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STRUCTURAL, LITHOLOGICAL AND PETROPHYSICAL CHARACTERIZATION OF THE RECÔNCAVO AQUIFER SYSTEM IN THE CAPIVARA RIVER BASIN, BAHIA STATE, BRAZIL

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ABSTRACT. The hydrogeophysical features of the Recôncavo aquifer system in the area of the Capivara Grande and Capivara Pequena rivers, in Camaçari and Dias D'Ávila counties were studied through the analysis of 64 Schlumberger vertical electrical soundings expanded to AB/2 spacing of 1.000 m. This characterization was also supported by the analysis of lithologic logs of 29 water exploration wells, 14 of which have available geophysical logs. The results were useful to outline the structural configuration of the regional aquifer system in the area, from the surface up to 450 m in depth. The multi-confined component is the dominant portion of the system with the main storage being within São Sebastião sandstone bodies. The aquifer substratum is mostly represented by a thick shale sequence inter-layered with siltstones and fine shaly sandstones, referred by Lima (1999) as the Upper Shaly Sequence (SAS). The geometry of the aquifer system is basically controlled by normal faults oriented NNE and WSW, that transect the São Sebastião Formation in the area. A large undulated synclinal was recognized between Salvador Fault and the western water divide of Capivara Grande and Capivara Pequena river basins. The central zone of this structure, where the aquifer substratum is deeper, corresponds to the Capivara Grande river valley.

Keywords: Recôncavo aquifer system, vertical electrical soundings, geophysical logs, São Sebastião Formation.

RESUMO. As características hidrogeofísicas do sistema aquífero Recôncavo na área das bacias dos rios Capivara Grande e Capivara Pequena – municípios de Camaçari e Dias D'Ávila, Região Metropolitana de Salvador – Bahia, foram estudadas através da execução e interpretação de 64 sondagens elétricas verticais realizadas com arranjo Schlumberger com até 2.000 m de separação entre eletrodos de corrente. Foram usados também perfis geológicos de 29 poços exploratórios de água, além de perfis geofísicos de 14 deles. Os resultados permitiram delinear a configuração estrutural do sistema aquífero regional, desde a superfície até 450 m de profundidade. O componente multi-confinado constitui a maior parte do sistema na área estudada, com o principal armazenamento ocorrendo nos arenitos da Formação São Sebastião. Na maior parte, a base desse sistema é representada por espessos pacotes de folhelhos, intercalados com siltitos e arenitos argilosos finos, que constituem a Sequência Argilosa Superior (SAS) proposta por Lima (1999). A geometria do conjunto aquífero é basicamente controlada por sistemas de falhamentos gravitacionais de direções NNE e WSW que seccionam toda a Formação São Sebastião na área. Distingue-se uma ampla calha sinclinal ondulada entre a linha da Falha de Salvador e o divisor ocidental das bacias dos rios Capivara Grande e Capivara Pequena. A zona central mais profunda do aquífero corresponde ao vale do rio Capivara Grande.

Palavras-chave: sistema aquífero Recôncavo, sondagens elétricas verticais, perfis geofísicos, Formação São Sebastião.

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INTRODUCTION

Water is essential and indispensable to life. Therefore, rational use and sustainable management of water resources are of strategic importance and involve a precise assessment of their availability in any given region.

The Recôncavo sedimentary basin in Bahia State, Brazil, presents several important aquifers (PDRH, 1996). It is part of a tectonic asymmetric Cretaceous rift, which was filled by a thick continental clastic sequence (Milani, 1987). The upper part of this sequence, which constitutes the Recôncavo aquifer system, comprises fluvial-lacustrine deposits of sandstone, siltstone and shale, from São Sebastião, Marizal and Barreiras formations, with more than 1,500 m thick (Lima, 1995). The semi-confined part of the aquifer contains freshwater up to approximately 1,000 m depth. These water reserves are estimated at six hundred billion cubic meters (Lima, 2003).

This paper presents an overview about current geological and hydrological conditions of the Recôncavo aquifer system in the area of the hydrographic basins of Capivara Grande and Capivara Pequena rivers. This overview results from the integrated analysis of geophysical well logs and vertical electrical soundings (VES). Geophysical data from 14 groundwater exploration wells including electromagnetic induction logs of apparent resistivity and spontaneous electrical potential (SP) were interpreted. Some of these wells also feature natural gamma rays and compensated sonic velocity logs. Surface geophysics includes the execution and interpretation of 64 VESs obtained using the Schlumberger electrode configuration. The combination of geological and geophysical well and surface techniques allowed to define the geometry and petrophysical spatial variations of sandy-clayey formations, as well as to identify and map the structure of the main aquifer horizons in the area from the surface down to about 450 m depth.

As a result, we obtained a regional geohydrologic model for the Recôncavo aquifer system, with information about its depth extension, confinement conditions and the lateral variability of its storing and transmitting water properties. These data were used to model the hydraulic behavior of the aquifer under different operational scenarios and thus develop methods and optimized procedures for its exploitation with wells.

GEOHYDROLOGIC CONDITIONS

The basin areas of the Capivara Grande and Capivara Pequena rivers, tributaries of Jacuípe river, are located in the counties of Camaçari and Dias D'Ávila, Bahia. It is shaped as an irregular polygon bounded to the south and east by the Salvador Fault and to the north and west by the watershed of the Capivara river basin (Fig. 1).

The climate is classified as humid to sub-humid with relatively abundant rainfall and maximum temperatures ranging between 25.4 and 32.2° C, average between 19.4 and 24.6° C and minimum temperatures between 15.3 and 22.4° C. The average annual rainfall is 1,900 mm. The relative humidity is high, around 80%, typical of humid climate. The region is in the low latitude zone and presents megathermal climate (SIDE, 2011).

The Salvador Metropolitan Region (SMR) comprises two distinct tectonic domains (Figs. 1 and 3): (i) The Salvador Crystalline High, which consists of Precambrian metamorphic rocks with thin scattered patches of cenozoic sedimentary cover. It is a structural block elevated from the crystalline basement containing the oldest poly-metamorphosed rocks of the crust in Bahia, representing the core of the São Fransisco Craton (Almeida, 1977; Barbosa & Dominguez, 1996); (ii) The Recôncavo Sedimentary Basin, which extends to the west and northwest of the Salvador High and where a thick sedimentary sequence has accumulated. This basin contains one of the most important aquifers in the State of Bahia, the Recôncavo aquifer system interconnecting reservoirs from the Barreiras, Marisal and São Sebastião formations. Near the Salvador Fault, abundant clay matrix conglomerates that constitute the Salvador Formation were deposited (Viana et al., 1971).

The São Sebastião Formation is represented by cyclical intercalated fluvial-lacustrine deposits, consisting of clayey sandstone, siltstone and shale. The Marizal Formation encompasses a fluvial set of clayey sandstones with thin layers of siltstone and shale along with conglomeratic basal layers. Over the Recôncavo Basin sediments and crystalline rock basement occur alluvial fan deposits of the Tertiary from the Barreiras Formation, also composed of sandstone, siltstone and shale, and marine and fluvial deposits of the Quaternary. The stratigraphic column of Figure 2 summarizes the main characteristics of the geological formations of the Recôncavo basin. The geological formations located below the São Sebastião Formation, in the study area, are virtually saturated with brackish and salty water and therefore do not belong to the Recôncavo aquifer system.

According to Lima (1999), there are two aquifer systems in SMR defined as: (i) the unconfined aquifer system of Salvador High, consisting of the fractured basement, the weathered zone of soil and the sedimentary deposits from the Barreiras Formation and quaternary coastal plain; and (ii) the Recôncavo aquifer system, unconfined and multi-confined components, represented by the Barreiras, Marizal and São Sebastião formations.

