The use of electrical logs to predict groundwater quality in multilayered aquifers

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RESUMEN

En áreas con sistemas acuíferos multicapa, es imprescindible la realización de registros geofísicos en los sondeos justo al finalizar su perforación para definir con rigor la columna definitiva, ya que estos registros proporcionan informaciones muy importantes sobre las condiciones hidrogeológicas locales. En el sistema multiacuífero Cretácico del Bajo Vouga (Aveiro), instalado en la parte septentrional de la Orla Mesocenozoica Occidental Portuguesa, es de máxima importancia, para la finalización correcta de los pozos, un análisis muy detallado de los registros geofísicos que atraviesan los diferentes conjuntos multicapa superpuestos, y que se presentan con distintas piezometrías y aguas de calidad química diferenciada.

En este ejemplo se presentan registros geofísicos de SP, SPR, resistividad normal de 16” y 64” y resistividad lateral de 6’, realizados en un sondeo que atraviesa formaciones Cuaternarias y Cretácicas. Mediante la utilización de métodos semi-cuantitativos clásicos se ha procedido a la predicción de la calidad del agua subterránea. De la correlación con logs de otros sondeos de la misma zona de estudio resulta evidente la importancia de estos métodos para la realización de pozos con aguas de buena calidad y de costos no demasiado elevados. Desde luego, la interpretación de los logs realizada con posterioridad a la finalización de los propios registros geofísicos, ha demostrado ser de cierta forma conclusiva sobre las características químicas del agua, en ausencia de cualquier análisis químico.

ABSTRACT

In areas with complex multilayered aquifer systems, borehole geophysics just after drilling and before casing the borehole is very important and offers an important insight about the local hydrogeological conditions. In the Cretaceous Multiaquifer System, located in the Lower Vouga, Portuguese Western Meso-Cenozoic Border, a careful analysis of the electrical logs that cross several aquifer layers with different water quality and piezometry is of most importance to elaborate a correct well completion. This example uses electrical logs done in a borehole that crosses Quaternary and Cretaceous formations for predicting groundwater quality using the classical semi-quantitative methods, through the joint interpretation of SP, SPR, normal resistivities 16” and 64” and lateral resistivity 6’. Correlation with other logs from surrounding wells also demonstrates how important these tools are when considering all the aspects of an effective and inexpensive well completion. In fact, the log analysis carried out long after the logging procedure has proved to be somehow conclusive regarding the chemical characteristics of the water, in the absence of a chemical analysis.

1. INTRODUCTION

Evaluating water quality immediately after drilling in multilayered aquifers assumes a particular importance, since wells often cross several different aquifers with different characteristics concerning native water quality. The importance of a perfect identification of these layers is crucial to screen projecting in this type of environments. From both technical and economical points of view, there is a clear need for a logging survey with the aim of confirming information from drilling cuttings and evaluating groundwater quality. A set of electrical logs just after drilling, may be the difference between a successful and productive well and a serious problem to handle with, which may implicate well cementations or even, in the most extreme cases, well abandoning. To avoid these technically difficult and expensive situations, a careful interpretation of electrical log data may lead to important conclusions about groundwater quality, and therefore, to the best screen location options. This paper describes how important these interpretations are in the Cretaceous multilayered aquifer located in the Vouga Basin, Portugal.

2. GEOLOGICAL AND HYDROGEOLOGICAL CHARACTERISTICS OF THE AREA

The study area is located in Portuguese Western Meso-Cenozoic Border or Lusitanian Basin, which is composed by sedimentary formations. The stratigraphic sequence is discontinuous and ranges from Upper Triassic to Holocene formations. They lie, in unconformity, over hercynian bedrock (composed by schists), which crops out to the north and east area of Aveiro. In this area, the hercynian bedrock is expected to be found at about 130 meters depth (Marques da Silva & Soares de Andrade, 1998). Before reaching this hercynian bedrock, the sequence crosses several aquifer Cretaceous formations with waters showing variable mineralisations, piezometries and transmis-

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sivities. The study sub-zone is marked in figure 1 with a grey circle. It is located in the northern part of the Lower Vouga River, Cacia.

