Hydrogeophysical characterization of groundwater conductors and storage geological structures through Audiomagnetotelluric and Electrical Resistivity Tomography Methods

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Abstract

Caxambu, Minas Gerais county, is part of a large tourist complex known as Parque das Águas, known worldwide for its hydrothermal richness and therapeutic character of its waters. Geological, geochemical and hydrogeological studies have already been carried out in order to understand and characterize hydrothermal sources. The geophysical study, this work objetive, will produce information on how the underground water of the region behaves, in terms of flow and path traveled in the aquifer. For this, the geophysical methods used were those of Electrical Resistivity Tomography (ERT) and Audiometrytelluric (AMT). For the MT and AMT data processing, Egbert's robust code will be used and, for future inversion, will be used the three-dimensional magnetotelluric inversion algorithm, called *ModEM*. For the electrical data, the program used was the *AGI EarthImager 2D*. The results generated through the three methods will be interpreted jointly, associated to the *priori* hydrogeological information. The Project is financed by the *Companhia de Desenvolvimento de Minas Gerais* (CODEMGE), has the geological studies developed by Universidade Federal de Minas Gerais (UFMG) and Universidade do Estado do Rio de Janeiro (UERJ) and the Observatório Nacional (ON) is responsible for geophysical studies.

Introduction

The *Circuito das Águas* is located in the south of Minas Gerais and is known for its hydrothermal wealth with medicinal and therapeutic properties and is important for the economy and local tourism. In the Serra da Mantiqueira, the Tourist Complex of the *Parque das Águas* integrates ten municipalities, being Caxambu and São Lourenço pole cities. The project has a major focus on the city of Caxambu which is a true sanctuary of mineral waters, possessing the largest concentration of carbogasous waters of the planet, with twelve different chemical compositions sources.

Some studies already developed in the region have gained a better understanding of the processes that involve the formation and characterization of hydrothermal vents. From geochemical, geological and hydrological studies, it is known that groundwater is exploited at different depths and its residence times vary considerably, as well as its CO_2 content (CPRM, 1999). However, the distribution, flow and pathway that the water travels underground is still unknown.

Geophysics plays an important role in the rocks characterization for groundwater studies, thus, water is not the target, but the geological situation in which it is inserted. Therefore, Electrical Resistivity Tomography (ERT) and Audiomagnetotelluric (AMT) methods were used in order to image the layers of conductive subsurface and water storage areas. Images result generated by the methods inversion integrated with previous hydrogeological information can characterize the course of underground water.

Methodology

The Magnetotelluric method, according to Tikhonov (1950) and Cagniard (1953), is based on the electromagnetic induction principle, where electromagnetic waves are generated by physical phenomena in the atmosphere (frequency $>$ 1) and terrestrial magnetosphere (frequency $<$ 1) and vertically focus on Earth's surface. Induction of electric current on Earth occurs generating a secondary electromagnetic field. Horizontal (Hx and Hy) and vertical (Hz) magnetic field components are measured at the surface in a frequency range of 10^{-4}Hz a 10^{4}Hz using induction coils and the components of the electric field (Ex and Ey) using non-polarized electrodes.

The AMT method is a MT method variation where, in this case, frequency used is between 10 Hz and 10 kHz. In the frequency domain(w), the horizontal electric E(w) and magnetic H(w) fields can be related through the complex 2x2 impedance tensor Z(w):

$$\begin{bmatrix} E_x(\omega) \\ E_y(\omega) \end{bmatrix} = \begin{bmatrix} Z_{xx}(\omega) & Z_{xy}(\omega) \\ Z_{yx}(\omega) & Z_{yy}(\omega) \end{bmatrix} \begin{bmatrix} H_x(\omega) \\ H_y(\omega) \end{bmatrix} \tag{1}$$

From each impedance tensor complex component, the apparent resistivity (Eq. 2) and phase (Eq. 3) can be calculated. These parameters can be used to characterize the medium geoelectric conductivity ($\rho(x,y,z)$). Characteristics of the conductivity spatial distribution are known as geoelectrical dimensionality, which can be described as 1D, 2D and 3D.

$$\rho_a = \frac{1}{\omega\mu}\frac{|E_x|^2}{|H_y|^2} = \frac{1}{\omega\mu}|Z_{xy}|^2 \tag{2}$$

$$\phi = \arctan\left[\frac{\Im(Z(\omega))}{\Re(Z(\omega))}\right] \tag{3}$$

The ERT is a shallow resolution method and also provides contrast information of the resistivity between subsurface layers, consisting in application of an artificial current source in the ground through the electrodes in a contact line (Telford *et al*,1990). The procedure objective is to measure the electrical potential difference between two points, associated with induced electric currents distribution in the study medium, using Ohm's law ($V = RI$) as a basis. The geometry of the electrodes will depend on the level of detail and the depth to be investigated.From this it is possible to derive the equation ref eq: rho, considered the basic equation for calculating apparent resistivity for any electrode configuration (Kearey et al, 2013).

