Geoelectrical analysis from electroresistivity and TDEM data applied to geological and hydrogeological studies in Taubaté Basin

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Abstract

In this research, we have performed a geoelectrical analysis from electroresistivity (ER) and time domain electromagnetic (TDEM) data to study the geology and hydrogeology in Taubaté city, that is on the Taubaté Sedimentary Basin, which is characterized by half-grabens. ER method is more accurate for resistive structures and presents good resolution for shallower layers, on the other hand, TDEM method is more accurate for conductive structures and can reach great investigation depth, therefore these methods are complementary to each other. The preliminary results permit to define the top of the shallow sedimentary aquifer and the contact of the Quaternary and Tertiary sediments. The next step will be to perform a 2D TDEM/ER joint inversion using a new methodology developed by Bortolozo (2016), which uses the advantage of both methods to minimize the ambiguities and characterize 2D structures with more accuracy.

Introduction

In geophysics applied to natural resources exploration, the ambiguities in the results interpretation are always present. One way to reduce such ambiguities is to jointly use more than one geophysical method. With a wider range of data, the ambiguities can be reduced and the final interpretation becomes more reliable. The problem consists of looking for physical properties information of the subsurface. For example, the electrical resistivity can be obtained through electrical and electromagnetic methods.

In the ER method, the electrical resistivity is obtained by injecting an electric current in the subsurface through two electrodes (A and B) and the potential is measured by another two electrodes (M and N). For TDEM method, the resistivity is obtained as a function of the time response of the medium, i.e., the transient magnetic field.

The study area is located in Taubaté basin, next to Taubaté city, São Paulo State, Brazil (Figure 1). According to Riccomini et al. (2004) Taubaté basin is the largest basin of the Continental Rift of Southeastern Brazil (CRSB) with 170 km length and 20 km width, covering an area of about 3200 km^2. Figure 2 shows a geologic map of Taubaté Basin. The basin is elongated in NE-SW direction and presents normal faults in NW-SE direction, it presents a rift architecture and is characterized by a series of half-grabens with ~850 m thickness of sediments.

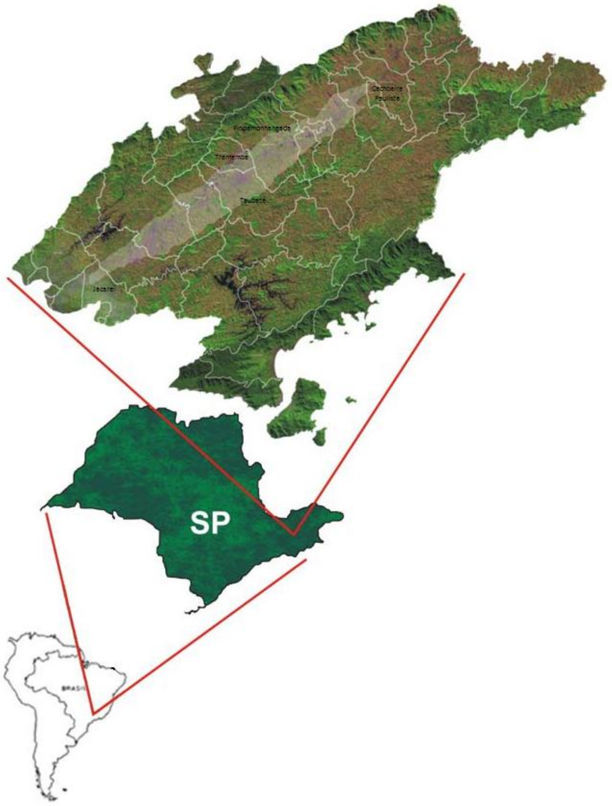

Figure 1. Taubaté Basin, São Paulo State, Brazil (Ribeiro, 2010).

The study aims to characterize the geoelectrical stratigraphy of the subsurface to locate the contact of the Quaternary and Tertiary sediments, to map the shallow sedimentary aquifer, to define the top of the basement rocks and to determine the fault zones that form the half-grabens.