The multilayer aquifer in this area is formed mainly by Cretaceous sediments, overlayed by Quaternary deposits. Several types of sandstones, clays and carbonate formations compose it. Detailed descriptions and characterisation of these units can be found in Marques da Silva (1990). Generically, from bottom to top, they are (Marques da Silva, 1990): C^{1-2} – Lower Sandstone Formation (Belasian); C^{2} – Carbonate Formation; C^{3} – Micaceous Sandstone; C^{4} – Upper Sandstone Formation; C^{5} – Aveiro Clays, Q – Quaternary. From a hydrogeological point of view, the most productive units and with the lowest salinity levels correspond to the top of unit C^{1-2}, the entire unit C^{3}, and the bottom of unit C^{4}.

Some of these formations can be considered as guide-layers, as they clearly identify the main Cretaceous aquifer set (Marques da Silva, 1992). In fact, in the western area of the Vouga Basin, unit C^{1-2} (Lower Sandstone Formation) indicates the lower limit of the aquifer, with very characteristic SP and SPR logs (Marques da Silva, 1990, 1992). Natural gamma radiation registers indicate a slight lithofacies change from bottom to top, with carbonate fraction decreasing and clayey fraction increasing (Marques da Silva, 1990, 1992). The importance of these guide layers is related with the identification of the aquifer limits. This identification makes possible, not only a good well completion, but also the determination of some hydraulic parameters of the aquifer (Marques da Silva, 1992). On the other hand, unit C^{3} (Micaceous Sandstone) is known to be the best aquifer formation in the entire main Cretaceous aquifer set, producing water with the best quality and water flows (Marques da Silva, 1992). The limits of this unit are well defined with two guide-layers, the upper with a dark micaceous clay layer and the lower with a greyish micaceous marl-clay layer (Marques da Silva, 1992).

The importance of good well logging interpretation is clear under these geological and hydrogeological conditions, since the identification of the best aquifer formation (unit C^{3}) is fundamental to the water quality to be produced by the well.

3. LOGGING INTERPRETATION

The main well mentioned on this example was drilled in 1982. Just after drilling, natural gamma radiation, SP, SPR, short normal resistivity 16", long normal resistivity 64" and lateral resistivity 6' were carried out. Total depth was 122m, when it reached a reddish-brown clay layer, which lies over lower beds. From previous and later experience with other wells (figure 6), these lower beds contain more mineralised water.

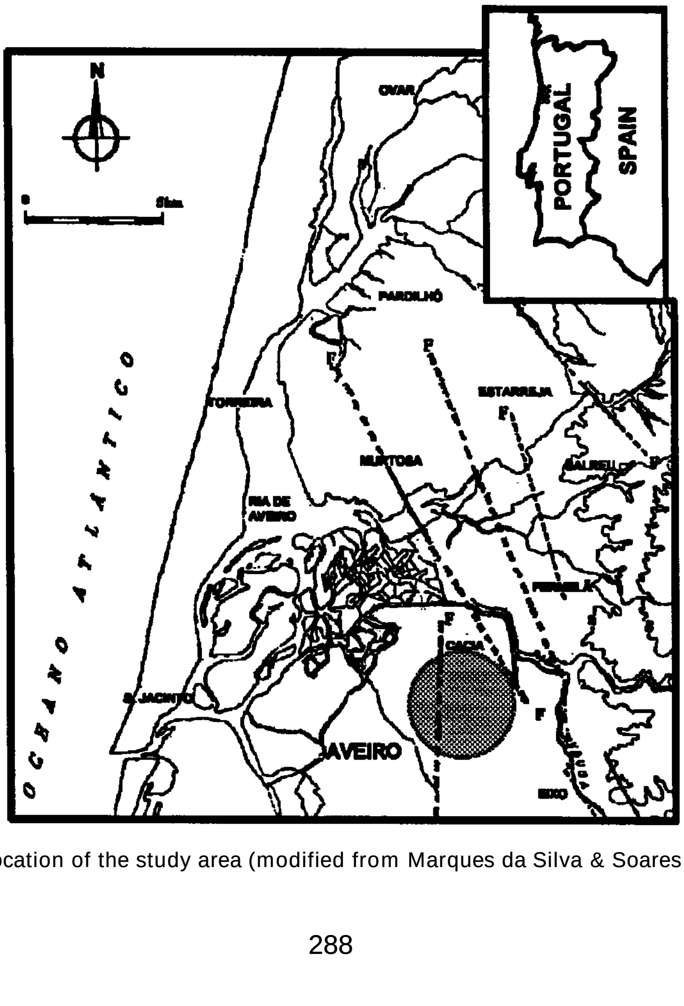

Figure 1 – Regional location of the study area (modified from Marques da Silva & Soares de Andrade, 1998).