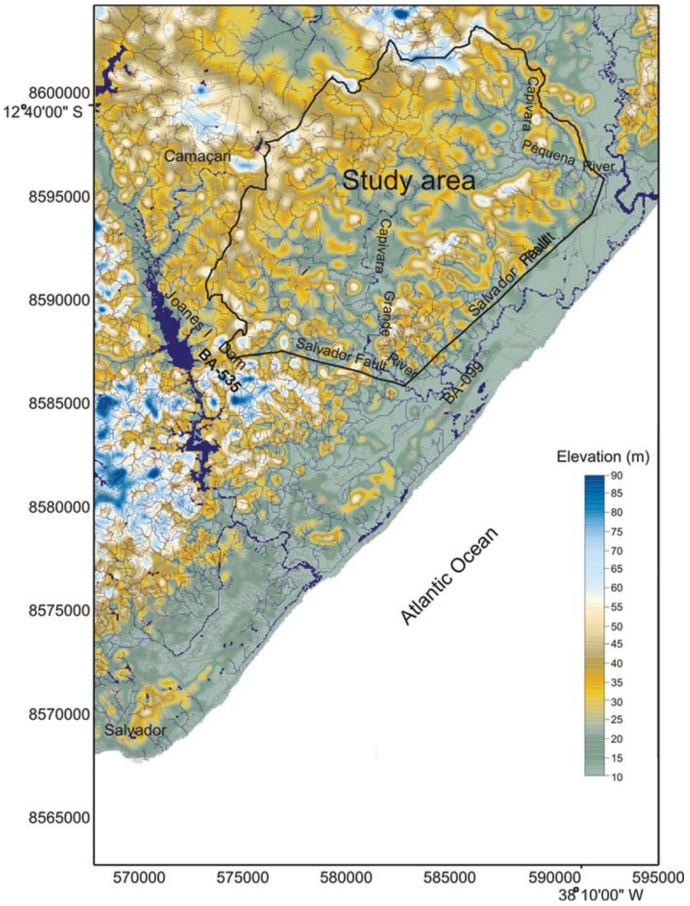

Figure 1 – Topographic, hydrologic and localization map of the study area.

The hydraulic role of the Salvador Fault is an important hydrogeological matter. The conglomerates of the Salvador Formation are excellent sealing material and excluding the fractured zones associated with faults, the crystalline rock has an impermeability effect. These conglomerates are virtually absent only at the level corresponding to the top of the São Sebastião Formation (Joanes River Member). Therefore, much of the contact between the two aquifers should be impermeable, with upward dominant flow. Along fracture zones crossing the Salvador Fault, like the one of Joanes river valley, there may be water transfer from clastic to crystal system. These facts may account for the abundance of lakes and wetlands that extend east of the Salvador faulting zone.

SURFACE GEOPHYSICS

The electrical and electromagnetic methods of geophysical exploration involve the analysis of the propagation of electrical currents in the geological environment, based on Ohm's law, in the principle of conservation of electric charges and in the Maxwell equations for the electric and magnetic fields (Telford et al., 1990).

The electrical resistivity ρ of the upper earth crust rocks is basically controlled by the amount of aqueous electrolytes percolating through pores, cracks and fractures in underground formations. The dominant response, which derives from content and salinity of the water, in effect makes these methods suitable for hydrogeological, geotechnical and geo-environmental investigations (Lima et al., 1995; Sharma, 1997; Cavalcanti et al., 2002; Cavalcanti, 2006).

The electrical methods apply continuous or low frequency alternating current, which can be treated mathematically as continuous current. Thus, geoelectrical problems are solved by finding a solution to the Laplace equation for the electric potential, which satisfies appropriate boundary conditions of the formulated problem.

The solution for a point source of current located on the surface of a homogeneous and isotropic half-space is applied together with the superposition principle, to define an apparent resistivity function (ρ_a) measured on a plot with four-electrode

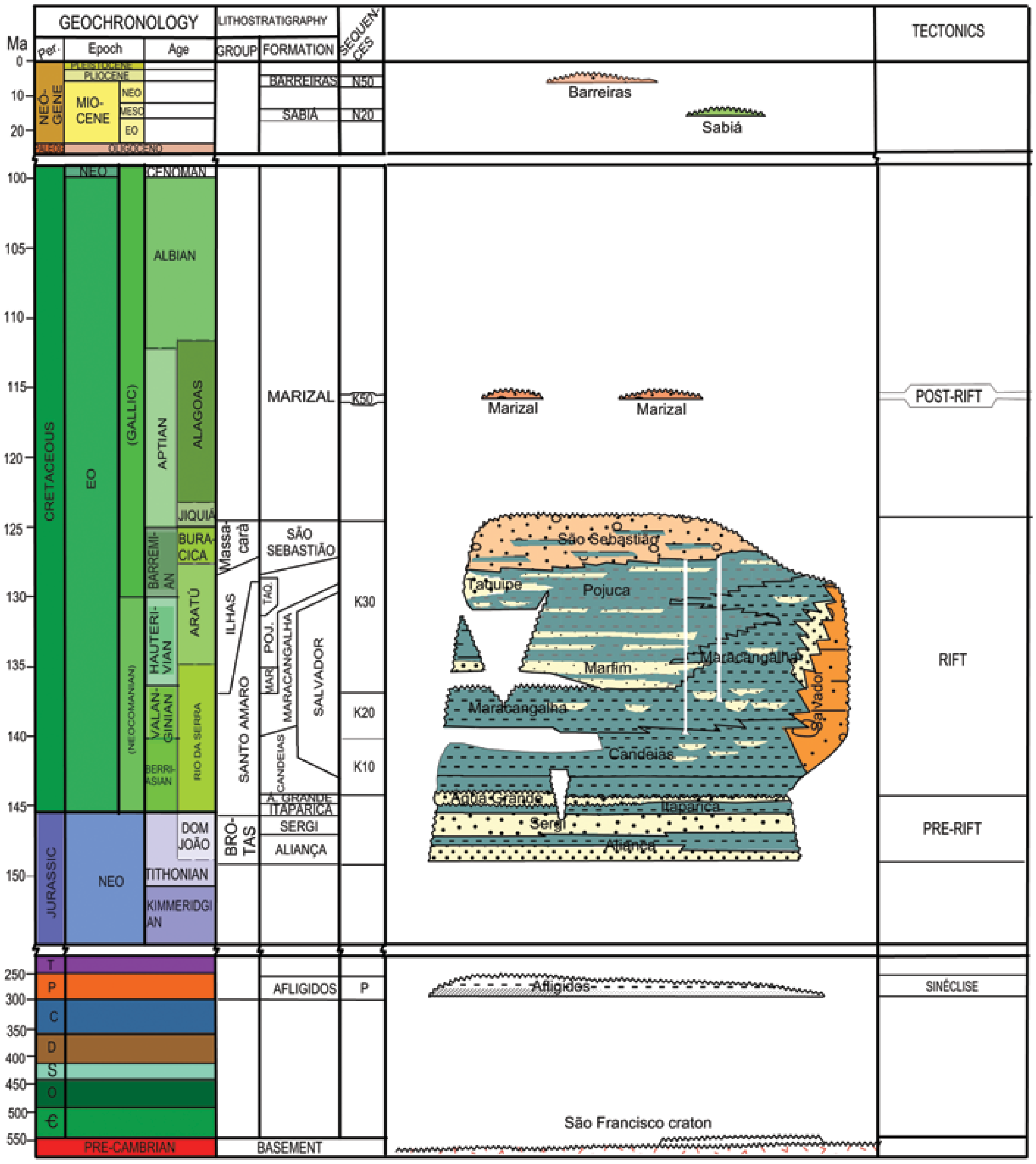

Figure 2 – Stratigraphic column of the Recôncavo basin (modified from Silva et al., 2007).

arrays according to the expression

$$\rho_a = K\frac{\Delta U}{I}\,, \tag{1}$$

where K is a geometric factor related to the four electrodes relative position, I is the input and output current between two electrodes (A and B) and ΔU is the difference of potential between the other two electrodes of the array. In the specific case of Schlumberger array used in this work, we have:

$$K = \frac{\pi a^2}{b}\left(1 - \frac{b^2}{4a^2}\right), \tag{2}$$

where a is the half-distance between the current electrodes (A and B) ($a = \overline{AB}/2$) and b the distance between the potential electrodes (M and N) ($b = \overline{MN}$).

In this work, the vertical electric sounding (VES) was used, with maximum AB/2 spacing of 1.000 m. The positions of the

VES centers were defined considering the local accessibility. Efforts were made to distribute these centers as regularly as possible to cover the whole extension of the selected basin (Fig. 3). In some situations, the presence of flooded areas, especially in the valley lows, prevented the access and, consequently, the execution of the sounding.

The interpretation of the apparent resistivity curves was obtained automatically using two inversion programs successively: (i) the RES1D from Geotomo Software, with the option of not providing the initial model. In this case, the program uses a procedure proposed by Zohdy (1989) in which the inversion is performed by a model with a number of layers equal to the number of points measured in the sounding; (ii) based on the analysis of the model obtained in (i) an initial model is built, with a number of layers compatible with the sounding curve and resistivity and thickness values calculated by grouping the layers that are electrically closer to each other. This initial model is submitted to the RESIST program, developed by Vander Velpen & Sporry (1993), which provides tools to define or delimit model parameters in its automatic nonlinear inversion procedure. Some soundings were conducted near wells with available geophysical logs and these data were used to calibrate the final inversions.

