METODOLOGIA GEOFÍSICA INTEGRADA NUM ESTUDO HIDROGEOLÓGICO NA PLANÍCIE COSTEIRA NORTE DO ESTADO DO RIO DE JANEIRO - BRASIL

Integrated Geophysical Methodology in a Hydrogeological Study in the Northern Coastal Plain of Rio de Janeiro State – Brazil

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RESUMO: Um estudo geofísico piloto foi realizado na Planície Litoral Norte do Estado do Rio de Janeiro (Brasil), próximo da cidade de Rio das Ostras, 200 km ao NE da cidade do Rio de Janeiro. Esta região é caracterizada pela escassez de água potável e pela existência de intrusão salina, causada principalmente pela presença de uma geologia complexa do Quaternário e por uma exploração excessiva do aqüífero. A pesquisa foi realizada através do emprego de métodos geofísicos magnéticos e eletromagnéticos (domínios do tempo - TEM e freqüência - FEM), a fim de avaliar a eficácia destes métodos nessas condições geológicas, como também, formular uma pesquisa hidrogeológica mais abrangente da região no futuro. A interpretação unidimensional (1D) dos dados dos perfis FEM e das sondagens TEM foram capazes de revelar as diferentes formações geológicas, localizando o aqüífero e revelando o contato das águas doce – salina. Por outro lado, o método magnético mostrou a presença de uma falha geológica com direção NE-SW, a qual fica localizada no contato geológico entre areia e argila, coincidentemente com o contato das águas doce - salina. Os resultados indicaram um futuro promissor para a utilização de métodos geofísicos eletromagnéticos na região em prospecções de pequena escala e as possibilidades de uso do método magnético em estudos regionais, na indicação dos locais mais adequados para localizar poços produtivos de água potável.

Palavras-Chave: geofísica, métodos eletromagnéticos, método magnético, águas subterrâneas.

ABSTRACT: A geophysical pilot study has been undertaken in the Northern Coastal Plain of Rio de Janeiro State (Brazil), near Rio das Ostras City, 200 km NE from Rio de Janeiro City. This region is characterized by both scarcity of drinking water and the existence of saline intrusions, which is caused mainly by the presence of a complex Quaternary geology and excessive aquifer exploitation. The research was performed by employing magnetic and electromagnetic methods (time - TEM and frequency - FEM domains), in order to evaluate the effectiveness of these methods applied to these particular geological conditions, also, to help the formulation of a more comprehensive hydrogeological research in the region in near future. The interpretation of FEM profiles and one-dimensional (1D) TEM data were capable of depicting different geological formations, to locate the main aquifer and to localize the fresh-saline water contact. On the other hand, the magnetic method showed the presence of a NE-SW direction geological fault, which is located just in the geological contact between sand and clay, which is coincident with the fresh-saline water contact. The results evidenced a promising future for using electromagnetic geophysical methods in this region, in small scale surveys, as well as the adequacy of using the magnetic method for regional survey to indicate the most suitable places to locate productive fresh-water wells.

Keywords: geophysics, electromagnetic methods, magnetic method, groundwater.

INTRODUCTION

Geographically, Rio de Janeiro State can be divided in two main regions: the Highlands region and the Coastal area. This research was developed in a sector located in the northern portion of the Coastal area, near São João Mount and Rio das Ostras City (Figure 1). This area´s geological map shows the predominance of rocks with pre - Cambrian age, with fractures in NW/SE and NE/SW preferential directions (Figure 2). These pre-Cambrian rocks are constituted by the association of gneisses - biotites, gneisses, granites, porphyiroblast - gneiss and migmatites. Locally, there are valleys filled with Quaternary sediments, which were deposited in flooding plains near the coast (DRM/PETROBRAS, 1997).

