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DETECTION OF A FRACTURED AQUIFER THROUGH MULTIPLE VERTICAL ELECTRIC SOUNDINGS AND BY MULTILEVEL ELECTRIC PROFILING

José Agnelo Soares and Juliana Targino Batista

ABSTRACT. This paper analyzes the effect of adoption of different configurations of electric resistivity method to investigate the occurrence of potential fractured aquifers. In an area where there is a subvertical fracture zone in the crystalline basement the techniques of multiple vertical electrical soundings (VES), using the Schlumberger array, and electrical profiling using the multilevel gradient array, were applied. Three different configurations were tested in a same line whose direction is approximately perpendicular to the fracture plan. The results show that the multilevel gradient array presented better clarity in detecting fracture zone than the settings using vertical electrical soundings. However, such subvertical structures could still be detected by VES, since it is adopted a proper separation between the VES centers. Obtained geoelectric sections indicate the presence of a groundwater accumulating structure composed by a crack-induced stream. Additionally, the electric gradient profiling presents operational advantages in relation to other arrays, being more practical and fast for data acquisition in the field.

Keywords: hydrogeophysics, electric resistivity, crystalline basement.

RESUMO. O presente trabalho analisa o efeito da adoção de diferentes configurações do método da eletrorresistividade para investigar a ocorrência de potenciais aquíferos fissurais. Em uma área onde reconhecidamente existe uma zona de fraturas subverticais no embasamento cristalino foram aplicadas as técnicas de múltiplas sondagens elétricas verticais (SEVs), utilizando o arranjo Schlumberger, e o caminhamento elétrico utilizando o arranjo gradiente multinível. Três diferentes configurações foram testadas em uma mesma linha cuja direção é aproximadamente perpendicular aos planos das fraturas. Os resultados obtidos mostram que o caminhamento elétrico multinível pelo arranjo gradiente apresentou maior clareza na detecção da zona de fraturas em relação às configurações utilizando sondagens elétricas verticais. No entanto, tais estruturas subverticais ainda poderiam ser detectadas por sondagem elétrica, desde que adotado um afastamento adequado entre os centros das SEVs. As seções geoelétricas obtidas pelas configurações testadas indicam a presença de uma estrutura acumuladora de água subterrânea do tipo riacho-fenda. Adicionalmente, o caminhamento elétrico pelo arranjo gradiente apresenta vantagens operacionais em relação às demais configurações, sendo mais prático e rápido nos trabalhos de aquisição de dados no campo.

Palavras-chave: hidrogeofísica, eletrorresistividade, embasamento cristalino.

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INTRODUCTION

The semi-arid northeastern region of Brazil in the last past six years went through a period of serious water restriction caused by the occurrence of a dry weather phenomena that lately seems to perform with greater intensity than usual. As a result of this dry season, the surface water sources such as ponds, rivers and dams are in their vast majority dried or almost empty. In this context the groundwater resources are one of the most secure and reliable sources for the human water demand.

According to the Agência Nacional de Águas - ANA (2017) this scenario resulted in a significant increase in the quantity of drilled tubewells in northeastern Brazil, influenced, among other factors, by the water shortage in recent years. Vicente et al. (2018) state that about 51% of Brazilian municipalities are supplied by groundwater. The public water supply of capital cities like Maceió and Natal is entirely carried out by groundwater. The States of Piauí and Maranhão have a percentage of groundwater utilization above 80%. In 2018 August, the Paraíba State featured 19,363 tubewells registered in SIAGAS (CPRM, 2018), highlighting the importance of groundwater resources for population of the Northeast region of Brazil.

The study area of this work is located in the city of Campina Grande, Paraíba State. This region is characterized for presenting an annual average rainfall of 765 mm and high evapotranspiration rates throughout the year, with drainage network consisting of intermittent seasonal watercourses. About 70% of the substrate of this region is composed of igneous and metamorphic rocks, where the main form of movement and storage of water occurs along the surfaces and/or plans of discontinuities, featuring in this way, a fractured aquifer. The combination of these factors results in the low infiltration and recharge rates of aquifers in the area, thus underground water potential of the municipality depends on the density, connectivity and opening of pre-existing fractures (Coriolano, 2002).

Preliminary evaluations conducted by Souza Filho et al. (2016) for tubewells data registered by CPRM (the Brazilian Agency for Mineral Resources Prospection) from Campina Grande and surroundings, showed that of a total of 1720 selected wells,15% of these wells presents flow rates up to 0.3 m^3/h, 36% of these wells have flow rates between 0.3 and 1.0 m^3/h, 39% between 1.0 and 5.0 m^3/h and only 10% have flow rates greater than 5.0 m^3/h, with a median of 1.0 m^3/h.

Traditionally, since the 1960's, the methodology used in hydrogeological prospecting in northeastern Brazil, and other crystalline terrain, has been based on the use of geological criteria, through the analysis of aerial photographs and geology of surface (Siqueira, 1963; Medeiros, 1987). However, the investigation of the fractured zones in hardrocks represents a constant challenge for hydrogeologists, whereas the index of failure associated with the locations of wells is quite high.

According to Medeiros (1987), in tapped wells from Bahia, another Northeastern Brazilian State, the location failure index using the traditional method, is around 30%. The wells in the city of Campina Grande are often located at short distances from each other, within the same area. This is due to the location of wells being performed most often with no or little prior geological study in function only of its proximity to other productive well or due to the locations being of easy access.

Due to the complexity of the fractured aquifers, the present work aims to identify the most suitable setting of the electric resistivity method for recognition of discontinuities, such as faults and fractures, in the crystalline rock which can be potential reservoirs of groundwater. Several authors (Palacky & Kadekaru, 1979; Carruthers & Smith, 1992; Hazell et al., 1992; Gallas, 2000; Gallas, 2003; Vouillamoz et al., 2003; Yadav & Singh, 2007; Aizebeokhai & Oyeyemi, 2014; Gupta et al., 2015; Yeh et al., 2015) report in their works the effectiveness of application of geophysical methods in electrical characterization of fractured aquifers, allowing the determination of the thickness of the weathering mantle, the rock top depth, the presence of fractures filled by water and the location of greatest favorability sites for drilling tubewells.

