Preliminary analysis of the induced magnetic field in the TDEM method: Applications in fractured aquifers

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Abstract

The time domain electromagnetic method (TDEM) has been widely used throughout the world for hydrological studies, due to its great sensitivity to map the subsurface conductive layers. In this work, authors will present the acquired TDEM data at Termas de Ibira region, countryside of Sao Paulo state, Brazil. The measurements were made through the fixed transmitter loop technique (Tx) with a moving 3D-coil receiver (Rx). The data analysis of the secondary magnetic using the 3D Rx coil aims to understand how these fields propagate in the subsurface, and also relating them to structures present in a fractured aquifer within the basalt layer of the Serra Geral Formation in the Parana basin. The results suggest the presence of fractures zones in the basalt that can be filled with water. The induced magnetic field profile showed the field behavior throughout the late times in the subsoil for each frequency.

Keywords: TDEM, magnetic field profile, Parana Basin, Termas de Ibira, Brazil.

Introduction

The main objective of geophysical studies with electromagnetic induction (EM) is to infer the distribution of electrical conductivity in the subsurface. This is accomplished based on terrestrial/marine/airborne/well electromagnetic field measurements, which are produced in response to transient excitation of the subsurface for one or more internal or external, natural or artificial sources (Everett, ME, 2009).

The electromagnetic method in the time domain (TDEM) was developed in the 80s and has since been widely used around the world as a robust geophysical exploration technique in which electric and magnetic fields are induced by transient pulses. Their use for hydrogeological studies had increased in recent years due to its versatility and great sensitivity to find conductive layers in the subsurface.

The increasing demands for greater depth of exploration along with a better definition of the underground structure require the application of transient electromagnetic (TEM) methods of large-scale with its inherent ability to generate rapid diagnostic data. The TDEM method has been used successfully for stratigraphic mapping of sedimentary basins, groundwater exploration and mining, among others (McNeill JD, 1990).

The TDEM method is a strong tool for in-depth exploration of the subsurface and offers a wide range of applications in hydrogeological studies. Usually, measure only the vertical component (z) of the secondary magnetic field and obtained the resistivity of the subsurface layers. In this study secondary field measurements are made in the three directions, namely the three spatial components will be measured (x, y, z) by providing a wide range of subsurface analysis capabilities. In this work, the measurements were to do by using a 3D receiver coil consisting of three coils directed along the three axes of the space. The study area is located in the Ibirá region, countryside of São Paulo State, Brazil (Figure 1). When the stratigraphy of the survey area is effectively flat, a coil of a single component (z) is usually appropriate. The response of the sub-vertical structure, however, is three dimensional, then, the measurement of all three components of the secondary magnetic field will result in a more accurate interpretation.

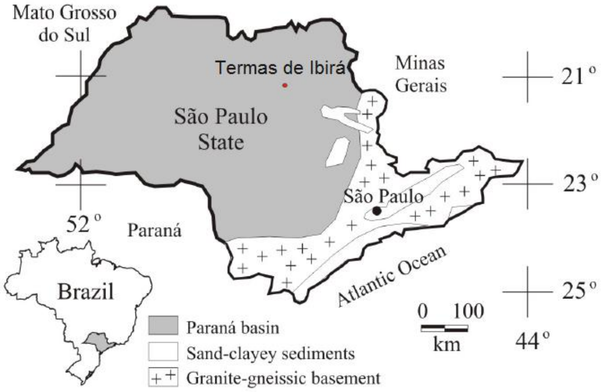

Figure 1. Location of the TDEM soundings in Ibirá region. Sao Paulo State, Brazil

The 3D coil with air core allows the gathering of cleaner data, which contributes to a more realistic geological interpretation, and therefore more suitable for the mapping of areas of probable fractures filled with water in basalt layer of the Serra Geral formation, Paraná Basin, where this research is developed.

Previous work has shown how the TDEM method is useful in searching for fracture zones in basalt (Almeida, 2011; Bortolozo, 2011; Porsani et al., 2012a). However, in the literature there is a lack of studies using 3D measurements of the secondary magnetic field, which is the motivation of this research oriented to a better understanding of the field components in the presence of structures in the subsurface.

