is kept fixed while the other is moved away from the first.

In this work the data was acquired by moving the GPR using the technique of constant offset, the antenna frequency was 250 MHz, and the sampling interval between the traces was 5 cm. The shoots and trace records were registered continuously with the use of a calibrated wheel. The data were processed in ReflexW software, version 7.0 (Sandmeier 2012). The 2D data processing routine consisted of converting from *.rd3 format to *.dat, set time zero, filters 1D (dewow and bandpass frequency), gains (linear and exponential) and conversion time to depth. The velocity used for converting the sections from time to depth was 0.09 m/ns, obtained by the hyperbolic adjustment of diffractive points found in the area. The same parameters for gain and filters were applied to every section with the intention of comparing the signal amplitudes.

3.2. Direct Investigation Method

In an environmental characterization program it is essential to collect and analyze the soil and/or water samples to identify the contaminants and their concentrations. The soils from 5 boreholes in the study area were sampled. The positions of the boreholes were suggested based on the results obtained from the processed geophysical images, which allowed the identification of areas with geophysical signatures that could be associated with slag material. The boreholes were performed to the depth of 1 meter below the layer of asphalt.

4. Geophysical sites

In the study area, a geophysical survey was carried out in the town of Santo Amaro with the GPR method. The acquisition of GPR data was carried out mainly along paved roads, with the intention of verifying the existence of the slag in the subsoil. The data acquired in the common offset mode consists of 22 profiles (denominated P01 to P22) in a total of 6,805 meters. The profiles P02 and P22 were selected for this paper, which are located at the Sacramento and Doutor Bião streets (Fig. 1).

5. Presentation of Results and Discussion

5.1. GPR data interpretation

The analysis of the GPR results is done through the correlation between the geometry and the amplitude of the reflecting events. Radar profiles show distinct reflection patterns that translate the electrical behavior of the medium into high-frequency electromagnetic fields.

The first observed reflection pattern (Figures 2 and 3) has high amplitude, horizontal and continuous reflectors, and corresponds to the characteristic pattern of urban street paving. This pattern is recorded in both profiles in the superficial part.

The second reflection pattern (Figures 2 and 3) is characterized by reflectors with amplitude variations, horizontal and inclined, continuous and discontinuous, which indicates the heterogeneity of the medium and corresponds to the soil pattern mixed with the material of the slag (resistive material). This pattern is observed just below the first reflection pattern.

The third reflection pattern (Figures 2 and 3) is characterized by low amplitude, chaotic and totally discontinuous reflectors, and occurs just below the second reflection pattern. This pattern of reflection marks the region in which the electromagnetic signal of GPR is absorbed by the medium. This absorption is an effect of the attenuation of the electromagnetic signal by the presence of electrically conductive layers of the massapê soil (clayey to very clayey) characteristic of the study area.

In addition to these three reflection patterns, GPR profiles show hyperbolic reflectors and strong reflectors (from a depth of 1 meter) related to anthropogenic interferences (manholes, train lines, pipelines, ducts, etc.).

5.2. Direct Investigation Method Result

The positions of the boreholes were suggested based on the results obtained from the GPR method. The boreholes were performed in specific positions to the depth of 1 meter below the layer of asphalt (Figures 4 and 5).

FIGURE 1 - Study area, GPR survey locations and borehole locations.

