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The use of Ground-penetrating radar (GPR) for the characterization of the Vitória massif (Espírito Santo, southeastern Brazil)

Utilização da técnica de GPR (Ground Penetrating Radar) para a caracterização do Maciço Vitória (Espírito Santo, Sudeste do Brasil)

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Abstract: This study aims to characterize, by electromagnetic method, the geological unit Maciço Vitória in the metropolitan region of Vitória-ES, using the technique of GPR- Ground Penetrating Radar. Secondary objectives are to investigate lithotypes and geological structures, to delineate contacts between landfills and Precambrian basement, to investigate and describe geological structure arrangements and to demonstrate the geophysical signature of the studied units. The study area corresponds to the Pedra da Cebola Park area, which belongs to the Maciço Vitória unit, in turn, one unit is located in Vitória, capital of Espírito Santo. Four (4) geophysical profiles were performed in different orientations, so that the different subsurface characteristics were addressed and represented in the radargram. The acquisition of GPR was performed with a 270 MHz (two hundred and seventy megahertz) antenna, the walking was performed using the constant distance method where the antennas rem0ain at a constant distance from each other. The GPR profiles were processed through the RADAN7® program, using advanced data processing until the image obtained showed well-defined reflectors and anomalies. The data of the radargrams showed two important geological aspects: limit of geological units quite delimited and presence of geological structures. Faults and fractures of NE-SW direction and secondarily NNW-SSE and E-W were found, these structures correspond to the regional trend. These structures may be associated with lithostructural controls and neotectonic tensions. The method demonstrated an easy and fast application, highlighting here an optimization of time and cost for analysis of material in subsurface.

Keywords: Ground Penetrating Radar; Fracture; Geophysics.

Resumo: Este estudo tem como objetivo caracterizar, através de método eletromagnético, a unidade geológica Maciço Vitória na região metropolitana de Vitória-ES, utilizando a técnica de GPR- *Ground Penetrating Radar*. Objetivos secundários visam investigar litotipos e estruturas geológicas, delimitar contatos entre aterros e embasamento Pré-Cambriano, investigar e descrever arranjos de estruturas geológicas e demonstrar a assinatura geofísica das unidades estudadas. A área de estudo corresponde a área do Parque Pedra da Cebola, que pertence a unidade Maciço Vitória, por sua vez a unidade fica localizada em Vitória, capital do Espírito Santo. Foram realizados 4 (quatro) perfis geofísicos, em diferentes orientações, de forma que as diferentes características de subsuperfície fossem abordadas e representadas no radargrama. A aquisição de GPR foi realizada com antena de 270 MHz (duzentos e setenta megahertz), o caminhamento foi realizado utilizando o método do afastamento constante onde as antenas permanecem a uma distância constante uma da outra. Os perfis de GPR foram processados através do programa RADAN7®, utilizando processamento avançado de dados até que a imagem obtida apresentasse refletores e anomalias bem demarcados. Os dados dos radargramas mostraram dois aspectos geológicos importantes: limite de unidades geológicas bastante delimitados e presença de estruturas geológicas. Foram encontras falhas e fraturas de direção NE-SW e secundariamente NNW-SSE e E-W, essas estruturas correspondem ao trend regional. Essas estruturas podem estar associadas a controles litoestruturais e tensões neotectônicas. O método demonstrou uma fácil e rápida aplicação, destacando-se aqui uma otimização de tempo e custo para análise de material em subsuperfície.

Palavras-chave: Ground Penetrating Radar; Fraturamento; Geofísica.

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1. Introdução

Espírito Santo lacks geological and geophysical information on a scale that details its lithological units and structural features. In recent decades, studies have been conducted at regional scales (SILVA *et al*., 1987; CPRM, 2015) aiming to develop the geological and scientific knowledge of Espírito Santo.

The city of Vitória, the state capital, has a little-studied geological context, with subsurface studies generally performed through SPT (*Standard Penetration Test*) drilling, mostly directed to the construction industry, since the city has several types of real estate developments. There is a need to use techniques that make it possible to delineate the geological units and their respective structures with greater precision. Due to paving, embankments, and soil sealing, it is important to use indirect subsurface investigation techniques through geophysics; the most widely used in urban areas is GPR (*Ground Penetrating Radar*).

GPR is scientific equipment used in Earth science research that employs the electromagnetic method based on the propagation of electromagnetic waves in the subsurface. GPR has been applied in science for a few decades now, but only in recent years has there been substantial development for several fields of applications, some of these fields are: i) Geotechnics; ii) Environment; iii) Hydrogeology; iv) Forensic Investigations; v) Coastal Studies; vi) Geomorphology; and vii) Geology (NEAL *et al*., 2000).

Espírito Santo uses the technique in several Geosciences fields, mainly Geotechnics, Geological Mapping, Sedimentary Geology, and Hydrogeology. The deficiency in the use of the technique lies mainly in the almost non-existence of equipment and manpower specialized in geophysical methods.

In Brazil, several universities (UFRJ, UERJ, USP, UFPA, UFC, UnB, ON-RJ, among others) develop studies in shallow geophysics, using GPR, aiming to characterize geological structures and lithologies in the most diverse geological environments (PORSANI, 1999).

Thus, this research addresses the use of GPR technique in different geological-geomorphological environments in Espírito Santo, such as crystalline basement and landform zones, proposing to delimit geological units and point out geological structures in the subsurface.

Study area

The study site is in Vitória, Espírito Santo, Southeastern Brazil. Espírito Santo borders the states of Bahia to the north, Minas Gerais to the west and northwest, Rio de Janeiro to the south, and the Atlantic Ocean to the east. The main access roads to the study area are federal highway BR-101, state highway ES-010, and Fernando Ferrari Avenue. Fernando Ferrari avenue is an important highway in Vitória, responsible for connecting neighborhoods such as Goiabeiras, Jardim da Penha, and Jabour, and the state highway ES-010 connects the city of Vitória to the coastal fraction of the city of Serra.

In the studied point (Figure 1), four (4) profiles were made in different directions and sizes. The profiles were made in the NE-SW, E-W, and NW-SE directions and are between twenty-nine (29) and thirty-four (34) meters long and have a maximum depth of six (6) meters.