Method

The TDEM method has as objective the estimation of the geology of a determined place by the measurement of an induced magnetic field in presence of a primary alternated magnetic field generated in the surface. However, the electromagnetic methods in the frequency domain have a common issue: All the secondary magnetic field measurements, referred as the behavior of the materials in the subsurface, are done under the influence of the primary magnetic field, that is, the field generated by the equipment source. This aspect involves the correct removal of the influence made by the primary magnetic field. Moreover, due to its greater intensity (compared to the secondary magnetic field) its removal is highly susceptible to noise and loss of accuracy (JD McNeill, 1990).

This is where TDEM method is strong. The fact that the measurements are not made under the influence of the generated magnetic field, commonly called “primary field” makes the measure of the induced magnetic field “secondary field” the only, therefore, an easier data management.

A procedure commonly utilized for ground exploration using transient techniques is to lay a large loop near the area to be examined. A steady current is caused to flow in the loop for a sufficient long time to allow turn-on transients in the ground to dissipate. The current is then sharply terminated in a controlled fashion; for example, the current is then turn-off may be linear-ramp waveform. In accord with Faraday´s Law rapid reduction of the transmitter current, and thus also of the transmitter primary magnetic field, induces an electromotive force (*emf*) in nearby conductors. The magnitude of this emf is proportional to the time rate of change if the primary magnetic field at the conductor (Everet, 2009). For this reason is desirable to reduce a large transmitter current to zero in short time in order to achieve a large *emf* of short duration. This *emf* causes eddy currents to flow in the conductor with a characteristic decay, which is a function of the conductivity, size and shape of the conductor. The decaying currents generate a proportional (secondary) magnetic field, the time rate of change of which is measured by a receiver coil. The apparent resistivity value is calculated from the *emf* value (*V*) as (Kaufman and Keller, 1983):

$$\rho = k\left(\frac{M}{V(t)}\right)^{2/3}\frac{1}{t^{5/2}} \tag{1}$$

Where *M* is the magnetic momentum, *t* is the time and *k* is a constant calculated by:

$$k = -\frac{\mu_0}{\pi}\left(\frac{an}{20}\right)^{2/3} \tag{2}$$

μ_0 is the magnetic permeability of the vacuum, a and n are effective area and the number of wire loops in the receiver coil respectively.

Analysis of the nature of the transient decay is carried out by sampling the amplitude at numerous intervals if time (and over many cycles of the transmitter pulse in order to enhance the signal-to-noise ratio). A typical system block is illustrated in the Figure 2.

In summary, as the currents circles the transmitter loop, the eddy currents also have an associated magnetic field and this posteriorly is measured in the surface. Due to Joule effect the energy of the eddy currents it´s transformed into heat, this attenuates the currents as time passes. Therefore, the attenuation of the eddy currents is associated to the conductivity/resistivity of the geologic medium: the more conductive the medium, the lesser the loss of energy of the eddy currents and more time is required to its attenuation.

Acquisition Array

There are several acquisition arrays and procedures, each one having its own advantages. The array configuration, size and other parameters depends exclusively of the object of study. The TDEM method is capable of being used in terrestrial, marine or airborne measurements of electromagnetic fields, making it quite versatile for different environments and situations.

The central loop array has the benefit of having a good relation signal/noise. In this configuration, the receiver coil is located at the center of the transmitter loop. In our case It has a 1m of diameter giving a minimum limit of 40m in the sides of the transmitter loop, this in order to avoid auto-inductance effects.