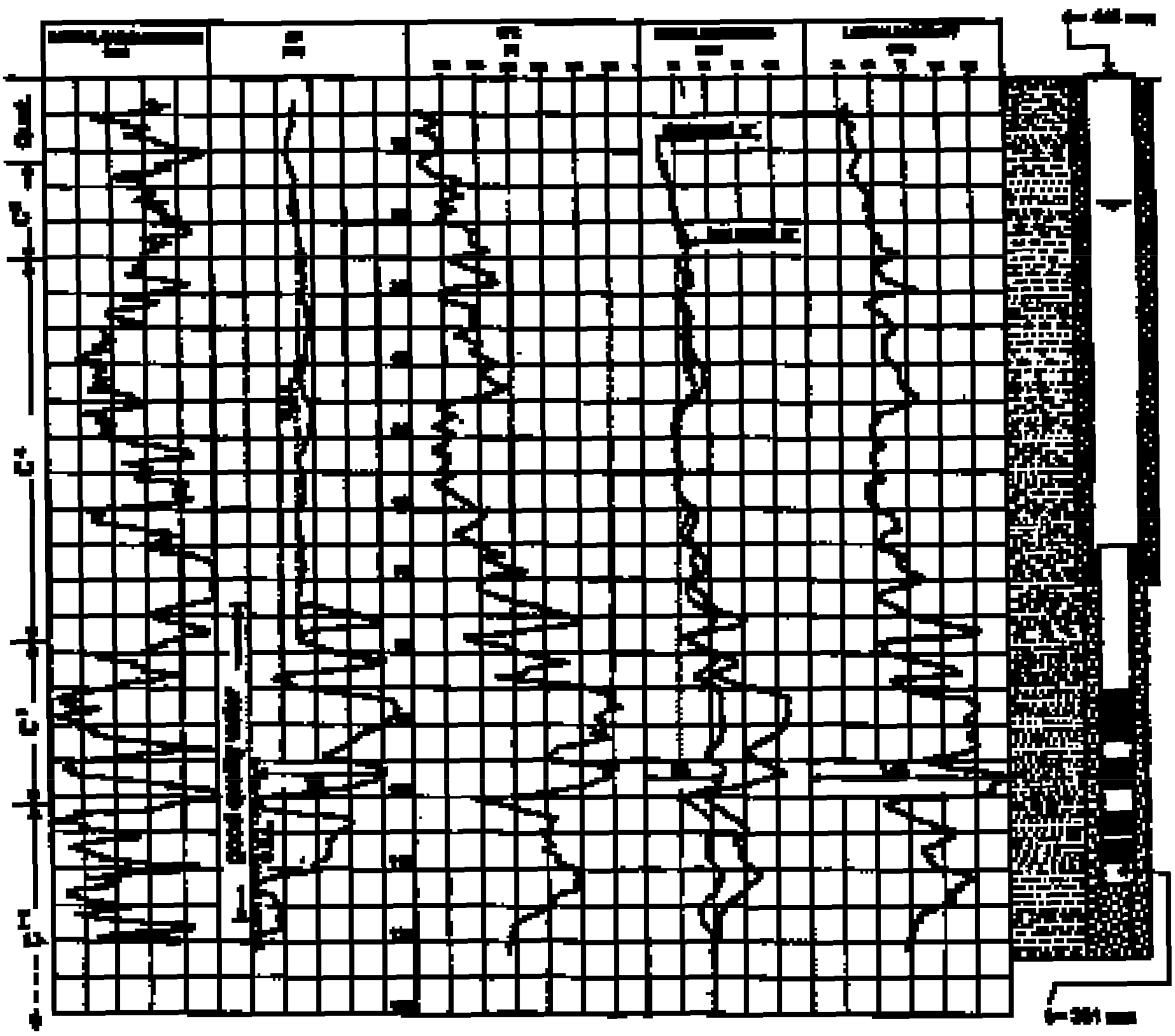

Figure 2 – Natural gamma radiation, SP, SPR, normal resistivities 16'' and 64'' and lateral resistivity 6' for the example well. C.B.L. represents clay baseline. C^{1-2} - Lower Sandstone Formation (Belasian); C^3 - Micaceous Sandstone; C^4 - Upper Sandstone Formation; C^5 - Aveiro Clays; Quat. - Quaternary (Marques da Silva, 1990)

Bentonitic mud was about 17 ºC, density = 1.37, pH = 6.7 and Cl^- = 650 mg L^{-1}. Surface Quaternary is composed by muddy sands with low permeability and mineralised. Besides this aquifer, only the multilayered aquifer located between 74 and 114 meters deep is detected, which is clearly seen in the suite of logs. Positive deflections on the SP register indicate, besides potentially permeable horizons, also low water mineralisation. Short normal resistivity log 16" confirms this assumption, with higher resistivity values in this zone. High natural gamma radiation values, also allows detecting clayey horizons (K^+ rich) in the permeable set. The high natural gamma radiation values registered between 67-74 and 98-102 meters deep is due to micas (increasing K^+ content) and organic mater (increasing U content) in those clayey beds. On the other hand, resistivity logs allow estimating, with good accuracy, native water and invaded zone resistivities. This multilayered set belongs to unit C^3 and upper C^{1-2}. Carbonate Formation unit is not present, although lower and upper C^4 can be considered as an aquifer formation (Marques da Silva, 1990) with less mineralisation.

