Electrical Resistivity (ERI and VES), Inductive Electromagnetic in Frequency Domain (FDEM) and Time Domain IP (TDIP) geophysical methods applied to groundwater exploration in Fractured Basalts for sustainable agriculture.

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Abstract

Geophysics was applied in this research as a tool to identify the most favorable points for drilling a producing groundwater well, whose main objective was to define the best groundwater producing zones in fractured basalts, covered by soil, for sustainable maize agriculture in the rural zone of Cândido Mota city, located in southwest of São Paulo state. The region of the geophysical surveys is located in the northwest edge of the Paleozoic Paraná Basin, whose geology is dominated by outcrops of ancient basaltic flows (135 My), which are currently part of the Serra Geral formation.

Electrical Resistivity geophysical methods (ERI and VES mode), Electromagnetic in the Frequency Domain (FDEM) and Time Domain Induced Polarization (TDIP) surveys were carried out over an area located about 7 kilometers southwest of the urban area of Candido Mota, where shallow soils (<15m) overlap basalts and there is a real need for access to groundwater for sustainable maize agriculture. These basalts have layers with vesicles and tonsils of altered and/or fractured zones, and the presence of intra-spills paleosols, which are known as the best aquifers, as well as high permeability basalts fractured zones.

The Serra Geral Aquifer System (SGAS) has an excellent water retention capacity, due to its intense basalt fracturing and, in this region, the SGAS is much shallower than the Guaraní Aquifer System (GAS), whose depth of occurrence is estimated at 900 meters, which makes it impossible to drill wells for agriculture, mainly for small producers, due to the high cost of drilling.

The acquisition of electrical resistivity data was carried out in the field using two types of arrangements, with 6 Electrical Resistivity Imaging - ERI being carried out, to evaluate the lateral resistance variation, and 6 Vertical Electrical Soundings (VES), to evaluate the resistivity variation with the depth, which also served as a checkpoint for ERI quality, since most of the VES data were acquired along the ERI acquisition lines.

The electrical resistivity methods showed an excellent correlation between the zones of low resistivity and the occurrence of fractured basalt, making it possible to differentiate zones or layers of fractured and/or altered basalts from massive basalts, which even successfully guided a drilling water well.

Data from 03 *Slingram* EM Array were also acquired by the Frequency Domain Electromagnetic Inductive Method (FDEM), named as FDEM-02, FDEM-03 and FDEM-04, by the Geonics EM-34 equipment. This acquisition was carried out on the same lines of 03 Electrical Resistivity Imaging (ERI) surveys, which followed the same numbering, ERI-02 (CE-02), ERI-03 (CE-03) and ERI-04 (CE-04). The conductivity/resistivity interpretation data showed an excellent correlation between them.

The acquisition of Time Domain Induced Polarization (TDIP) data occurred in vertical sounding mode, having been acquired in the same VES Schlumberger array, in a total of 06 surveys, so that the correlation of resistivity and chargeability, in relation to depth, could be evaluated.

A groundwater production well was drilled in a low resistivity zone along the ERI-03 (CE-03) line, as suggested by the results of the joint interpretation of these three geophysical methods, with promising results for use in agricultural irrigation.

Introduction

The Serra Geral Formation occurs in a large part of the São Paulo state countryside, whose geological substrate is formed by compact, and sometimes fractured, basaltic rocks, which have an excellent water retention capacity and, with the increasing demand for this singular mineral, mainly for sustainable agriculture, the importance of these rocks as an aquifer has increased.

In the prospecting phase, in order to assess a potential point for a good drilling production well, it is important to know the geological characteristics of these volcanic reservoir rocks, which influence their potential as an aquifer, such as the degree of fracturing, the presence of vesicles, as well as the occurrence of paleosols and intertrapped sandstones between ancient basaltic flows.

