Georadar Application for Site Characterization of a Waste Disposal on Quartzite Soil

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Abstract

Poorly managed disposal of solid waste on permeable soil may have serious environmental concerns which can greatly benefit from quick site investigation using non-invasive and cost-effective methods. Therefore, the present research examines the efficiency and agility of ground penetrating radar (GPR) in dumpsite characterization. A case study was conducted on the Alto Paraíso de Goiás dumpsite (Brazil), where the natural ground is composed of coarse-grained quartzite soil. The GPR data were acquired with 200 MHz shielded antennas, at a sampling interval of 0.05 m, covering the dumpsite and its adjoining. A commonly adopted processing workflow, and as a result, four predominant reflection patterns and a discontinuous surface were identified and interpreted in terms of site stratigraphy, contaminant pathways, and plume geometry. The GPR interpretation was enhanced by incorporating the lithological information from nearby monitoring wells. The study shows the potential of applying the GPR method as an effective geophysical characterization tool for waste disposal sites on quartzite.

1. Introduction

Recent trends of urban population growth and consequent unsustainable use of natural resources have led to environmental impacts limiting the quality of life. Thus, there is an increasing demand for research related to environmental contamination, geotechnical investigations, urban planning studies (among others) to gain a better knowledge of the subsurface in support of sustainable land use and management.

The improper disposal of solid waste is one of those serious environmental concerns, given the increase in infectious diseases transmitted by animals attracted by waste (e.g., insects, birds, rats, cats, and dogs) and by the human waste pickers. The disposal in the form of leachate can pollute surface water and groundwater releasing toxic gasses (methane and carbon dioxide) and thus contaminating plants and animals (Cozzarelli et al. 2011; Epstein 2015; Naveen et al. 2017).

Leachate is produced by excessive rainfall and water present in the garbage. The huge content of organic matter present inside enhances the biogeochemical processes in the waste, and consequently accelerates the production of gasses (e.g., methane, carbon dioxide, and ammonia), and the leaching of heavy metals (e.g., cadmium, chromium, copper, lead, nickel, and zinc) from the residues (Lisk 1991; Vodyanitskii 2016). In addition to the metals and ammonia, inorganic macro components such as calcium ($Ca2^+$), magnesium ($Mg2^+$), sodium ($Na2^+$), potassium (K^+), iron ($Fe2^+$), manganese ($Mn2^+$), chlorides (Cl^-), sulfates ($SO42^-$) and hydrogen carbonate ($HCO3^-$) are also present (Christensen et al. 1994).

Therefore, the disposal site selection requires detailed investigations in order to curtail the hazardous impacts of these dumpsites. However, in the case of developing countries such as Brazil (hosting approximately 3000 dumps or landfill sites in areas where soils and rocks have high hydraulic transmissivity - hydraulic conductivity > 10^{-8} m/s) little attention has been paid to such investigations (Abrelpe 2019). Most of these sites are situated in small municipalities and have little or no budget attributed to the management of solid waste (Costa et al. 2019). Consequently, there is a lack of planning without any geotechnical criteria for site selection or any design utilizing geosynthetic (geomembrane) or other waterproofing material (clays) to prevent leachate percolation into the subsurface. An example of this is Alto Paraíso de Goiás dumpsite (APGD) constructed on coarse-grained quartzite soil of high hydrodynamic parameters such as porosity and permittivity. Such hydrogeological conditions are very conducive for the rapid movement of contaminants by leachate and associated hazards (Christensen et al. 2001; Bjerg et al. 2003).

Under these conditions, there is an urgent need for an environmental impact assessment of such hazardous dump sites using suitable site characterization techniques. The most common techniques that are in use for the assessment of soil contamination by leachate include: direct sampling and testing of soil (Cossu & Raga 2018; Youcai 2018), chemical analysis of surface water and groundwater (Baird 2017; Szymański et al. 2018), and measurements of gas concentrations in gas extraction wells (Sabel & Clark 1984; Al-Yaqout et al. 2005). These techniques are important and have been very useful, however, these are invasive, expensive, and time-consuming. Geophysical methods (GMs) are non-invasive imaging techniques and can be adopted as cost-effective and quick alternatives (Olofsson et al. 2005; Lopes et al. 2012) such as seismic, electrical, and electromagnetic with their own merits and demerits.

The successful application of GMs in environmental research (landfill/ dumpsite) depends on the physical characteristics of the waste, contaminant type, its concentration, and hydrogeological characteristics of the study site (Geological Society of London 2002; Reynolds 2011). However, the choice of GM also depends on the study objectives, for example, the seismic methods are considered more effective in delimiting the solid waste package, since the density of the waste is lower than that of the surrounding geological strata regardless of the degree of subsoil saturation (Konstantaki et al. 2015). Also, the high concentration of salts in the leachate of solid waste causes high electric contrast between the subsoil and groundwater, justifying the application of electrical and electromagnetic methods (Triantafilis et al. 2013). Direct current electrical resistivity tomography is considered the most efficient method for mapping contamination plumes (Ogilvy et al. 2002; Maurya et al. 2017). Despite this advantage, its application requires good coupling with the ground, making the field operation difficult, labor-intensive, and time-consuming as compared to the electromagnetic methods especially, GPR.

The GPR method makes use of the propagation of high-frequency electromagnetic waves (10 to 2600 MHz) to identify variations in electrical impedances in the media (Jol 2009). Its depth of penetration increases with the decrease of the frequency of the antennas and the reduction of dielectric permittivity of the medium. Common GPR systems used in investigations of contaminated areas include antennas with frequencies below 200 MHz since a high attenuation of the electromagnetic signal is expected to be caused by the high electrical conductivity of the medium (clayey and/or contaminated soil by leachate). The application of GPR in leachate sites detects contaminated soils as the site of attenuated radar signals (shadow zone) which is proportional to the amount of salinity in the contaminant (Orlando & Marchesi 2001; Splajt et al. 2003; Porsani et al. 2004; Annan 2005). This attenuation makes the use of radar doubtful in determining the leachate base/depth and only determines the top and the lateral extents of the contaminants plumes with reasonable accuracy. The patterns/typologies of reflections associated with the soil contamination have been extensively reported in the literature (EPA 2000; Cassidy 2007; Che-Alota 2009; Godio et al. 2010; Cassiani et al. 2014).