REGIONAL GEOLOGY

Geologically the study area is located in the Borborema Province. This province is compartmentalized in geophysical/tectonic domains and subdomains according Oliveira (2008), where the Campina Grande geology map includes the São José do Campestre terrain and the Transversal zone, whose boundary is demarcated by the Patos Shear Zone (Fig. 1). The region comprising the investigated area in this work presents a geology dominated by crystalline terrains belonging mainly to the Alto Pajeú terrain (TAP) and the Alto Moxotó (TAM), inserted in the Transversal zone of the Borborema Province. Rodrigues & Brito Neves (2008) featured in this area vertical shear zones of dextral NW and sinistral NE directions that form, in the Eastern segment of the Patos Lineament, the conjugated system called Campina Grande shear system (Fig. 2). The rocks of this region are linked to the neoproterozoic Cariris Velhos and São Caetano units, where dominate the lithotypes orthogneisses, migmatites

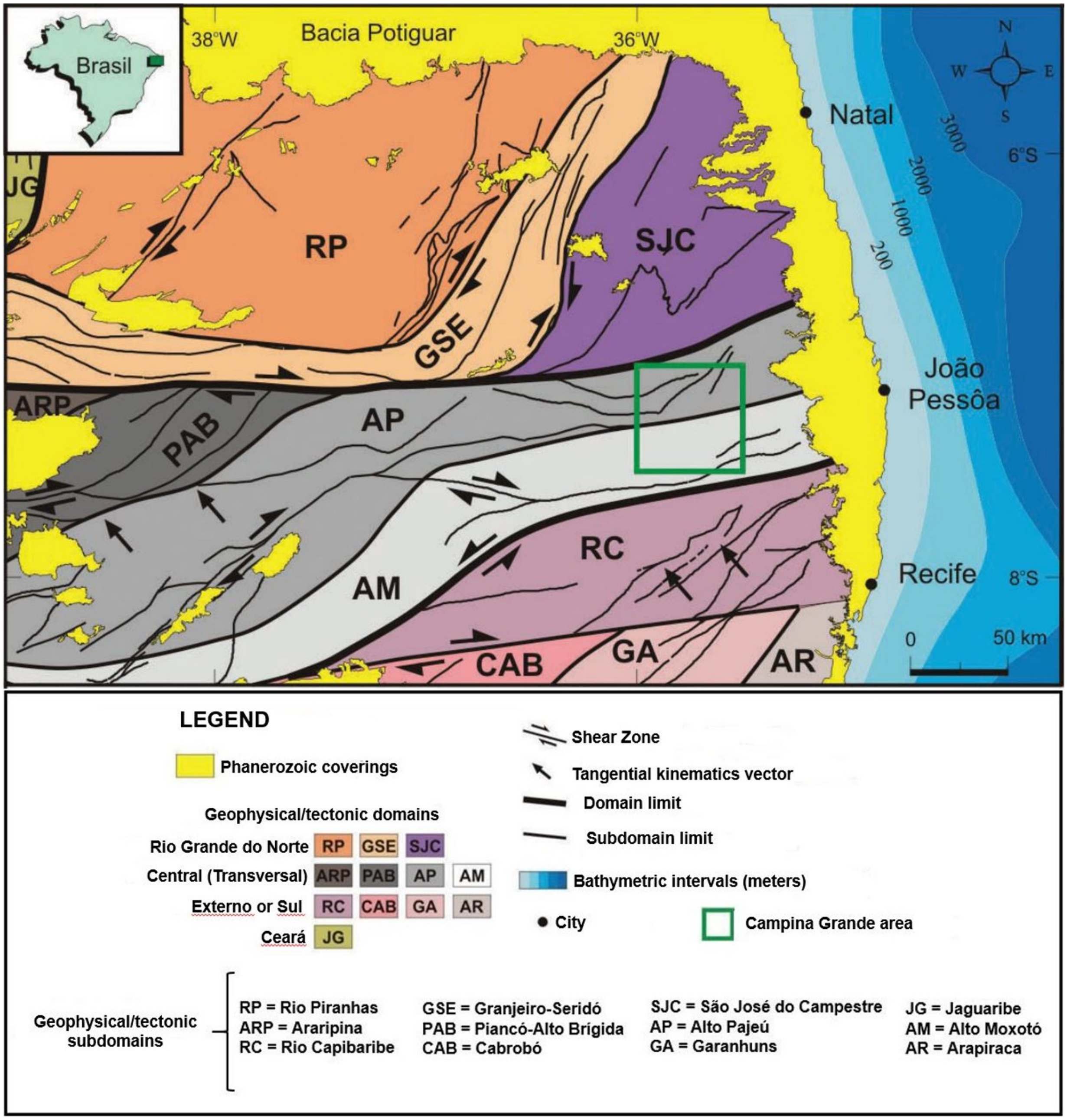

Figure 1 – Geophysical/tectonic domains and subdomains of the Borborema Province (adapted from Rodrigues et al., 2011).

and muscovite-biotite gneisses, schists, calciossilicatic rocks, granites and assorted milonites (Rodrigues et al., 2011).

STUDY AREA

The study area, known as Catarina site, is located NW of Campina Grande city and comprises a valley oriented NW-SE, approximately 8 km long, inside of the Puxinanã dextral shear zone (Fig. 3). Along the valley there is an intermittent stream, which contains surface water only in the rainy season.