Geophysics presents itself as an important tool for the evaluation of ideal locations for producing wells, since, according to prior knowledge of the geoelectric characteristics of the basalts of the Serra Geral Formation, it is known that these rocks, when presented with a low degree of alteration and/or fracturing and without vesicles, are characterized by high values of resistivity. As resistivity is inversely related to porosity (in this type of rock), the more compact, the higher of resistivity value, and it is common to find basalts with resistivities above 1,000 ohm.m. On the other hand, when there are zones of fractured, vesicular and/or altered basalt, the resistivity values tend to be much lower (< 100 Ohm.m), and such geoelectric nature invites the use of electrical and electromagnetic methods in geophysics, with emphasis on the ERI and VES methods.

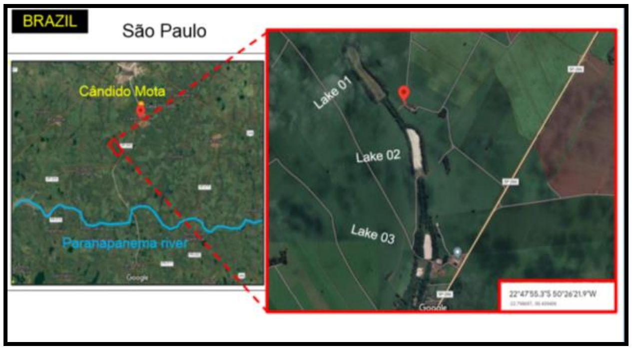

Figure 01 *– Location map research area*

Method

Three geophysical methods, whose acquisition geometry is shown in figure 02, were applied in this research:

1 - *Electrical Resistivity - ER* (2D resistivity model in Electrical Resistivity Imaging – ERI mode in *Dipole-Dipole* four electrodes array) and *Vertical Electrical Soundings – VES* (Schlumberger array);

2 - *FDEM - Frequency Domain Electromagnetic* in Low Induction Number (2D conductivity model), using the *Geonics EM-34*.

3 - *Time Domain Induced Polarization* (TDIP in Vertical IP Soundings);

The main objective was to differentiate possible zones or layers of fractured and/or altered basalts from massive basalts using resistivity/conductivity data.

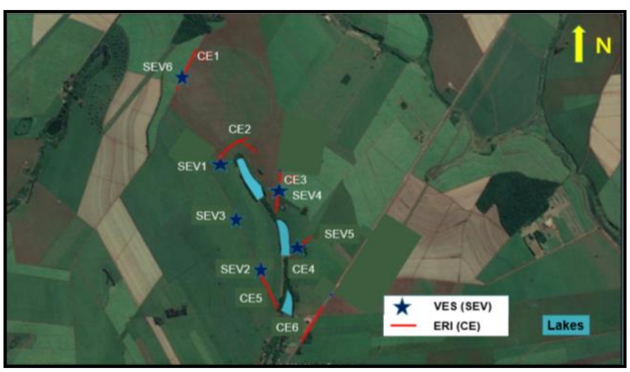

Figure 02 *- Acquisition geometry location of the 06 Electrical Resistivity Imaging ERI (CE) and the 06 Vertical Electrical Soundings VES (SEV).*

1- Electrical Resistivity (ER)

1.1 - Electrical Resistivity Imaging (ERI)

The four electrodes acquisition geoelectric arrangement applied in this groundwater research work was the ERI in Dipole-Dipole mode. In this type of acquisition, the entire array is moved laterally, in order to obtain a 2D section of the subsurface apparent resistivity lateral variation, up to a maximum depth defined by the geometry of the array.

The most important characteristic of the acquisition geometry by the Dipole-Dipole array method is that the spacing between the electrodes with the same function is always equal to the distance x, that means, AB=MN=x, and a notable difference in relation to the other four electrodes arrays, is that in this one a set of MN potential dipoles is used, which measure the potential difference simultaneously with each injection of current by the AB source dipole. In this arrangement, all the AB x MN dipole pairs are kept at a fixed distance, which is always a multiple of the distance x (*nx*), which defines an investigation point for each pair of *current x potential electrodes*, whose measurement point is located at the midpoint of the distance between the midpoints of each pair of electrodes considered (R/2), and each pair of AB x MN dipoles represents a level of in-depth investigation, which is estimated to also occur in R/2 depth.