With the available information and with drilling mud with this type of characteristics, groundwater quality may be estimated after formation factor, F (Archie, 1942, in Chappelier, 1992):

$$F = \frac{R_t}{R_w} = \frac{R_{xo}}{R_{mf}} \quad (1)$$

where R_t is the real formation resistivity of the uninvaded zone (Ω.m), R_w is formation water resistivity (Ω.m), R_{xo} is resistivity of the flushed zone (Ω.m) and R_{mf} is mud filtrate resistivity (Ω.m). Therefore:

R_{mf}(17 ºC) = 6 Ω.m (figure 3, point A, considering 650 mg L^{-1} $Cl^- \cong$ 1072 mg L^{-1} NaCl);
R_{xo} = 55 Ω.m (short normal resistivity log 16");
R_t = 145 Ω.m (lateral resistivity log 6').

$$F = \frac{R_{xo}}{R_{mf}} = \frac{55}{6} = 9 \quad (2)$$

$$R_w = \frac{145}{9} \cong 16\,\Omega\,\mathrm{m} \tag{3}$$

Water formation resistivity, R_w, corresponds to about 360 mg L^{-1} equivalent NaCl (figure 3, point B, at 17ºC), a little higher than TDS obtained through chemical analyses in wells nearby. Nevertheless, this value can be considered to be a good approach.

Although water is known to have bivalent cations of Ca^{2+} e Mg^{2+}, there is not a clear knowledge about groundwater from wells in this area; in these conditions, a comparison based on the activities can be done. A chemical analysis from water coming from this aquifer set in this area may be the one represented on Table 1.

Multiplying these values by Dunlap Factors gives 225 mg L^{-1} equivalent NaCl (Table 1), lower than the previous estimated 360 mg L^{-1}.