At this site a NE-SW geoelectric section, perpendicular to main shear zone was registered. The investigated area features corrugated relief with steep uphill to the North and South directions. Along the whole creek there is a quaternary sandy coverage. On the South bank of the stream the alluvium has a coarse sand particle size, while on the North bank the sediments

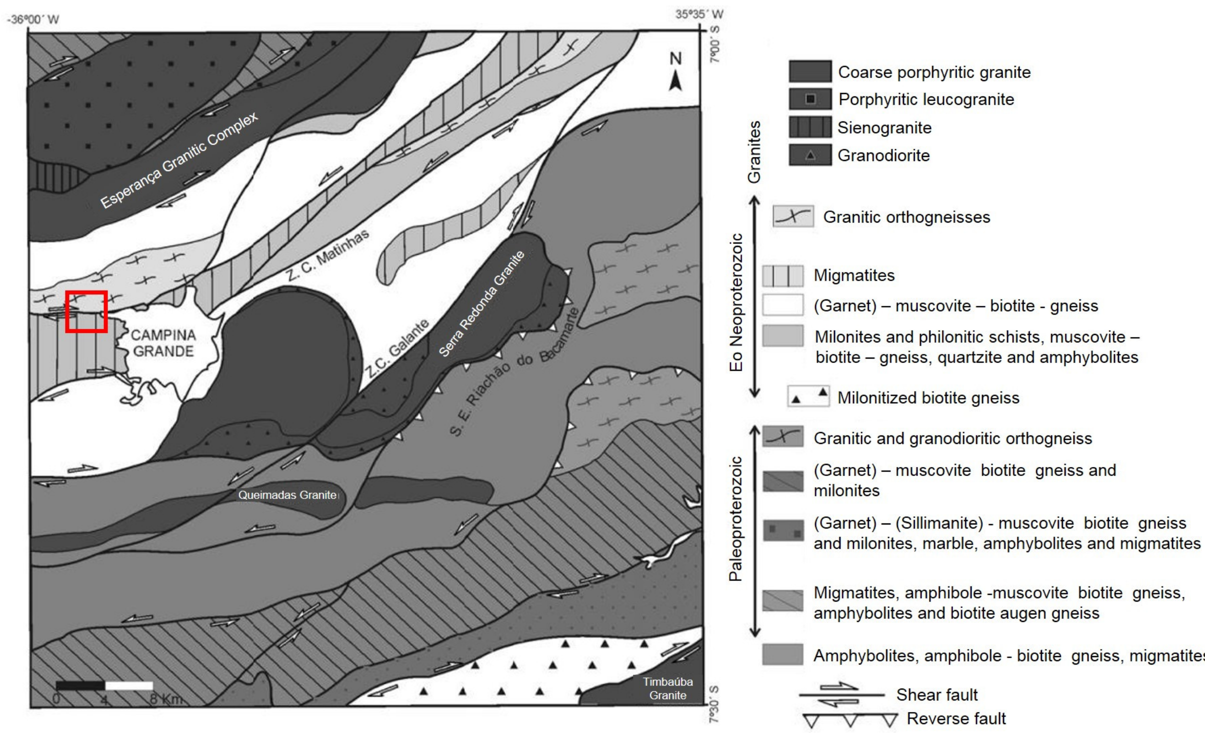

Figure 2 – Simplified geologic map of the Campina Grande region (adapted from Rodrigues & Brito Neves, 2008). The red polygon indicates the location of the study area.

are dominated by fine to average sand grain size. The presence of outcrops on the bed of the stream indicates that the bedrock consists of augen gneiss-granite, with vertical foliation of E-W strike.

The analysis of the structural data of the area through satellite imagery indicates that the drainage network is directed along the valley, allowing to classify the groundwater system as of the type crack-induced stream (Siqueira, 1963; Fig. 4). This model is characterized by the coincidence of the creek with the zone of fractures or with its edges, being the drainage network controlled by fractures, where the weathering and fracturing control the hydrogeological potential (Coriolano, 2002).

METHODOLOGY

The geophysical study carried out at the Catarina site consists of a DC resistivity survey. The principle of the method consists in the injection of continuous or low frequency (less than 10 Hz) alternating electric current through artificial sources (batteries or generators), which is introduced into the soil by means of two current electrodes (A and B). The resulting potential differences are measured on the surface through two potential electrodes (M and N) (Orellana, 1972).

Field acquisition techniques adopted in this methodology were the Vertical Electrical Sounding (VES) and Electrical Profiling (EP), held simultaneously along the investigated lines. The choice of using the combination of these two techniques is related to the aim of the geophysical survey. VES investigates the vertical variations of electrical resistivity in subsurface, through a configuration of electrodes arranged symmetrically in relation to the center of the arrangement, aiding in the delineation of saturated zone, bedrock top and thickness and geometry of the layers. The survey with multiple VES allows the interpolation of the electric vertical profiles or perform joint inversion of multiple VES, generating an electric vertical section. The VES technique is more commonly applied to investigate sedimentary strata, although may be also used to investigate fractured aquifers.

Electrical profiling is indicated to detect lateral variations of subsurface resistivity at one or multiple depths approximately constant, through the shift of the set of electrodes with fixed spacing, which can identify faults and fractures, mapping geological contacts, structures and bodies which have a lateral heterogeneity of electrical resistivity (Madrucci et al., 2005; Keary et al., 2009). In this study the multilevel electric profiling was adopted, which registers the lateral variation of resistivity in