The paper presents a case study that aims at further examining the efficiency of GPR in the site characterization of APGD, which is composed of coarse-grained quartzite soil. The investigation started with the survey planning followed by an acquisition geometry covering the peripheries and top of the dumpsite including the locations of monitoring wells. The processed results as reflection patterns (georadar facies and georadar surfaces) are interpreted in terms of the presence of pebble paths and the dimensions of plumes. The interpretation is further enriched by incorporating the geological information from the nearby boreholes.

2. Material And Methods

2.1 Site description

Alto Paraíso de Goiás is the main city within the Chapada dos Veadeiros National Park which still disposes of solid waste in the open (dump). The APGD is located approximately 6 km from the urban area, on the left bank of the BR010 highway (Figure 1). The collection of solid waste in the municipality and consequent deposition in the APGD began in 1993 (Oliveira Jr 2017). The solid urban waste was disposed of in the open until 2016. After that, the city authorized the excavation of ditches and the burial of residues without any type of waterproofing. This increases the flow of leachate into the ground, which also increases the risk of pollution as compared to the surficial through of wastes (Figure 2).

The national solid waste policy (LEI No. 12,305), sanctioned (on 2nd of August, 2010), that the dumps be extinguished and replaced by landfills within four years after the publication of the Law. However, after expiration the Brazilian government continues to extend this limit. The estimated production of solid waste in the municipality is 2.4 tons per day (Pfeiffer et al. 2017). If superficial or underground leachate flows out of the APGD area, the drainage to be compromised is the São Bartolomeu River that passes through the eastern part of the city (Figure 1).

The APGD is situated on the PP4ts2 lithofacies of the Arraias Formation (Campos et al. 2013; Figures 3A and 3B). The authors individualized these lithofacies according to the presence of micaceous quartzites with intercalations of metasiltites. Quartzites are characteristic of an interlaced fluvial environment, since they are medium to thick quartzites, have a low degree of selection, and presence of cross-tabular and channeled stratifications (Alvarenga et al. 2007).

Few boreholes were drilled for the installation of water level monitoring wells indicating the presence of a quartzarenic neossol (medium quartz sand) with a thickness of up to 7.5 m (Figure 3C). This soil type in *Chapada dos Veadeiros* region has an average hydraulic transmissivity of 10-5 to 10-6 m / s (Almeida et al. 2006). According to NBR 13896 (non-hazardous waste landfills design criteria, implementation, and operation), the implantation of areas for the disposal of solid waste is restricted to places with soils or geotechnical structures that have hydraulic conductivity less than 5×10^{-7} m / s (ABNT 1997).

The photographs along with the field visits are used to divide the APGD into different zones such as trash piles, trenches, sewage lagoons, solid waste trenches, and the proximity to houses and civil engineering structures as roads (Figure 2). These marked features aid the planning of the geophysical surveys in the later acquisition stage.

Thus, due to the geological, pedological, and hydrogeological characteristics of the APGD, it has a high potential for the development of a contamination plume. In the research of subsoil and groundwater contamination, the Brazilian Association of Technical Standards (ABNT) recommends the use of geoelectric methods (NBR, 15935). These consist of electrical resistivity, induced polarization, spontaneous potential, and GPR, the latter being used for shallow investigations. The shallow term is generic since the depth of investigation of the GPR depends mainly on the electrical properties of the medium (electrical conductivity and dielectric permittivity).

2.2 Data acquisition and processing

In order to verify the efficiency of the GPR method in the mapping of the soil thickness, buried residues and leachate percolation zones, the GPR profiles were taken at, peripheries and adjoining areas of APGD (Figure 4A).

Data were acquired using SIR-3000 equipment (manufactured by Geophysical Survey Systems Inc.) consisting of an acquisition module connected to a 200 MHz shielded antenna (Figures 4B, 4C, 4D, and 4E). The GPR configuration parameters were: time window of 400 nanoseconds (ns), time sampling interval (Δt) of 0.195 ns, spatial sampling interval (Δx) of 0.05 meter, 2048 samples per trace, and sampling frequency of 2550 MHz. The choice of the best GPR data processing routine to identify contaminated areas must take into account the maintenance of the recorded amplitudes since the application of gains or normalization filters can hide the electromagnetic signal attenuation zones, and consequently induce errors in interpretation. Thus, for this work, it was decided only to adjust the zero time, remove the gain applied during data acquisition (header gain), and apply a constant 1D linear gain. All routines for processing, visualizing, and generating 2D sections occurred in the ReflexW software (Sandmeier 2019).

The data were acquired along with the eleven GPR profiles (Figure 4). These profiles can be divided into three classes: (i) on dumpsite (L3, L6, L7, L8, and L10), (ii) its peripheries (L1, L5, L9, L11) and (iii) the adjoining areas (L2, L4). This dense coverage is deployed to achieve the research objectives of leachate detection as well as tracking its mobility in the surrounding areas.

To obtain the medium velocities on the APGD, information on the depths of the rocky top inferred from the monitoring wells was used (Figure 5). The intersection of the GPR L5 section and the PM02 well (50 m section position), shows a strong section reflector at 137 ns (Figure 5B). Similarly, at PM01 (position

300 m from the section), there is also a strong reflector at 38 ns (Figure 5C). Thus, the speeds of the GPR wave in the medium were calculated from the travel times recorded at T_{PM01} and T_{PM02} as 0.102 m/ns and 0.105 m/ns, respectively. Thus, an average speed value of 0.10 m/ns was used for time to depth conversion.

3. Results And Discussion

For the analysis of the results, Neal's classification (2004) was used, which recommends the individualization of the formation patterns according to the shape (free of reflections, planar, sinuous, concave, convex, and sigmoid), diving (horizontal and diving), continuity (continuous, moderately continuous and discontinuous) and the relationship between reflections (parallel, subparallel, non-parallel oblique, tangential oblique, divergent oblique, and chaotic oblique).

The RFF pattern is associated with the attenuation of the GPR signal caused by the presence of leachate in the soil. The SROD pattern is associated with the solid urban waste (household waste) because of its high amplitude, chaotic reflectors and is always in discontinuous contact with the CRCD pattern, typical of residue ditches (Lago et al. 2008). The CRCD pattern represents the material that makes up the region's soil, composed of small rocks fragments, plant roots, and animal bills. The local rocks are represented by the DPROD pattern since the inclination of the reflectors coincides with the foliations and beddings of the rocks in the region, as well as the presence of discontinuity at the top.