WELL GEOPHYSICS

Well logging consists of using geophysical tools to measure rocks physical properties. With geophysical logs the tops and bases of aquifers and their confining layers can be identified very accurately, and petrophysical characteristics such as porosity, permeability and clay content in the formations can be determined (Ellis, 1980).

The analysis of conventional electric logs (spontaneous potential (SP), short-normal, long-normal, lateral and induction (ILD)) helps to identify and correlate layers of interest. When this information is combined with data obtained from additional logs (caliper, acoustic and/or radioactive), the interpretation becomes analytic and quantitative. The main SP logging applications are to identify permeable zones, differentiate between clean and clayey formations and estimate resistivity of the formation water. The locations of the studied wells are shown in the map of Figure 3.

SP logging results from a measurement of a natural electric potential developed within a well referenced to a grounded potential on the surface. The SP variation curve is characteristic: facing clayey lithologies that are impermeable to ions, it defines a baseline, while facing permeable layers, it has positive or negative deflections (ΔU_{SP}), whose amplitudes depend on the nature of the dissolved salts and the salinity contrast between native water and mud into the hole, as well as the clay content in the permeable formation (Jorden & Campbell, 1986). Therefore the following expression can be used:

$$\Delta U_{SP} = -C \log \frac{R_{mf}}{R_2}\,, \tag{3}$$

where C is a constant depending on the nature of the dissolved salts, R_{mf} is the resistivity of the mud filtrate and R_w is the resistivity of the formation water.

The resistivity tools are designed to obtain measurements of two distinct regions in the vicinity of the borehole wall: (i) the region washed by the mud filtrate that was used in well drilling, denominated R_{xo}, in which the electrolyte has resistivity R_{mf}; and (ii) a virgin region of the formation unaffected by mud, with resistivity denominated R_o (aquifer) or R_t (oil reservoir), where the pore electrolyte (formation native water) has resistivity R_w. For clayey sandstones, with clay minerals uniformly covering the sand grains like shale shells, Lima et al. (2005) proved the validity of the following equations to calculate the electrical resistivity of the formation as a function of effective porosity ϕ_e, electrical conductivity of the electrolyte and volumetric conductivity of the solid sandstone matrix σ_{cs}.

$$\sigma_o = \left[\phi_e \sigma_w^{1/m} + (1-\phi_e)\sigma_{cs}^{1/m}\right]^m\,, \tag{4}$$

$$\sigma_{cs} = \frac{p\sigma_{sh}}{3-p}\,, \tag{5}$$

which are easily estimated from electric logs if electrical resistivity of the interstitial fluids (σ_w and σ_{mf}) are known, where m is the cementation index proposed by Archie (1942). For sand and sandstone, m varies between 1.3 and 2.2; for rounded and consolidated sandstones $m = 1.8$ is usually used (Jorden & Campbell, 1986). Equation (4) can also be used to calculate σ_w measuring σ_o and knowing σ_{cs} and ϕ_e by other means.

Equation (5) applies to grain sandstones covered by uniform shale shells. The volumetric ratio p of clay in a sandy matrix can be obtained from the relation $p = (1-\phi_e)V_{cl}$, with clay content V_{cl} calculated according to expression (10) defined below.

Also for clayey sandstones, Lima & Sri Niwas (2000) developed the following semi-empirical expression for the intrinsic permeability (k) in terms of the solid matrix electrical parameters

$$k = \alpha_o \left[\frac{\phi_e^{(m-1+1/q)}}{1-\delta_c\sigma_{cs}}\right]^q\,, \tag{6}$$

where α_o is a geometrical constant of dimension L^2, δ_c is a lithological parameter which depends on the particle size distribution of sand and clay and the exponent q depends on the shape

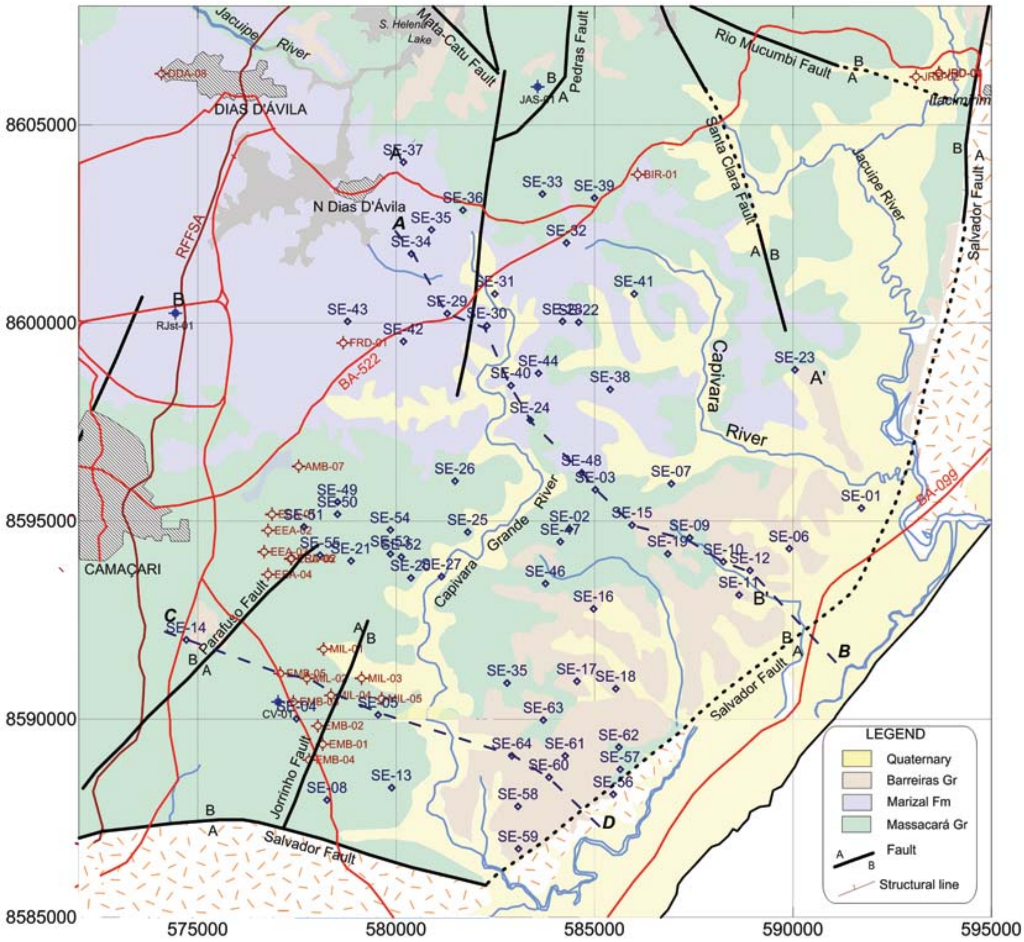

Figure 3 – Geologic map of the studied area, with access roads and localization of VES centers and analyzed wells.

of the covered grain and the packing degree of the sandstone. In general, α_o ranges from about 180,000 μm^2 in fine sandstones ($r_{cs} = 10\,\mu$m) to 50,000 μm^2 in medium grain sandstones ($r_{cs} = 300\,\mu$m) and q, the fractal dimension of the pore space varies from 2.0 to 3.0. Hence, one can describe the intrinsic permeability variations along the sandy sections of the well.

There is a strong correlation between the sonic transit time and the porosity of consolidated formations (Ellis, 1980). The expression of sonic porosity (ϕ_s) for clean sandstone is given by the equation of Wyllie et al. (1956, 1958)

$$\phi_s = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}\,, \tag{7}$$

where Δt_f is the transit time in the electrolyte, Δt is the time read in the sonic log and Δt_{ma} is the sonic transit time in the rock matrix. For clayey sandstones, equation (8) is used

$$\phi_s = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \cdot \frac{100}{\Delta t_{sh}} - V_{cl}\frac{\Delta t_{sh} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}\,, \tag{8}$$

where Δt_{sh} is sonic transit time in shale cover (clay + water), taken from the sonic log of a pure shale identified in the hole.