1.2 – Vertical Electrical Soundings (VES)

The geometry field used in VES data acquisition was the Schlumberger array, shown in figure 04, which also uses four electrodes. Two of which are used to maintain the subsurface current flow *I* (A as an injector and B as return), and two of them (MN) are used to measure the potential difference *dV* in Volts (M and N).

All the electrodes' pair (AB, MN) are arranged in a straight line along the central point, defined by half of the distance between M and N, which thus defines the point of vertical measurement of the apparent resistivity ρ_a, considering that "*the main characteristic of this arrangement is that the distance MN must be very small in relation to AB, always trying to satisfy the relation MN < AB/5*" (SOUZA, 2007).

The 1D vertical apparent resistivity in the Schlumberger array is defined by equation 01, that shows us that the electrical resistivity in the subsurface is determined by multiplying the electrical resistance (*dV/I*), measured between the two potential electrodes (MN), multiplied by a geometric factor defined by the distance between the four electrodes in surface (r_1, r_2, r_3 and r_4).

$$\rho_a = \frac{dV}{I} 2\pi \left[\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4})\right]^{-1} \quad (01)$$

The Schlumberger geoelectric acquisition method basically consists of varying the spacing between the AB current electrodes in each acquisition step, which will provide information on the apparent resistivity as a function of depth. Data interpretation is performed by analyzing the plotting of the half spacing curve between current electrodes (AB/2) as a function of the apparent resistivity data ρ_a (Ohm.m), calculated by equation 01.

2 – Frequency Domain Electromagnetic (FDEM)

The FDEM method was applied not only to reduce ambiguity in the interpretation of Electrical Resistivity (ER) data, but also to enrich the discussion of the science involved in the application of this not invasive method.

The principle of electromagnetic induction is applied to shallow geophysical prospecting with a transmitting source coil (Tx) device, in the horizontal or vertical position, that generates a primary magnetic field that propagates in all directions, aligned with a receiving coil (Rx).

In the electromagnetic method in the frequency domain, a sinusoidally alternating voltage is applied to the Tx coil, which then passes through an electric current, sometimes clockwise, sometimes counterclockwise, originating a primary magnetic field (Hp) also sinusoidal and alternate, which propagates in all directions, including the underground. The energy of the primary field Hp, obeying the Faraday's law, induces body currents (Eddy currents) in the conductive layers, at the same frequency as the primary source, which, in turn, will generate a secondary magnetic field (Hs) in the subsurface, which will also propagate in all directions.

The receiving coil Rx measure the vector sum of the signals emitted by the primary field Hp, which propagates through the air, with the secondary field Hs, which propagates first through the geological environment and then through in the air until it reaches the Rx coil and, in this way, a Hp + Hs signal will be registered in the receiving coil, at the same operating frequency as the primary source Hp signal.

The geological medium apparent conductivity (σ_a), measured by the EM-34, is directly proportional to the ratio between the amplitudes of secondary quadrature component field by primary field (Hs/Hp), whose intensity is directly measured by the electronic device logic, which can thus be calculated for each specific depth by equation 02.

$$\sigma_a = \frac{4}{\omega \mu_0 s^2}\left(\frac{H_S}{H_p}\right) \qquad (02)$$

σ_a = the apparent conductivity in mSm/m;

$\omega = 2\pi f$, where f is the operating frequency in Hz;

μ_0 = magnetic permeability in vacuum;

s = spacing between coils in meters (m).