$$\rho = \frac{\Delta V}{I}\left\{\frac{2\pi}{\frac{1}{r_A}-\frac{1}{r_B}-\frac{1}{R_A}+\frac{1}{R_B}}\right\} \qquad (4)$$

Data acquisiton and processing

The data acquisition in the city of Caxambu was realized in two parts. The first one was acquired by CODEMGE team in 2017 and the second part by the Observatório Nacional team between April 15th and May 14th, in 2018.
Within the *Parque das Águas*, the field project consisted of a total of four profiles, where three profiles were dip (P1, P2 and P3) and one strike (P4) (Figure 1). The methods used in this locality were ERT and AMT, which objective was to investigate shallow geological structures with greater detail.

Figure 1: Location of the profiles surveyed the park (ERT + AMT) in Caxambu [from Pedrosa et al, 2018 (edited)].

The purpose of MT data processing is to obtain the impedance and tipper functions. From impedance are obtained resistivity and phase curves, and tipper that provides the induction vectors. These functions and their attributes allow to represent the internal electrical resistivity of the Earth.

In order to obtain the impedance tensor, the robust code of Egbert (1997) was used, which is a technique analogous to least squares estimation. The method minimizes differences between observed and predicted values and assigns weights to errors that vary within an iterative process until convergence is achieved.
From the impedance tensor, the geoelectric distribution can be known. This work uses a FORTRAN code, called WALDIM (Martí *et al*, 2009). It is a tool of analysis of dimensionality from a crude or synthetic data MT, based on the WAL criterion and considers data noise. Thus, by verifying the dimensionality of the data collected inside the *Parque das Águas* in 2017 (Figure **??**) and 2018 (Figure 3), it is possible to verify, mainly, 3D structures in subsurface. Then it is possible to know what model will look like to be inverted. For now, only the 2D results of the AMT data inversion were obtained. However, the results of three-dimensional inversion are expected to be close to the two-dimensional result, and are also similar to those obtained by the ERT method. Thus, the results will complement and provide a better understanding of how groundwater behaves in the region in question. In this work, the three-dimensional AMT inversion algorithm of Egbert (2017), called ModEM, was used. This code allows the inversion of the real and imaginary part of total impedance (Z) tensor, phase tensor (PT), tipper and the resistivity and phase.
Geophysical inversion models from the ERT data, measured within the Parque das Águas de Caxambu, were obtained through the 2D inversion code using the finite element method. The parametrizations used are limited to a root mean square (rms) of 1%. A smoothing method was used to suppress some outliers to general data set.

Results

The ERT profile P1 in NW/SE direction features the inverted 2D model with rms of 1.99 and L2 norm of 0.77. Resistivity values between 1 and 1000 were found. Some geological structures are being associated to resistivity values found in the final model. The Fracture Zone (FZ1), subvertical, is located under the channel of Bengo River. The bluish coloration in the model with conductivity around 100Ωm indicates an intensely fractured area of altered and saturated rock. The lenses that appear more conductive (C1, C2 and C3), may contain water with differentiated salinity. The resistive block R2 is positioned at 60 m depth and represents little fractured rock and/or rock without significant change. ERT profiles P2 and P3, also in NW/SE direction (Figure 5), parallel and distanced from each other of 35 m, exhibit an excellent lateral correlation of the identified structures, as can be seen in the similarity between the two profiles. The adjustments were between 3 and 5%, and resistivity ranged from 1 to 1000 Ωm. Fractured zones following in depth can be visualized in the center of conductive anomalies (C3) in two profiles and show subvertical diving near by Bengo River channel. These areas are saturated and high conductivity may be associated with altered rocks. The profiles top shows conductive lenses indicated as C2, made up of alluvial deposits. The R1 resistor indicates the occurrence of sane rock at the Morro de Caxambu basis and on a conductor (C1), as occurs in P1 profile. The conductor C1 is sealed by resistive blocks.