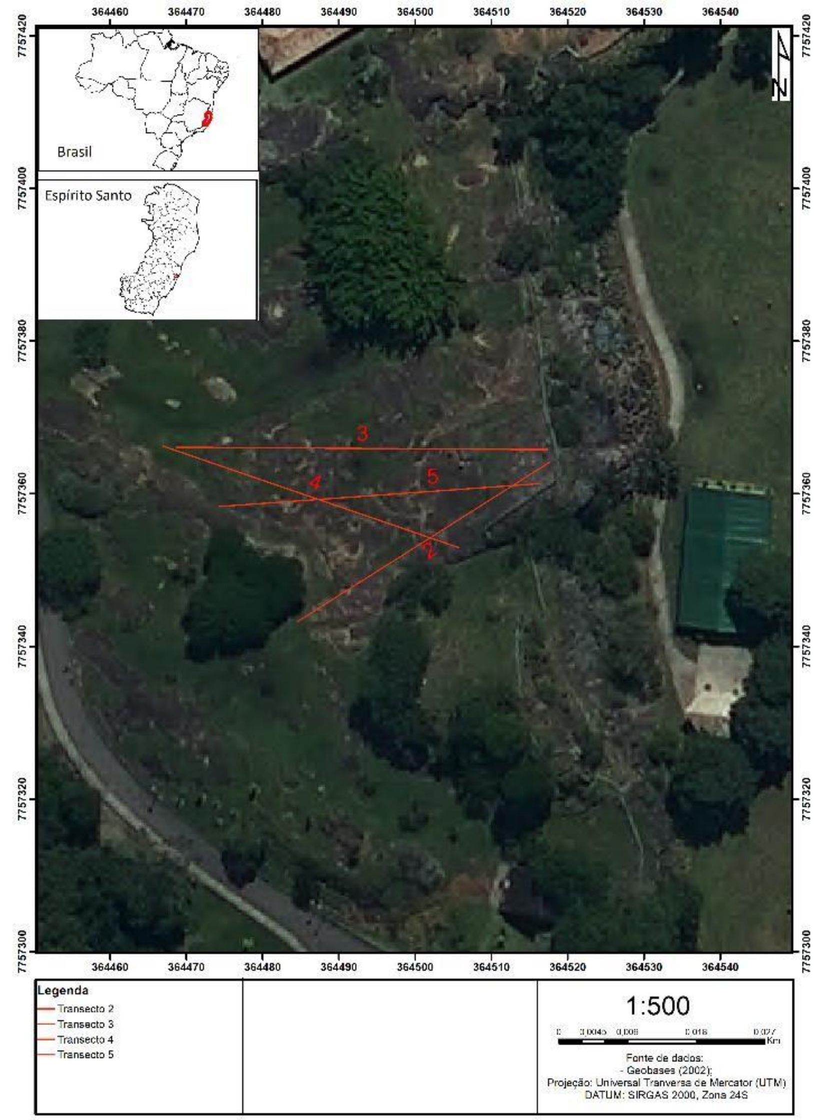

Figure 1 - Map of transect locations in the Pedra da Cebola area.
Source: Authors (2019).

Regional geology

The state geology of the study area (Figure 2) can be divided into two main compartments: i) Precambrian basement consisting basically of igneous and metamorphic rocks; and ii) Cenozoic sedimentary deposits, consisting of the Barreiras Formation and Quaternary deposits of the Espírito Santo basin (BRICALLI, 2011).

The rocks corresponding to the Precambrian basement of the study area were generated during the Brasiliano Cycle and are linked to a complex association of igneous and metamorphic rocks of the Mantiqueira Province. In the state of Espírito Santo, the Araçuaí and Ribeira orogens predominate (TUPINAMBÁ *et al*., 2013).

The Araçuaí Orogen extends from the São Francisco Craton to the Atlantic coast and is between parallels 15 and 21. On the 21st parallel, a transition from the Araçuaí Orogen to the Ribeira Orogen can be observed. This same transition is characterized by changing the NNE direction structure in the north to NE in the south (HEILBRON *et al*., 2004).

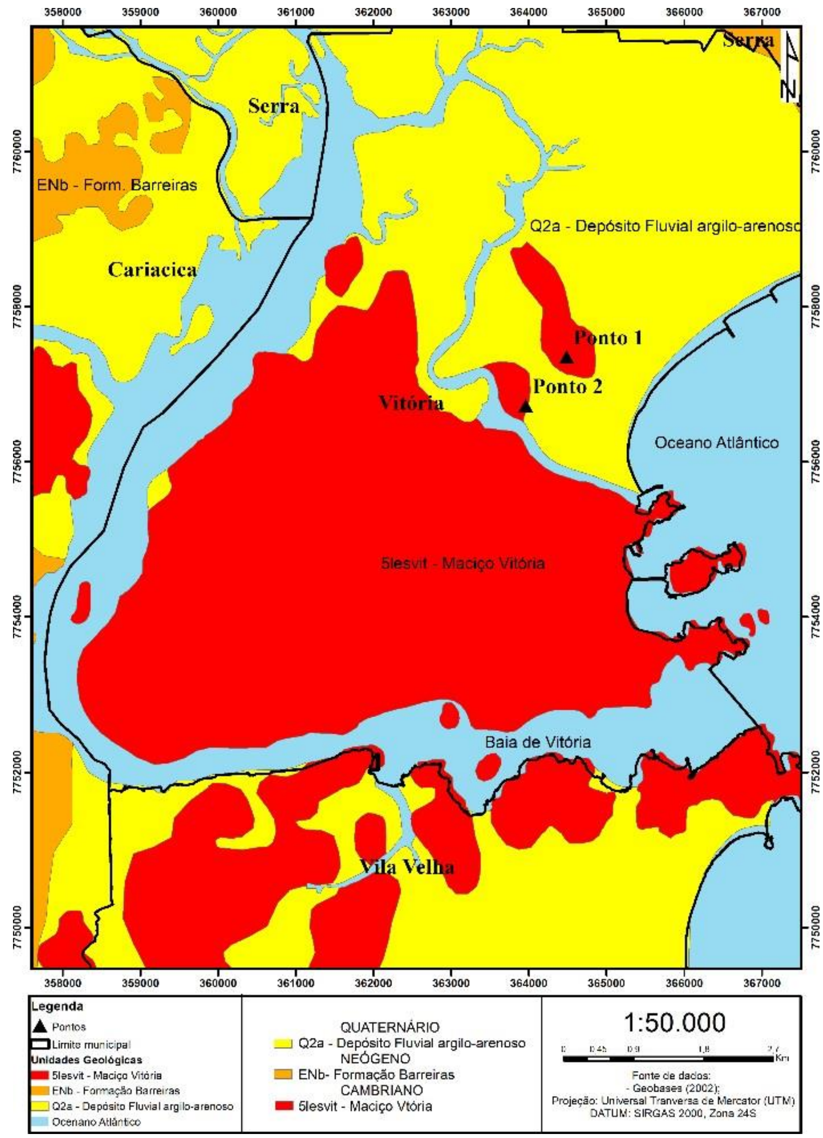

Figure 2 - Geological map of the study area.
Source: Authors, 2019.