In the APGD area, four predominant reflection patterns (e.g., RFF, SROD, CRCD, and DPROD) and a discontinuous surface were identified (Figure 6). Each reflection pattern has its own specific characteristics and is interpreted accordingly. The RFF pattern is characterized by the absence of reflectors and/or the presence of reflectors with amplitude close to zero (Figure 6B). The SROD pattern shows sinuous, oblique, and divergent reflectors, with high amplitude values (Figure 6C). Convex, chaotic, discontinuous, and low to high amplitude reflectors represent the soil pattern (CRCD, Figure 6D). Dipping planar, oblique, and discontinuous flat reflectors, with high amplitude, characterize the DPROD (Figure 6E). Between the reflection patterns CRCD and DPROD there is a discontinuous surface having a continuous to discontinuous reflector of high to medium amplitude diverging from the other reflectors in the GPR sections.

The interpretation of the sections based on the reflection patterns made it possible to carry out an analysis of the extent of contamination in and around the APGD. In the four sections closest to the limits of the APGD (GPR L1, L5, L9, and L10) the reflection patterns CRCD and DPROD are present (Figure 7). The sandy soil (PSL) has thicknesses between 0.5 m to 7.5 m and reaches the maximum depth in the southwest part of the area. The GPR results obtained across these four sections indicate that the leachate does not exceed the limits of the APGD.

GPR sections inside the APGD, show several points where leachate seepage can be seen (Figure 8). On the GPR L3 section (Figure 8B), only one site of disposal of buried solid waste was identified on the profile between 21 to 25 m from the beginning having a maximum thickness of about 1.8 m. In the section below, the electromagnetic signal was attenuated over the waste making an attenuation or shadow zone. Thus, with the identification of this shadow zone, the geological structures below cannot be mapped. This attenuation makes the use of radar doubtful in determining the leachate base/depth and only determines the top and the lateral extents of the contaminant plumes with reasonable accuracy. The GPR record shows a maximum soil thickness of ~3.2 m on this profile.

In the GPR L6 section (Figure 8C), two possible solid waste disposal pits are identified: (i) the first between 145 to 152 m from the beginning which is about 2 m thick, and (ii) the second between 175 and 230 m with a maximum thickness of ~2.3 m. The leachate percolation zones occur below these disposal pits, however, in the second waste disposal site, the percolation does not happen below all the waste but is located between the positions of 175 to 184 m, and another between the positions of 195 to 203 m. The soil in this section has a thickness range from 0.7 to 6.0 m, with an average value of 3.8 m.

On the GPR records of section L7, four potential areas of electromagnetic signal attenuation are noted (Figure 8D). However, only one of them shows buried waste (between the positions of 72 to 80 m). In these areas of GPR signal absorption without the presence of residues on the top, may indicate leachate of the previous residues, which increases the electrical conductivity of the soil. This leachate infiltration has made it impossible to imagine a greater depth of the GPR between the position of 100 to 245 m from the section (Figure 8D).

On the GPR L8 section (Figure 8E), two leachate zones are delineated as follows. The first, located between 40 to 70 m, is related to the leachate. In contrast, the second, located between the 242 positions and the end of the profile, relates to the leaching of buried waste at a depth of 3 m. The thickness of the soil in this section reaches a depth of 8 m.

4. Conclusions

The present study was carried out for the georadar based site characterization. The scope of work included delineating the distinctive electromagnetic patterns which were attributed to soils, rocks, solid waste disposal pits, and leachate percolation zones in and around a Brazilian dumpsite on highly conductive soil using the information from nearby monitoring wells. The following conclusions have been drawn.

The sandy soil from the weathering of the region's quartzites enabled overall a good penetration of the GPR signal up to a depth of 18 m using a 200 MHz shielded antenna. However, there is an exception in the presence of solid waste and their percolating zones where the radar signal is attenuated at shallow depths. Furthermore, the particular radar facies are used for the determination of soil thickness and rocktop after calibration with the lithological information from the well.

The foliations and erosional surfaces in the bedrock were delineated as the sites of attenuated radar signals. These have an influential impact on the movement of contaminants, possible pathways for the future environmental hazard associated with the leachate percolation in the surroundings. At some places of the GPR sections, the RFF (no reflections) veins are observed without a presence on any surficial solid waste pits at the top. These are interpreted as the sites where the solid waste has already been percolated downward as leachate. These zones have severely affected the depth of penetration of GPR signals.

Although the current APGD site is an unsuitable area for waste disposal, the GPR results show that the leachate (from the leaching of waste) did not seep out of the APGD boundaries. However, the presence of highly foliated bedrock and hydrodynamic deposits may have caused a rapid propagation of contaminants in the adjoining areas.

Thus, in similar environments, the GPR proves to be a very agile, effective, and less costly tool for reconnaissance in the site characterization of a dumpsite for further detailed investigations applying geophysical, geotechnical and numerical simulation studies for better management of the natural resources. The results can aid the policymakers in their plans for sustainable management of the sources.

Declarations

Acknowledgment

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Competing Interests

The authors declare no conflict of interests.

Data Availability Statement

Data will be made available on email request to the corresponding author.