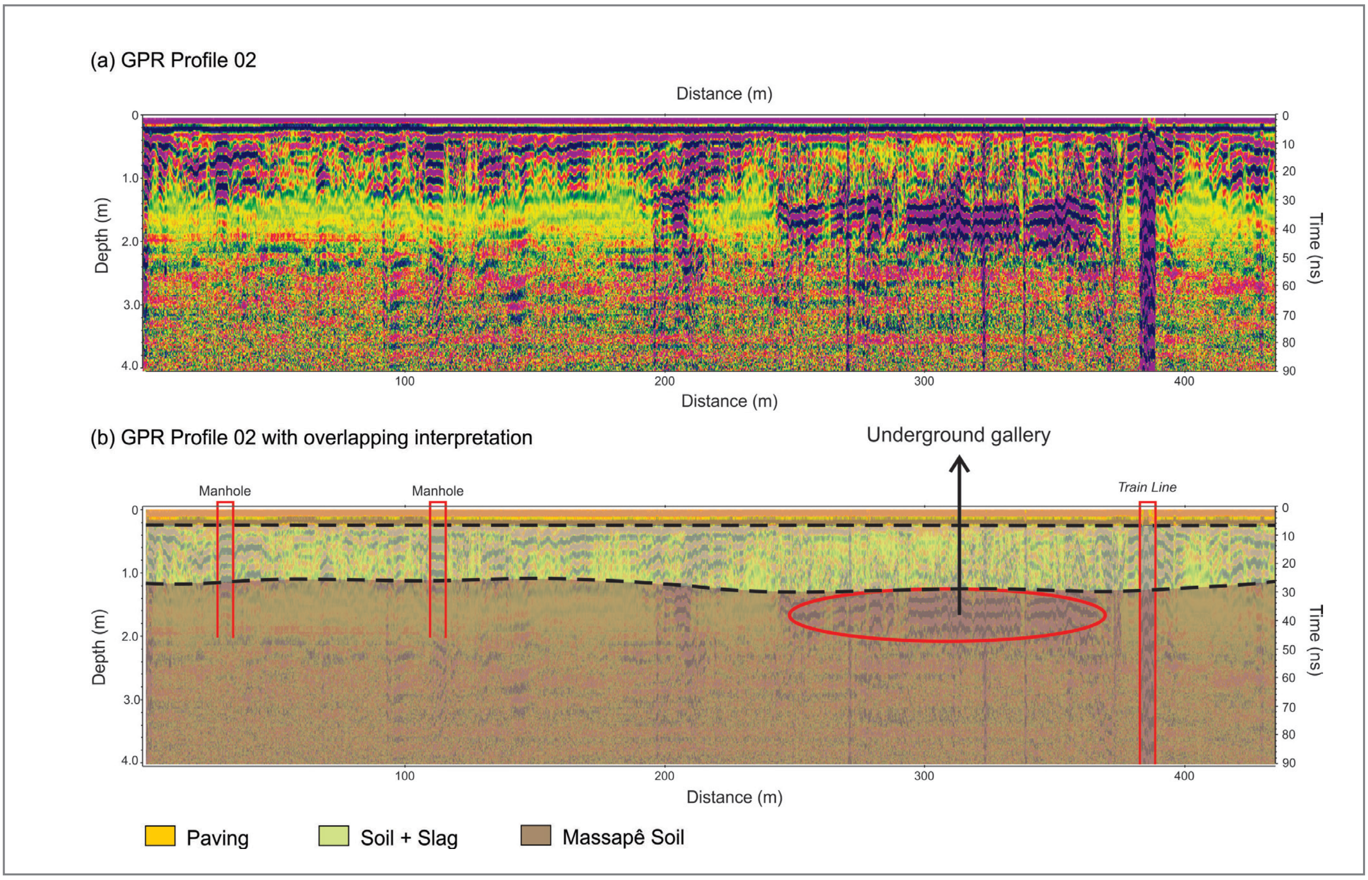

FIGURE 2 - GPR profile 02 carried out at Sacramento Street and the interpretation superimposed on it.