Through the analysis of figure 4, cation activities are:

- 62 mg L^{-1} Na^+ (water) correspond to

$$\langle Na^+\rangle_w = 0.0025 \text{ (fig.4, point A)};$$

- 24 mg L^{-1} Ca^{2+} + Mg^{2+} (water) correspond to

$$\sqrt{\langle Ca^{2+}\rangle_w + \langle Mg^{2+}\rangle_w} = 0.021 \text{ (fig.4, pointB)};$$

- 422 mg L^{-1} Na^+ (mud filtrate) correspond to

$$\langle Na^+\rangle_{mf} = 0.016 \text{ (fig.4, point C)}.$$

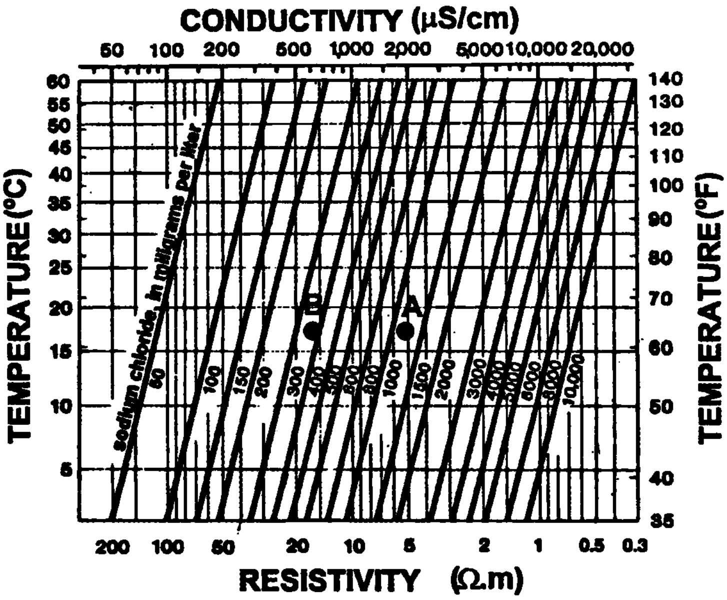

Figure 3 – Electrically equivalent sodium chloride plotted as function of conductivity or resistivity and temperature (adapted from Keys, 1990).

$$\sqrt{\langle Ca^{2+}\rangle_{mf} + \langle Mg^{2+}\rangle_{mf}}$$

is supposed to be identical to the formation water.

Since there is no chemical analysis of the mud filtrate and both formation water and mud filtrate contain bivalent cations, through the equation (Chappelier, 1992):

$$SP = -K \log \frac{\langle Na^+\rangle_w + \sqrt{\langle Ca^{2+}\rangle_w + \langle Mg^{2+}\rangle_w}}{\langle Na^+\rangle_{mf} + \sqrt{\langle Ca^{2+}\rangle_{mf} + \langle Mg^{2+}\rangle_{mf}}} \tag{4}$$

where K is the electrochemical constant which depends on the temperature (figure 5), $\langle Na^+\rangle$, $\langle Ca^{2+}\rangle$ and $\langle Mg^{2+}\rangle$ are respectively sodium, calcium and magnesium activities from formation water and mud filtrate.

K = 69 (17 ºC, fig. 5, point A)

$$SP = -69 \log \frac{0.0025 + 0.021}{0.016 + 0.021} \cong +14\,\mathrm{mV} \tag{5}$$

The logs represented on figure 2 register SP values between +10 and +15 mV for the main Cretaceous aquifer set. These values can be considered as accurate, and therefore, the chemical analysis on Table 1 can also be considered to be representative of the water from the aquifer set composed by units C^4, C^3 and last sequence of unit $C^{1\text{-}2}$.

Ion	Concentration (mg L^{-1})	Dunlap Factor	Equivalent NaCl (mg L^{-1})
Cl^-	65.3	1.00	65.3
HCO_3^-	78.1	0.27	21.1
SO_4^{2-}	26.9	0.50	13.45
Na^+	62.0	1.00	62.0
K^+	9.9	0.85	8.42
Ca^{2+}	15.2	0.95	14.44
Mg^{2+}	8.8	2.00	17.6
			225.05

Table 1 - Ideal chemical composition of a water sample from a well in the area

As a comparison, another well much older than the previous (about 20 years), located 25 meters away from well represented in figure 6, has reached 190 meters deep and has SP and SPR logs available; as it can be seen, both wells have correlated logs until 120 meters deep. However, SP log has symmetric registers to the other well, resulting from low chloride content in the drilling mud, causing higher R_{mf} than R_w (Chappelier, 1992).