According to Pedrosa-Soares *et al*., (2013), the Araçuaí Orogen is characterized as a Neoproterozoic-Cambrian orogenic set, which belongs to the reentrance originated by the Congo and São Francisco cratons, its geotectonic components evidence a collisional orogenic system that succeeds an accretionary orogenic system of active margin. The Orogen has an intrinsic characteristic, that is, its confinement to reentrance, it implies the partial connection of the San Francisco and Congo cratons during the taphonomic traphogenesis (2 Ga) until the opening of the South Atlantic through the Bahia-Gabon Cratonic Bridge.

Machado *et al*., (1996) characterized the genesis of the belt as originating during the Brasiliano orogeny and identified that its large-scale structures result from compression against the São Francisco craton in the north and central part. The area comprises a series of stacked pulses under crustal scale amphibolite grade metamorphic conditions.

Tupinamba *et al*., (2013) address that much of the State of Espírito Santo is contained within the Cambuci Domain, i.e., the Eastern Terrain. According to the author, this terrain consists of a metavolcanic-sedimentary succession metamorphosed into high amphibolite and granulite facies, intruded by several generations of granitoid rocks.

Machado *et al*., (1996) discuss that the central part of the Ribeira Orogen, which constitutes a significant part of Espírito Santo, is divided into litho tectonic domains: i) Coastal Domain, the domain responsible for the litho tectonic features in the coastal part of Espírito Santo; ii) Paraíba do Sul Domain; iii) Juiz de Fora Domain; and iv) Andrelândia Domain. The Coastal Domain has as main lithotypes a variety of igneous and metamorphic rocks with a predominance of orthogneisses with mafic lenses and monzogranites. The Coastal Domain is largely the result of crustal remobilization that occurred during the Brazilian orogeny.

2. Methodology

For the elaboration of this study, two (2) essential steps were considered: i) office analysis and ii) field analysis.

The office analysis consists of making the lineament map and processing the field data.

The lineament map was made by manually extracting the lineaments, for which a Digital Elevation Model (DEM) was prepared. The DEM was extracted from http://srtm.csi.cgiar.org/ (REUTER et al., 2007) corresponding to the *Shuttle Radar Topography Mission* (SRTM-NASA) orbital survey from February 11 to 22, 2000. The image was processed and applied 315° (azimuth) artificial illumination obtained from the "*Hillshade*" tool of ArcGis 10.1™ (ESRI, 2012). The solar elevation used was 45º and the establishment of the "*Z-factor*" was calculated from the average between the values of the latitudes encompassing Espírito Santo, using 0.00000934 (BRICALLI, 2011). Then the lineaments were extracted using the ArcGis 10.1™ editing tool (ESRI, 2012), considering these identification elements: ridge alignments, valleys, river and lake *trench's*, and elongated depressions (LIU, 1984).

The field analysis stage consisted of subsurface radar investigations (Figure 3) aiming at geophysical profiling and geological data collection.

Figure 3 - GPR GSSI3000 with the 270MHZ antenna, 1) Complete equipment, operator view; 2) Equipment in profile; 3) Control unit; 4) 270 MHz antenna.
Source: Authors, 2019.

The GPR equipment used corresponds to the SIR3000 model from GSSI (*Geophysical Discovery Systems Inc*.), belonging to the Graduate Program in Geography (GPGP) of the Federal University of Espírito Santo (UFES).

The equipment consists of a digital control unit and an antenna unit, which in turn consists of two antennas, a transmitter, and a receiver, shielded by a resin case. In this research, the equipment was used in a transporter car, one of the wheels of which contains an odometer that, connected to the control unit, is responsible for measuring the distance traveled in the profiles surveyed. The data collection was conducted in two simultaneous ways, the performance of the geophysical profiles and the description of lithologies and structures at the studied points.

The geophysical profiles were performed in Common-offset mode (Figure 4), which is the most conventional survey method and has the characteristic of positioning the antenna perpendicular to the survey line:

Reflection Profile with Constant Offset (*Common-offset*)

This technique consists of a geometry that keeps a fixed distance between the transmitting antenna (Tx) and the receiving antenna (Rx) along a profile, thus obtaining an image where the horizontal axis represents the position of the antennas and the vertical axis the variations of dielectric properties in the subsurface (BORGES, 2004). The time between wave transmission, reflection, and reception is measured in nanoseconds (10^{-9} s), called *two-way travel* (TWT). The first wave pulse received is called the *airwave*, and the second is the *ground wave*, these two pulses were neglected since they do not represent the subsurface and mask the first reflectors (ROCHA, 2013).

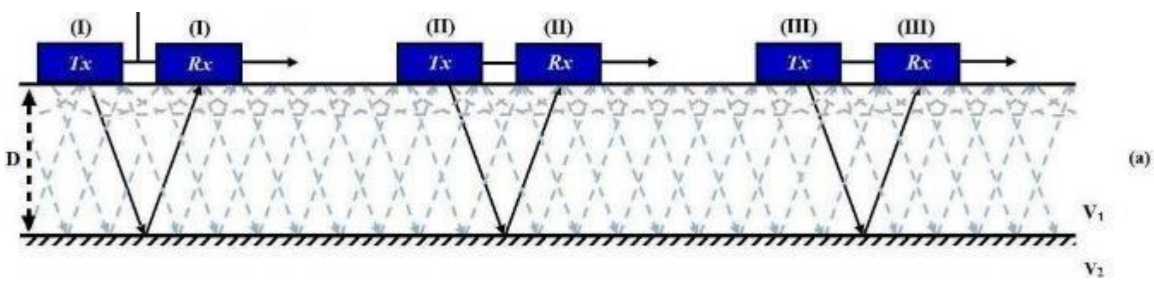

Figure 4 - Constant distance reflection profile acquisition technique.
Source: Furtado (2010).

The location of the profiles respected the previous data survey of the area and the field surveillance, so they were arranged in directions that would facilitate obtaining the best radargram possible. The walkthroughs were conducted within the area where there was borehole data in field campaigns conducted from January to April 2018, this way it is possible to compare the different responses of the radargrams with the lithological variations in the subsurface when it was not possible to walk under the exact spot of the borehole, it was moved to have the greatest possible correlation between the borehole data and the radargrams.

The field data were processed in the RADAN7 software, developed by GSSI and licensed to the Graduate Program in Geography (PPGG) of the Federal University of Espírito Santo (UFES), the program offers a practical and didactic interface for data processing considering the geophysical properties of the environment.

The data processing step starts with the verification of the field acquisition parameters. For Jol (2008), the transformation of data into information can follow two paths: i) the first is correlated to geophysical methods where the GPR response is represented in sections, spreadsheets, or volumes indicating anomalous targets, and ii) the second path consists in quantifiably extracting variables correlated with waving properties (velocity, attenuation, and impedance) and then translating the same properties into quantitative data.