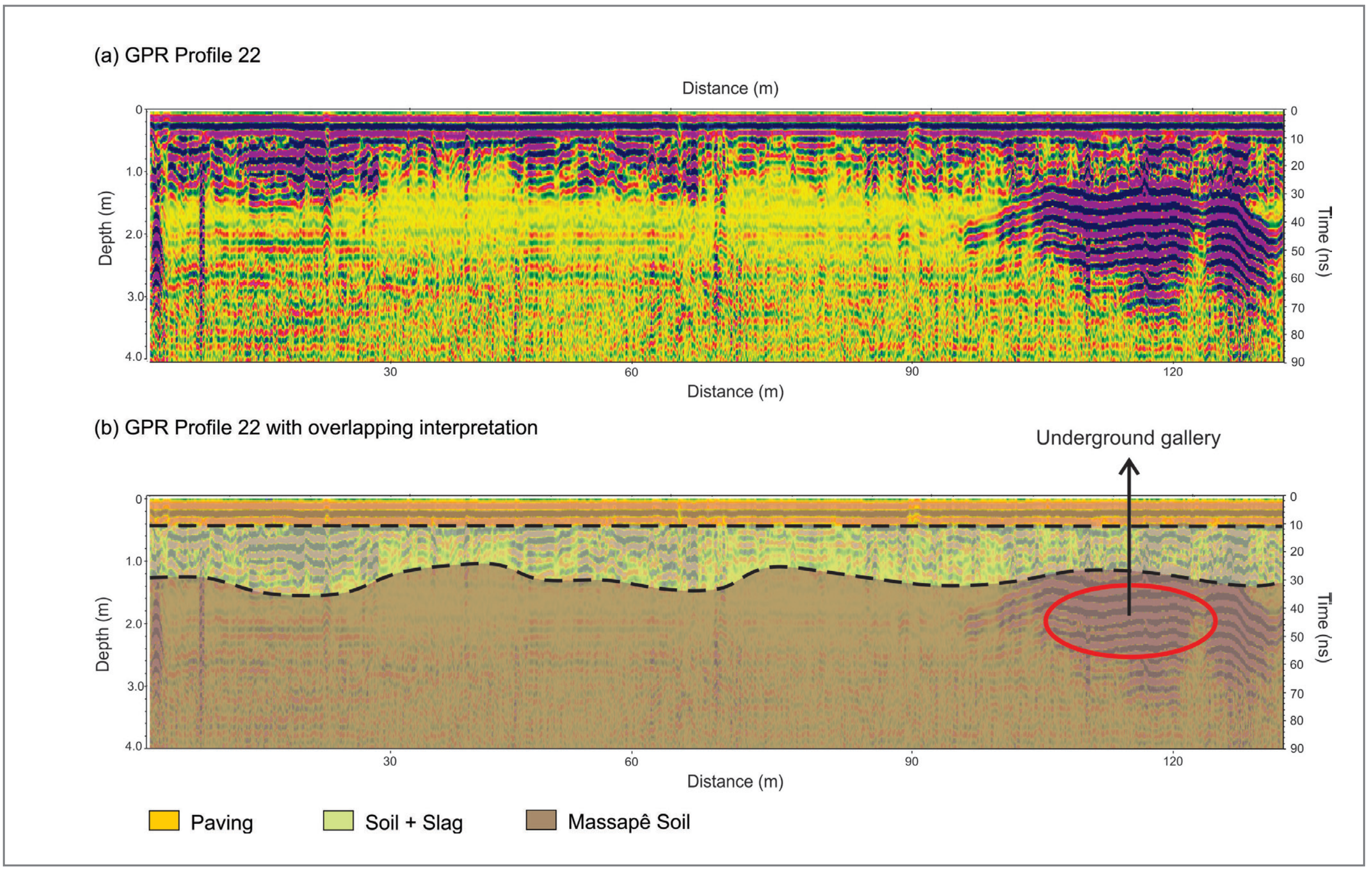

FIGURE 3 - GPR profile 22 carried out at Doutor Bião Street and the overlapping interpretation.

The direct research conducted at points where the geophysical investigation suggested the presence of slag material actually confirmed the existence of this material concentrated below the asphalt layer and cobblestone streets. The values of the heavy metals obtained for the soils in the samples S1 to S5 are shown in Table 1.

The results obtained for the soil samples show higher lead concentration in the S1, S2 and S3 boreholes; while in S4 the values are equal to, or lower than, the limit of quantification of the analytical equipment (0.2 mg/kg). High grades of aluminum, calcium, iron and magnesium are also observed in soil samples. The lead content that was detected in the soil samples in the first three boreholes (Figure 4) is derived from the metallurgic activities that existed in the region, which had the objective of processing lead ore and generating a hazardous waste site. This material (slag) was used by the Santo Amaro city hall to pave the streets and backyards of the residences and has lead as its main chemical component. The soil of the region is massapê, very clayey, which presents low permeability and high retention capacity of heavy metals.

On the other hand, the soil samples from the S4 and S5 boreholes show very low lead contents due to their sandier composition and corresponding high permeability and low retention capacity of heavy metals.

6. Conclusions

The results obtained by this study show the potential of applying the GPR method to the environmental characterization of the subsoil of paved streets in the town of Santo Amaro, making it possible to identify the resistive material contaminants (lead slag) as well as the various layers: paving, soil-slag and massapê soil.

These layers are characterized by distinct reflection patterns. The first reflection pattern has high amplitude, horizontal and continuous reflectors. The second reflection pattern is characterized by reflectors with amplitude variations, horizontal and inclined, continuous and discontinuous, which evidences the heterogeneity of the medium. The third reflection pattern is characterized by low amplitude, chaotic and totally discontinuous reflectors.

GPR data also enabled the identification of reflectors associated with anthropogenic interferences (manholes, train lines, pipelines, etc.). Borehole samples confirm the existence of the contaminant (lead slag). Anomalous concentrations of heavy metals, mainly lead, were observed in the locations indicated by the geophysical results using the GPR method, showing the importance of the use of geophysics in environmental characterization programs.

TABLE 1 - Results of soil chemical analysis.