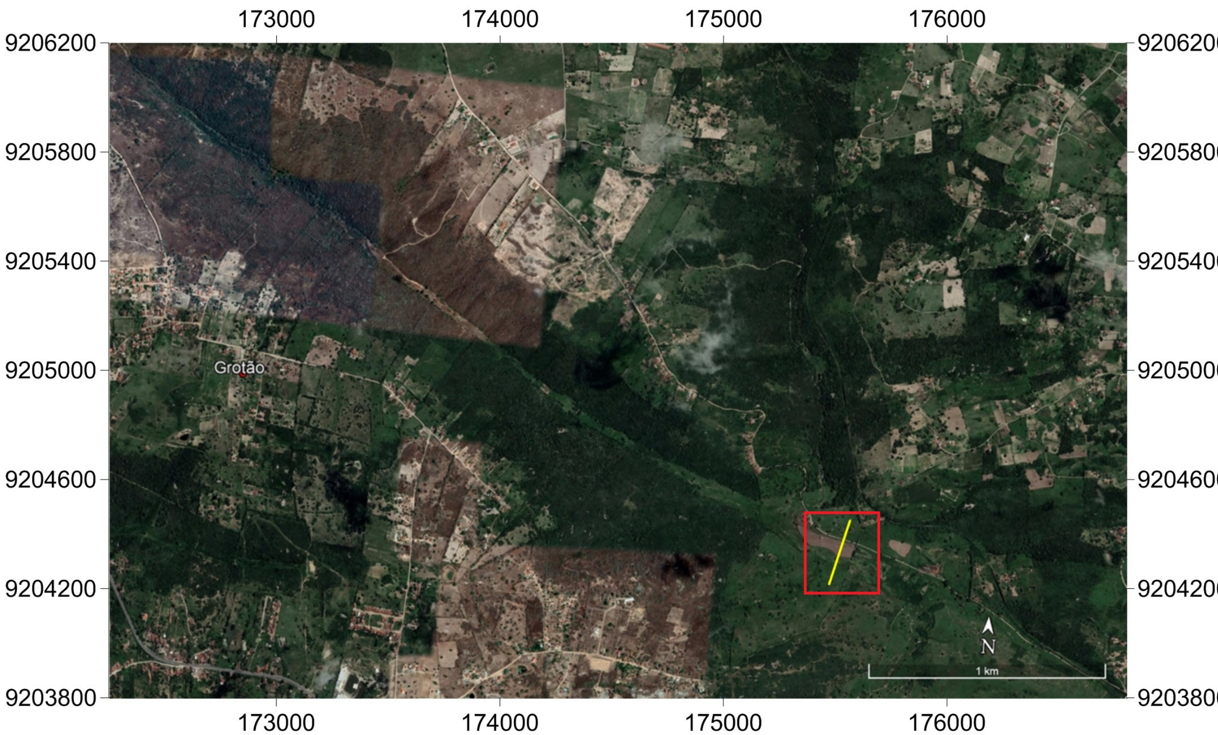

Figure 3 – Satellite image of the study area (red square), known as Catarina site, near Campina Grande city.

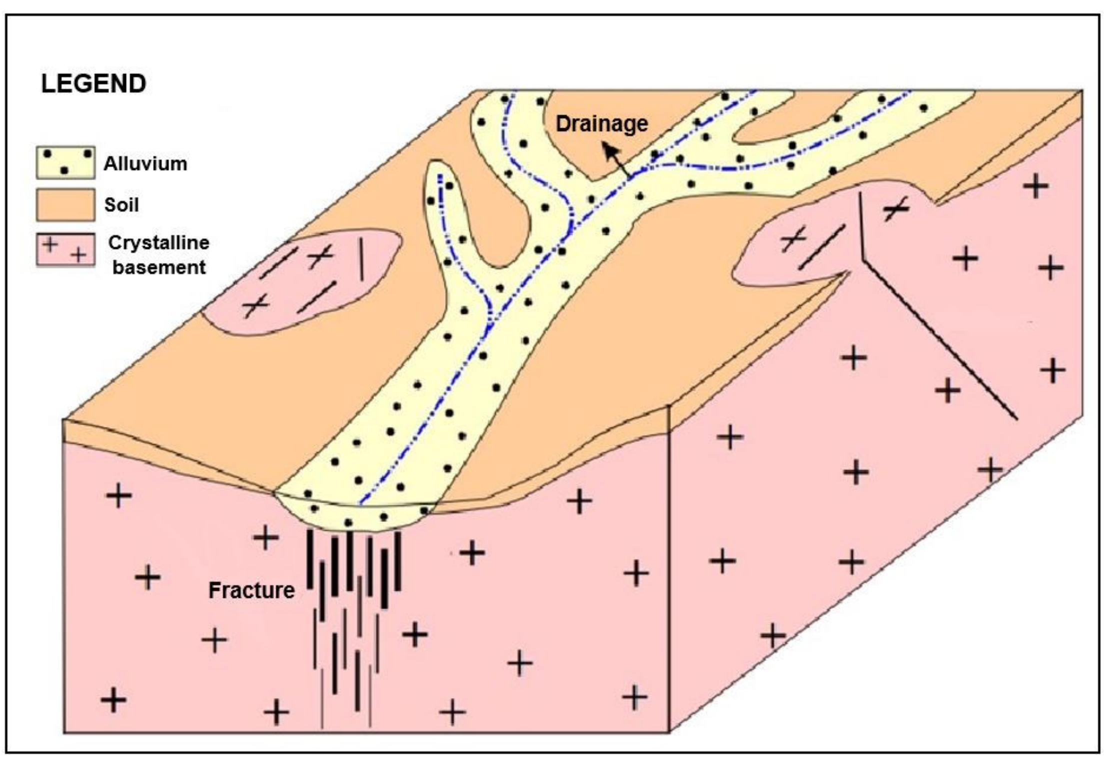

Figure 4 – Crack-induced stream model for groundwater system. Fractures are coincident with the drainage network, both at surface and at subsurface (adapted from Coriolano, 2002).

multiple depth levels. This technique results in two-dimensional geoelectric sections.

The choice of the electrode array used in this study was made taking into consideration the logistics of field in relation to fast data acquisition, associated to the characteristics to be outlined for the geological structures, the heterogeneity degree of subsurface, the sensitivity of the electrode array to vertical and lateral resistivity variations in subsurface and the effective depth of investigation of the survey. Taking into consideration these factors for the implementation of field techniques, the Schlumberger array was applied to VES and the multilevel gradient array was adopted to EP.

Schlumberger array is characterized for keeping potential electrodes M and N fixed, while the current electrodes A and B feature a growing separation relative to the center of the array, keeping MN $\leq$ AB/5 during the development of VES.