Equation 02 is valid *under condition of low Induction Number B* (McNEILL,1980), which occurs in situations where B<<1. The induction number is defined by the ratio of the spacing between the coils (s) in relation to the Skin Depth (δ) (equation 03).

$$B = \frac{s}{\delta} \qquad (03)$$

The Skin Depth (δ) is defined by the *maximum depth of penetration of the electromagnetic signal*, which was defined under the condition that the maximum depth of penetration of an electromagnetic signal occurs when up to the point where the amplitude of the magnetic field generated in the transmitting coil (Tx) is reduced by a factor e^{-1} compared to its surface value. The relationship of Skin Depth with the medium and acquisition parameters is presented in equation 04.

$$\delta = \sqrt{\frac{2}{\mu_0\ \omega\ \sigma}} = \frac{503{,}8}{\sqrt{\sigma f}} \qquad (04)$$

The Skin Depth range depends on the frequency of the signal and the medium conductivity, which the magnetic field propagates, since the electromagnetic fields suffer attenuation during their passage through the geological medium to the depth, and, as showed in Equation 04, *the maximum depth of penetration of a subsurface magnetic field is inversely proportional to the frequency used and the conductivity of the medium*, which forces us to state that the greater the frequency used, the smaller the depth investigated, as well as, the greater the conductivity of the medium, the smaller the investigated depth.

3 – Time Domain Induced Polarization (TDIP)

The last acquisition methods (IP) was carried out to bring different information from those obtained by the ER methods, because the IP provides chargeability of the investigated layers, and the joint interpretation of these three data may prove to be interesting in hydrogeological research, whose approach is, in most cases, only in relation to conductivity or resistivity, which is predominantly influenced by the interstitial rock's fluid, that in some geological tasks can masking the information about the reservoir rock itself, including its clay content, which can be obtained by the chargeability data, measured by IP method.

The Induced Polarization (IP) effect is an electrical phenomenon that occurs in the application of the any electrical resistivity method, caused by the transmission of underground currents from the AB electrodes. The phenomenon is observed as a voltage decay over time in the potential electrodes MN, after interruption in the supply of the electric current, showed in figure 03.

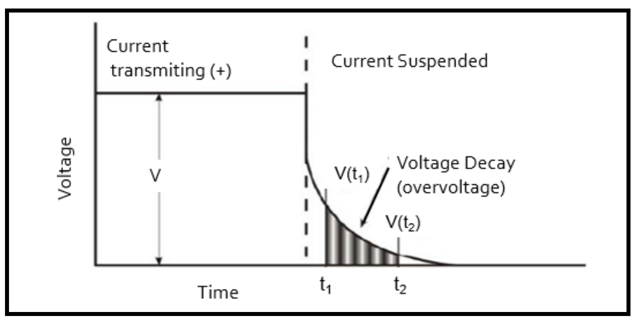

Figure 03 *- Illustrative IP effect in time domain (GLASER, 2007).*

The IP effect occurs due to the electrical polarization of some types of rock, which have high chargeability (M), which in geophysical prospecting is a parameter that indicates the geological capacity to accumulate electrical charge.

The electrical energy stored in the rocks takes place by electrochemical processes, and the process of accumulation and release of charge varies according to the nature of the constituent minerals of each lithotype, and for this characteristic, this is a method widely used to estimate the mineral rocks content, with obvious applications in mineral prospecting, since the IP response is promising in detecting metallic minerals, “even for very small amounts, in which sulfide disseminations of the order of 0.5% in metallic volume have been identified by the method” (SUMMER, 1976)

The physical parameter to be determined in the IP method in the time domain is the chargeability (M), usually measured in *ms,* which is defined by equation 05:

$$M = \frac{1}{V_C}\int_{t_1}^{t_2} V(t)dt \quad (05)$$

Where V_C is the source voltage (AB), t_2 and t_1 the time limits of integration, and V(t) the voltage in MN electrodes, over the decay time (figure 03).