Data processing for the present research consisted of: i) editing the data; ii) basic processing; iii) advanced processing; and iv) visualization/interpretation of the processing (JOL, 2008). To achieve the level of interpretation required in this research, it was necessary to use advanced processing methods, and for this purpose, techniques of time filters, depth filters, signal gains, migration, and zero-time correction were employed.

According to Jol *et al*., (2003), radargrams are interpreted by observing the principles of reflection seismic (Figure 5), i.e., this interpretation is made through the concept that the reflections obtained in the radargram are results of bedding surfaces and subsurface unconformities.

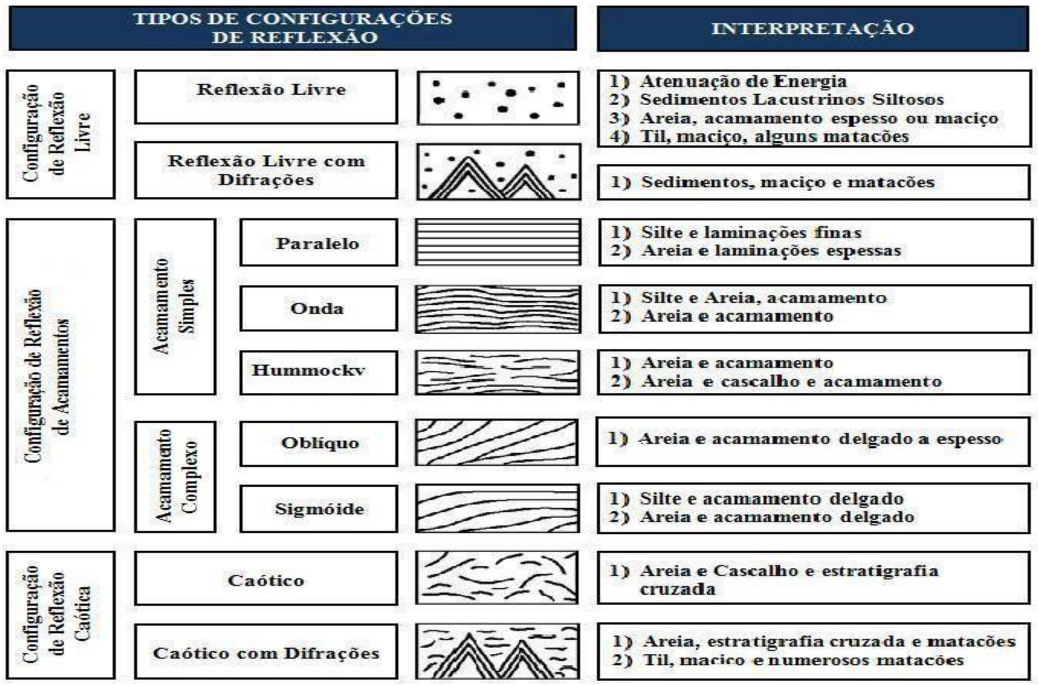

Figure 5 - Types of reflections found in various lithologies.
Source: Haeni (1988, apud Furtado, 2010).

From the configuration of the reflectors obtained in the radargram, it is possible to associate them with different types of substrates, be they lithological, artificial, or even lithostructural if we consider rocky substrates affected by structures such as fractures, faults, joints, dissolution structures, dikes, and veins.

A good understanding of the response of the GPR technique to different media is a facilitating tool, it is important to know how to differentiate the types of responses possible when working in highly fractured or massive media. Fractured massifs will have a more chaotic reflection pattern, while reflections attached to sedimentary layers show laminated, sub-horizontal, concordant, and coherent patterns (XAVIER NETO, 2006). According to Haeni's (1988) classification, the most frequently encountered reflection patterns are free reflection, free with diffractions, wave, oblique, and chaotic.

3. Results and discussion

Lineament analysis

The lineament map (Figure 6) was made manually, at the scale 1:75000, covering the area of the RMGV and with a total of 122 (One hundred and twenty-two) lineaments. The rosette diagram shows a higher concentration of lineaments in the NE-SW, N-S, and NW-SE directions. The longest lineaments have a NE-SW direction.

Another interesting observation is the density of lineaments, it is observed that the density of the largest lineaments (14 - 42) has a NE-SW orientation. Correlate the directions corresponding to the Colatina Belt, with an NW-SE and NE-SW structural trend in the most Cenozoic portion of the area (sandy clay Fluvial Deposits and Barrier Formation) and with an NW-SE trend further south of the area.

The observed patterns show a clear distinction even at a local scale, so we can conclude that it reflects the regional patterns observed in a previous study (BRICALLI, 2011; RIBEIRO, 2010).

The lineaments found to show that there is a predominance of NE-SW structures, followed by NNW-SSE lineaments. The predominance of NE-SW lineaments can be explained by the predominance of NE-SW faults, fractures, and foliations, related to the structuring of the Ribeira Belt, cut almost perpendicularly by NW-SE oriented structures (MACHADO FILHO *et al*., 1983; PEDROSA SOARES and WIEDEMAN-LEONARDOS, 2000; BRICALLI, 2011);

The NNW-SSE lineaments may be associated with the Colatina Belt, the most important structural feature in Espírito Santo.