Sample	Depth of sampling (cm)	Al (0.01%*)	Pb (0.20 mg/kg*)	Ca (0.01%*)	Fe (0.01%*)	Mg (0.01%*)	Na (0.01%*)
S1	15 - 30	2.47	1.60	1.50	7.37	1.58	0.12
	30 - 55	1.22	0.80	1.46	2.11	0.75	<0.01
	55 - 80	0.69	2.60	0.71	1.67	0.27	<0.01
	80 - 100	1.01	2.70	0.54	4.80	0.61	0.68
S2	0 - 30	1.5	2.10	4.03	2.78	1.46	<0.01
	30 - 50	4.63	2.40	13.1	7.22	4.51	0.42
	50 - 80	1.54	1.50	2.50	5.03	2.26	<0.01
S3	0 - 20	1.23	0.90	2.29	2.08	0.31	<0.01
	20 - 35	0.84	0.50	2.46	1.06	0.62	<0.01
	35 - 50	0.80	0.60	0.85	7.59	0.71	<0.01
	50 - 80	1.56	<0.20	3.45	1.46	1.77	0.68
	89 - 95	0.71	0.20	0.64	2.67	0.43	<0.01
S4	0 - 30	2.72	<0.2	0.41	1.3	0.54	<0.01
	30 - 50	2.26	<0.2	0.83	1.1	0.76	<0.01
	50 - 100	1.96	<0.2	0.43	0.98	0.15	<0.01
S5	0 - 30	0.61	<0.2	0.6	1.55	0.19	<0.01
	30 - 40	3.45	<0.2	10.2	5.94	0.61	<0.01
	40 - 80	3.37	<0.2	1.38	6.95	2.2	<0.01
	80 - 100	0.24	<0.2	0.3	1.78	0.08	<0.01
	100 - 110	0.15	<0.2	0.05	0.94	<0.01	<0.01