The AMT profiles were positioned on the ERT profiles in order to obtain a higher resolution in shallow part. The AMT profiles P2 and P3 (Figures 6 and 7) show conductor C2 as a large and deep water-saturated fracture zone, located below the channel of Bengo River. At the top of the profiles can be seen the conductor C1, associated to the alluvial deposit, which is also observed in the ERT profiles. Below C1 it is possible to identify the conductive range C3 related to altered and shallow fractured rock.In P3, the two resistive discontinuities (RD) can be seen, one of them being closer to NW, and closer to each other, and also the C4 conductor in the form of a horizontal lens, possibly associated to a fractured zone filled with more conductive fluid and of differentiated density.

Conclusions

The results obtained so far were very original and significant. They begin to give indications about the main storage and conducting structures of groundwater that feed the hydromineral aquifer of the *Parque das Águas* in Caxambu. ERT and AMT results show some conductive structures that are associated with local geology. The structure identified in the 2D ERT and AMT geophysical models is shown as the conductor C2 of the ERT profiles P2 and P3 (Figures 4 and 5) and the conductor C3 of the AMT profiles P2 and P3 (6 and 7). This conductive structure is shown to be a subvertical ruptil zone (failure), which feeds the aquifer, and spreads horizontally in the much-missed altered set of rock that is closest to the surface to a depth of about 60 m. The ERT and AMT results show some conductive structures that are associated with local geology, such as the conductive structures associated with a ruptil zone that feed the aquifer. Then, it is expected that those ERT and AMT results already acquired will together with the geological and hydrogeological information, they explain the groundwater behavior in this region.

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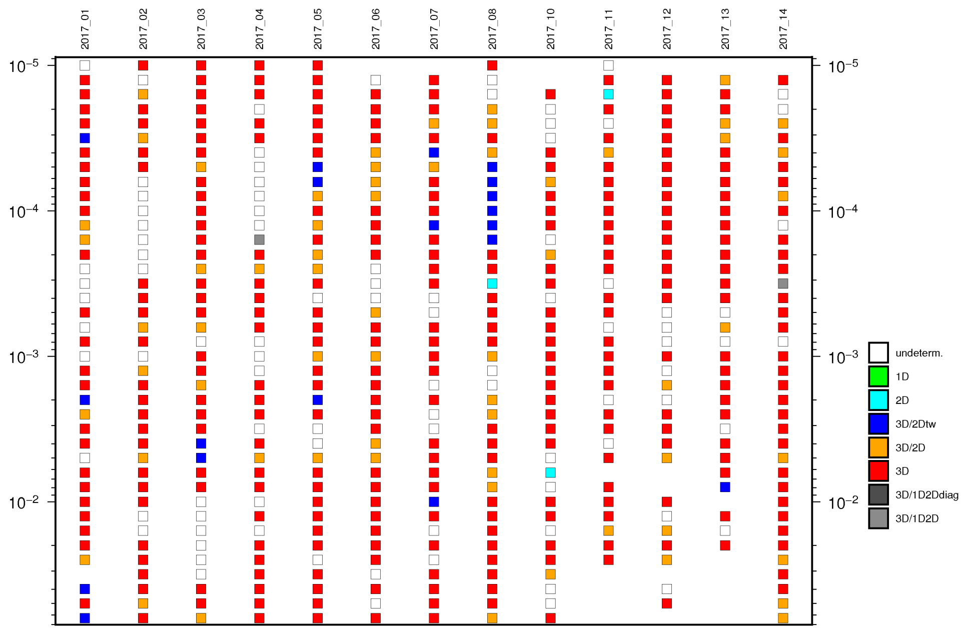

Figure 2: Dimensionality analysis made on AMT data collected inside the *Parque das Águas* in Caxambu in 2017. The result shows most are 3D structures.