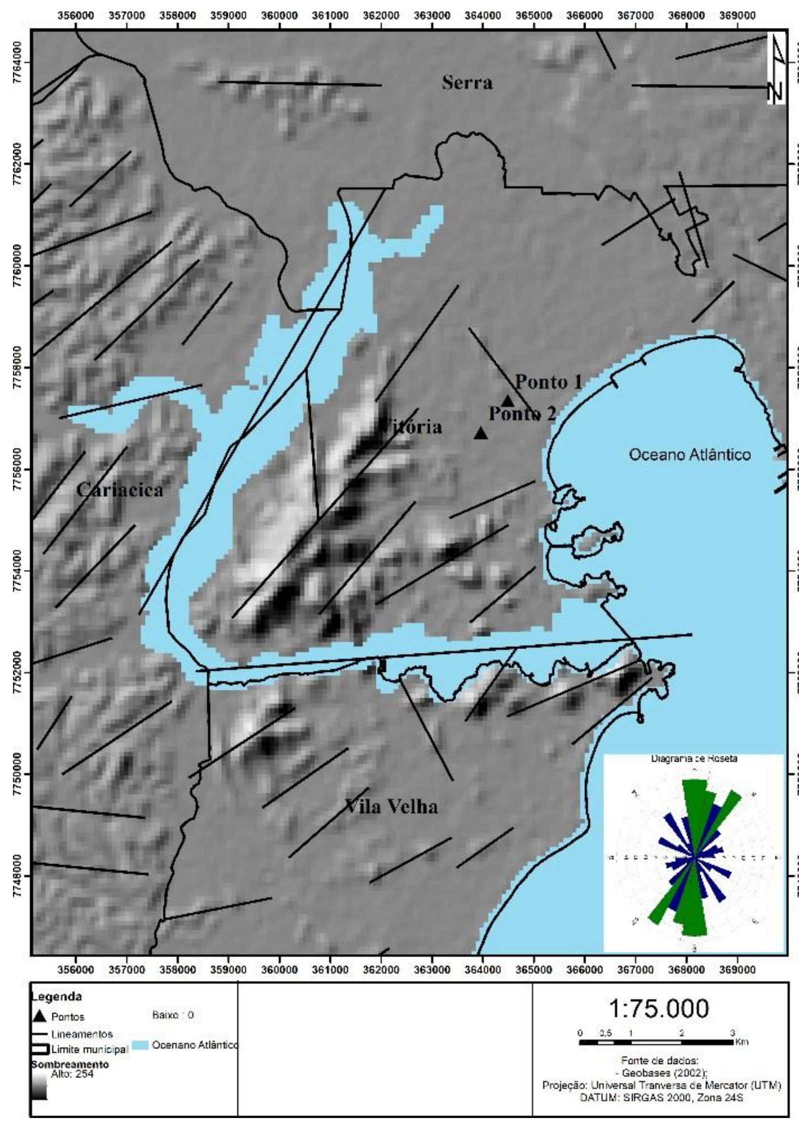

Figure 6 -Lineament map of the area encompassing the studied points on DEM at 315° illumination. Rosette diagram demonstrates the highest density of lineament orientations (green), the median orientation (red), and the others. Source: authors, 2019.

Geophysical analysis

The rock lithology in this area consists of black-colored mafic rocks with an index of melanocratic crystals oriented toward the magmatic flow. The rocks present an anisotropic structure with holocrystalline, unequigranular, phaneritic texture, medium to coarse-grained with feldspar porphyries. Mineralogically the rock is composed of quartz, biotite, and plagioclase.

Families of joints (Figure 7) perpendicular to each other was found in various portions of the rock, this pattern was interpreted as planes of weakness in the rock.

Figure 7 - Granite with soil-filled fractures at the study point.
Source: Authors, 2019.

Two fracture families in the SW portion of the outcrop show distinct behaviors. The first pattern refers to the uppermost part of the outcrop and presents 180/65 planes, NNE-SW orientation. The second pattern is almost orthogonal to the first family, so it has planes with measurements of 270/43 and 275/50, E-W orientation.

Radargram 02 (NE-SW)

The first transect (02) has a NE-SW direction, is six (6) meters deep, and is twenty-nine (29) meters long.

Radargram 02 (Figure 8) shows a reflector zone of up to 40 ns. In this area, we can observe horizontal reflectors in the central portion of it; Already, in the extremes of the radargram 02 profile, it is possible to observe sub-horizontal reflectors and some hyperbolas, these two areas were interpreted as places where there is the presence of families of asymmetric joints filled by soil.

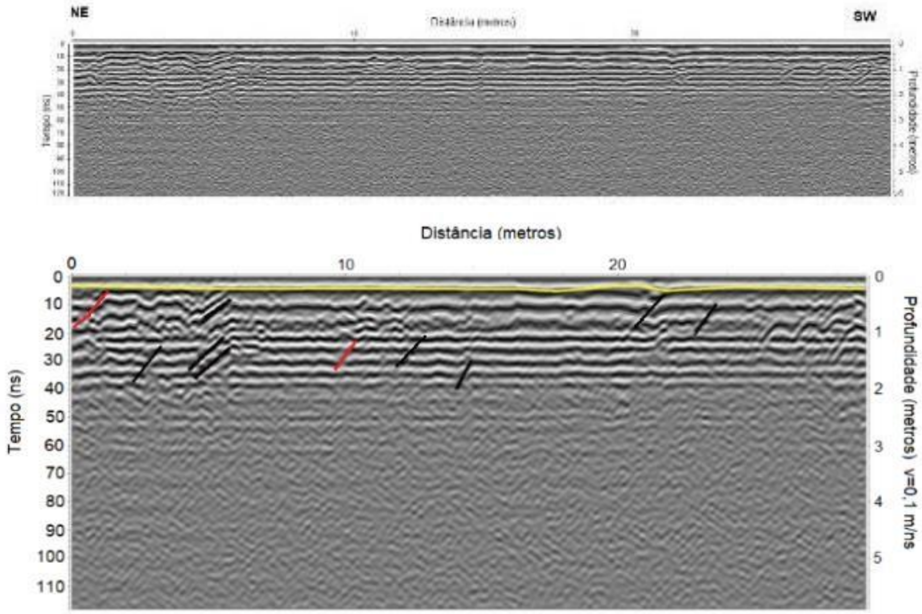

Figure 8 - Radargram 02, an area located in Pedra da Cebola Park.
Source: Authors, 2019.

<u>Sub-surface lithotypes and geological structures</u>

The radargram shows a geologically homogeneous area, where almost the entire area shows reflections characteristic of granite belonging to the Precambrian basement, that is, it shows horizontal to sub-horizontal reflections. Some structures are identified in the area, presenting breaks in the continuity of the reflectors, and are identified as a product of rock fracturing, having representations in the uppermost layers and the deeper layers, also filled by soil (Figure 9).

<u>Contact between Precambrian basement rocks and technogenic deposits</u>

Shallow, bulging reflectors characterize the contact between the ground and the basement at four (4) meters and twenty-two (22) meters. Due to the inexpressive soil portion at these points and throughout the rest of the profile, there is no typical, well-demarcated reflector representative of the contact between the two mentioned units. The interpretation of the presence of soil at the site was only possible by comparing the field photos and the radargram (Figure 9).

<u>Geophysical signature of the main lithotypes</u>

The studied point demonstrated two (2) geophysical signatures (Figure 10) that stand out within the radargram: i) the first is formed by horizontal reflectors with small breaks in their continuity, thus being interpreted as fracture zones, as can be demonstrated by the structural patterns observed on the surface; ii) the second signature is formed by subhorizontal to horizontal reflectors that demonstrate the presence of fractures and the accommodation of the soil in them.

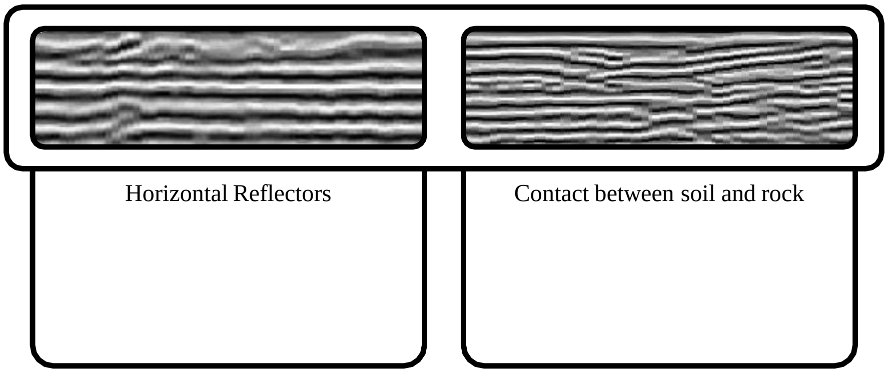

Figure 9 - Main geophysical signatures of the studied point.
Source: Authors, 2019.