Results

1- ER Interpretation

1.1 – ERI

Based on the information on the geoelectric characteristics of these volcanic reservoir rocks, the inversion of the Electrical Resistivity data (ERI and VES) was carried out. The inversion of the 06 profiles of the Electrical Resistivity Imaging (ERI) was carried out with the aid of the RES2DINV Software, which performs the inversion by the finite elements method. Two interpreted 2D ERI inversion sections are presented and discussed in detail below, in the figures 04 and 05.

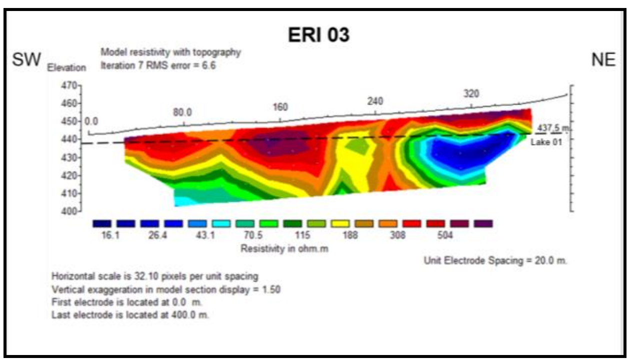

Figure 04 *– Electrical Resistivity Imaging 03 (ERI-03) with the topography. Note the indication of the lake 01 bathymetric surface elevation and the excellent correlation with the top of the layer of lower electrical resistivity.*

The ERI-03 section, whose acquisition geometry is shown in Figure 02, was survey with a 21 electrodes array, with 20 meters of spacing, that investigated the subsurface resistivity in a total linear displacement of 400 meters, located along the eastern edge of Lake 01. The maximum investigation depth allowed for this array was 60 meters.

The inversion was performed by the RES2DINV software, that minimized the inversion error by 6.62% after the seventh iteration, indicating a robust result and, according to the figure 08, a low resistivity layer (< 26 Ohm.m) was found from the 437 meters bathymetric elevation, where is assumed to exist the top of the aquifer of the SGAS - Serra Geral Aquifer System - and where the fractured basalts reservoir is expected to be found.

The elevation of the low resistivity layer, identified in the 2D apparent resistivity section, is coincident with the bathymetry of Lake 01. Another notable feature is the small thickness of the first most resistive layer and the lateral variation in resistivity from NE to SW, that shows a possible variation in the permeability of the SASG aquifer, or even some type of geological structure, such as a fault, which would have placed two different lithologies side by side, corroborating the idea that the SW high resistivity zone was formed by sandstone/soil sediments that filled the space left by a collapsed block.

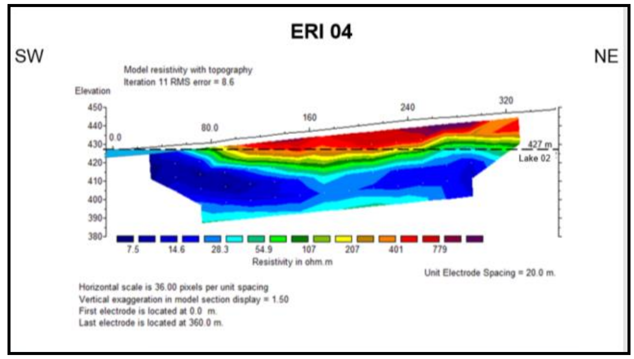

Figure 05 *– Electrical Resistivity Imaging 04 (ERI-04) with topography. Note the indication of the lake 02 bathymetric surface elevation and the excellent correlation with the top of the layer of lower electrical resistivity.*

The ERI-04, whose acquisition geometry is shown in Figure 02, was survey with a 19 electrodes array of, maintained at a spacing of 20 meters during the array displacement. The ERI-04 investigated the subsurface resistivity in a total linear displacement of 360 meters, located along the southern edge of lake 02. The maximum investigation depth allowed for this array was 60 meters.