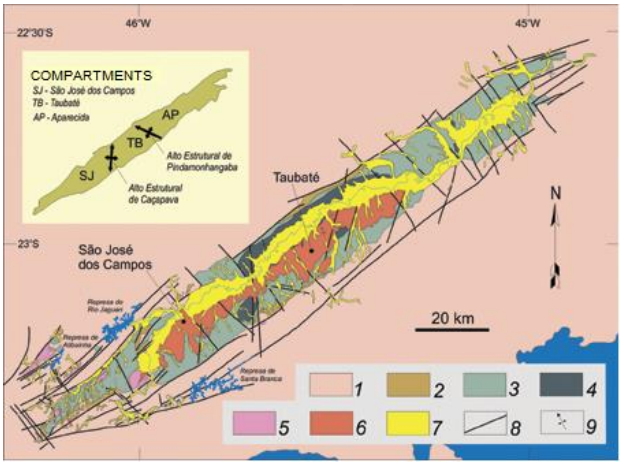

Figure 2. Geologic map of the Taubaté Basin: 1) Precambrian basement rocks; 2) Resende Formation; 3) Resende Formation; 4) Tremembé Formation; 5) São Paulo Formation; 6) Pindamonhangaba Formation; 7) Quaternary sediments; 8) Cenozoic faults, in part reactivated from Precambrian basement shear zones; 9) main fold axes (adapted from Riccomini et al., 2004).

Method

Electroresistivity

ER is a geophysical method widely used in the investigation of mineral deposits, groundwater exploration, evaluation of contaminated areas, among others (Telford et al., 1990). The method consists in injecting electric current (I) into the ground through metallic electrodes (AB current electrodes), and measuring the potential (ΔV) by another two electrodes (MN potential electrodes). Electrical resistivity values can be estimated because the spatial arrangement of the electrodes is known. According to Koefoed (1979), the apparent electrical resistivity (ρ_a) of the subsurface can be expressed as:

$$\rho_a = k \frac{\Delta V}{I} \tag{1}$$

where k is the geometric factor, which depends on the spacing and arrangement of the electrodes chosen for the survey. The investigation depth depends on the medium and the separation of the electrodes. Greater depths are achieved when the array size is increased.

Increasing centered arrangements on the same point constitutes the investigation procedure called Vertical Electrical Sounding (VES), which investigates the vertical variation of the resistivity (1D investigation). On the other hand, the electrical resistivity imaging (Figure 3) allows to map the lateral variation of the resistivity (2D investigation), used in this study.

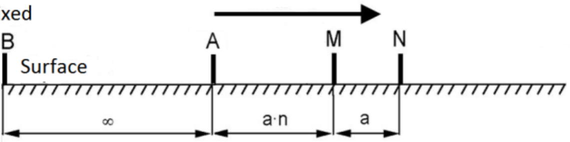

Figure 3. Electrical resistivity imaging, pole-dipole array (adapted from Bortolozo, 2016).

Time Domain Electromagnetic Method

The TDEM method investigates the lateral and vertical variations of the electrical resistivity of rocks in subsurface through the induction of electric currents in the interior of the Earth, being based on the principle of electromagnetic induction (Christiansen et al., 2006). It consists of having a square transmitter loop and a receiver coil, both on the surface. Initially a continuous current is injected in the transmitter loop, then this current is switched off and in the interval, in the order of microseconds, that the current goes to zero, the primary electromagnetic field varies in time and induces a secondary electromagnetic field, also variable in time, in the subsurface materials. The variation of the secondary magnetic field is measured by the receiver coil.

According to McNeill (1994), the apparent resistivity in late times is expressed by the equation:

$$\rho_a(t) = \frac{k_1 M^{2/3}}{V(t)^{2/3}\, t^{5/3}} \tag{2}$$

where $\rho_a(t)$ is the apparent electrical resistivity (Ohm.m), $k_1 = \mu_0^{5/3} M/20\pi$ ($\mu_0 = 4\pi \times 10^{-7}$ H/m, which is the vacuum magnetic permeability), M is the magnet moment that is equals to the product of the current (A) by the area (m^2), V(t) is the normalized voltage measured by a unit coil with 1 m^2 area and t is the interval given in seconds.