Radargram 03 (E-W)

The second transect (03) was made in an E-W (East-West) direction, with a depth of 6 (six) meters and a length of 34 (thirty-four) meters.

Radargram 03 (Figure 11) shows a reflector area that goes up to 40 ns with horizontal reflectors ranging from 30 ns to 40 ns. Above this area are horizontal and sub-horizontal reflectors. Radargram 03 profile shows at positions four (4), fourteen (14), and twenty-six (26) meters reflections associated with families of soil-filled joints. In the last position (26 meters), an area with soil has already formed, thus observing the contact between the basement and the soil, delimited by joints.

Sub-surface lithotypes and geological structures

The radargram shows another area that is also geologically homogeneous. Its reflectors are characteristic of granite belonging to the Precambrian basement, i.e., it shows horizontal to sub-horizontal reflectors with little contrast with reflectors of other shapes.

At this point, you can see some portions with concave reflectors, where well-formed soil portions have been observed. The area is similar to the other points in terms of the structures present, demonstrated in the radargram by breaks in the continuity of the reflectors, and is identified as a product of rock fracturing, with representations in both the upper and deeper layers and filled with soil (Figure 11).

Contact between Precambrian basement rocks and technogenic deposits

You can see on the radargram, just below the airwave characterized by the horizontal reflectors, an area approximately one (1) meter thick that extends along the entire length of the radargram. Subhorizontal reflectors form this same area amidst more chaotic patterns. In certain portions, well-demarcated reflectors can still be observed along with small reflection breaks, so it can be interpreted that this area corresponds to the interaction between juvenile soil and a shallower fracturing of the porphyritic granite belonging to the basement. Portions where the soil is better formed, have strong reflectors establishing the contact between this unit and the sotopposite unit (Figure 10).

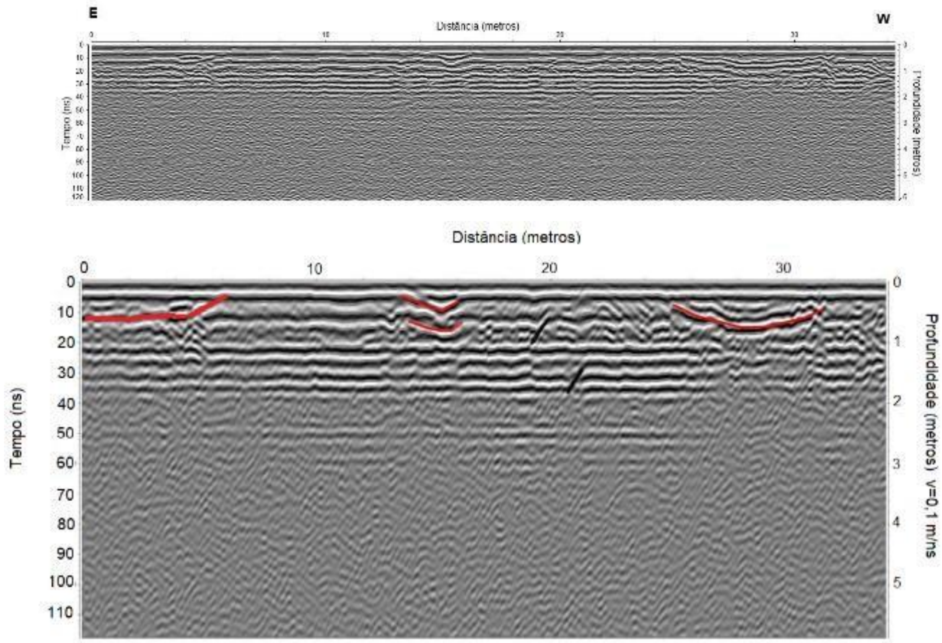

Figure 10 - Radargram 03, an area located in Pedra da Cebola Park.
Source: Authors, 2019.

Geophysical signature of the main lithotypes

The studied point demonstrated two (2) geophysical signatures (Figure 11) that stand out within the radargram: i) the first is formed by horizontal to subhorizontal reflectors referring to the porphyritic granites represented in the area; ii) the second geophysical signature of the area is subhorizontal and concave reflectors that demonstrate fracturing of the area with accommodated soil parcels preening them.

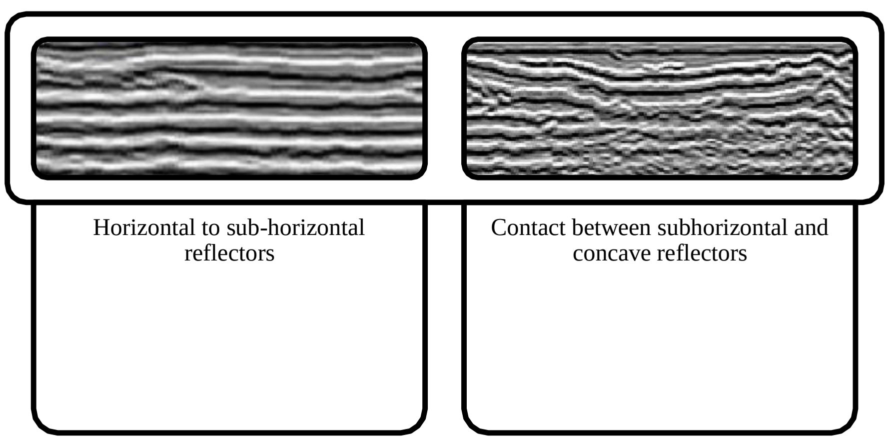

Figure 11 - Main geophysical signatures of the studied point.
Source: Authors, 2019.

Radargram 04 (NW-SE)

The third transect (04), conducted in the NW-SE direction, is six (6) meters deep and twenty-two (22) meters long. Radargram 04 (Figure 12) shows reflections up to 40 ns, and signal loss is observed at 30 ns in some areas. In almost the entire radargram, reflections with a horizontal pattern are observed. In the central portion of the profile (approximately 10 to 12 meters), hyperbolas are observed and may be associated with unfilled joints, as families of joints overlain by clay material are observed above them. The other areas of the radargram, with the pattern of horizontal reflectors, are associated with the lithology (porphyritic granite) that predominates in the area.