The main use of a gamma ray logging is to differentiate between shale and no shale and to determine the content of clay minerals in the formations (Ellis, 1980). The clay content V_{cl} of a formation is estimated from the gamma ray ratio I_{GR} given by:

$$I_{GR} = \frac{GR_{\log} - GR_{\min}}{GR_{\max} - GR_{\min}} \tag{9}$$

where $GR_{\min}$ and $GR_{\max}$ are, respectively, the $\log$ minimum and maximum values and $GR_{\log}$ each reading along the GR curve. Argilosity V_{cl} is then calculated using the empirical expression (Asquith & Gibson, 1982):

$$V_{cl} = 0,33\lfloor 2^{2I_{GR}} - 1,0 \rfloor\,. \tag{10}$$

In this work, well logging was used to:

(i) produce a vertical lithofaciological zoning of the units of the São Sebastião Basin Formation;

(ii) simulate theoretical curves of vertical electrical soundings based on electric layering observed in the logs;

(iii) calibrate the interpretation of the parametric electrical soundings; and

(iv) compute values of effective porosity, intrinsic permeability and clay content in solid matrices of rocks, and in some cases, estimate electrical resistivity of the formations interstitial fluids.

Typically, the clay content was estimated from natural gamma ray logs. SP logging was used to determine the resistivity of the formation fluid in situations where there were no direct electrolyte samples measurements. Based on data from electric logs, values of effective porosity and permeability were estimated, using the equations proposed by Lima & Sri Niwas (2000) and Lima et al. (2005), as discussed above. Sonic porosity or formation density data were used as calibration for these interpretations.

PETROPHYSICAL CHARACTERIZATION

Figures 4, 5 and 6 show geophysical logs of three water wells, representative of the basin, denoted AMB-07, EMB-5A and FRD-01, whose locations are shown in the map of Figure 3. Effective porosity and clay contents were estimated for all three wells, using data from compensated sonic and gamma ray curves and Equations (8), (9) and (10). The permeability curves were calculated with the equations (4), (5) and (6). The curves of the spontaneous electrical potential of the two wells show many irregularities and anomalies that make it difficult to define the approximate shale baseline. Besides, due to lack of resistivity measurements of mud and its filtrate, the electrical resistivity of water (R_w) that saturates the various sandy sets traversed by the holes, could not be estimated.

Thus, to determine R_w another strategy was adopted. From the values of V_{cl} and S_{sh} and using Eq. (5), the σ_{cs} vertical distribution of the wells lithological columns is obtained. Using resistivity data from logging of deep investigation (LL and/or ILD) and Eq. (4), the R_w of the formations native waters is computed. Using Eq. (6) the vertical distribution of intrinsic permeability of sandstone is determined.

In all three wells, water resistivity varied irregularly with depth (indicated by ellipses in the log of Fig. 5). Such variations, however, are more related to variations in sandstone clay content, with the highest values being probably the most correct.

A lithofaciological correlation of geophysical data from all wells studied, with emphasis on electric logs of wells RJst-01, FRD-01 AMB-07 and EMB-05, using the shales electrical signatures as guides, has shown that the Recôncavo aquifer system in the study area is a confined system, with at least three sandy horizons (J1, J2 and J3) separated by extensive and continuous shale layers with thicknesses of 10 to 15 m (Fig. 7). The column shows the vertical variability in the study area in São Sebastião Formation (members Joanes River and "Passagem dos Teixeiras"). A high sandstone/shale ratio is noted, with 75% or more sandstone in the wells sections. Therefore, it was deemed appropriate to simulate vertical electrical sounding curves using geoelectrical stratification observed in geophysical logs.

A regularization of the induction electric log of the well FRD-01 helped define its electrical stratification with a model of 15 horizontal layers, as shown in Figure 6. For this model the Schlumberger electric sounding curve was computed, shown in Figure 8. It is noted that the simulated curve is expressed primarily as a geoelectrical structure of only four horizontal layers.

The simulated curve was inverted using the two procedures described in the Surface Geophysics section. Figure 8 shows the results of these inversions. In the final adjusted model the uppermost shale levels/layers are combined in a single layer of 21.3 Ω.m resistivity and 32 m thickness. The other shales, dispersed and of small thickness, decrease the average resistivity of the whole sequence, in comparison to sandstone resistivity (ranging between 150 and 180 Ω.m and reduced to 103 Ω.m).

VES simulations on other logs showed similar results, suggesting that, the actual electrical soundings conducted in the area generally allow to assess accurately the total thickness of the predominantly sandy sequence of São Sebastião Formation, but only allow to identify the hydraulic nature of the aquifer system when adequate conditions are defined by the relationship between thickness and depth of shale layers occurrence.

AQUIFER DELIMITATION

Figure 3 shows the boundaries of the study area, including geological faults, the location of the wells and the centers of VESs performed, as well as the directions of the geological-geophysical logs constructed. Most VESs obtained show well behaved apparent resistivity curves and compatible with models of horizontal layers, in most cases ascending-descending (KQ) or ascending-double descending (KQQ) type curves. They were

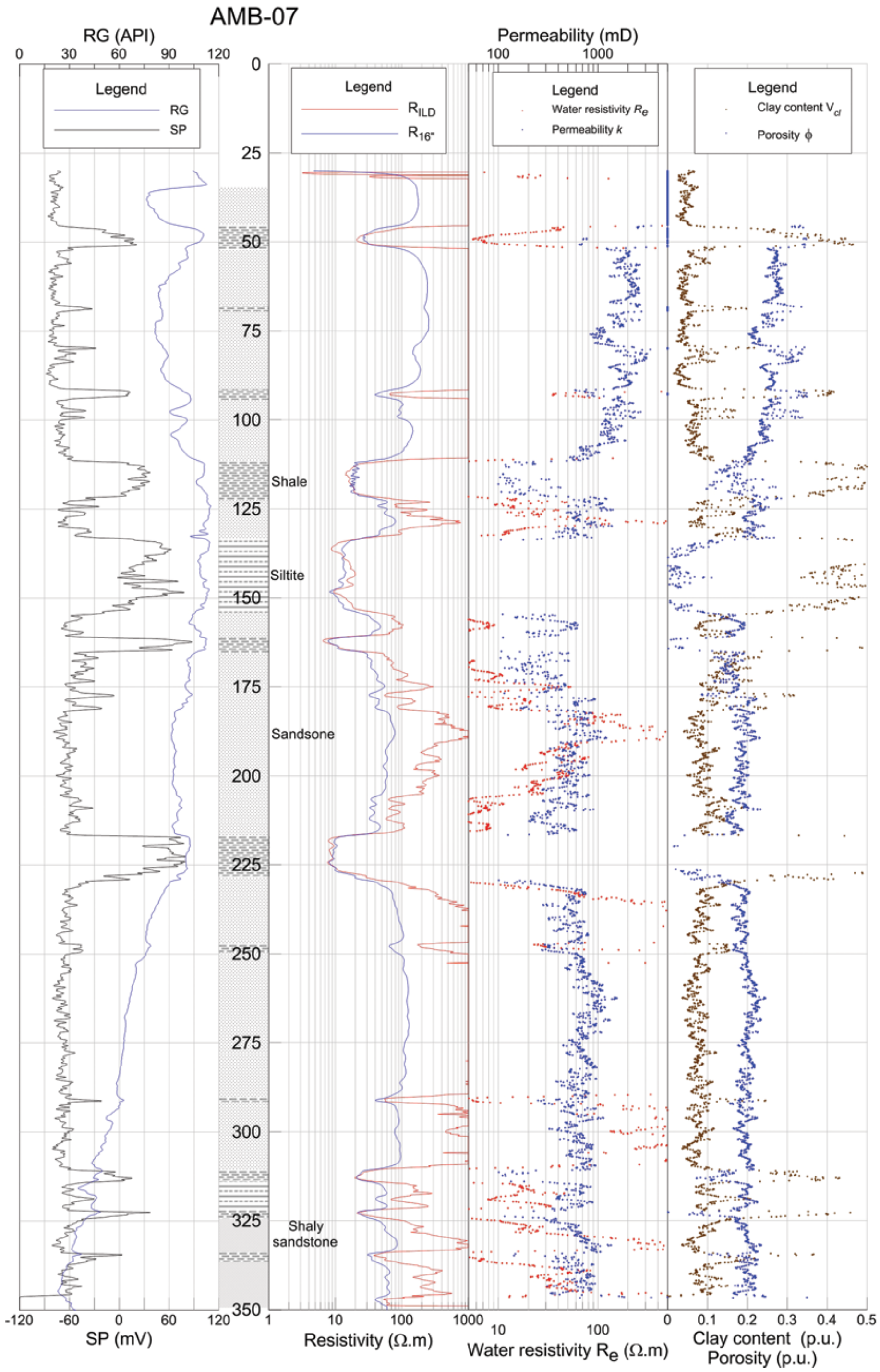

Figure 4 – Geophysical, lithological and petrophysical logs of well AMB-07.

easily interpreted considering stratified one-dimensional models.