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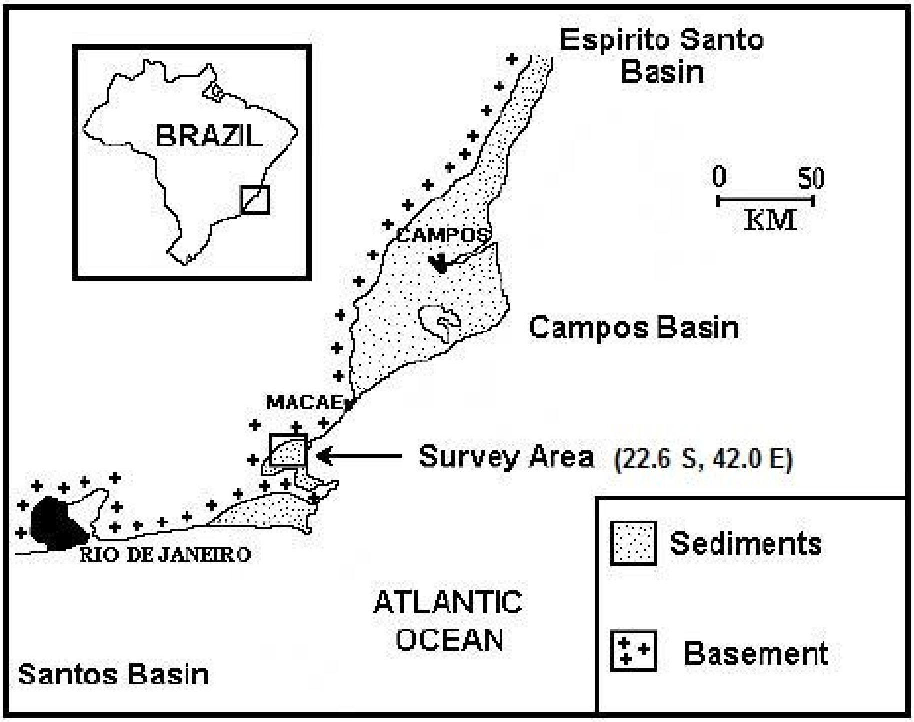

Figura 1: *Localização da área de estudo.*
Figure 1: *Location of survey area.*

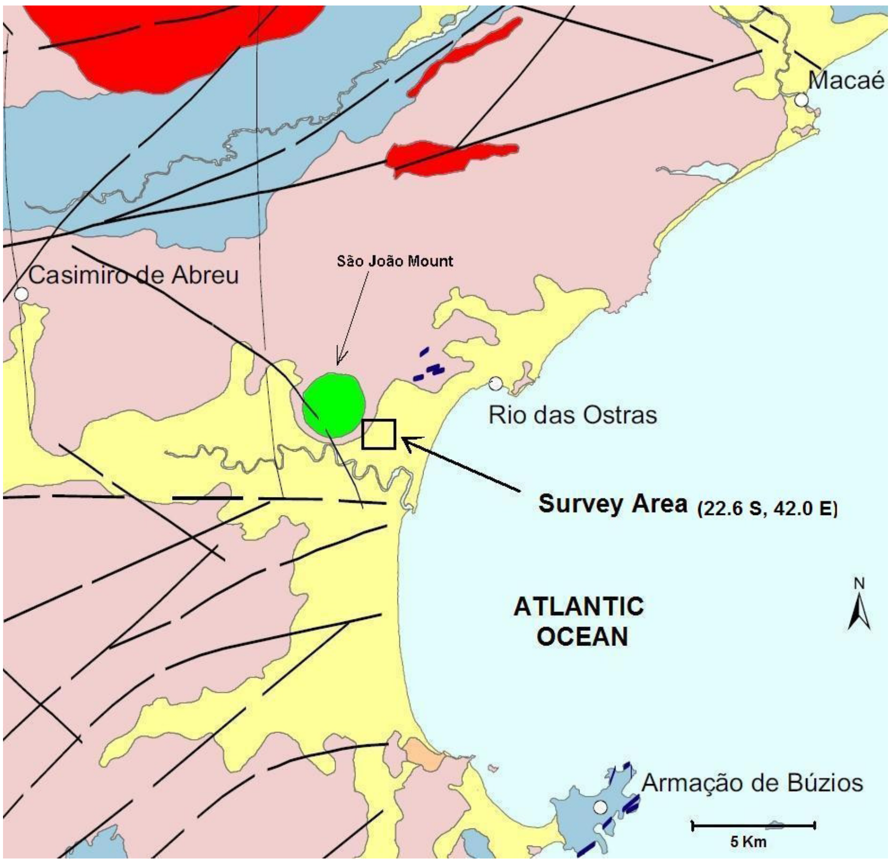

Figura 2: *Mapa geológico da área estudada: granitos homogêneos (vermelho), rochas metamórficas derivadas de rochas sedimentarias (azul), rochas magmáticas alcalinas (verde), sedimentos cuaternários (amarelo), rochas metamórficas derivadas de rochas ígneas (rosa) e sedimentos terciários (laranja).*
Figure 2: *Geological map of studied area: homogeneus granites (red), metamorphic rocks derived from sedimentary rocks (blue), magmatic alkaline rocks (green), quaternary sediments (yellow), metamorphic rocks derived from igenous rocks (pink) and tertiary sediments (orange).*