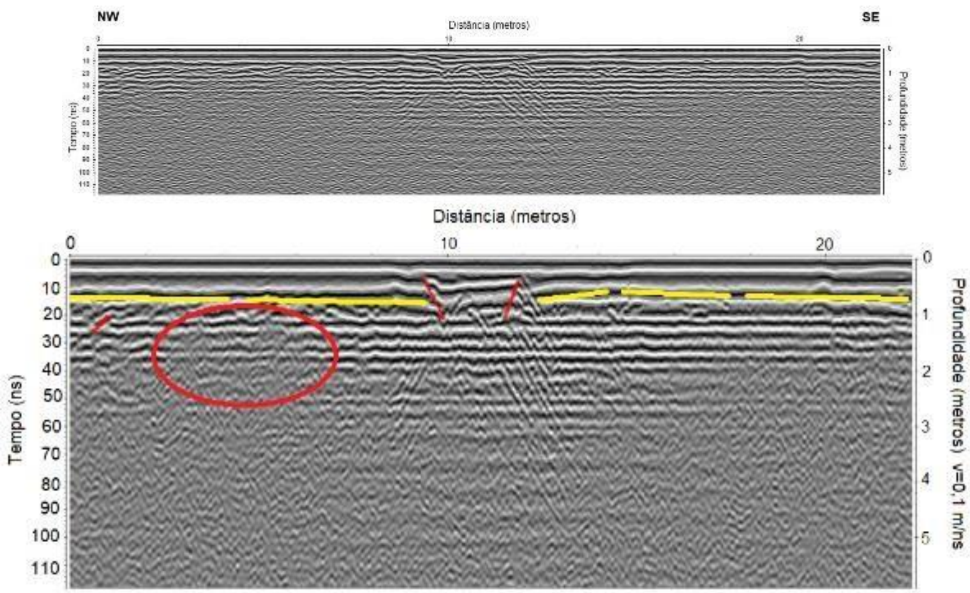

Figure 12 - Radargram 04, an area located in Pedra da Cebola Park.
Source: Authors, 2019.

<u>Sub-surface lithotypes and geological structures</u>

Horizontal to sub-horizontal reflectors can be seen on the radargram just below the airwave area on almost the entire radargram, which can be interpreted as the Precambrian basement.

Approximately 10 (ten) meters in length can be observed a fractured area on its edges, with the center constituted by reflectors that stand out from the rest of the profile. This area was interpreted as fractured granite with the filling of the fractures by soil overlain by a region consisting of soil. The structure is classified as an inverted flower structure characteristic of sedimentary environments with strong structural control.

At approximately six (6) meters in length of the profile, there is an area of shading possibly caused by water in fractures in the basement or by a portion of wet soil on the ground. The area was interpreted this way due to the absence of reflectors at the site, caused by the sudden change in wave speed as it passed through a wet material and of composition very different from the studied medium.

<u>Contact between Precambrian basement rocks and technogenic deposits</u>

The area has well-demarcated reflectors in the two units that constitute it. There is a good separation with well-marked reflectors in the contact between them. This can be seen in the area encompassing the bloom structure, where contact between the basement and the soil reflector despite being separated on the sides by fractures in the deepest part (Figure 13).

<u>Geophysical signature of the main lithotypes</u>

The studied point demonstrated 2 (two) geophysical signatures (Figure 13) that stand out within the radargram: i) the first is formed by horizontal reflectors, sometimes discontinuous, associated with fractured granite; ii) the second signature is demonstrated by intensely discontinuous reflectors, which show intensely fractured areas.

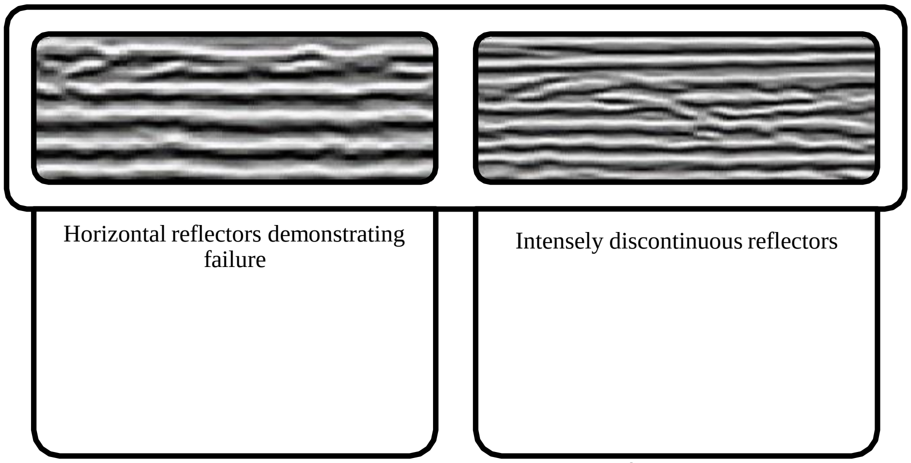

Figure 13 - Main geophysical signatures of the studied point.
Source: Authors, 2019.

Radagram 05 (E-W)

The fourth and last transect (05) was made in the E-W direction, is six (6) meters deep and twenty-nine (29) meters long.

Radargram 05 (Figure 15) shows reflections up to 40 ns, and its main reflectors are also in the horizontal and sub-horizontal patterns. In the first meters of the transect, some hyperbolas are associated with geotechnical tie-rods, and their presence is due to high granite turnover in this position. In some portions of the profile, mainly at 3 (three) meters and 8 (eight) meters, fractures varying from millimeters to decimetric can be found, i.e., outside the resolution range of the 270 MHz antenna and therefore poorly represented in the radargram, but evidenced by the presence of the ties in that position.

<u>Sub-surface lithotypes and geological structures</u>

Two bands of reflectors are observed on the radargram, the uppermost one shows subhorizontal to chaotic reflectors in some portions. In this area, the presence of soil, fractured rock with soil filled fractures, and geotechnical tie rods in the subsurface are observed. In the lower portion, the presence of parallel to sub-parallel reflectors is observed in almost all its extensions, however, this area is more fractured than the others, and this implies the presence of well-demarcated fractures in almost all the extensions of the radargram.

The initial part of the radagram (Figure 14) shows slightly marked hyperbolic characteristics of targets of completely different composition from the natural materials, which are identified as geotechnical ties used for rock mass stabilization. One notes the large presence of fractures where the hyperbolas are found at the expense of the other end of the profile.

<u>Contact between Precambrian basement rocks and technogenic deposits</u>

Strong reflectors are observed on the radargram separating the basement area from the underlying soil unit. In addition, the hyperbolas at the beginning of the profile are well marked and are characteristic of the presence of material with electromagnetic characteristics very different from the material in the rest of the area.