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Figures

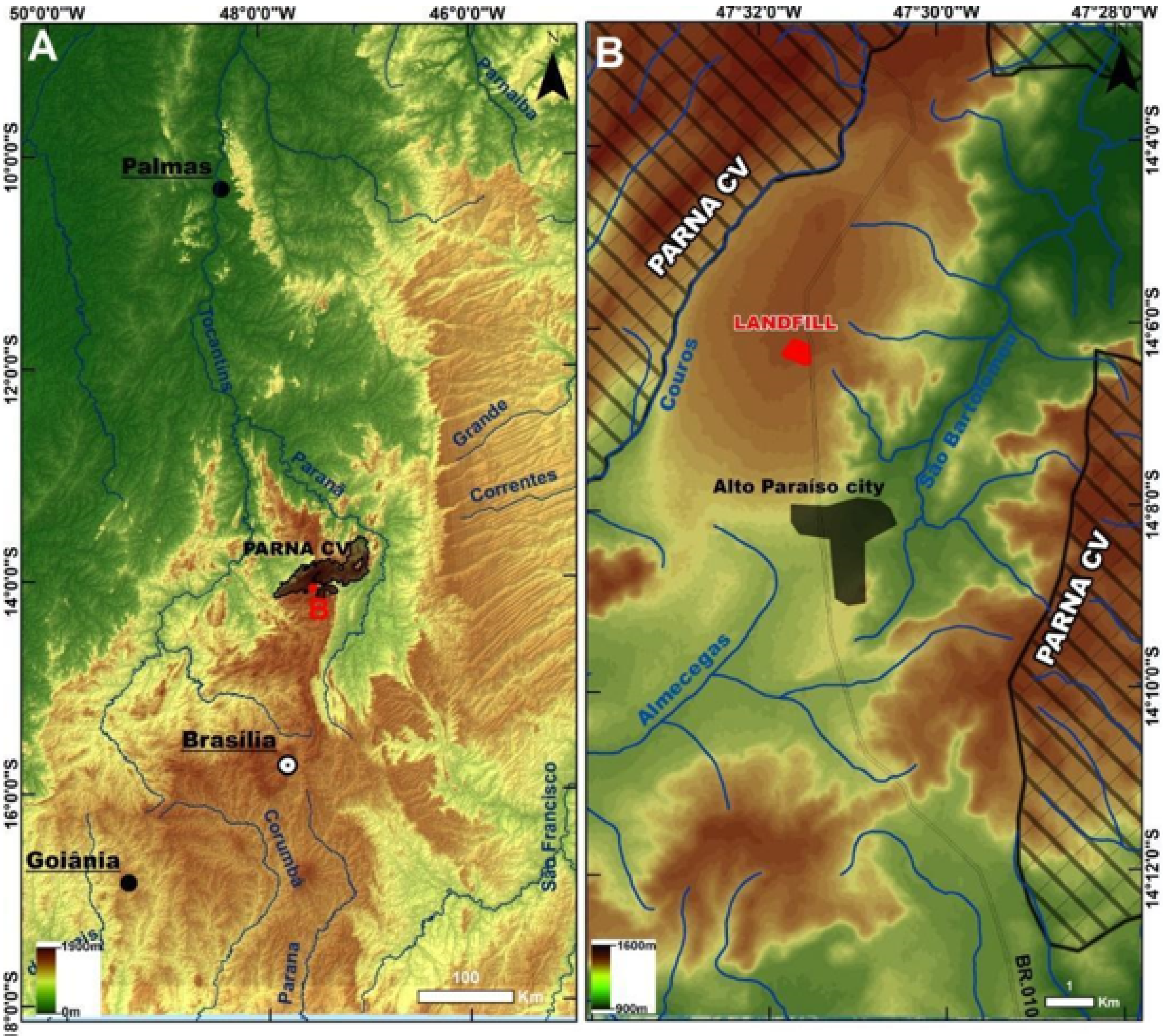

Figure 1

(A) Digital terrain model (DTM) showing the location of *Chapada dos Veadeiros* National Park (PARNA CV), (B) locations of the Alto Paraíso de Goiás municipality and the dumpsite.

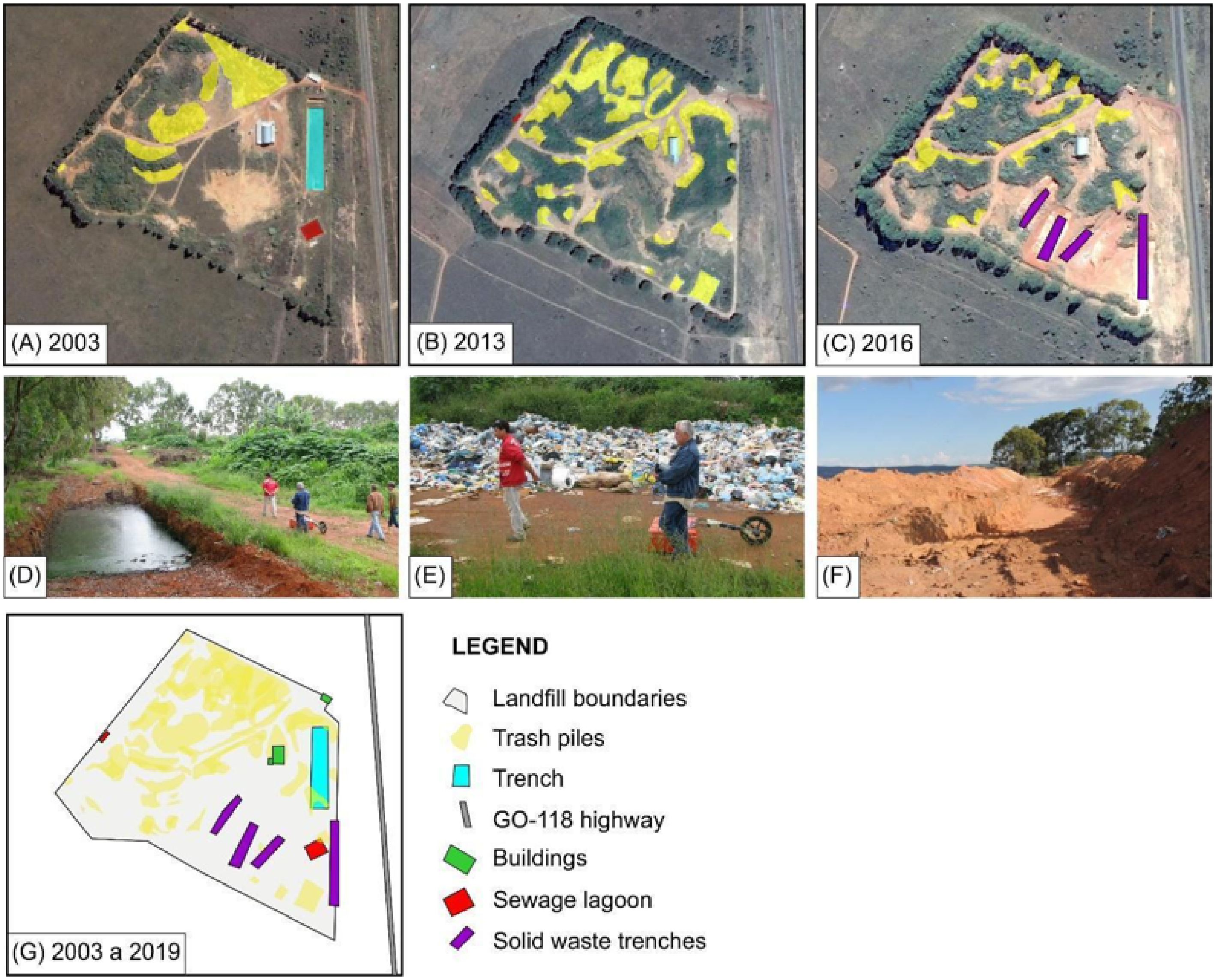

Figure 2

Aerial images of the APGD were taken in the years (A) 2003, (B) 2013, and (C) 2016. The photographs show the presence of (D) a sewage lagoon, (E) residues disposed on the surface, and (F) solid waste trenches.