The inversion performed by the *RES2DINV* software minimized the inversion error by 8.61% after the 11th iteration and, as showed in figure 09, the low resistivity layer (< 14 Ohm.m) was found in 427 meters bathymetric elevation, was interpreted as the top of the aquifer of the Serra Geral Aquifer System, where fractured basalts are expected to be found, which is coincident with the bathymetric elevation of Lake 02, but unlike the ERI-03 resistivity section, the notable feature here is the little lateral variation in resistivity of the least resistive layer, which indicates little or no geological structure at this location, in which an excellent lateral continuity of the SGAS aquifer can be interpreted.

1.2 – VES

The Vertical Electrical Soundings (VES) data were interpreted in their traditional way, through the parameterization curves, by the IP2WIN Software, in which the pairs of resistivity values per depth were manually adjusted for each layer, resulting in a layer thickness table with its respective estimate of apparent resistivity.

Most of the Vertical Electrical Soundings (04 out of a total of 05) were located along certain ERI lines, so that a vertical check point could be created between these two different acquisition methods, in order to reduce ambiguity, and, if so, the two VES adjusted curves will be presented together with the corresponding ERI.

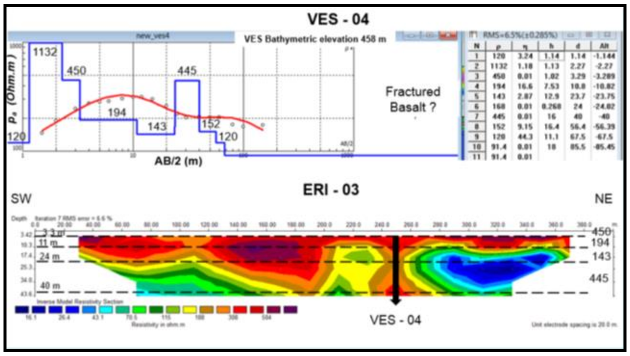

Figure 06 *– VES-04 curve adjustment by the IP2WIN program, compared to the ERI-03 apparent resistivity section without topography. Note the indication of the VES-04 acquisition location (black arrow), which was carried out in a place with high resistivity indication.*

The Vertical Electric Sounding 04 (VES-04) is presented in figure 06, along with its corresponding ERI-03 apparent resistivity section, whose location can be seen in figure 02. The VES-04 was survey with a maximum opening of 300m (AB_{max} = 300m).

The VES-04 curve adjustment by resistivity layers in depth was the most laborious of all VES, since numerous layers of small thickness had to be defined in order to achieve a reasonable fit to the survey data, and the result of the estimate shows a distribution of values from high to medium resistivities, and no correlation with the low resistivity zones previously highlighted in ERI section. This is the typical case in which it is necessary to look at the result of the inversion of ERI-03 and note that the VES-04 survey was located over a zone of high resistivity and, therefore, no fractured basalt water saturated is expected. The fractured volcanic reservoir possibly is in the undermined block of a fault of the NW-SE direction, perpendicular to the strike of the ERI apparent resistivity section, and the water table cannot be defined either, which appears to be masked by the capillary zone.

The last Vertical Electrical Sounding (SEV-05) is presented in figure 07, along with its corresponding ERI-04 apparent resistivity section, whose location can be seen in figure 02. The VES-05 was also survey with a maximum opening of 300m (AB_{max} = 300m).

The curve adjustment of VES-05 by layer resistivity in depth defined 2 initial and thin layers, with a high resistivity, estimated at 565 ohm.m up to a depth of 11.2 m, where it is interpreted to occur a dry soil, decreasing to 20.1 ohm.m up to a depth of 18.4 m, that was interpreted a more saturated water layer, perhaps still within a sandy matrix and, soon after, at a depth of 18.4 meters , the fit shows another decrease in resistivity, around 10.8 ohm.m, which should correspond to the top of the fractured and water-saturated basalt.