The Brazilian Geological Survey (CPRM) undertook magnetometric and gamma-spectrometric air surveys covering most of Rio de Janeiro State (*Mourao,* 1995). The results of these surveys evidenced the major geological trends and were used as an initial guide in the present study. In another study, in the adjacent area in São Vicente District, Araruama County, MELLO (1995) made a geophysical prospecting using DC – resistivity, and the interpretation of these data revealed the existence of a granite-gneiss weathering basement with apparent resistivities (ρ_a) of 2300 - 2800 Ωm, which shows localized fractures or faults saturated with water ($\rho_a \approx$ 900 - 1800 Ωm), besides fracture-saturated C weathering ($\rho_a \approx$ 215 Ωm) and impermeable B ($\rho_a \approx$ 620 Ωm) horizons. Above the basement and in the form of a lithological discordance, there is quartz - feldspatic sandy or clayey sedimentary package, which is saturated ($\rho_a \approx$ 27 - 35, 78 - 100, 165 - 230 Ωm) and has an average thickness of 35 m. Thus, it can be concluded that, excluding the bedrock, the highest values of ρ_a are associated with geological formations presenting coarse grains and greater porosity and permeability, embedded in non-saline saturated solution. Consequently, there are plenty of conditions to find fresh water in the studied region, as much as in the crystalline fractured rocks at the portions where exist a thick sediment package. Therefore, with the estimation of the electrical resistivity, it is also possible to detect the subsurface zones filled by saline water due to the occurrence of sea water intrusion, which has low ρ_a values.

METHODOLOGY

In this study, it was employed electromagnetic (EM) geophysical methods in time (TEM) and frequency (FEM) domains, as well as the potential magnetic method. Applying the FEM method, the EM survey was performed using a conductivity meter GEONICS EM-34, (GEONICS Ltd., Mississiauga, Canada) (GEONICS Ltd, 1990). This equipment is a two-man portable system comprising of a couple of coils, where one is a transmitter (Tx) and another is a receiver (Rx). When Tx is energized with an alternating current at audio frequencies (100 - 5000 Hz), the time varying magnetic field arising from this effect induces very small currents on subsurface, which is assumed uniform. These currents generate a secondary magnetic field (H_s), which is sensed together with the primary field (H_p) by the receiver, in the form of total field (H_T). Thus, H_s is a complicated function of the inter-coil spacing (s), the operating frequency (f) and the ground conductivity σ (MCNEILL, 1980). With the measured signals, it is possible to study different characteristics of H_T as a real (*R*, in phase) and an imaginary (*I*, quadrature) component amplitudes, out-of-phase between them or dip of H_T regarding H_p, using an electrical contact between transmitter and receiver loops through a wire. In dip measuring, receiver coil is dipped until achieve the minimum or maximum values, having accurate results only when the anomaly has a high conductivity. Measuring *R* and *I* components, the greater values for a specific component depends if the sub-superficial body is a good or a bad conductor, with the *R/I* ratio increasing with a non-homogeneous conductivity (σ=1/ρ). However, the EM-34 is designed to directly measure linear conductivity under certain constraints, defined as *operation under low induction numbers* by simply measuring the ratio between H_s and H_p. Given H_s/H_p, the apparent conductivity σ_a (mS/m) indicated by the instrument is defined as:

$$\sigma_a = \frac{1}{\rho_a} = \left(\frac{4}{(\omega\mu_o s^2)}\right)\left(\frac{H_s}{H_p}\right) \qquad (1)$$

where ω is the angular frequency (ω = 2πf), μ_o is the permeability of free space (1,2566X10^{-6} m kg C^{-2}) and *s* is the inter-coil spacing (in m). In this case, results are generally showed in contour maps or surface profiles (WARD, 1990). The EM response at low induction numbers with either horizontal or vertical transmitter/receiver dipole orientation is based on the assumption that a) all current flow is horizontal and, b) all current loops are independent of all other current loops. This allows the construction of a function, which gives the relative response to H_s at the receiver, from a ground´s thin layer at any depth. On the other hand, the coils must always be coplanar, but may be used in a vertical position or lying horizontally on the ground. The vertical coil configuration (horizontal dipoles – HD, also known as horizontal loop electromagnetic - HLEM) is the most sensitive to near surface materials and the response decreases with depth. The horizontal coil configuration (vertical dipoles – VD, also known as vertical loop electromagnetic - VLEM) has better response to materials located at a depth of approximately 0,4 s. However, materials at a depth of 1,5 s also contributes significantly. Thus, the depth of exploration is mainly a function of coil separation and orientation. The EM-34 has separate coils connected by a cable, which can be

10, 20 and 40 m long. The effective investigation depths are 7,5 m (HD) and 15 m (VD) for a frequency of 6,4 KHz and separation of 10 m. For a separation of 20 m and frequency of 1,6 Hz, the effective investigation depths are: 15 m (HD) and 30 m (VD), in addition, for the separation of 40 m and frequency of 0,4 Hz, the investigation depths are: 30 m (HD) and 60 m (VD) (GEONICS, 1990).