The interpretation of the 64 VESs resulted in models with 4, 5, 6 and up to 7 geoelectrical layers with a predominance of models with 5 layers (42%). In general, these VES curves reveal strong electrical resistivity contrasts associated with sandstone-shale interfaces. Invariably, they reflect the presence of a thick conductive substrate, interpreted as shale composing the Upper Shaly Sequence (SAS) proposed by Lima (1999). Resistivity variations in the aquifer set are related to clay content variations or the presence of thin layers of shale intercalated in the sandstones.

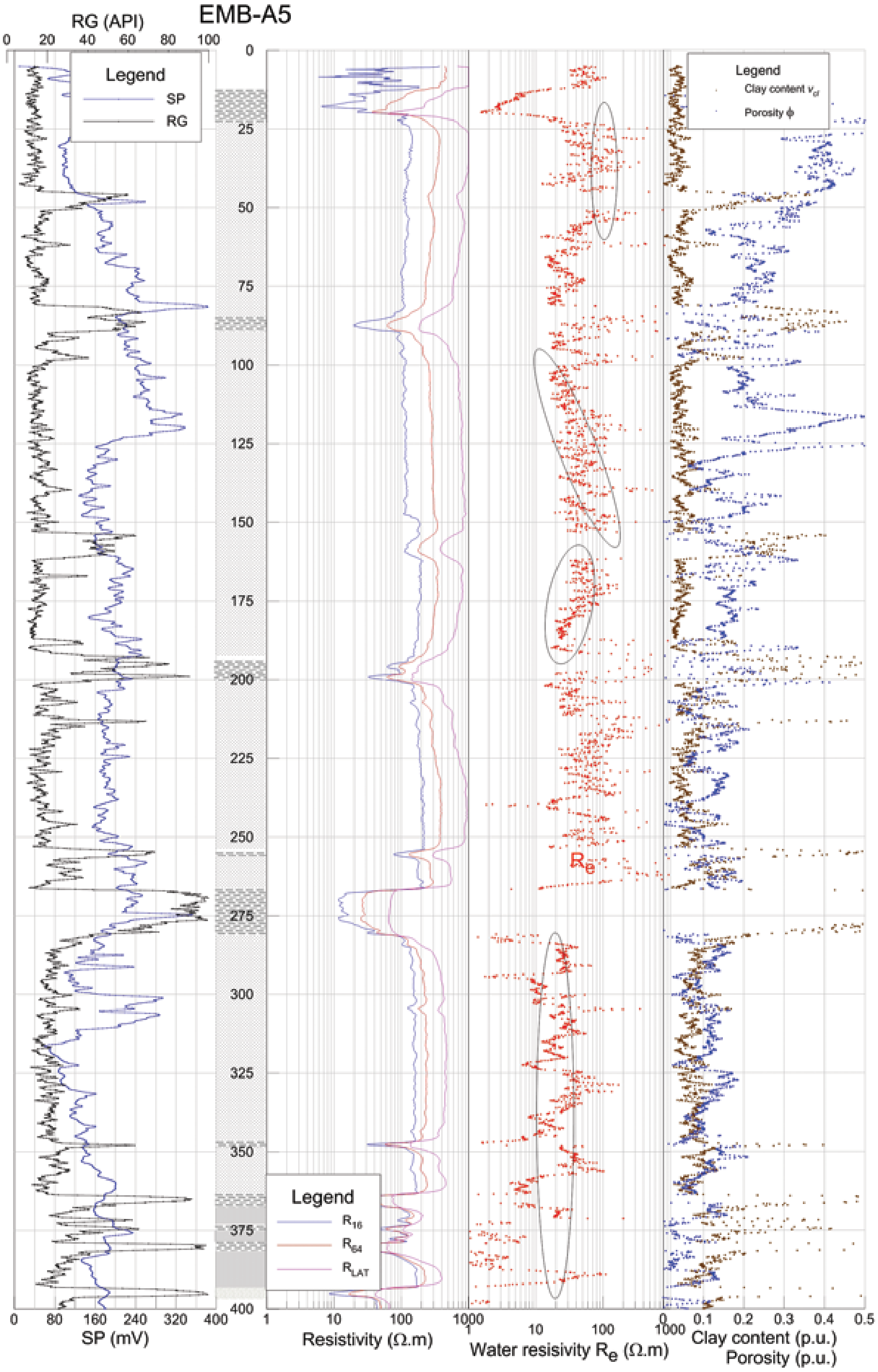

Figure 5 – Geophysical, lithological and petrophysical logs of well EMB-A5.

The sounding SE-03 (Fig. 9) was interpreted using an initial model of six geoelectrical layers. The upper part with three high resistivity layers represents Marizal Formation sandstones. Two predominantly clayey layers confine two thick sandy layers. The conductive substrate in this location extends below 313 m deep. A model of six layers prevails also in SE-14 (Fig. 10), with three high resistivity sandy sets interspersed with shale predominating horizons/layers.

Figure 11 contains three examples of VESs inverted with initial models of six (SE-40 and SE-64) and seven (SE-34) layers.

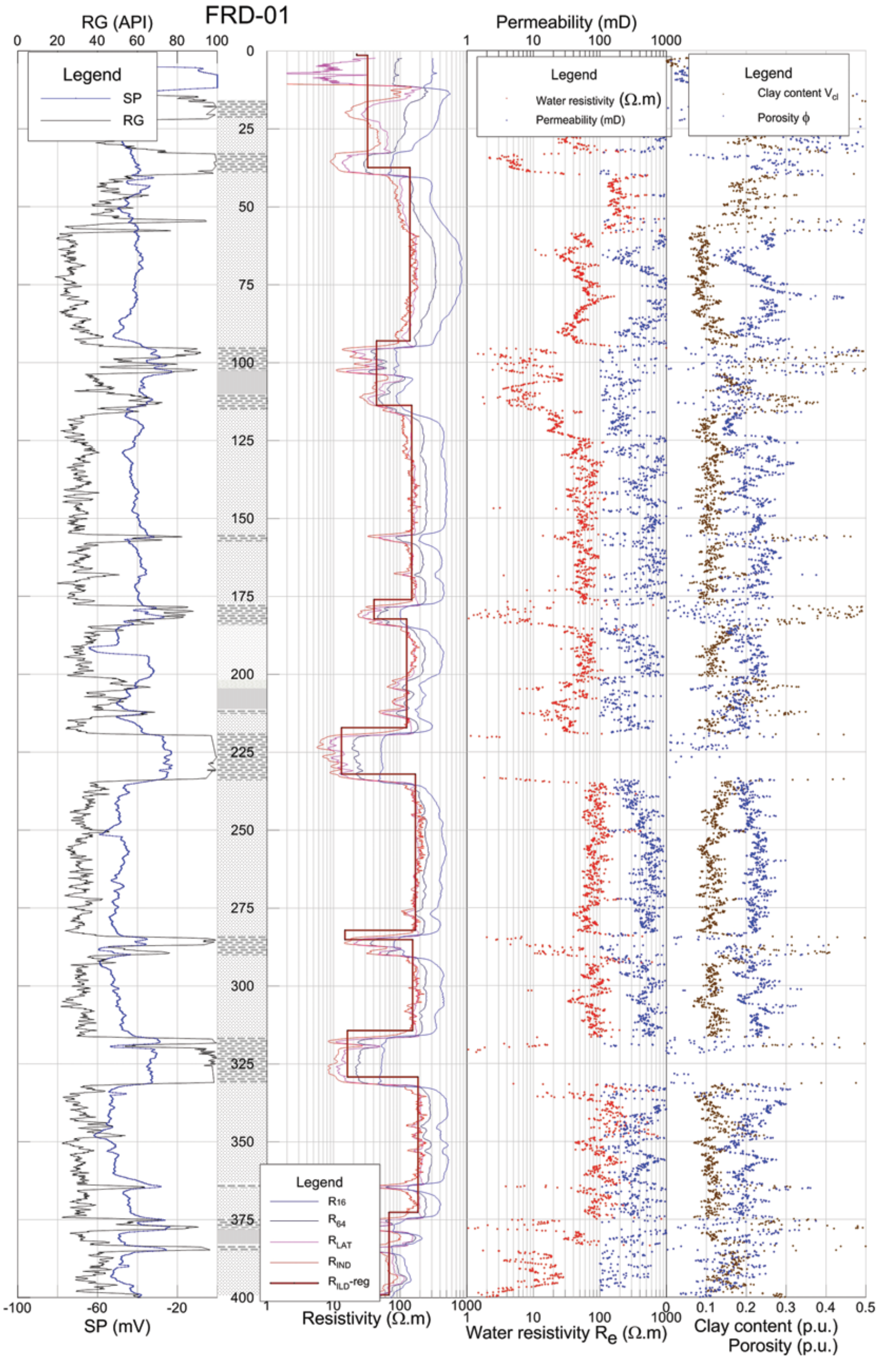

Figure 6 – Geophysical, lithological, petrophysical and ILD normalized electrical logs of well FRD-01.