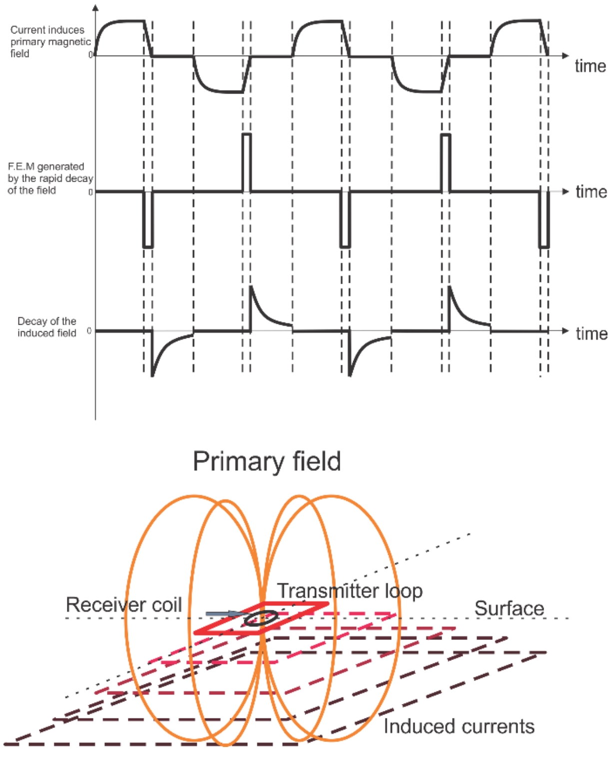

Figure 2. Diagram of the current cycles and the primary magnetic field in order to generate an *emf*.

However, using the fixed loop array is it possible to cover a greater area as the transmitter loop stays and the receptor coil moves throughout the area.

This method has also the advantage of being easy to implement in the practice, this saves time in the field making it a good method for industry and academy.

Equipment and data acquisition

The equipment consist basically, of a transmitter (Tx) and a receiver (Rx). The transmitter is connected to a current generator in order to produce de primary field. The receiver coil is about 1mt of diameter and is connected to the receiver equipment that manages the signal from the transmitter and the collected data from the receiver coil. In our case, the equipment is the TEM57 transmitter, 3D coil and the PROTEM digital receiver from the Geonics Canadian enterprise. The array is set in such way that the area of study is in the center of the arrangement and where the receiver coil is placed (Central Loop Array).

Measurements were taken using a 200x200m loop and moving the receptor coil trough the centerline of the array within 25m of space between soundings (Figure 3). This with the objective of make a symmetric profile and ease the search for contrasts and compare differences if any.

Figure 3. Schematics of the acquisition in the area of study.

Preliminary Results

In the time of the submission of this article, just the the Z component was analyzed for the three frequencies available in the equipment (30Hz, 7.5Hz and 3Hz). Several plots are displayed in order to visualize the behavior of the secondary magnetic field in the subsurface.

Figures 4 to 6 show the diffusion of the induced field with the evolution in time. As the equipment has standard time intervals of measuring, it was able to connect the received voltage measurements for the gates of each sounding in each frequency to create a magnetic profile.

It can be noted the amplitude of the signal is heavily related to the geometry of the array. Spatially it is stronger and positive inside the loop and becomes weaker when far from it. The vicinity around the loop has negative values with amplitude comparable to the values inside the loop pointing that the induced field is stronger near the cable that conforms the transmitter loop. This applies also for the time evolution and dissipation through soil since in early times the voltage in the receptor coil has a major value and decreases as time goes and the induced field dissipates deeper in the subsurface.

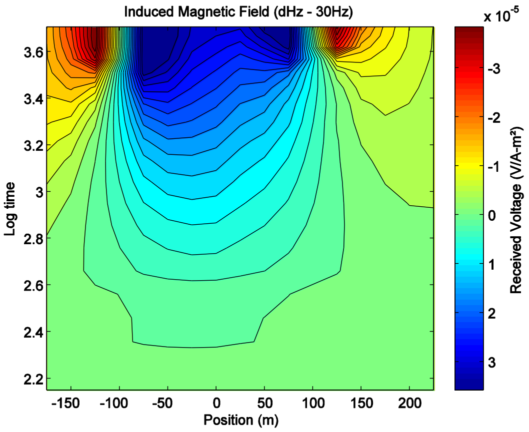

Figure 4. Induced magnetic field in the Z component for the 30Hz frequency.