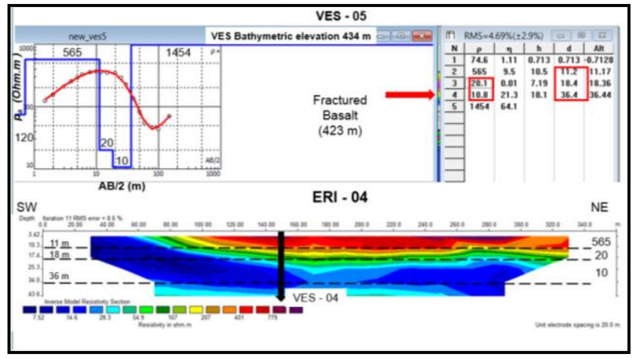

Figure 07 *– VES-05 curve adjustment by the IP2WIN program, compared to the ERI-04 apparent resistivity section without topography. Note the indication of the VES-05 acquisition location (black arrow).*

The joint interpretation of VES-05 with ERI-04 is one of the most interesting examples from the geophysical point of view, since the adjustment of this VES was also able to define the interface of the base of the fractured basalt of the SGAS with the unfractured basalt (compact) from a depth of 36 meters, where there is a significant increase in resistivities, greater than 1000 ohm.m, in the same way as it is noticed in the ERI-04, that presents an increase in resistivity with depth, from 36 meters onwards.

2- FDEM

The equipment used in this EM geophysical survey is generically called a conductivity meter, being built in such a way as to allow the direct reading of the conductivity in milli Siemens per meter (mS/m), in predetermined depths of 7,5 m, 15 m and 30 m, from openings of 10 and 20 meters respectively, in both HCP and VCP modes.

Three field surveys were carried out over the same line of ERI electrical survey, following the same number. The objective to use the FDEM method was to reduce the ambiguity in the geoelectric interpretation, by another geophysical method of acquisition, based on distinct physical principle, and thus determine the conductivities at the predetermined depths of investigation to compare them.

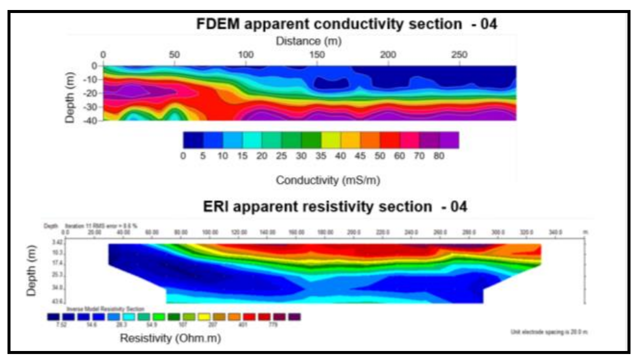

Figure 08 *– FDEM-04 and ERI-04 sections.*

3- IP

The field device used in the survey to obtain the chargeability data was the same used in the VES survey, the Syscal R2 (*Iris Instruments*, France), which was assembled in sounding mode for use in time domain IP mode, using the Schlumberger array, in order to obtain the variation of chargeability (M) with depth (z). The acquisition points were the same as for the vertical electrical soundings, following the same numbering as those, so that resistivity and chargeability data could be compared.

The operation of the IP effect acquisition equipment in the time domain is similar to the VES data survey operation, because for each distance from the AB electrodes, a current flow is applied in underground and a voltage is recorded at the MN electrodes, and the only difference is that, in this method, the source is turned off, and only after that the IP signal is recorded, making it clear, that it is possible to carry out VES and IP acquisitions simultaneously.

Once survey in the same configuration, the chargeability data can be interpreted together with the resistivity data, including using the same interpretation programs. In certain situations, the joint interpretation of the IP effect with the resistivity data helps to solve doubts about the mineral content in certain layers, as well as it can indicate the amount of clay in a groundwater reservoir, which directly impacts the pore space estimate, being an important information for hydrogeological studies applied to sustainable agriculture.