Applying the TEM method, one strong direct current is passed through a non-grounded loop or a grounded electric dipole. At time t = 0, this current is interrupted and another receiving loop measures H_s produced by geological heterogeneities in subsurface in absence of inductive H_p and in the form of a declining voltage. In this curve, the electric potential is measured in different times, which are related with different geological materials in subsurface. Field procedure consists in performing several EM soundings along a profile, to show resistivities changes in distance and depth (NABIGHIAN, 1989). Generally, the results can also be shown as soundings and its 1D interpretation, but, usually, they are presented in pseudo-section form. This technique has been used to delineate stratified structures of geological interest, as well as, to prospect groundwater, geothermal bodies, sulfide ores, deep graphite conductors and others. Recently, this method has been utilized as the most efficient technique to correct the static shift, which distorts the magnetotelluric soundings (MEJU *et al*., 1993). The survey performed by this work, used the equipment SIROTEM MK3 (GEOINSTRUMENTS Pty Ltd., North Ryde, NSW, Australia) (Buselli et al., 1985), which measures the decay rate of the induction vertical magnetic component in nV/A-m^2. The values obtained are transformed in ρ_a (Ωm) using the following equation (*Fitterman & Stewart*, 1986):

$$\rho_a = \left[\left(\frac{\mu}{4\pi t}\right)\left(\frac{b^2 A^2}{5tV}\right)\right]^{2/3} \qquad (2)$$

where μ is magnetic permeability (1,2566X10^{-6} m kg C^{-2}), b is the side of the transmitter loop (in m), A is the effective area of the receiver loop (area x number of coils), I is the electrical current in the transmitter loop (Amp), V is the transient voltage (Volts) and t, the time since the beginning of the transient (s).

The magnetic methods have a broad range of applications, for small-scale environmental, engineering and archaeological surveys to detect buried magnetic objects; to large-scale surveys for investigating regional geological structures. In this study, the magnetic data were gathered with two proton-precession magnetometers SCINTREX WALKMAG (SCINTREX Ltd., Concord, Canada) (SCINTREX Ltd, 2009), which measure the scalar magnitude of the total field in nanoTesla (nT). One of the magnetometers was fixed in a base station to measure the diurnal variation in the magnetic field intensity. This kind of magnetometer gives a series of discrete measurements at intervals of a few seconds, because of the polarizing and relaxing time taken by protons (SHARMA, 1997).

In the fieldwork, using these geophysical methods, it were performed profiles in a N-S direction, between São João Mount and the beach, taking 17 TEM soundings along 3 km of extension, in addition to FEM profiles performed in a small sector of the greater profile (beginning in the second station in W-E direction) with 330 m of extension and station spacing of 5 m. On the other hand, magnetometric profiles were developed in the same form and location, but only with 1 km extension, with station spacing of 1 m. Another two parallel magnetic profiles were made 250 m E and W from the first one, respectively (P1 and P2).

RESULTS

Figure 3 shows the FEM profiles with both VD and HD arrays. In the qualitative interpretation of these data, it can be observed a higher ρ_a (50 Ωm or more) at the initial stages of the curves, which is related with a dune sandy terrain. After 150 m, the ρ_a values decrease to amounts smaller than 10 Ωm, showing the presence of clayey terrain, probably saturated with saline water. HD profiles are smoother, whereas VD show larger ρ_a variations in subsurface caused by heterogeneities. These values decreased with depth (curves with Tx-Rx = 40, 20 and 10 m, and frequencies = 0.4, 1.6 e 6.4 KHz, respectively), possibly due to greater water saturation in the geological formations below the water table. On the other hand, at the end of the profiles, the VD curves show a heterogeneity that increase its size and with depth, possibly caused by local sand lenses.