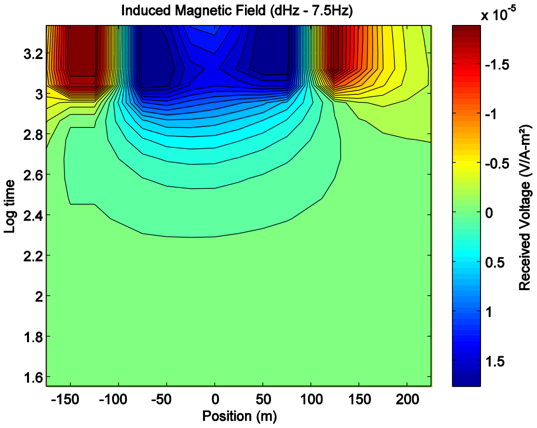

Figure 5. Induced magnetic field in the Z component for the 7.5Hz frequency.

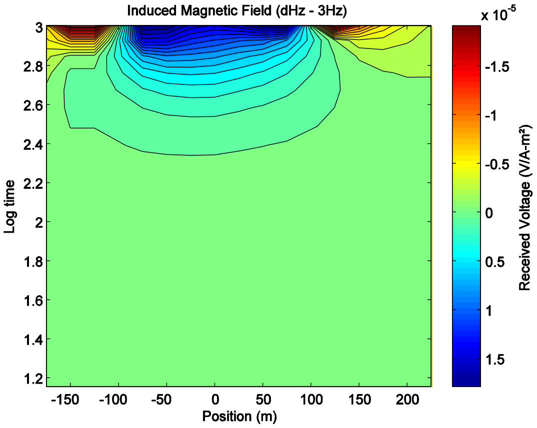

Figure 6. Induced magnetic field in the Z component for the 3.0Hz frequency.

It was also able to observe the so called ‘smoke rings’ and how they evolve in time. The Figure 7 shows the monotonic enlargement of the area covered by the induced magnetic field. This can be viewed as the enlargement of the area of the smoke ring generated by the transmitter loop.

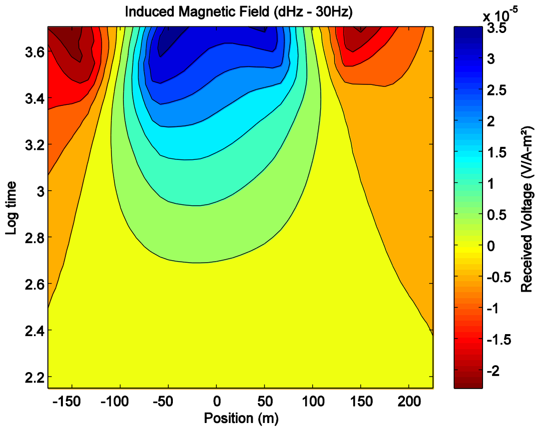

Figure 7. A different interpolation used to show the Induced magnetic field in the Z component for the 30Hz frequency and the evolution of the 'smoke rings'.

The frontier between the inside and the outside part of the loop is observed clearly, as the zones colored in blue indicate the interior part of the loop and the orange colored zones indicate the outside of it. The limit extends as a line separating these regions as time goes forming a cone that extends its area in the subsurface.

The figures 8 and 9 show the behavior of the induced magnetic field in the three frequencies, noting that the 30Hz frequency has the greater voltage values and the 3Hz frequency the lowest. The plot shows a rapid decay of the values in the 30Hz frequency and a 'sustained' amplitude for the middle region corresponding to the 7.5Hz frequency. The values corresponding to the last frequency were quite low in comparison to the previous ones.

Next, after the inversion process and the geoelectric model is generated, the regions in the plot are compared in order to relate the behavior of the magnetic field with the geoelectric layers.

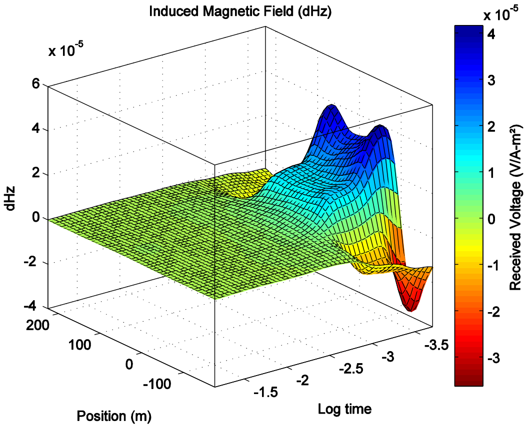

Figure 8. 3D rear plot of the induced magnetic field in the Z component for all the frequencies.