Setting the gradient array is characterized for keeping a current transmission line AB fixed with measurements made between the electrodes MN, which are displaced along an inner section of the line AB, being possible to perform various gradients at the same time, superimposed, with different extensions of line AB (Dahlin & Zhou, 2004). Dahlin & Zhou (2004) state that the multilevel gradient features high lateral resolution, allows greater data density and speed of data acquisition.

Data acquisition parameters

In this study some data acquisition parameters were tested such as VES center separation, minimal spacing between electrodes and maximum aperture of electrode array, in order to test the appropriate parameters in order to obtain 2D geoelectric models compatible with the field reality. The maximum aperture of the electrodes array directly controls the depth of investigation, while the spacing between electrodes controls the vertical resolution. The bigger the spacing between the electrodes AB greater the investigated depth. For the Schlumberger array the theoretical depth is usually considered as AB/5, while for the gradient array it is between 10% and 20% of the AB separation (Braga, 2016). The spacing between the VESs influences on lateral resolution of the profile. It was used a resistivemeter Bodenseewerk Geosystem GmbH model GGA 30 M.

In the early stages of data acquisition was decided to prioritize a greater depth of investigation. In this case, surveys were conducted with several spaces between the current electrodes. The setting 1 for the Schlumberger array used in preliminary analysis have a maximum aperture of 100 meters between the current electrodes (AB) at the borders of the data acquisition line, 200 meters at the intermediate part of the profile and 300 meters in the central part, with spacing of 50 meters between the VES centers, as showed in Table 1. However, the response obtained by this Schlumberger electrode setting did not generate satisfactory results regarding the detection of fractures in the crystalline basement.

Thus, it was decided to reduce the depth of investigation, reducing the maximum aperture between the current electrodes (AB) and the spacing between the VES centers, in order to increase the lateral resolution. With this goal was adopted the setting 2 for the Schlumberger array, where we used only one maximum spacing between electrodes for all VES (Table 1). The theoretical depth of investigation to be reached by geoelectric surveys at the Catarina site with the array setting 1 would be approximately 50 meters in the central part of the section, and with the setting 2 of 20 meters, being considered as satisfactory, since in the study area vertical fractures occur. The literature indicates that in northeastern Brazil and in similar crystalline terrains in Africa the fractures do not exceed the depth of 60 to 100 meters (Bourguet et al., 1981; Wright & Burgess, 1992). Figure 5 presents the disposition of the survey on the ground surface, with indication of the VES centers for the setting 2.

Based on the results obtained with the Schlumberger array, aiming to a deeper investigation with higher lateral resolution, and due to the effectiveness of the application of the gradient array for characterization of fissured aquifers as reported by Aizebeokhai & Oyeyemi (2014), another data acquisition campaign was performed with the multilevel gradient array, aiming a greater detailing of the fractured zones, in order to confirm the continuity of deep fractures.

On practical application of multilevel gradient array the choice of the parameters spacing between electrodes MN, number of measures in each survey segment and maximum aperture AB was made taking into account the joint analysis of the factors noise sensitivity, horizontal resolution and depth of investigation that want to be reached in the final geoelectric model. Taking into account these parameters the final multilevel gradient array setting is described in Table 2. Figure 6 shows a schematic representation of the gradient array used in the field.

Data processing

The data inversion was realized through the software RES2DINV (GEOTOMO, 2003) which generates a 2D geoelectrical model, dividing the subsurface in a finite amount of rectangular blocks, where the arrangement of the blocks is defined by the distribution of data in the pseudosection. The inversion of the data is

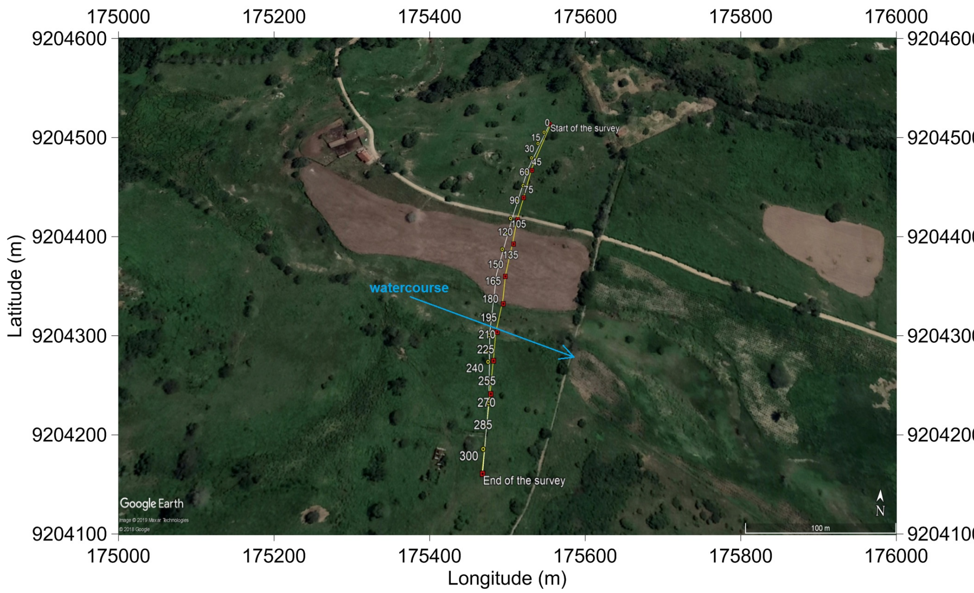

Figure 5 – Location map of the multiple VES surveys for setting 2 (red) and EP segment start points (yellow). The watercourse direction is indicate by the blue arrow.

Table 1 – Data acquisition parameters for the two Schlumberger array settings.