The voltage V(t) variation as a function of time is associated with the electrical resistivity variation of the subsurface materials.

Some of the main applications of the TDEM method include applications in groundwater prospecting in sedimentary aquifers (McNeill, 1994; Jens et al., 2003; Carrasquilla & Ulugergerli, 2006; Porsani et al., 2012a, 2012b), aquifers in fractured crystalline rocks (Porsani et al., 2012b), mineral exploration (McNeill, 1994) and contamination of the environment.

There are many acquisition arrays and field procedures. The array configuration, size and other parameters depends on the purpose of the research. The TDEM method can be used in different environments, terrestrial, marine or airborne, making it quite versatile for different situations.

The central loop array (Figure 4) has the advantage of having a good signal-to-noise ratio. In this configuration, the receiver coil is placed in the center of the transmitter loop. With the fixed transmitter loop array and the receiver coil mobile, it is possible to investigate the subsurface structures along the centerline of the transmitter loop. This array also has the advantage of being easy to implement and thus allows time saving during data acquisition.

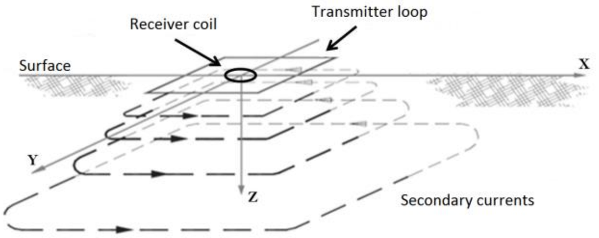

Figure 4. TDEM central loop array showing the secondary currents induced in the subsurface (adapted from McNeil, 1994).

Data Acquisition

ER data was acquired with the equipment Syscal (Iris Instruments) and it was done with the electrical imaging technique with pole-dipole array (Figure 3). The imaging line was 400 m length (Figure 5) and two profiles were done with 10 m and 20 m of electrodes spacing.

TDEM data were acquired with the equipment PROTEM-57MK2 (Geonics, 1998), which consist of a transmitter that is connected to a current generator to produce the primary electromagnetic field, and a 3D receiver coil of about 1 m diameter that is connected to a computer to record the signal of the secondary electromagnetic field induced in the subsurface. The transmitter loop was 200x200 m and the receiver coil were moved in the centerline of the array within 25 m spacing, in a total of 7 soundings points (Figure 5).

Figure 5. Data acquisition points in Taubaté city. The blue points show the starting and ending points of the ER imaging with 400 m length. The red square is the TDEM transmitter loop with 200x200 m and the points inside de loop (TDEM01, TDEM02, … TDEM07) are the TDEM acquisition points with 25 m spacing.

Well Information

Figure 6 shows a map with 40 wells (blue points) drilled in Taubaté and the study area (red square). These well information are available in the Groundwater Information System of the Brazilian Geological Service (http://siagasweb.cprm.gov.br/layout/index.php).

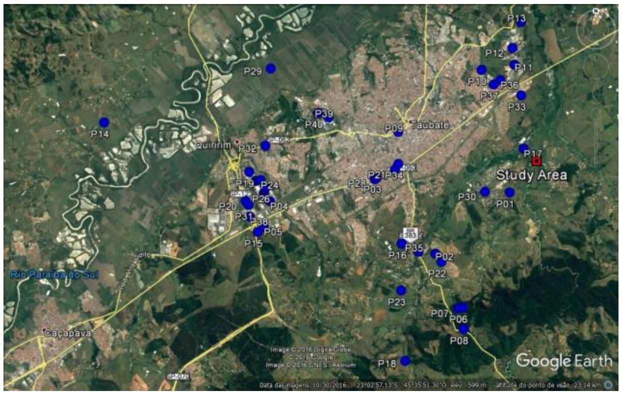

Figure 6. Map showing the wells (40) in blue and the study area in red.