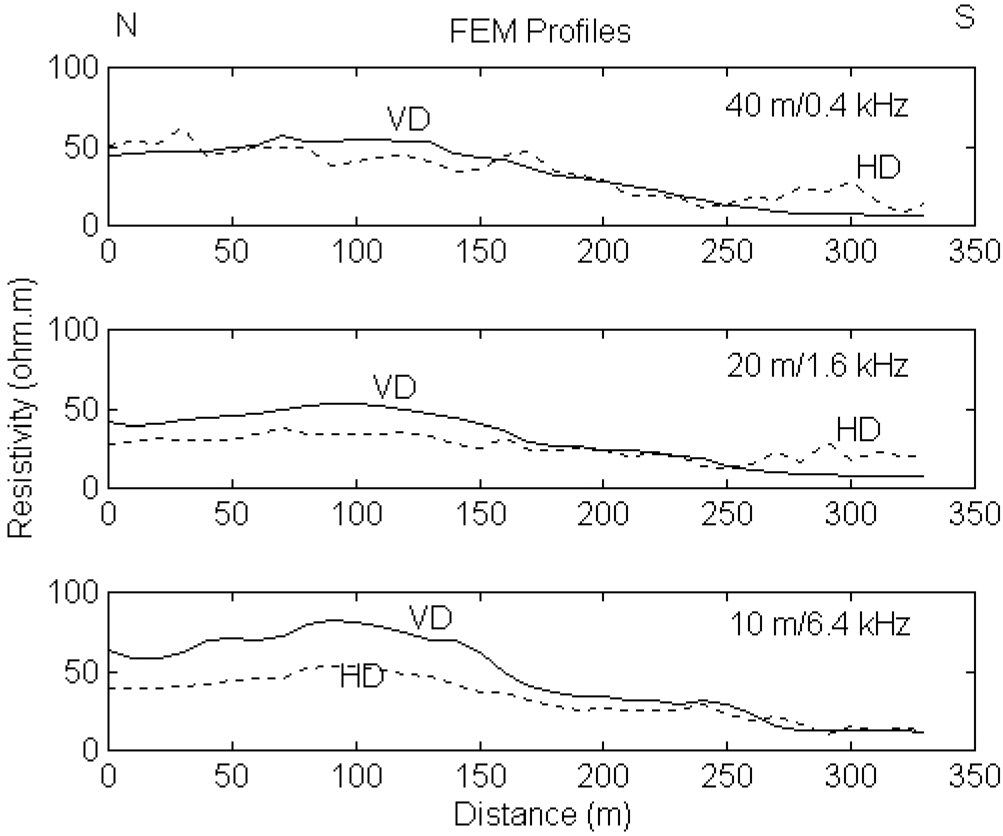

Figura 3: *Perfis FEM.*
Figure 3: *FEM profiles.*

In the TEM data interpretation, it was used the dumped least squares inversion algorithm for horizontal layers (ridge regression), using a computer program TEMIXXL (INTERPEX Ltd, Golden, Colorado, USA) (INTERPEX Ltd, 1996). The first one, corresponding to the Sounding 1, has 6% of fitting error and was performed in the sector W of the profile, above sandy terrains (Figure 4). The second one is the Sounding 4, which is located at Sector E, above clayey terrains, possibly saturated with salty water (Figure 5). The exact positions of two of these interpreted soundings are shown in Figure 6, in addition to the FEM profiles. The interpretation of the 17 soundings shows the presence of four horizons: a) the first one is the soil, with $\rho_a \approx 12$ Ωm and thickness varying between 10 - 24 m; b) the second is a resistive layer, located at the Sector W of the profile (with ρ_a between 40-105 Ωm, and $h \approx 4 - 30$ m) and a very conductive layer in the E part of the section ($\rho_a \approx 0{,}2 – 0{,}7$ Ωm and $h \approx 3 - 5$ m); c) the third is a slightly resistive layer, with $\rho_a \approx 100$ Ωm and $h \approx 30$ m, in Sector W, and, $\rho_a \approx 10$ Ωm and $h \approx 4 - 8$ m in Sector E; and d) the fourth, is the crystalline basement, with $\rho_a \approx 1000 - 5000$ Ωm. The geo-electrical section derived from the TEM soundings shows higher values of ρ_a in the Sector N (sand) compared to ρ in the Sector S (clay with salty water), as well as the presence of a crystalline basement at higher depths (Figure 6). In the same figure, between the distances of 370 m and 700 m, it is also shown the relative positions of FEM measurements, which present results with similar features to those from TEM, in both data sets the ρ_a values vary between 50 Ωm to less than 10 Ωm (compare Figures 3 and 6). The more resistive deep heterogeneity showed in the end of FEM profiles is also seen in the TEM geoelectrical section, near 700 m. In the coincident part of FEM profiles and TEM geoelectrical section, it is also evident that Sector W shows a resistive sandy material with larger values of porosities and permeabilities, where fresh water is known to exist. The larger aquifer thickness in the Sector W of the profile can be associated with the presence of a fracture or a geological fault with NE/SW strike direction.