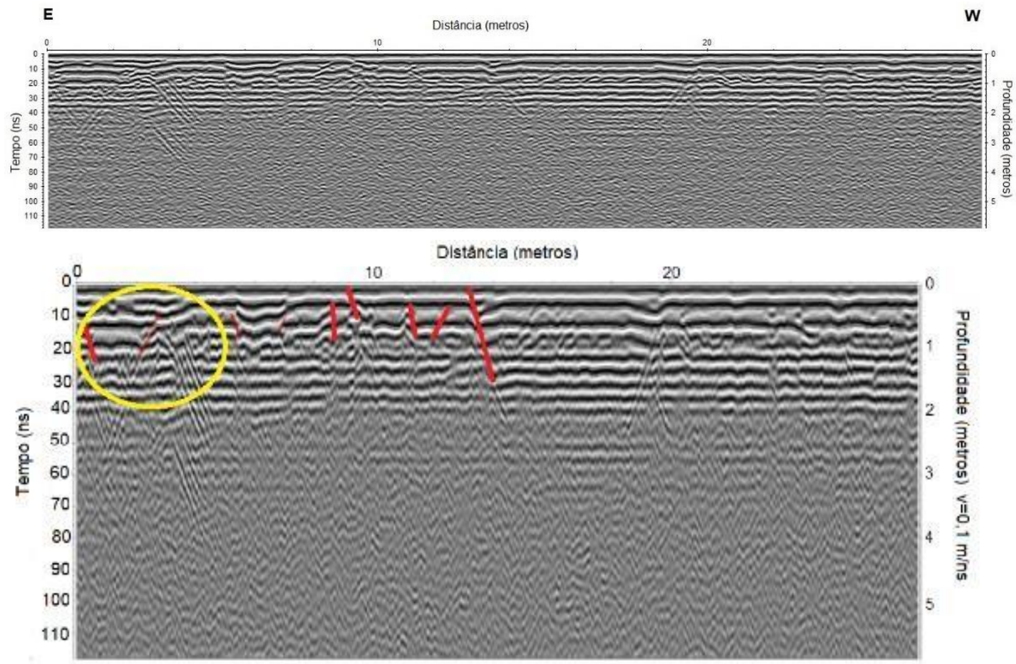

Figure 14 - Radargram 05, an area located in Pedra da Cebola Park.
Source: Authors, 2019.

Geophysical signature of the main lithotypes

The studied point demonstrated two (2) geophysical signatures (Figure 15) that stand out within the radargram: i)the first one is formed by horizontal reflectors characteristic of granitic rocks as in the rest of the studied points; ii) the second geophysical signature is formed by hyperbolas that are interpreted as representing material that is out of *the background,* and, in this case, is interpreted as representing the presence of geotechnical tie-rods present in this portion of the studied area.

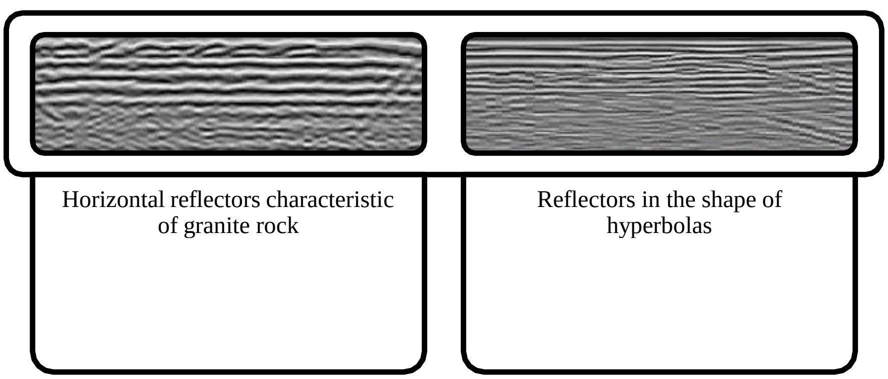

Figure 15 - Main geophysical signatures of the studied point.
Source: Authors, 2019.

4. Final considerations

Using the GPR technique to obtain high-resolution subsurface imaging has proven effective.

The quality of the products is directly linked to the compositional characteristics of the subsurface materials and their arrangement in the medium and the data processing. Due to the predominance of GPR research in the sedimentary area, as it provides higher-quality reflection patterns, this research presents different ways of identifying and interpreting reflectors in igneous terrain with intense structuring.

The radargram data showed two important geological features: the boundary of very striking geological units and the presence of geological structures.

Radargrams with interrupted reflectors were observed in certain regions, which shows the strong structural control present in the area, through the measurements taken in the field and the data mentioned above, it was possible to observe a predominance of NE-SW and NNW-SE fractures.

Both the lineaments on the image and the field measurements showed that the NE-SW structures are very well marked.

The predominance of NE-SW lineaments can be explained by the predominance of NE-SW faults, fractures, and foliations, related to the structuring of the Ribeira Belt, cut almost perpendicularly by NW-SE oriented structures (MACHADO FILHO et al., 1983; PEDROSA SOARES and WIEDEMAN-LEONARDOS, 2000; BRICALLI, 2011);

However, in addition to the association with the mentioned lithostructural controls, the lineament patterns in the area and the structural patterns in the field may reflect neotectonic stresses documented by Bricalli (2011) in the state of Espírito Santo, once the author highlights fracturing patterns verified in the Cenozoic Deposits Compartment presenting similarities to those found in the Precambrian Embasement Compartment in the state of Espírito Santo, thus affirming that it may reflect the neotectonic reactivation of preexisting structures, attested by the continuity of structural trends.

That being the case:

- the NNE-SW to NNE-SW orientations, found in the lineaments and the field, can be associated with fracturing patterns characterized by NE-SW normal faulting, related to a NW-SE oriented distensive tectonic regime, attributed to a Holocene age (BRICALLI, 2011);
- the set of lineaments with orientation in the NNW quadrant, found in the lineaments, is associated with fracturing patterns characterized by NW-SE normal faults, with less common NNW-SSE sinistral faults, both related to the E-W dextral transcurrence regime (BRICALLI, 2011);
- E-W lineaments, present in the field, can be associated with dextral faults with approximately this orientation, also related to the dextral E-W transcurrent regime (BRICALLI, 2011).

The results obtained, especially in the Pedra da Cebola radargrams, confirm the importance of neotectonic mechanisms in the structuring of the Brazilian continental margin, as has been discussed by different authors (HASUI, 1990; SAADI, 1993; MELLO, 1997; BEZERRA *et al*., 2001; FERRARI, 2001; RICCOMINI *et al*., 2004; BRICALLI, 2011).

The method has demonstrated easy and fast application, highlighting here an optimization of time and cost for analysis of subsurface material.

The GPR presented some limitations, such as the presence of water in the subsurface and the limitation regarding the depth observed in the radargrams that can be considered shallow for geological materials, these same limitations can be solved with the realization of other geophysical and geological data acquisition method, for example, we can cite boreholes and electrosensitivity profiles as long as the limitations of the physical environment, and the chosen method are respected.

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