The information include also a geological profile for each well. The closest well is P17, distant around 750 m from the study area, but its geological profile starts at 78 m depth and goes to 115 m depth. P01 is around 1780 m distant and has 124m depth. The deepest well is P40, with 647m depth, Table 1 shows its geological profile. P40 is around 9,5 km distant and it is in the same altitude as the study area, 567 m. We can observe that the geology is complex, with variegated shales, sandstones with different grain sizes, shale with gneissic pebbles bellow 400 m depth and the basement bellow 510 m depth is formed by gneisses.

Table 2 shows 9 wells with the water level information available from SIAGAS-CPRM. Note that the static water level varies from 0 to around 40 m depth. For wells P01 to P05 and P09, the lithology is mainly formed by claystone and sandstone and the static water level varies from around 7 to 42 m. For wells P06 to P08, the gneissic basement is shallower, around 10 m depth and the static water level is shallower.

All well information are very important for the results interpretation.

Table 1. Geological profile of well P40.

From (m)	To (m)	Lithology
0	4	Clayey soil
4	11	Variegated clays
11	16	Conglomeratic sandstone
16	401	Green shale
401	485	Shale with gneissic pebbles
485	493	Sandy shale
493	510	Shale with gneissic pebbles
510	650	Gneisses

Table 2. Wells with water level information.

Well	Depth (m)	Distance[1] (km)	Quota[2] (m)	SL[3] (m)	DL[4] (m)
P01	124	1.78	55	42	56
P02	186	6.30	27	17.6	75.47
P03	122.5	6.84	39	20.05	95.6
P04	120	11.47	22	18	110
P05	270	11.92	33	34.6	195
P06	80	7.00	90	2	56
P07	100	6.84	87	0	70
P08	156	7.67	121	0.2	33.5
P09	95	6.02	15	7.2	65.78

1. Distance from the study area
2. Altitude difference from the study area (all higher)
3. Static water level (before pumping)
4. Dynamic water level (after pumping)

Results

The electrical resistivity imaging data were inverted with the RES2DINV software (Loke 2004a), which uses the field data to automatically determine a two-dimensional model of resistivity for the medium. Figures 7 and 8 show the results for the array with 10 m and 20 m spacing, respectively. Both figures show: the field data (a), the synthetic pseudo-section (b), and the resulting inverted model (c). Analyzing both results, the resistivity sections (c) show three main zones. The first zone, from 0 to around 20 m depth, the resistivity varies from around 200 Ohm.m to 100 Ohm.m, which can be interpreted as clayey soil and unconsolidated sedimentary rocks. The second zone, from 20 m to around 40 m depth, the resistivity varies from around 100 Ohm.m to 20 Ohm.m, which can be interpreted as claystones and sandstones. The third zone bellow 40 m depth, with resistivity values lower than 15 Ohm.m, i.e., a conductive zone, can be characterized as rocks filled with water. This saturated zone possibly represents the top of shallow sedimentary aquifer.

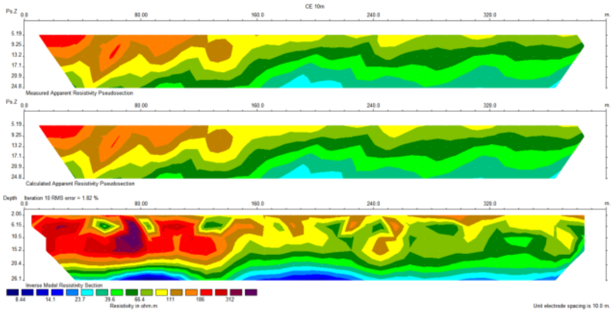

Figure 7. Resistivity section for the 10 m electrodes spacing.