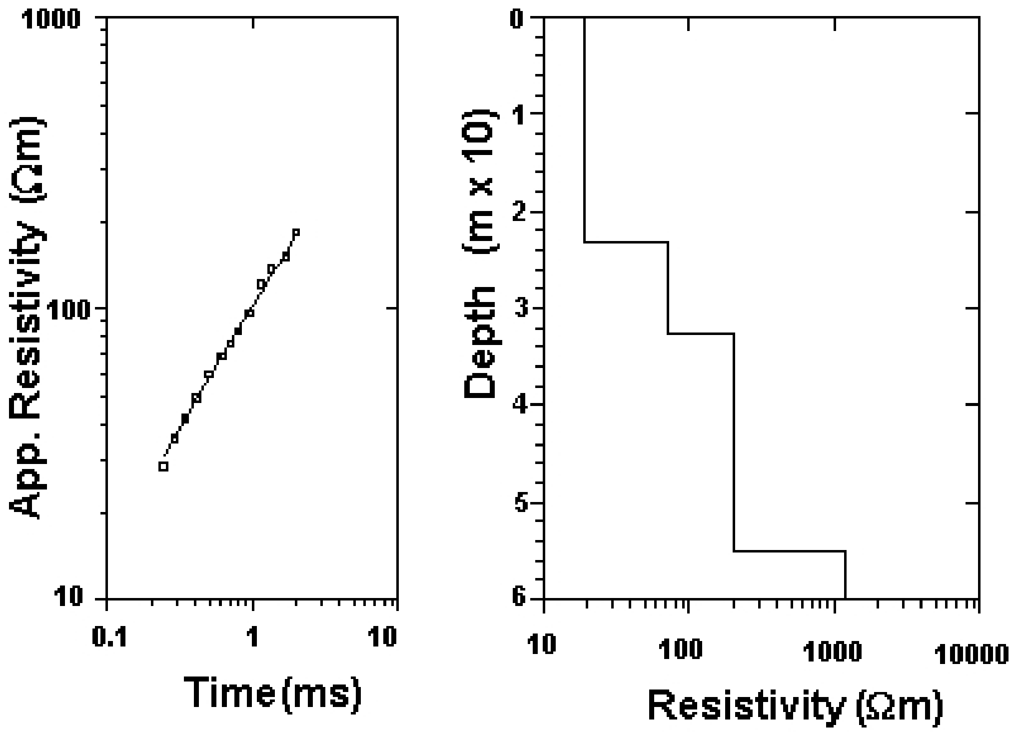

Figura 4: *Sondagem TEM 1 no Setor N e sua interpretação.*
Figure 4: *TEM Sounding 1 in Sector N and its interpretation.*

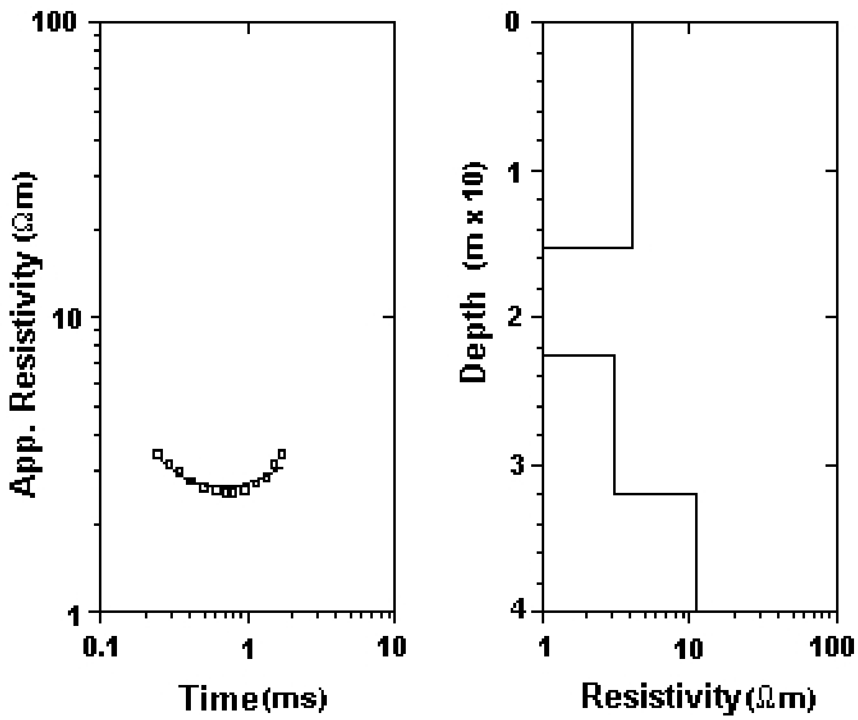

Figura 5: *Sondagem TEM 4 no Setor S e sua interpretação.*
Figure 5: *TEM Sounding 4 in Sector S and its interpretation.*