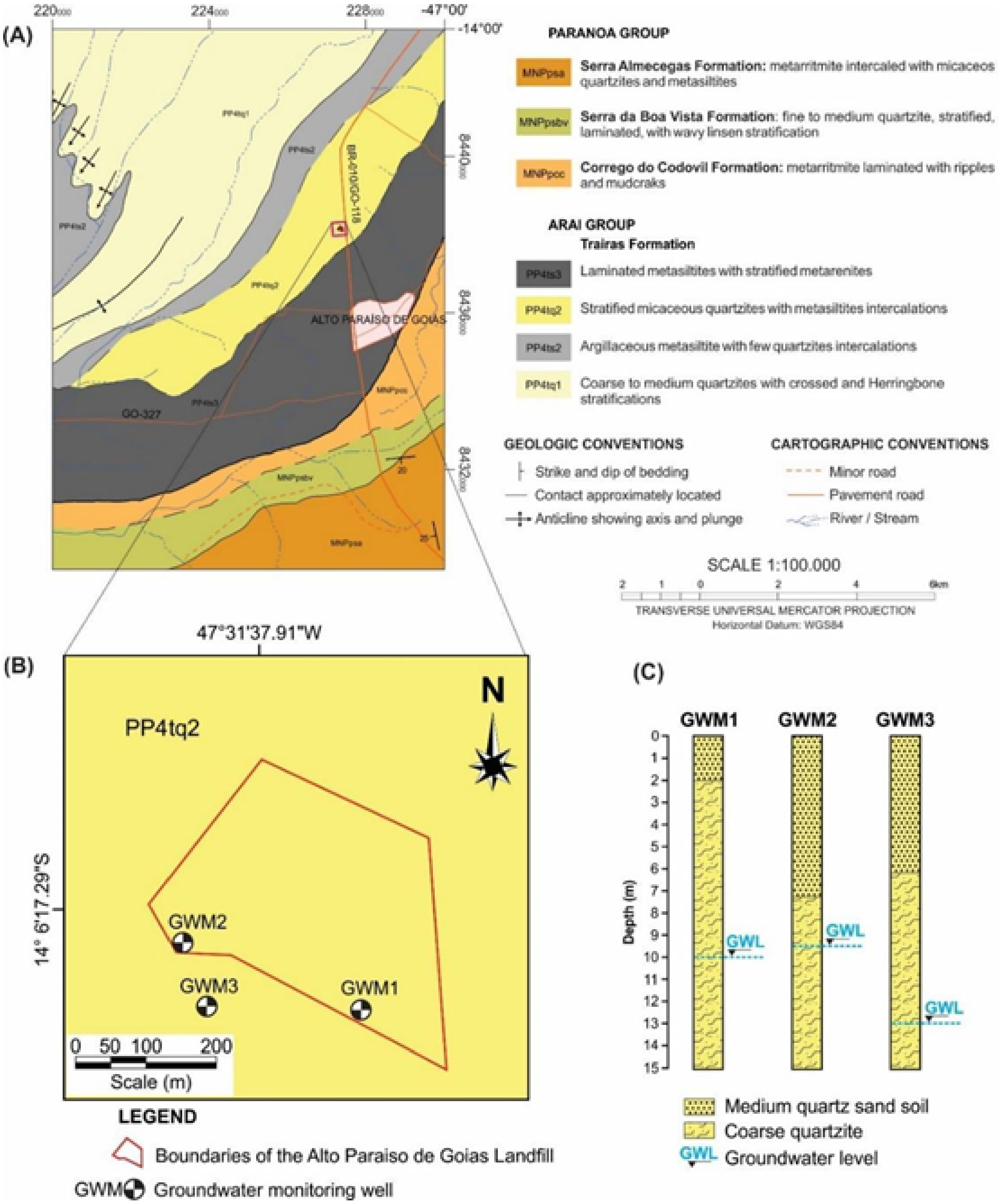

Figure 3

(A) Geological map of the Alto Paraíso de Goiás region modified after Campos et al. (2013), with details of the APGD area (B). (C) geological description of the drilling holes carried out in the APGD area, with the identification of the rocky top and the depth of the water level.