It is noteworthy the great variability of values of the layers closer to the surface, the presence of intercalated shale and siltstone sets (42 and 103 Ω.m) distributed in thick aquifer intervals and the conductive SAS sequence substrate.

The Recôncavo aquifer system, apart from its electrical variability characteristic of the vadose zone, can be described in terms of the following components: (i) an unconfined aquifer component formed by coupling sandstone of Marizal and São Sebastião Formations, (ii) a confined component represented by thick sandstone interspersed with layers of shale from 10 to 20 m thick, but with large lateral continuity, (iii) the aquifer substratum defined by the SAS sequence.

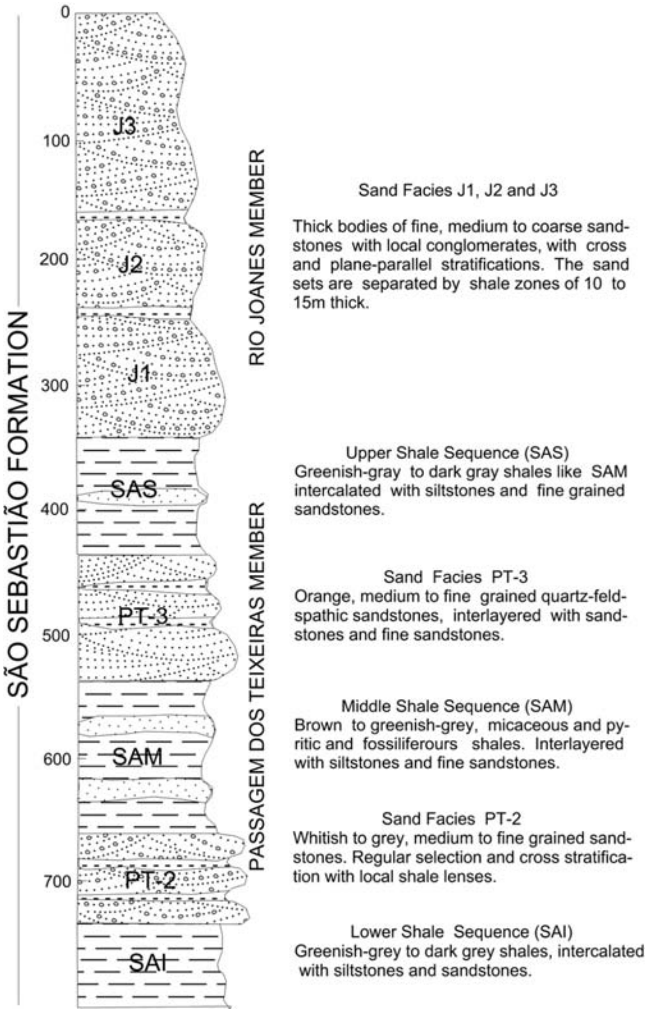

Figure 7 – Geological zoning of São Sebastião Formation based on the correlation of geophysical electric logs in the Capivara river basin area.

Two transverse geological profiles were constructed from the VES interpreted results (Fig. 11) and the correlations between VES results and the wells lithological and geophysical data (Fig. 12). The upper layer of the A-B profile between the saturated level and the ground surface, demonstrates resistivity variations attributed to both argilosity differences in the sandy surface layers and saturation index variations with depth, caused by changes in rainfall regimes and evapotranspiration between the dates of the soundings. This unsaturated zone results in several layers of small thickness, with strong lateral variations of resistivity. In the intermediate section, there are horizons dominated by sandstones saturated with freshwater, with resistivity ranging from 270 Ω.m and 1,850 Ω.m. The presence of a confining layer containing shale is revealed by lower resistivity values between 45 and 75 Ω.m. The unconfined and multi-confined components of the Recôncavo system have composite thickness ranging between 250 and 370 m in this profile. This delineates approximately the optimum depth range for drilling wells in the area.

On the west side of the C-D profile some clayey levels are observed, also indicated by low real resistivity values (23 Ω.m), intercalated with sandstone. These clay bodies, dispersed in the predominantly sandy sequence overlying the conductive substrate, reach 30 m in thickness and can produce a localized confinement. This is a multiple aquifer system, but with an important phreatic contribution. The uplift block located between the Parafuso and Jorrinho faults is hydraulically explored, as evidenced from the distribution of production wells shown in Figure 3. In this region, the SAS sequence is elevated, reducing the section in the phreatic aquifer to a maximum thickness of approximately 90 m. Other clay layers, defined basically by geophysi-

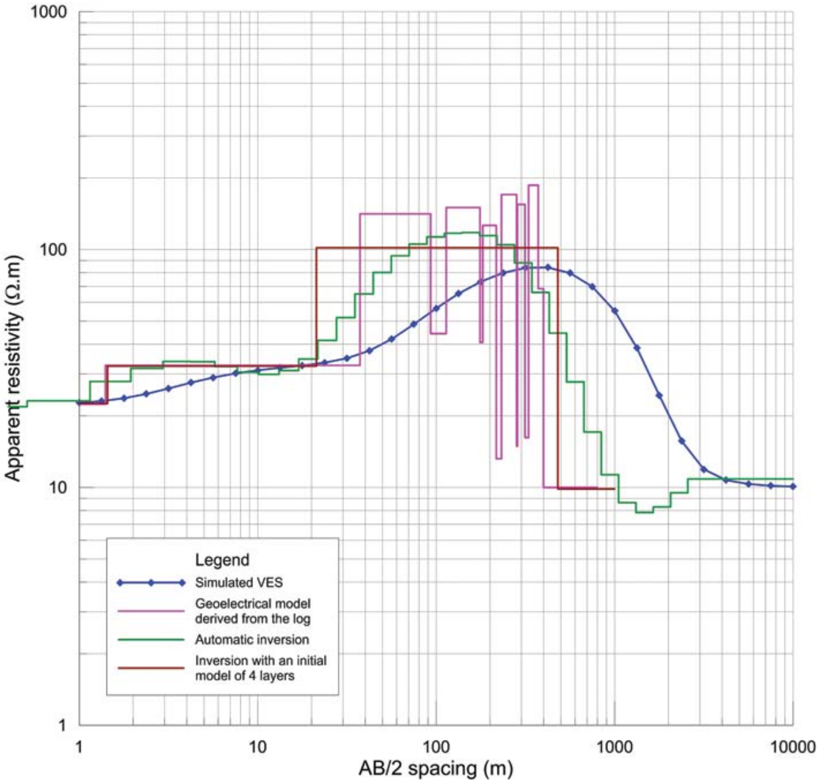

Figure 8 – Simulated electrical sounding curve based on the geophysical log of well FRD-01 and the results of its computational inversion.

cal data of wells, are observed in this section. The presence of a clay layer in the central section can confine partially the hydraulic flow. The general dip of the formations, associated with gravitational fault systems, results in very irregular confinement conditions. In this profile, the aquifer presents thickness from 250 to 380 m, and resistivity values ranging from 270 to 1070 Ω.m. The profile crosses the flooded area of the Capivara river basin which is difficult to access, making it impossible to run the VES along this stretch.

In both profiles, VESs end with low resistivity values of about 30 Ω.m, indicating the presence of a conductive substrate of regional extension, comprised of clay materials, which was interpreted as the SAS sequence.

The electrical soundings inversions made it possible to determine the depth of the static or groundwater saturation level (ranging between 0 and 25 m), the total thickness of the aquifer and the depth to the top of the clay basal sequence of the system. Aquifer thickness increases progressively from the edge to the center of the basin, which includes the valleys of Capivara Grande and Capivara Pequena rivers. Thus, it can be confirmed that the groundwater flow contributes to the surface water streams in the area.