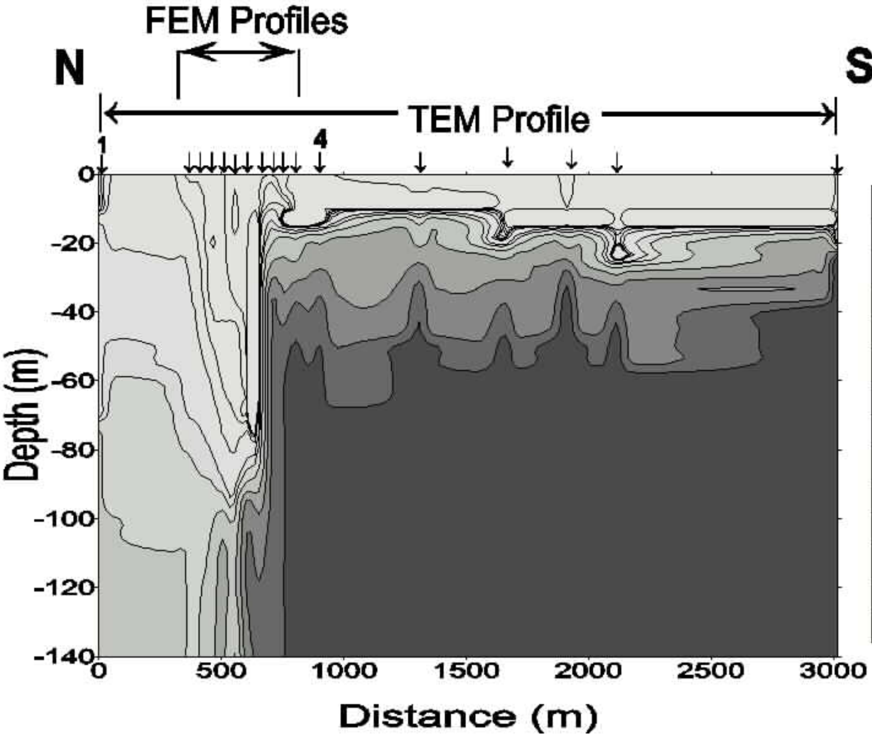

Figura 6: *Localização dos perfis FEM e Seção geoelétrica TEM.*
Figure 6: *FEM profiles location and TEM geoelectrical section.*

On the other hand, Figure 7 shows the magnetic map and profiles made in the survey area. It was performed three profiles in the area. One in the same position of the EM (TEM and FEM) profiles (P3) and the two others (P1 and P2) in parallel lines, separated by a distance of 400 m between each other. After common magnetic data processing (diurnal correction, regional – local separation, etc.), it was made the interpretation of one of the profiles (Figure 8), which clearly exhibits the pattern of fault anomalies (minimum of 23.600 and maximum of 23.700 nt), together with the relief of bedrock. The profiles interpretations were made using the software WINGLINK (GEOSYSTEM Srl, Milano, Italy) (GEOSYSTEM Srl, 2000). Thus, profile P3 shows coincident patterns with those detected with FEM profiles (Figure 3) and TEM geoelectrical section (Figure 6), i.e., presence of a fault and crystalline basement relief.

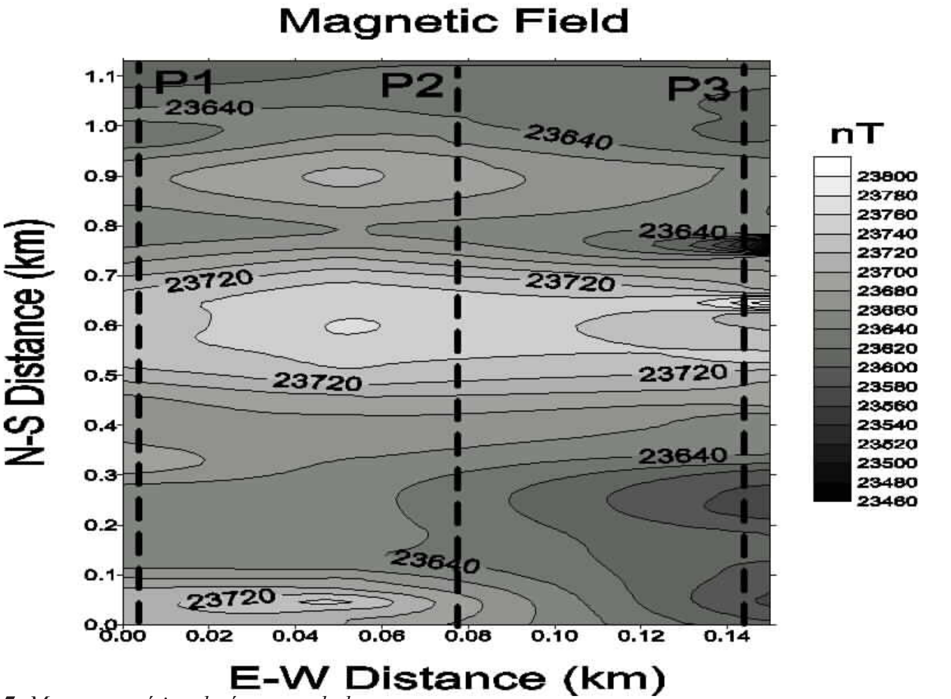

Figura 7: *Mapa magnético da área estudada.*
Figure 7: *Magnetic map of the studied area.*