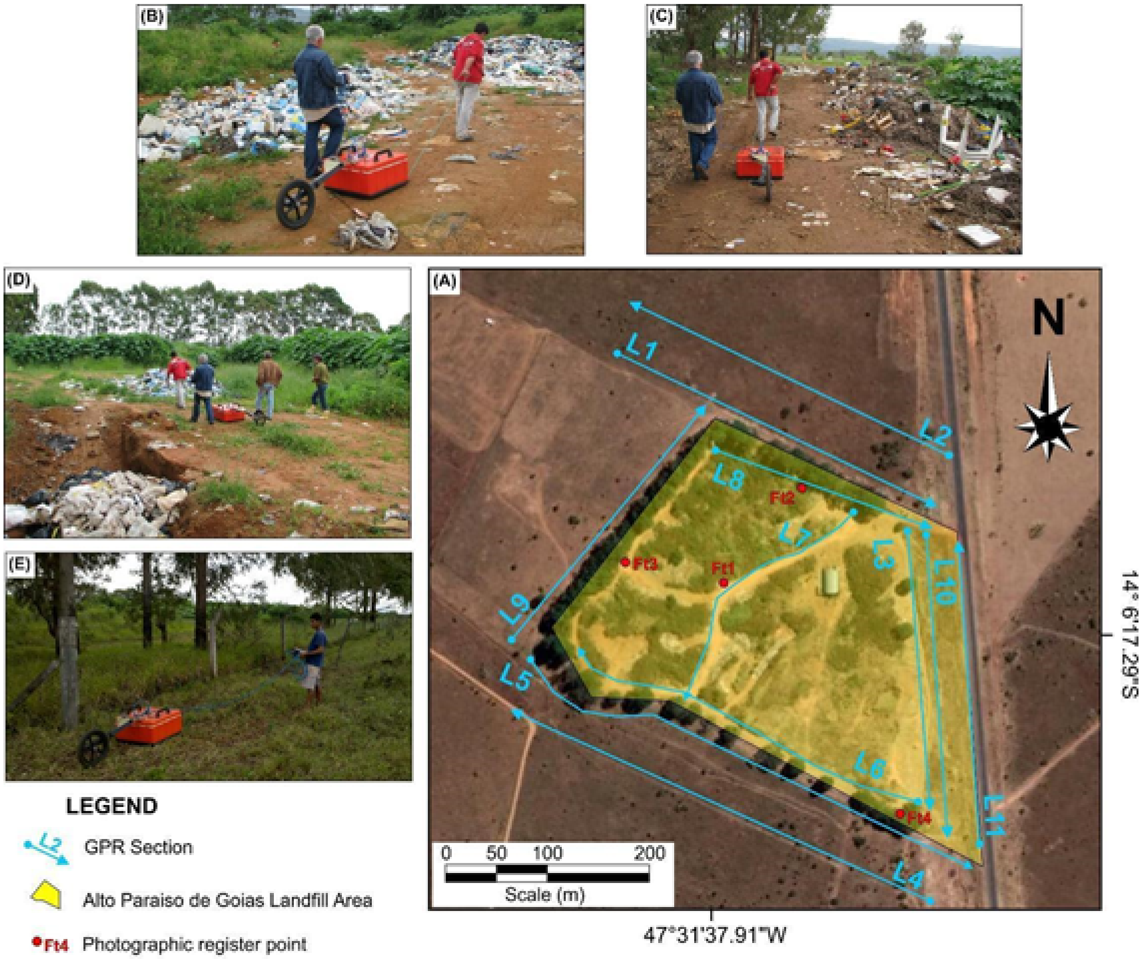

Figure 4

(A) Aerial image including the locations of the GPR sections in the study site. Photographs show (B) piles of garbage inside the area; (C) piles of garbage at the entrance of the dump; (D) near the garbage dumps; and (E) in the southeastern part of the dump.

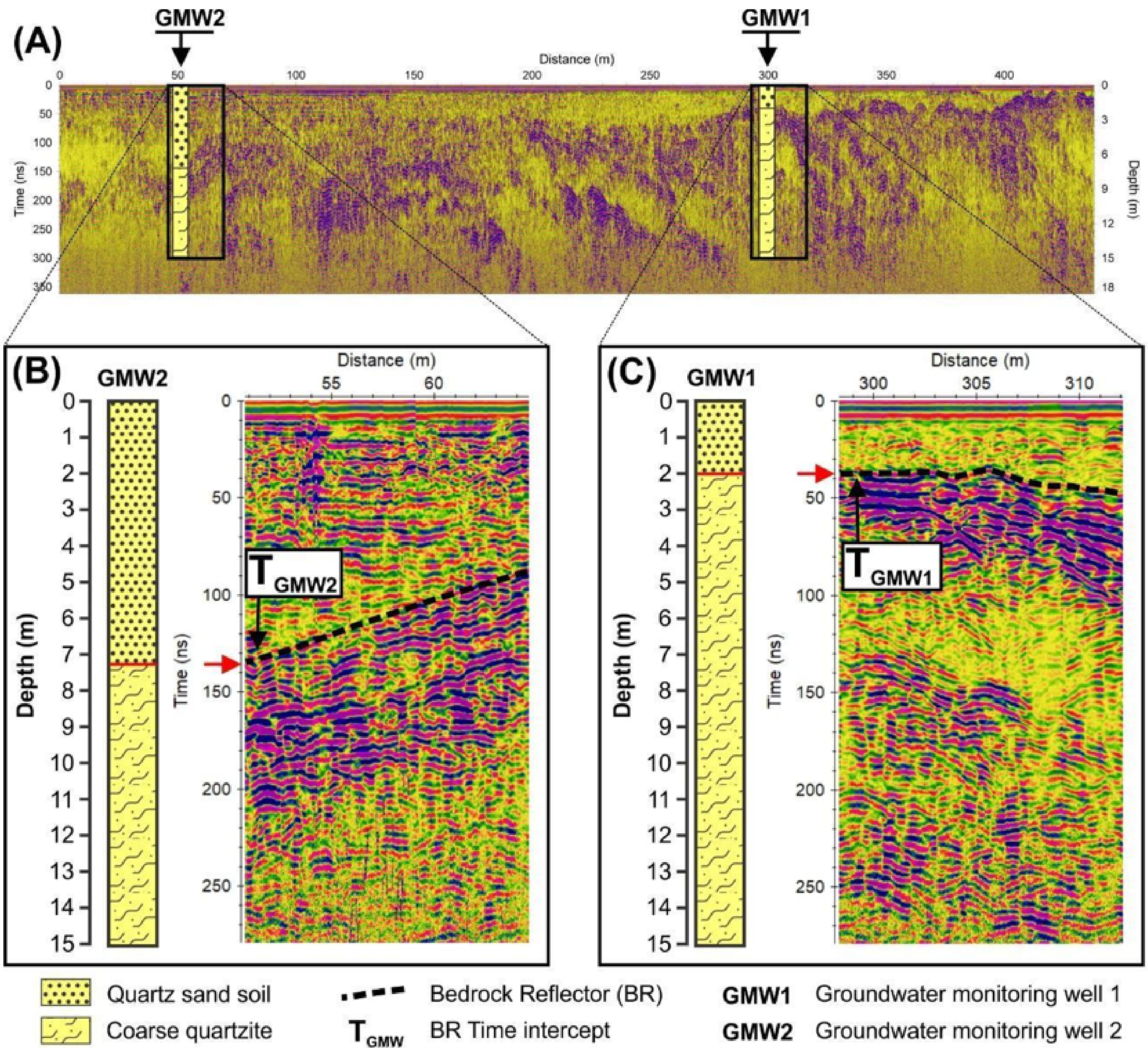

Figure 5

(A) GPR section of line 5 with the geological description of the groundwater monitoring wells. (B) and (C) geological loggings of GMW2 and GMW1 with part of GPR section and the radar intercept times (T_{GMW2} and T_{GMW1}) related to top of bedrock.