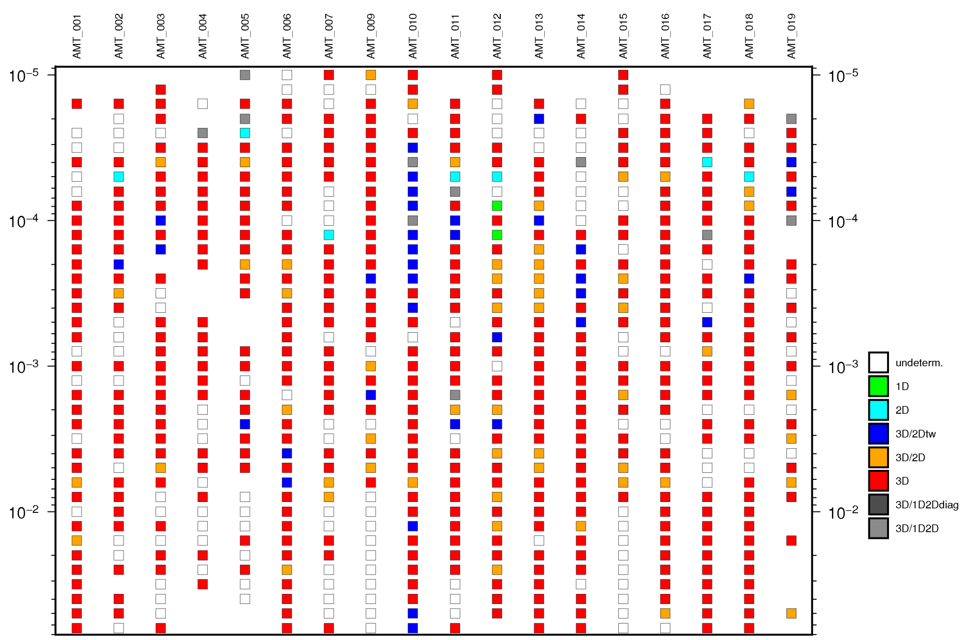

Figure 3: Dimensionality analysis made on AMT data collected inside the *Parque das Águas* in Caxambu in 2018. The result shows most are 3D structures.

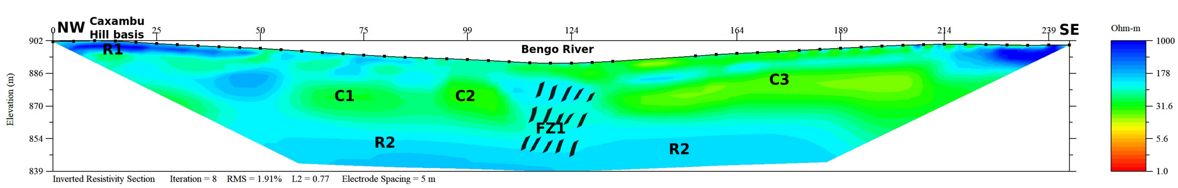

Figure 4: Inversion ERT model 2D, profile 1 known as P1 (dip), in Parque das Águas of Caxambu

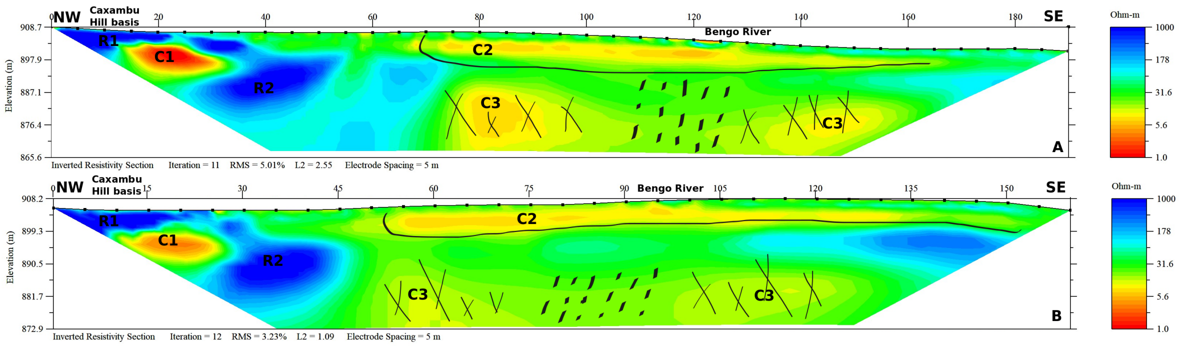

Figure 5: Inversion ERT model 2D profiles 2 and 3 (P2 (A) e P3(B)), in Parque das Águas of Caxambu.