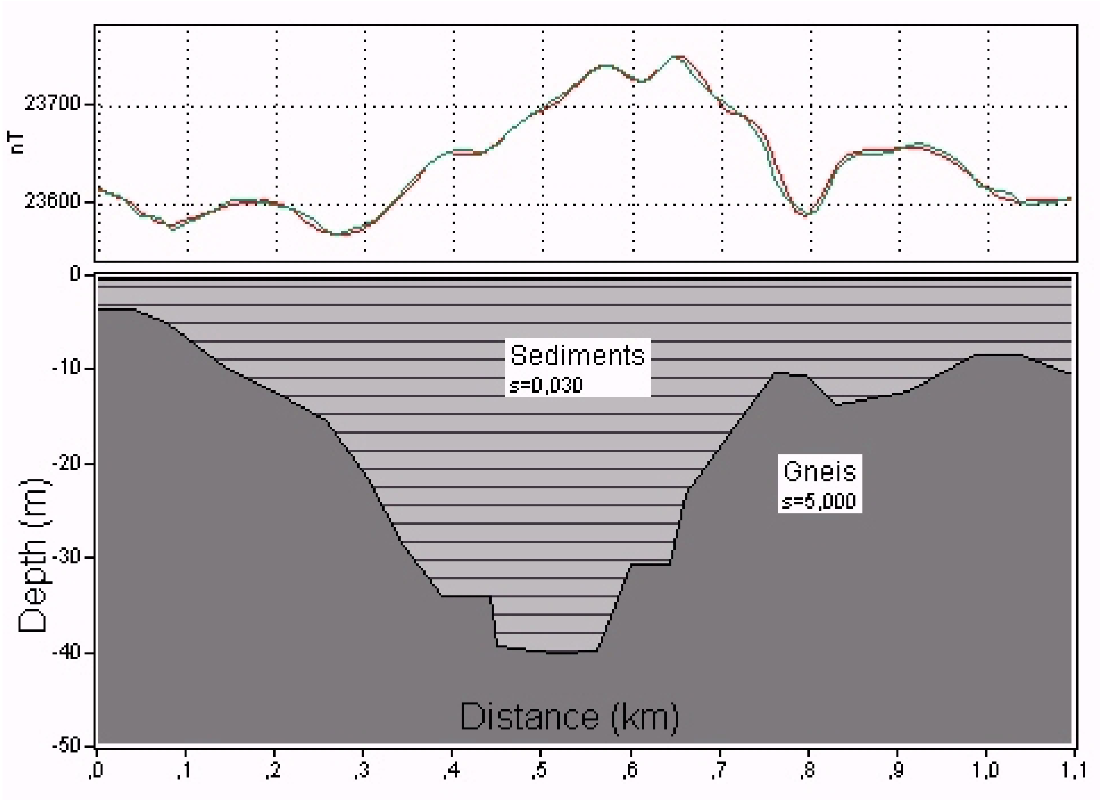

Figura 8: *Interpretação do perfil magnético P3.*
Figure 8: *Interpretation of the P3 magnetic profile.*

CONCLUSIONS

The results of this study show the feasibility of using EM and magnetic geophysical techniques to obtain very important information regarding to geological, hydrogeological and environmental aspects of the studied area, such as: the determination of fresh/saline water contact, the location of geological structures such as faults, the delimitation of the aquifers and the indication of the best locations to drill water wells in this sector of the North Fluminense Coastal Plains in Rio de Janeiro State, Brazil.

The TEM method was useful to identify the layered structure (sand, clay and bedrock) and to define the resistive/conductive contacts, marked with the presence of saline water intrusions and a fault in the crystalline basement, probably refilled with sandy material. On the other hand, the FEM method has proved to be useful as a quick recognizing technique to determine both lateral variations and fresh/saline water contacts in geological formations. Finally, with the addition of magnetic data, it was detected the existence of a fault in the NE/SW direction, as it is shown in the main family of faults of Figure 2, and the bedrock topography. These results suggested that the EM and the Magnetic methods together can be employed as complementary tools for extensive hydrogeological studies, as it is been planned to be done in a near future, in a larger region covering the studied area.

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