Parameters	**Setting 1**	**Setting 2**
Maximum extension survey	300 m	300 m
Number of VES	5	9
Spacing between electrodes MN	4 m (borders) and 10 m (central part) of the section;	2 m
Spacing between electrodes A	10 m	10 m
VES center separation	50 m	25 m
Maximum aperture AB	100 and 200 (borders); 300 m (central part) of the section;	100 m
Minimum aperture AB	10 m	10 m

Table 2 – Data acquisition parameters for the multilevel gradient array setting.

Parameters	**Survey – Gradient array**
Maximum extension survey	300 m
Number of survey segments	11
Number of measures in each survey segment	8
Spacing between electrodes MN	15 m
Spacing between EP segments	15 m
Maximum aperture AB	150 m

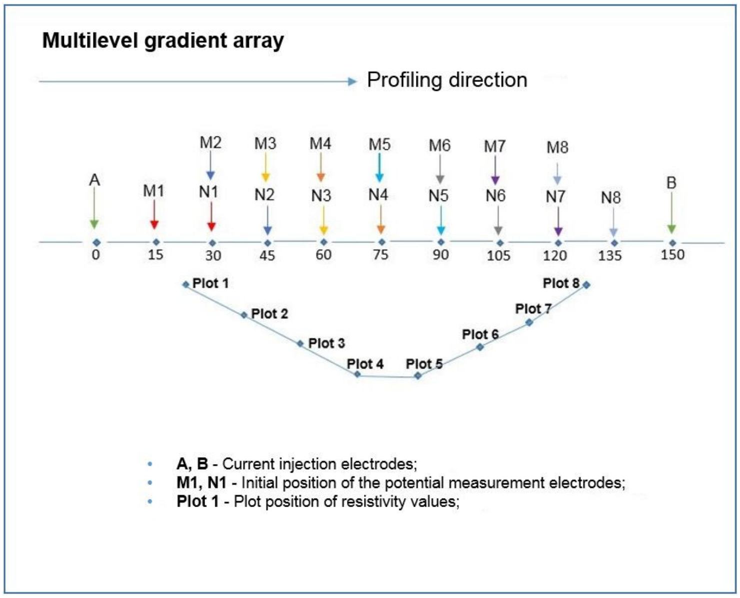

Figure 6 – Data acquisition scheme for the multilevel gradient array used in this work.

based on the method of least-squares, being used the inversion routine "smoothness-constrained least-squares", which consists of reducing the difference between the values of apparent resistivity calculated and the measured in the field, adjusting the resistivity of each block (Groot-Hedlin & Constable, 1990; Sasaki, 1992; Loke & Barker, 1996). The depth reached by the model is directly related to the geometry of the adopted electrode array and the resistivity values of geological units.

Structural geology data

In order to identify the attitude of structural features of the fault zone, we measured direction and dip of faults and fractures present in outcrops located in the prolongation of the fault zone, as shown in Figure 7, since there is no outcrops available in the study area.

Figure 8a is a rosette graph of the strikes observed in the faults and fractures, while Figure 8b is the graph of the corresponding dips. As can be seen, the fractures present WNW-ESE direction and subvertical dips.

RESULTS AND DISCUSSIONS

The results are presented in the form of geoelectric sections in NE-SW direction. The interpretations were made from the observed resistivity contrasts in sections related to the electrical resistivity values established in the literature for the various types of geological materials present in the subsurface. Based on the chromatic scale used to represent the values of electrical resistivity in sections, blue colors represent low resistivity anomalies and red colors represent the anomalies of high resistivity values.

With the setting 1 of the Schlumberger array it was possible to identify clearly the buried creek valley, however despite being observed in the model the presence of electrical resistivity contrasts between the edges of the section and the central part, indicative of contrast between lithologies, it has not been possible to clearly map the presence of fractures, coincident with the drainage network of the valley as expected (Fig. 9).

In this way, a new configuration was adopted for the Schlumberger array (setting 2) which prioritizes the lateral resolution of the profile, obtaining a gain in resolution without a significant loss in the investigation depth, as can be seen in the geoelectric section of Figure 10. It was possible with this new array setting identify in the positions of the VES 3 and VES 6 the presence of conductive vertical and subvertical fractures, represented in the section by the red lines. The observed geometry is compatible with the hydrogeological crack-induced stream model proposed by Siqueira (1963), since fractures are consistent with a drainage network. Additionally, the directions and dips of the faults and fractures observed in the geoelectric sections are also compatible with those recorded in the structural features observed in outcrops (Figs. 8a and 8b). Usually the fractures are identified in geoelectric sections as anomalies of low electrical resistivity, docked in a background more resistive, since the presence of fractures/cracks in the rock facilitates

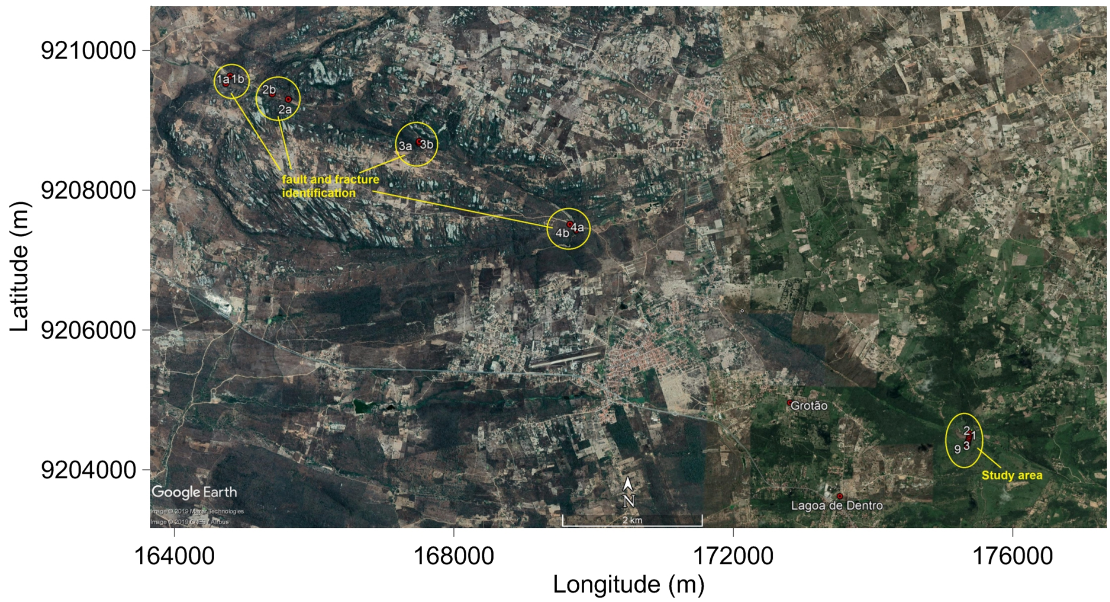

Figure 7 – Location map of the visited outcrops for measuring of structural features attitudes.