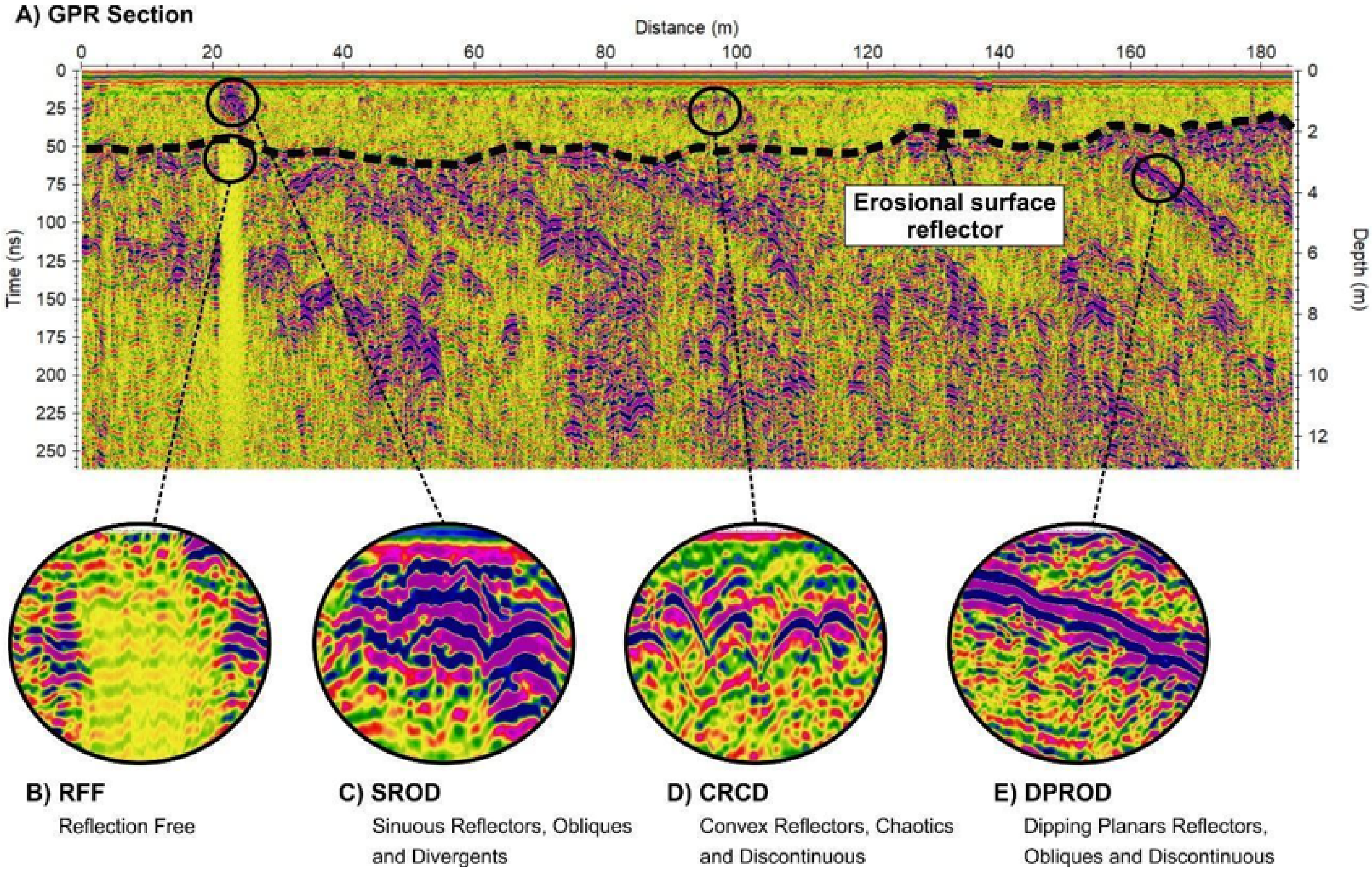

Figure 6

(A) GPR L3 section that highlights all the reflection patterns identified in the study site. (B) RFF, (C) SROD, (D) CRCD and (E) DPROD.