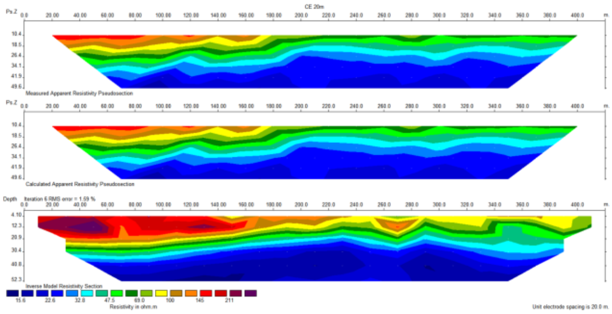

Figure 8. Resistivity section for the 20 m electrodes spacing.

The TDEM soundings were processed with the IX1D software (Interpex Limited). The inversion process consists of determine the electrical resistivity and thickness of the subsurface layers from the data. Figure 9 shows the inversion result for the central loop sounding TDEM04. In the left side is the apparent resistivity (Ohm.m) versus time (ms) and, in the right side, the geoelectrical model, depth (m) versus resistivity (Ohm.m). It was possible to interpret 6 geoelectrical layers up to 500 m depth. We limited the depth in 500 m because bellow that the method loses resolution.

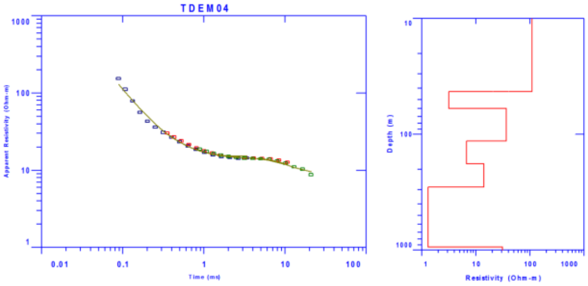

Figure 9. Inversion result for the central loop sounding TDEM04.

The first layer up to 40 m is consistent to the ER result, resistive with around 100 Ohm.m, which represent the clayey soil, claystone and sandstone. The second layer is also consistent with the ER result, from 40 m to 60 m depth, conductive with around 3 Ohm.m, which possibly represent the shallow aquifer. The third layer, from 60 m to around 110 m is moderately resistive, around 30 Ohm.m, which can represent a drier sedimentary rock, maybe shale, that has lower porosity and permeability. The forth layer from around 110 m to 200 m is conductive, around 8 Ohm.m, can be a saturated rock, probably with higher sand content, presenting higher porosity and permeability. The fifth layer from around 200 m to 300 m is still conductive, with the resistivity a little bit higher than the forth, around 12 Ohm.m. Finally, the sixth layer bellow 300 m is very conductive, around 1 Ohm.m, it is in the limit of the TDEM method resolution.

From the second to the fifth layers can be interpreted as the Tertiary sediments of Taubaté Group, a conductive zone with the resistivity varying from 3 Ohm.m to 30

Ohm.m, where the second layer possibly represent the shallow aquifer and it is consistent with the water level from the wells information (Table 2). Taubaté Group presents a very variable lithology and the resistivity can vary a lot too. More resistive zones can have lower porosity and permeability, probably shales, and more conductive zones can represent saturated rocks with a higher sand content and, consequently, higher porosity and permeability.

To summarize, based on the Taubaté Basin geology and the well information, combining ER and TDEM results, we have interpreted three main zones, that are presented in Table 3.

Table 3. Results Interpretation summary.

Zones	ρ (Ohm.m)	Depth (m)	Age	Interpretation
1st	200 – 100	0 – 20	Quaternary	Soil and unconsolidated rocks
2nd	30 – 3	20 – 300	Tertiary	Conglomerate, sandstone, siltstone, claystone and shale (Taubaté Group)
3rd	<15	40	Tertiary	Top of shallow sedimentary aquifer

Conclusions

The results have shown a great potential for the application of the combined ER and TDEM methods to the geoelectrical characterization of the Taubaté Basin, making it possible to identify the contact between Quaternary and Tertiary sediments and the top of the shallow aquifer. The results are consistent with the Taubaté Basin geology described in the literature and with the well information.

With the 2D TDEM/ER joint inversion, that is the next step in the project, we expect to define 2D structures, such as the half-graben faults. We will also have ER and TDEM data in N-S direction and seismic data to collaborate the interpretation.

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