Using geological data from drilling and VESs performed in the area, we determined the geometric and structural conformation of the aquifer through the topographical representation of the top of its substrate, defined as a predominantly clay sequence which is a regional landmark of the hydrogeological system. The traces of Jorrinho, Parafuso and Salvador faults can be seen in Figure 14, at the inner boundaries of the Capivara river hydrographic basin. The curves depict contours of the top of the shale sequence, which forms the substratum of the studied aquifer. The topographic conformation of the SAS sequence is a large basin with a small rise in the center, which can be compared to a horse saddle. In the studied area, the Recôncavo aquifer system is multi-confined down to the investigated depth of 450 m. The dynamics of groundwater circulation in the Recôncavo system is complicated because its hydraulic characteristics vary laterally, particularly in relation to gravitational faults that cross the system in various scaled structural blocks. The extension north of the Jorrinho Fault was established based on geophysical studies discussed in this paper.

The lateral variability of the hydraulic properties of the Recôncavo aquifer system in the area can be inferred from the changes observed in the electrical resistivity of the formation.

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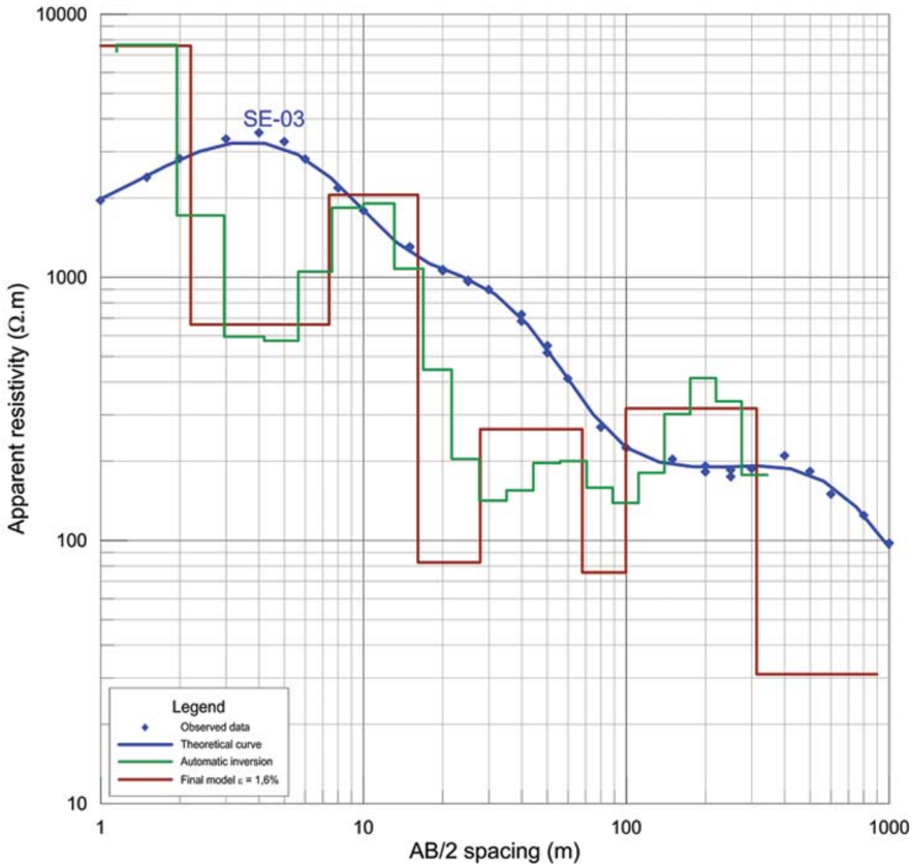

Figure 9 – Curve of the VES SE-03 with automatic inversion and using an initial model with six layers.

The areas with higher resistivity values indicate the presence of clean sandstones, while areas with lower resistivity values represent more clayey sandstones. The distribution patterns of resistivity with depth observed in well logs also reflect lithological variations in the bodies of sandstones and confirm the VES interpreted data.

CONCLUSIONS

The complete interpretation of 64 deep vertical electrical soundings, and a joined study of 14 geophysical logs of water exploration wells, provided not only a better hydrogeological understanding, but also the representation of the hydrogeological conditions of the Recôncavo aquifer in the Capivara river hydrographic basin in the counties of Camaçari and Dias D'Ávila, Bahia.

The geohydrological model produced for the Recôncavo aquifer, in the studied area, consists of a multi-confined aquifer in a shape of a large basin with inclined edges and base thickness ranging from 240 to 450 m. The aquifer has been extensively exploited for domestic and industrial use, with drilled wells producing between 90 and 450 m^3/h of water.

The movement configuration of the blocks of Salvador, Parafuso and Jorrinho faults is in accordance with the VES results. The application of the resistivity method for hydrogeological characterization was low cost, fast and with no environmental impact when compared to invasive methods of subsurface investigating. The results prove the electrical methods in hydrological studies adequate, thus providing an important tool for defining areas more favorable to exploiting groundwater resources.

The depth of clayey substrate is between 250 and 450 m, which defines the exploration range of the aquifer in the area. The sandstones comprising this aquifer have electrical resistivity that vary laterally as a function of their clay content, between 220 and 1850 Ω.m. Therefore, both porosity and permeability of the system also vary laterally. The conductive substrate which forms the base of the aquifer system shows electrical resistivity values about 30 Ω.m.

The Recôncavo aquifer system is defined by a broad syncline structure almost centered along the main course of the Capivara

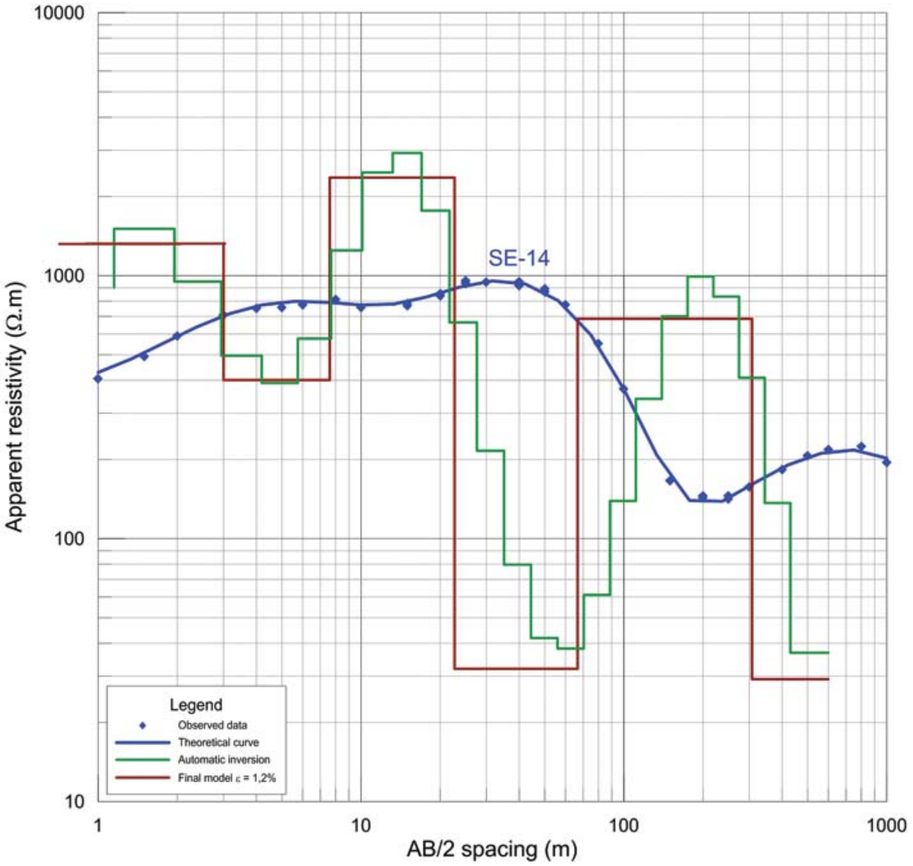

Figure 10 – Curve of the VES SE-14 with automatic inversion and using an initial model with six layers.

Grande River. This structure is split lengthwise by Jorrinho fault, which separates the studied area in two blocks. The west block defines a synclinal with NW-SE axis. The east block contains a synclinal with an axis virtually parallel to the fault, but it is undulated, producing a saddle structure in the center of the area. As the Jorrinho regional fault overlaps laterally clayey sandstones, it is inferred that its hydraulic behavior is of a permeable zone and there is good continuity of groundwater flow.