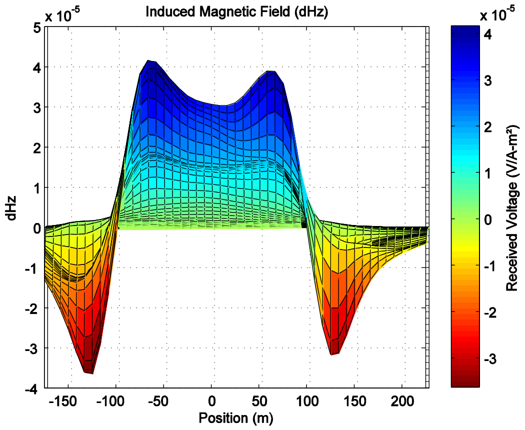

Figure 9. 3D front plot of the induced magnetic field in the Z component for all the frequencies.

The inversion for the central loop was carried out first, as the magnetic field is stronger inside the loop and this array have been consistently probed a good method to determine the top of the basalt zone and the geometry of the shallow aquifers (Porsani et al., 2012b). Only the Z-component of the induced magnetic field was used in the inversion process.

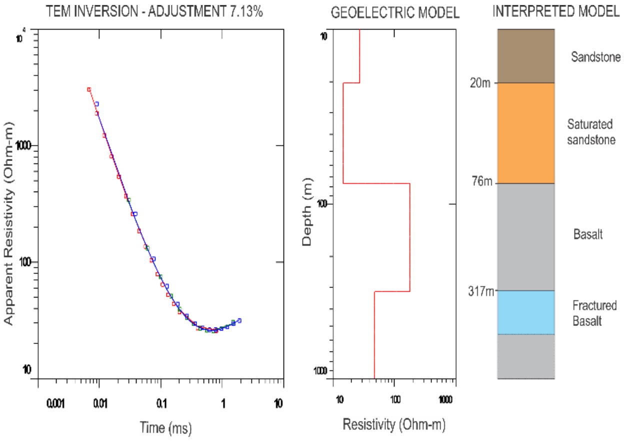

Figure 10. Inversion of TDEM central loop sounding. Geoelectric and interpreted model are shown on the right.

Geoelectric model showed in the figure 10 displays resistive and conductive sediments related to sandstones and saturated sandstones of Adamantina formation (~20m), respectively. The top of basalt layer (Serra Geral formation) encounters at ~76 m depth and is related to a resistive layer in the plot (gray regions). In this area, basalt layer features 400-600 m thickness. Though, It can be noted in the geoelectric model that clear conductive layer within of basalt layer appears around 317m, suggesting the presence of a fracture zone filled with water, attributable to its high electrical conductivity (~30 Ohm-m). The shallow results are in agreement with lithological information from wells located in the area. The Ibirá region is quite known as a high-density basalt fracture area; however, there were not deep wells near this particular zone to corroborate the basalt fracture layer.

The correlation between the geoelectric model and the induced magnetic field profile can be made in terms of the geoelectric layers and the variations in amplitude of the induced magnetic field. Rapid-change regions in the magnetic profile (Figures 8 and 9) can be related to resistive areas where the amplitude decays considerably between gates. This is in concordance with the resistive layers in the geoelectric model interpreted as basalt (~150-200m). On the other hand, conducive layers of the geoelectric model can be viewed in the magnetic field profile as sustained amplitude regions, corresponding to the middle and final part of the plot in Figure 9 and a possible fracture zone around 300m depth. This is explained by the difference in energy loss as the eddy currents passes from one medium to another. Resistive layers propitiate rapid energy decays and conductive layers a more sustained and slow decay.

Conclusions

The behavior of the induced magnetic probed to be spatially symmetric and was possible to see its diffusion and evolution in the subsurface through time.

The ‘smoke rings’ were observed clearly as the magnetic field propagated in the subsurface. Positive and negative voltage values delimited the area of these rings and showing their enlargement over time.

The results from the inversions inside the loop were in concordance with the geoelectric model and the geology in the area.

Resistive and conductive layers were able to associate with rapid and slow decay zones in the induced magnetic field profile.

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