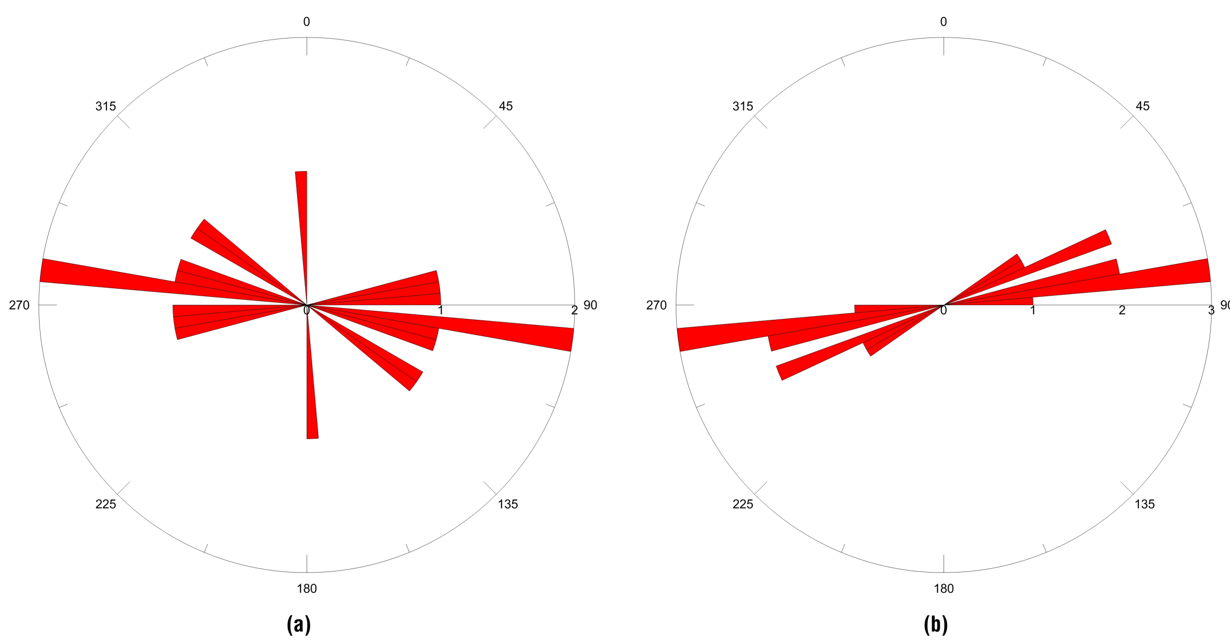

Figure 8 – Fracture and fault strikes **(a)** and dips **(b)** measured on outcrops along the fault zone.

the infiltration of water and rock alterations, resulting in the reduction of the high electrical resistivity of the non-fractured rock. Three resistivity domains were determined: a conductive layer, with approximately 8 meters thick of clay-sandy sediments, showing values of electrical resistivity of up to 35 ohm.m. Altered metamorphic rocks, showing resistivity values ranging between 60 and 600 ohm.m, and 18 meters deep and below rocks of high electrical resistivity (> 1000 ohm.m) which indicates non-fractured rocks. There is still between the VES 4 and VES 6 a zone of high resistivity, up to 6 meters deep, interpreted as rock blocks rolled from the creek flanks.

Figure 11 presents the geoelectric section for the multilevel gradient array. It is observed that the region of vertical fractures was clearly identified with a higher vertical continuity in relation

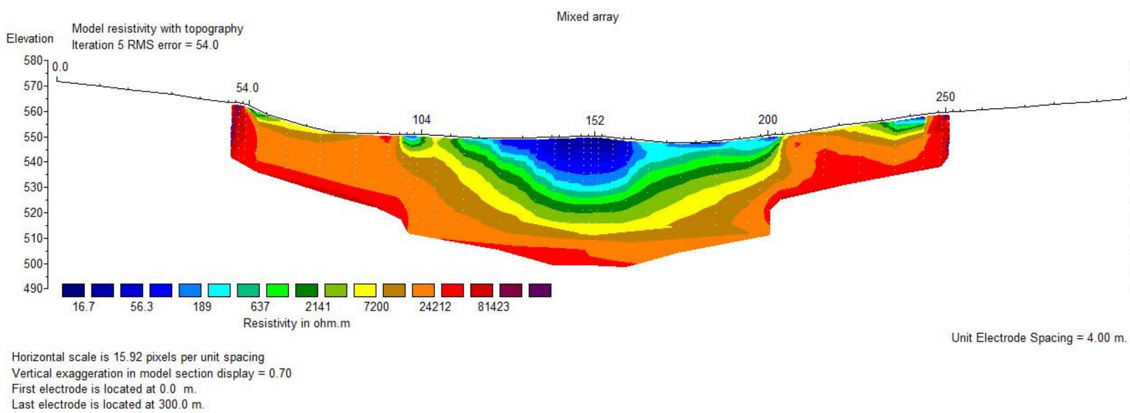

Figure 9 – Geoelectrical section from multiple VES with the Schlumberger array – setting 1.