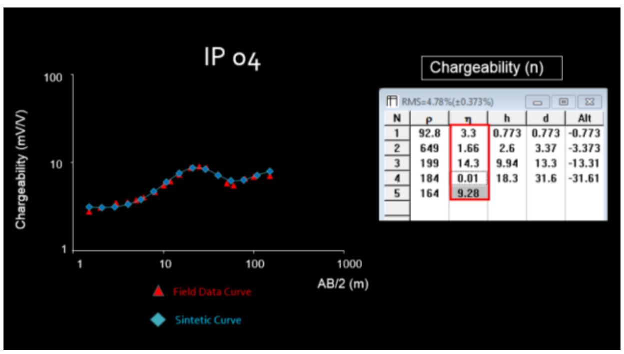

Figure 09 *- IP 04 data adjustment at the same location as the VES-04 (see figure 02), with a maximum opening of 300 m (AB_{max} = 300m). Field data in red and adjusted curve in blue. 5-layer model shows low chargeability values.*

The table showed in figure 09, determined from the synthetic curve adjustment to the real IP data, presents us, in general, a sequence of values with low chargeability (n) and high resistivity (ρ) then, a high rock clay content is not expected in this location, which is according to the place of sounding survey, because the IP-04 was carried out over a region of high resistivity, the same of VES-04 along the ERI-03 section (see figure 06) seem to have been survey over a depressed region, where it was not possible to estimate the water table depth.

4 – Well Drilling

A well was drilled at the location indicated in figure 10, along the ERI-03 line, reaching a depth of 120 meters. The drilling began on 10/29/2021, and was completed 25 days later, and found soil in the first 5 meters, followed by altered rock up to 13m, when it reached the top of the basalt of the Serra Geral Formation, thus determining the top of the SGAS, remaining in the basalts of Serra Geral Formation (basaltic rocks) until the final depth of 120 meters.

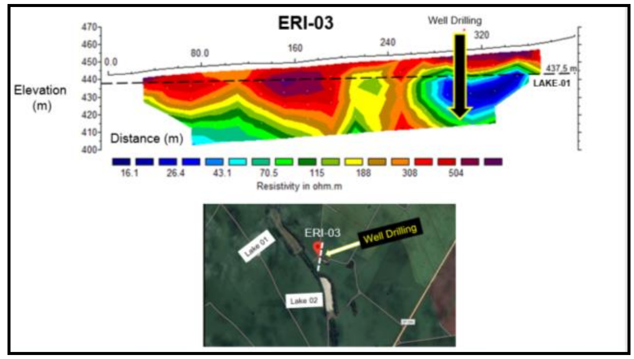

Figure 10 *– Well drilling location*

Water inflows occurred at 4 different depths, at 26 m, 53 m, 79 m and 112 m, by basalt fracture systems, with the following occurrences being reported during drilling:

The outflow test showed that the well reached water production stability of 49,600 liters/hour, after 30 hours of testing, with an interval of 3 hours for the well to recover the static level, with the dynamic level set at a depth of 82,44 m.

Conclusions

All the geophysical methods applied in this research contributed, in some way, to the excellent result achieved by the production water well located along the ERI-03, but undoubtedly, for the hydrogeological objective, the electrical resistivity methods (ERI and VES) stand out, which indicated several promising regions in places of low resistivity, or even excluding others, as well as the FDEM, which helped to reduce the ambiguity of the interpretation, which indicated the zones with high conductivity, and probably with high water pore saturation by another physical principle.

The Schlumberger depth chargeability surveys brought results that were interpreted as more clayey or less clayey, with the vast majority of IP data showing low chargeability values (< 50 mV/V), not being sensitive to the saturated zone (as expected) and presented a small growth with the increase of the depth.

The drilling data from the producer well proved that the most conductive zone of ERI-03 (from the depth of 18 m), was indeed formed by the fractured basaltic rock, and that the increase in resistivity from 36 m, was due to compact basalt, corroborating the geophysical interpretation.

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