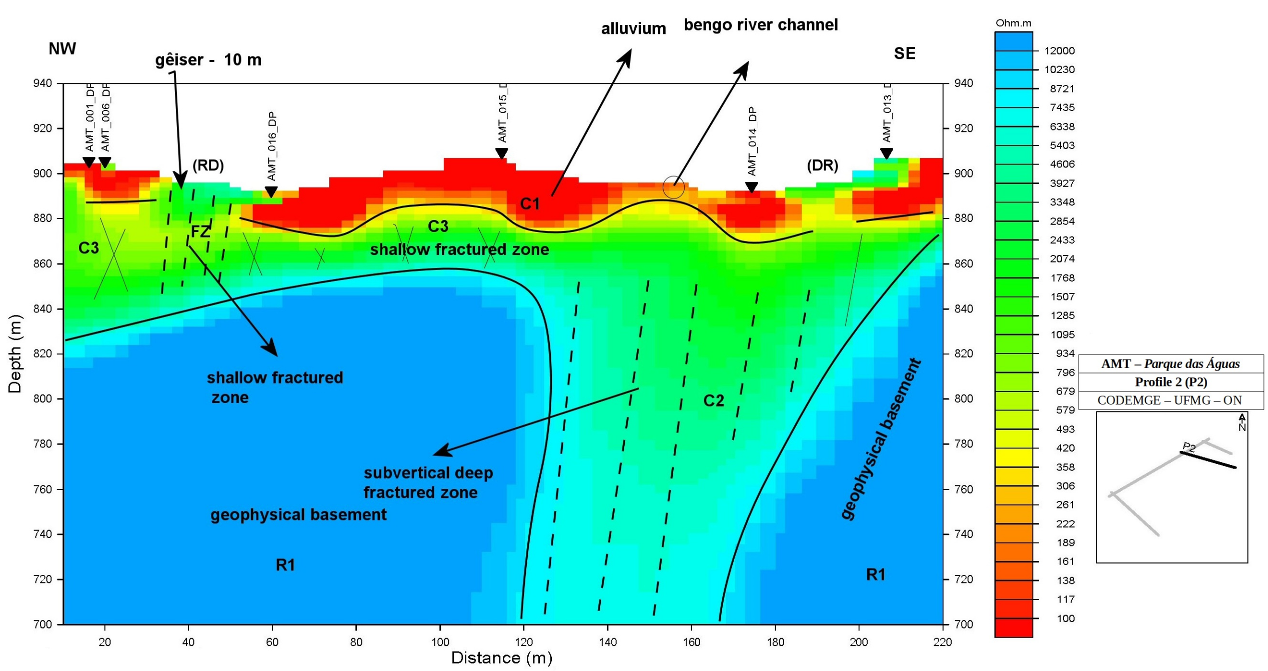

Figure 6: Inversion AMT model 2D, profile 2 (P2) in Parque das Águas of Caxambu.

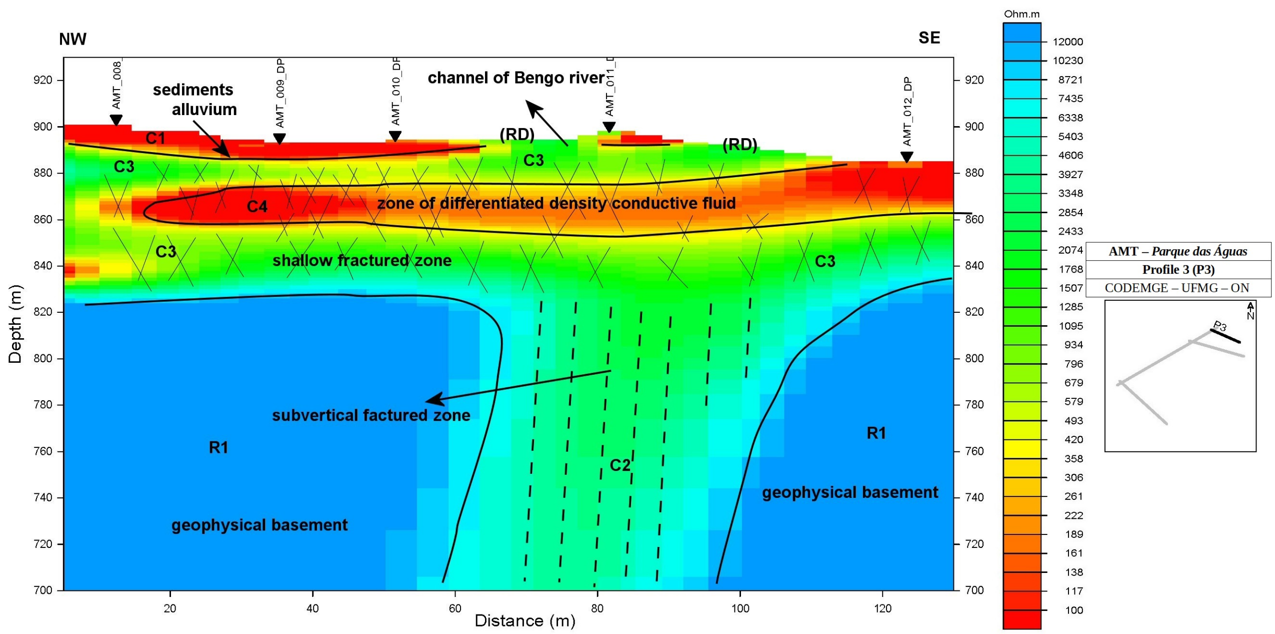

Figure 7: Inversion AMT model 2D, profile 3 (P3) in Parque das Águas of Caxambu.