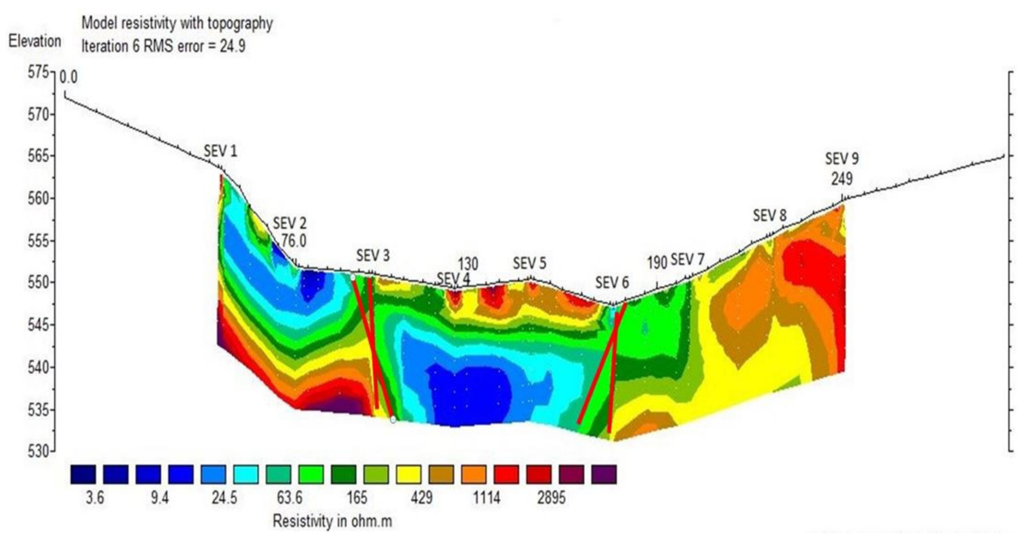

Figure 10 – Geoelectrical section from multiple VES with the Schlumberger array – setting 2.

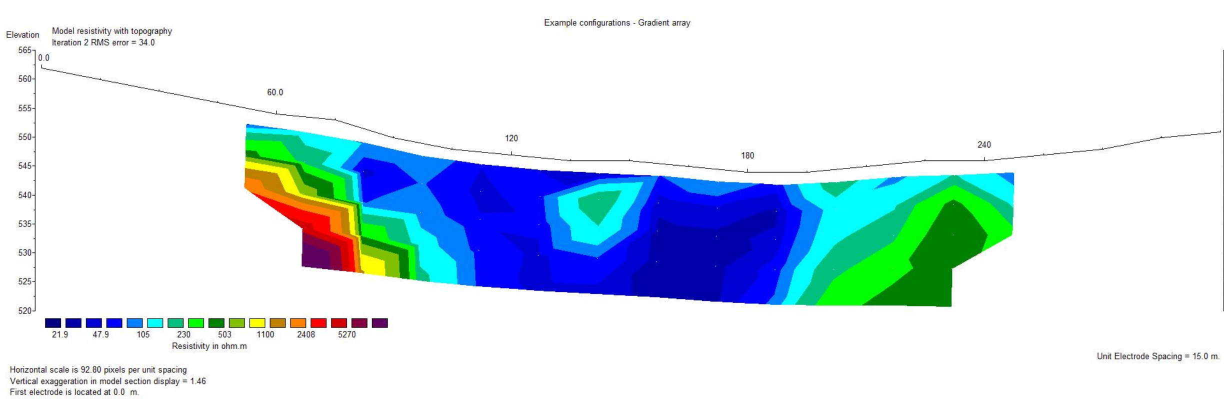

Figure 11 – Geoelectrical section from electrical profiling with the multilevel gradient array.

to Figure 10. However, in the section of Figure 11 the high resistivities interpreted as rolled blocks were not observed, as viewed on section of Figure 10.

When compared the used arrays - Schlumberger and gradient – and the used survey techniques – VES and EP - on acquisition of profile data, regarding your effectiveness, it was possible to observe that both arrays and techniques identified clearly the presence of the fractured zone corresponding to the stream. In the preliminary analysis it was obtained an image with lower resolution and greater depth of investigation in the area of the creek. In the second configuration with the Schlumberger array it was obtained an image with good resolution but with smaller depth of investigation. The configuration with the multilevel gradient array presents an image with both intermediate resolution and depth of investigation.

CONCLUSIONS

The results obtained show that the adopted settings resulted in geoelectric sections with some matching features, but also with some differences among them. All the settings adopted detected the presence of a conductive anomalies in the center of the line, which coincides with the alluvial cover and the fractured area of the basement. However, the resistivity values varied significantly in sections obtained by the different configurations.

The first setting resulted in a maximum depth of investigation, in the center of the line, around 50 meters and a relatively low resolution. Its geoelectric section indicates that below 20 meters deep, in the center of the line, high electrical resistivity values occur, indicative of non-fractured rock.

The second setting resulted in a geoelectric section with low depth of investigation (about 20 meters) but, due to the smaller spacing between the centers of the VES, a higher horizontal resolution. Unlike the other settings, a resistive anomaly in the shallow center of the section was observed, which was interpreted as being due to rock blocks rolled of valley sides. Locally there is no visible records of the presence of such blocks.

In the multilevel gradient array configuration it was noted clearly the presence of a conductive zone coinciding with the trough of the creek, which represents the saturated alluvial and subvertical fracture zone located immediately beneath the alluvium, resulting in the groundwater accumulation model of the crack-induced stream type, where the fractures recognized in geoelectric sections coincide with the drainage network.

For the detection of vertical to subvertical structures, as the fractured area of the basement analyzed in this work, the electric profiling technique with the multilevel gradient array proved to be the best performance setting, the one whose geoelectric section it was clearer in locating such structures. Secondly, the setting of multiple VES with Schlumberger array and VES spacing equal to one-fourth of the maximum aperture of the current electrodes can also be adopted.

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