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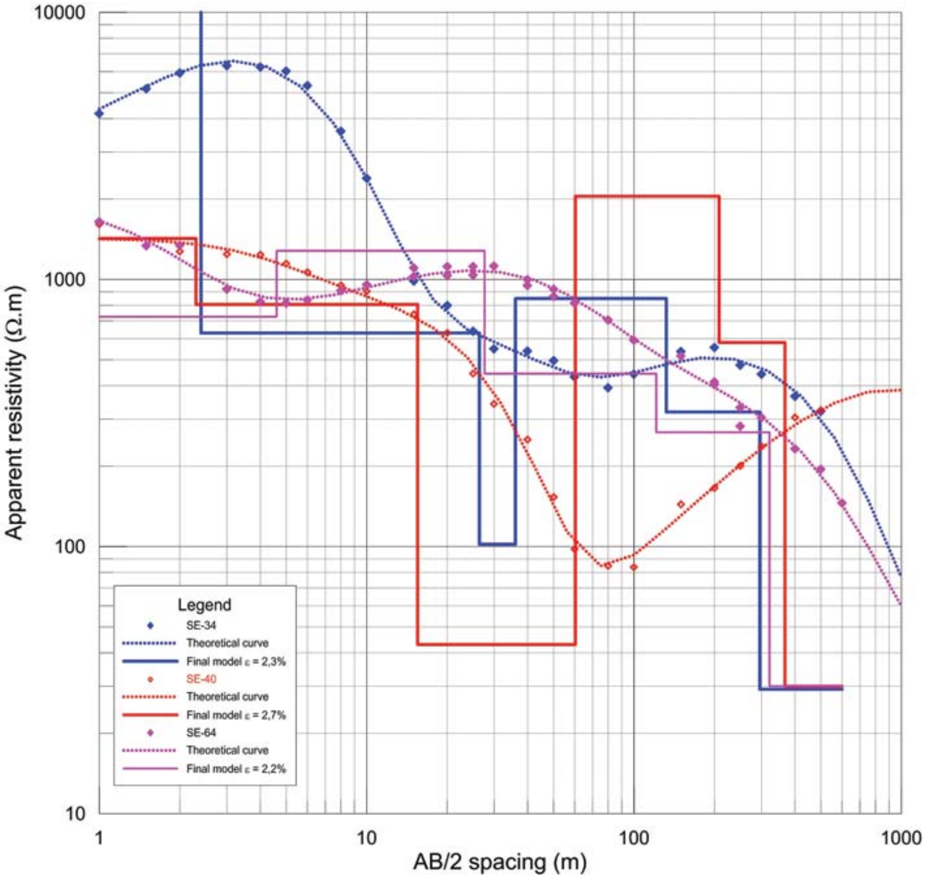

Figure 11 – Curves of VESs SE-34, SE-60 e SE-64 and their final interpreted models.

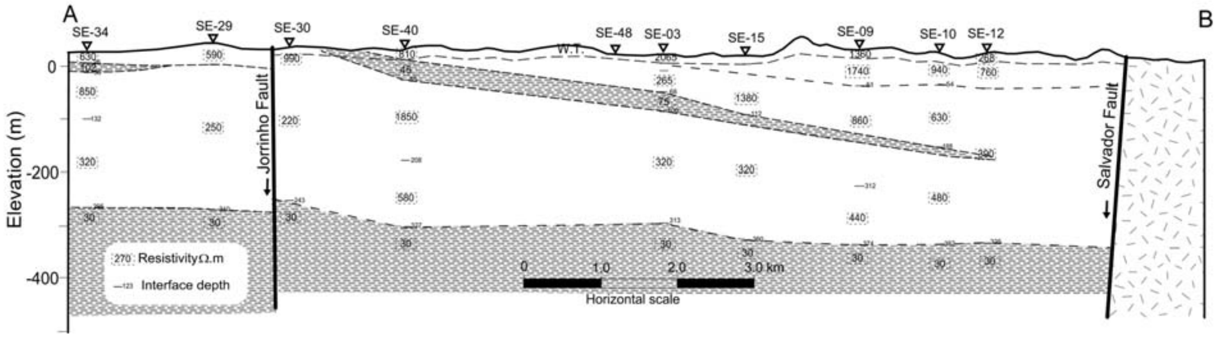

Figure 12 – Geological profile along traverse A-B constructed using inverted VES data.

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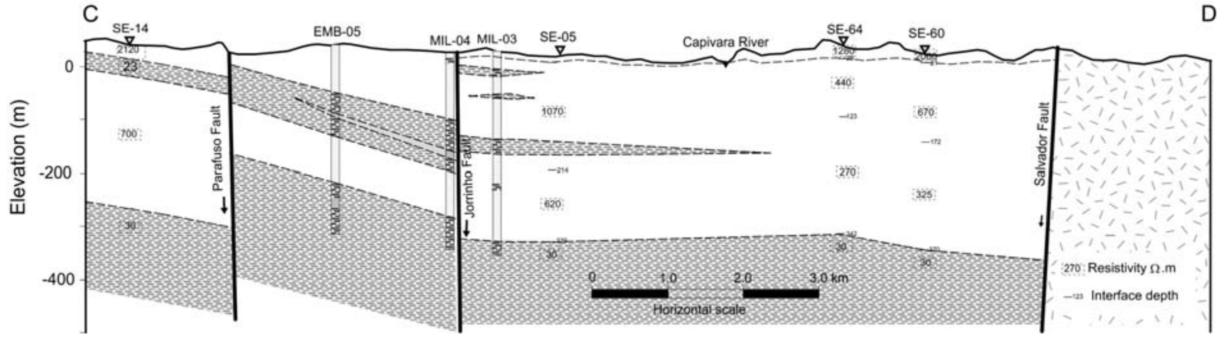

Figure 13 – Geological profile along traverse C-D constructed using inverted VES and well data.

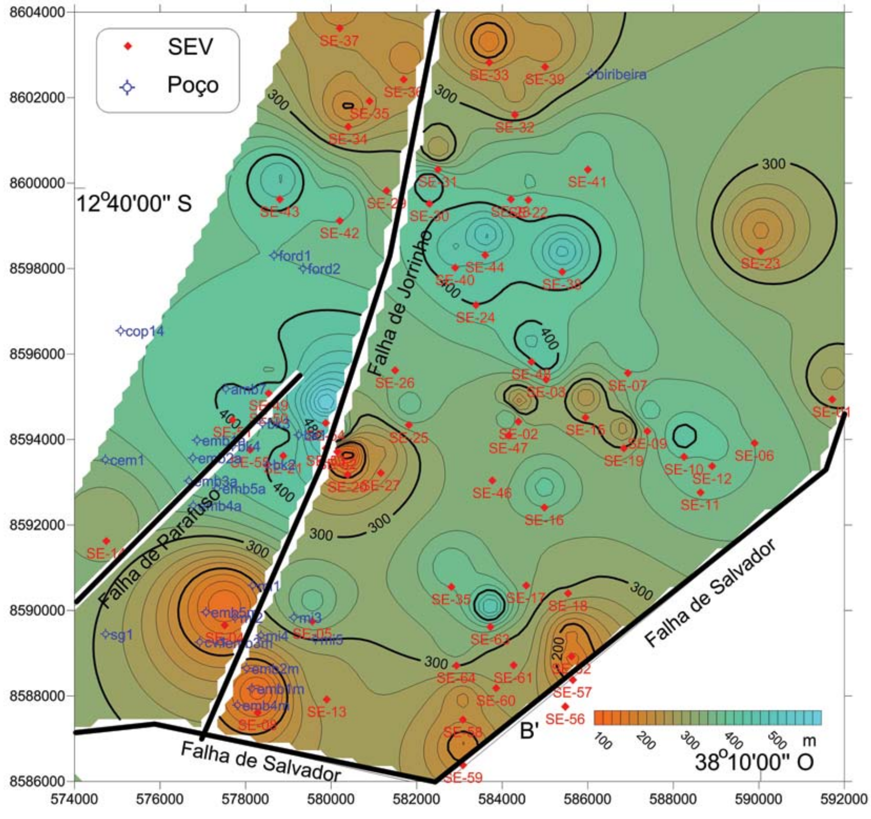

Figure 14 – Structural contour map of the top of shale layer that acts as substratum for the studied aquifer system.

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