* Maximum allowed concentration

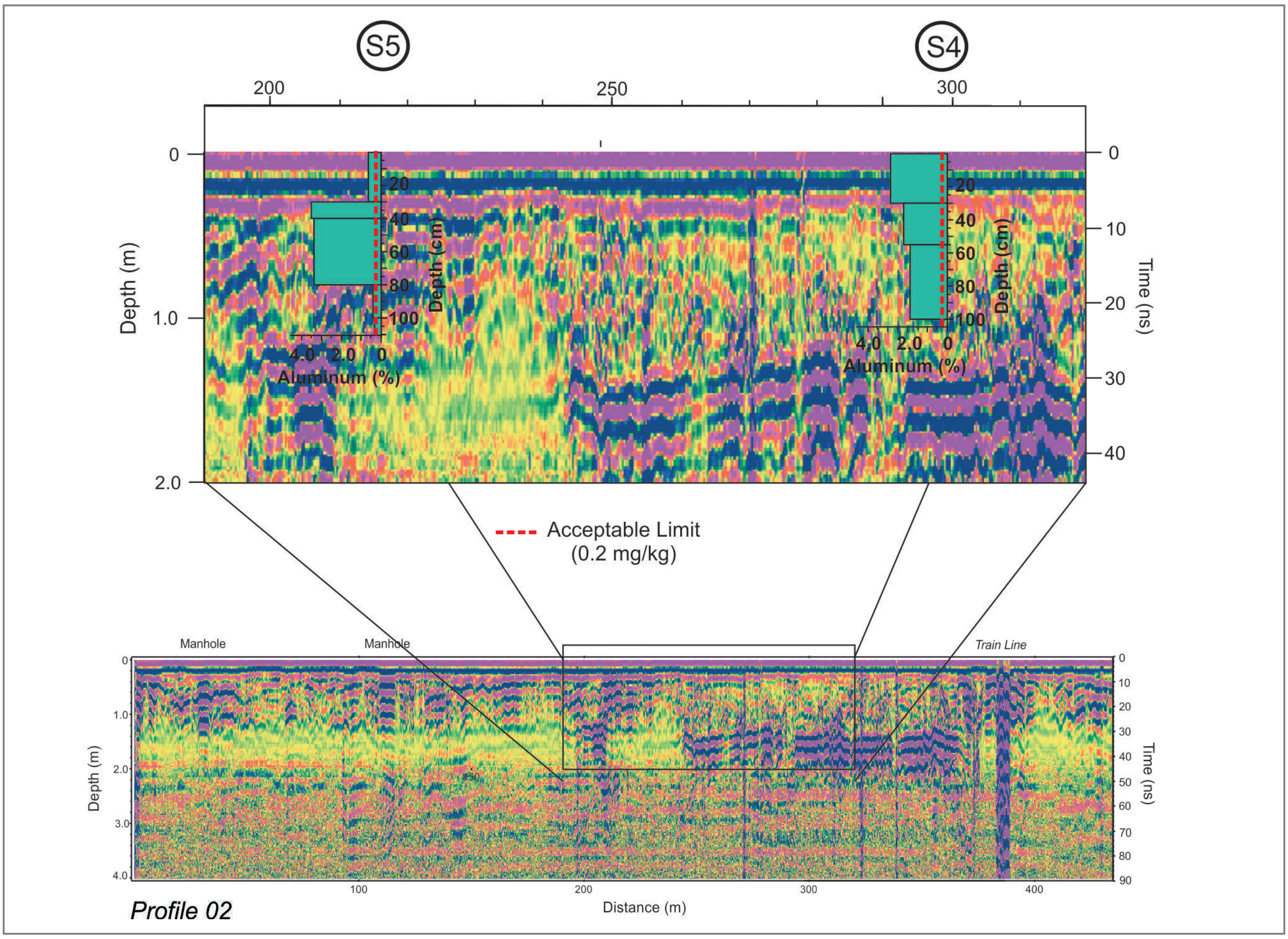

FIGURE 4 - GPR profile 02 with the S4 and S5 borehole positions and the lead levels in depth.

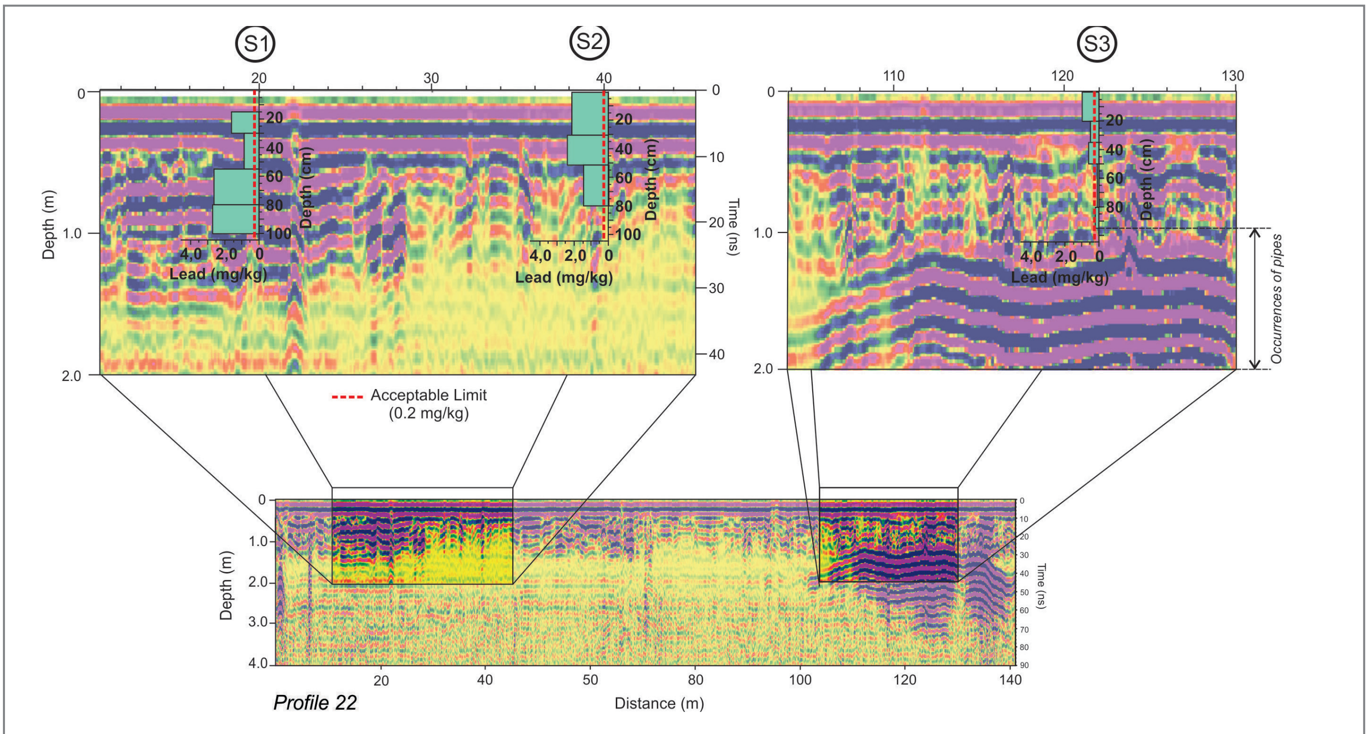

FIGURE 5 - GPR profile 22 with the S1, S2 and S3 borehole positions and the lead levels in depth.

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