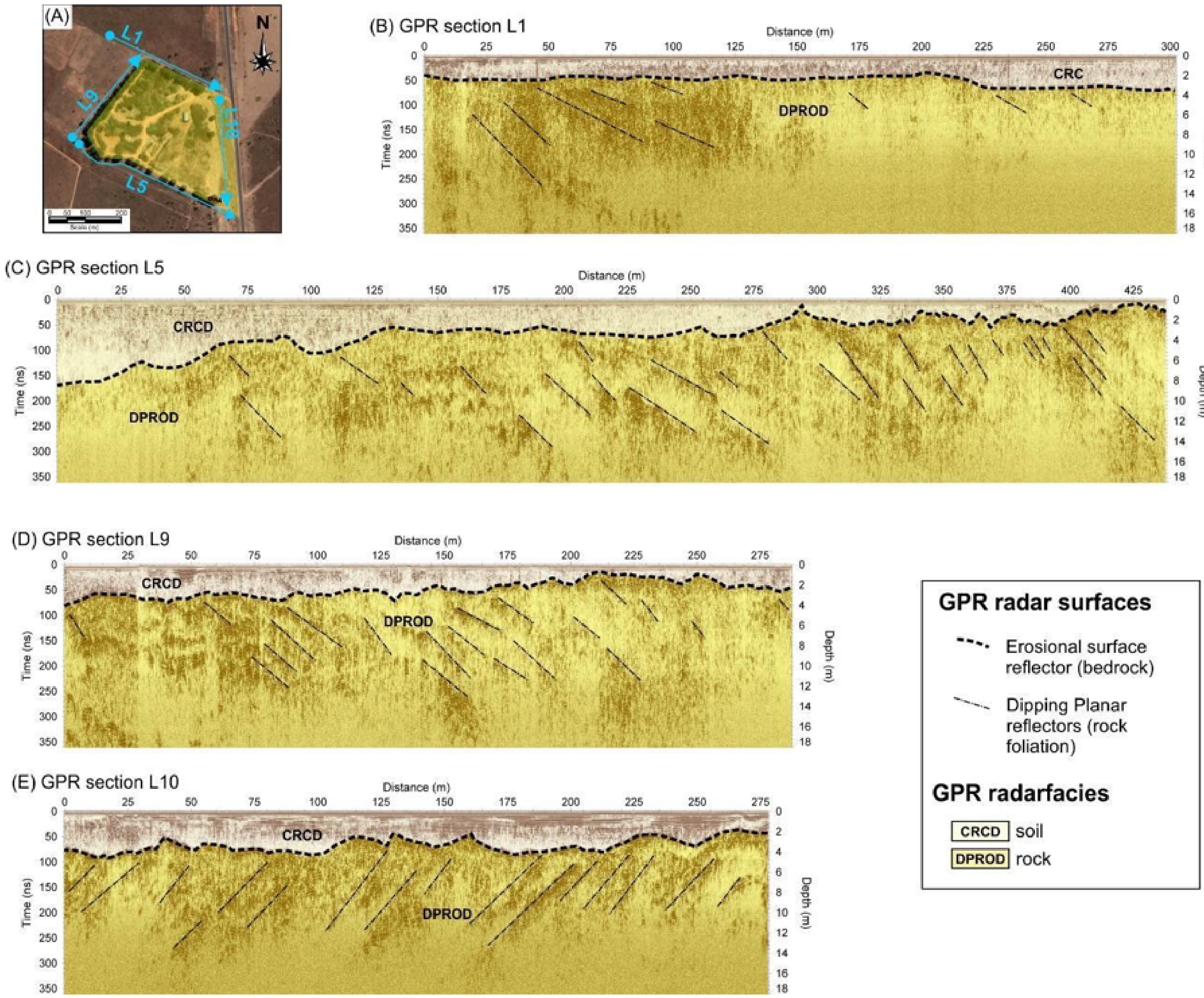

Figure 7

GPR sections along the boundaries of the APGD indicate the reflection patterns related to soil (CRCD) and rock (DPROD). On the sections, the reflectors related to the tops of the rocks and the reflectors interpreted as the lodging/foliation structures. (A) Location of the GPR sections within the boundaries of the dumpsite. GPR sections of line L1 (B), L5 (C), L9 (D), and L10 (E).

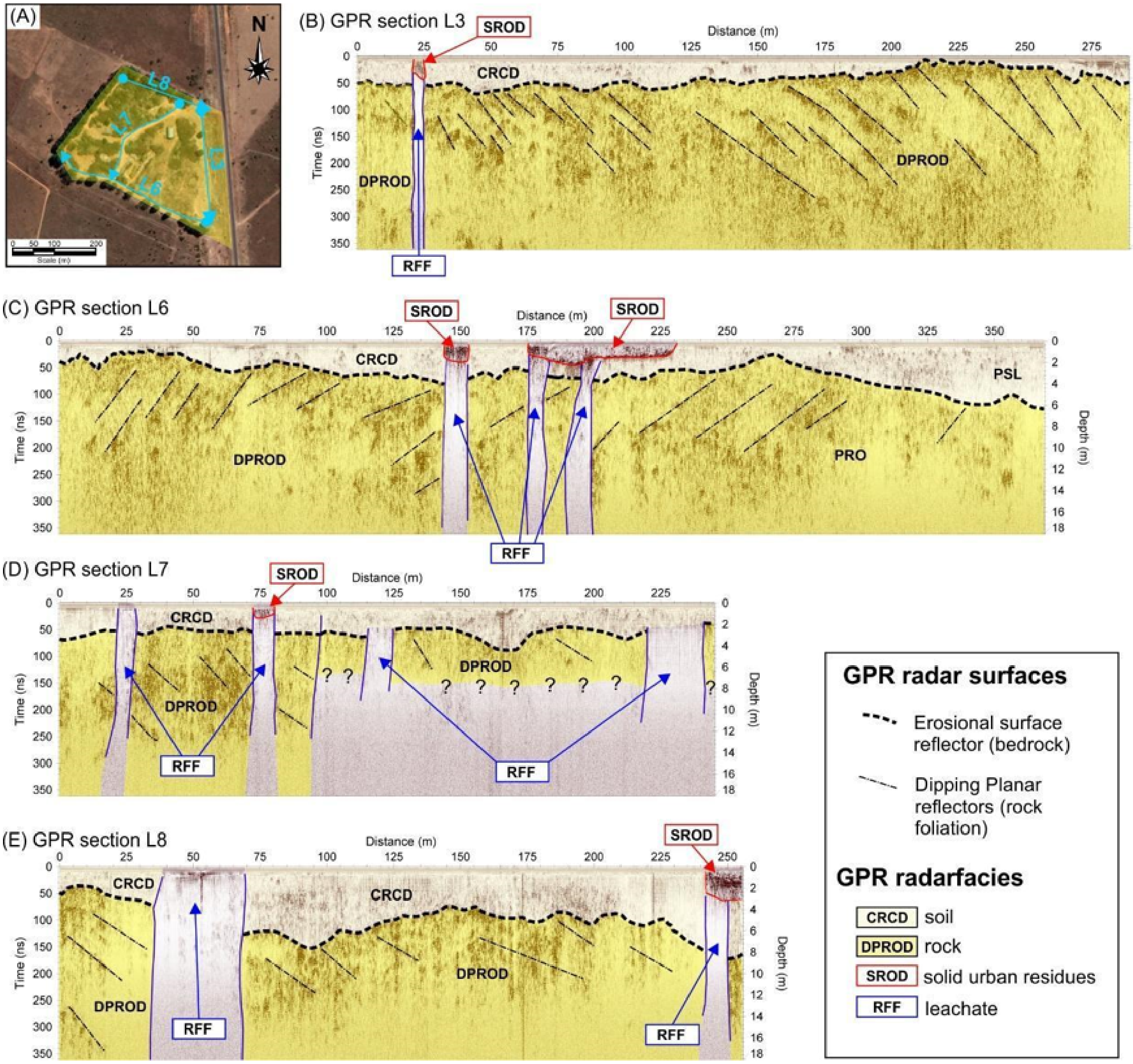

Figure 8

GPR sections are carried within the boundary of APGD, indicating trenches with solid waste (SROD), leachate percolation zones (RFF), soils (CRCD), and rocks (DPROD). (A) location of the GPR sections inside the dumpsite. Sections of Lines L3 (B), L6 (C), L7 (D), and L8 (E) with overlapping interpretations.