In spite of the absence of a chemical analysis allowing a semi-quantitative interpretation, it is evident the existence of three different sets in the permeable Cretaceous (Marques da Silva, 1990):

1- Upper set, containing fresh water (between 74-114 meters deep). Just like in the previous case, it includes the bottom of unit C^4, unit C^3 and last sequence of unit C^{1-2}. SP deflections are negative but small. SPR log is also similar to the previous case.

2- Second set, under the first, reaching 150 meters deep, with much more negative SP deflections. SPR values fall when compared with first set, indicating more mineralised water.

3- Lower set, between 150 meters and schist bedrock with the most negative SP deflections, while SPR values are even lower than the previous set. This is a direct consequence of the highly native water mineralisation, which was confirmed with partial pumping tests carried out with packers (Marques da Silva, 1990).

As it can be seen in figure 6, the well was later cemented to exclusive exploitation of the main Cretaceous aquifer set.

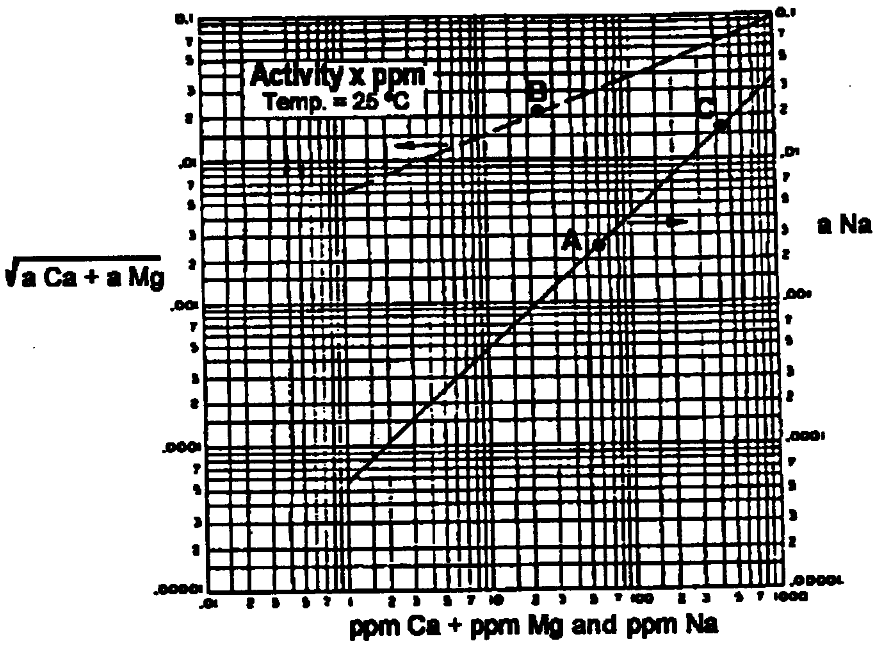

Figure 4 – Activity of a solution as function of concentration (adapted from Chappelier (1992)

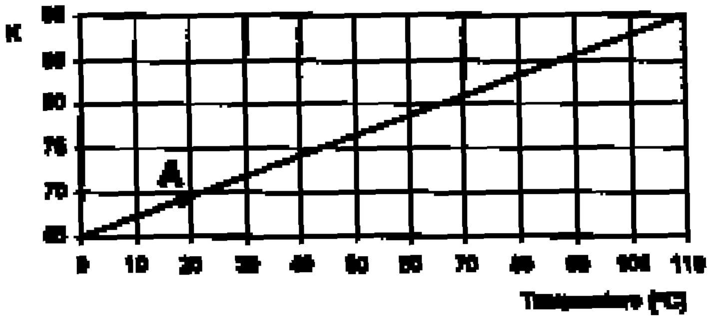

Figure 5 – Electrochemical constant plotted as function of temperature.

4. FINAL DISCUSSION

These examples clearly show that in this type of multilayered aquifers, logging surveys, namely electrical logs may be very important to predict groundwater quality. In fact, if there is some knowledge about the chemical composition of formation water (such as, for instance, the type of water that is expected to be found), an ideal chemical analyses can be created if some electrical logging data are known. However, since many unknown factors may disturb well logging results in these conditions (such as, for instance,

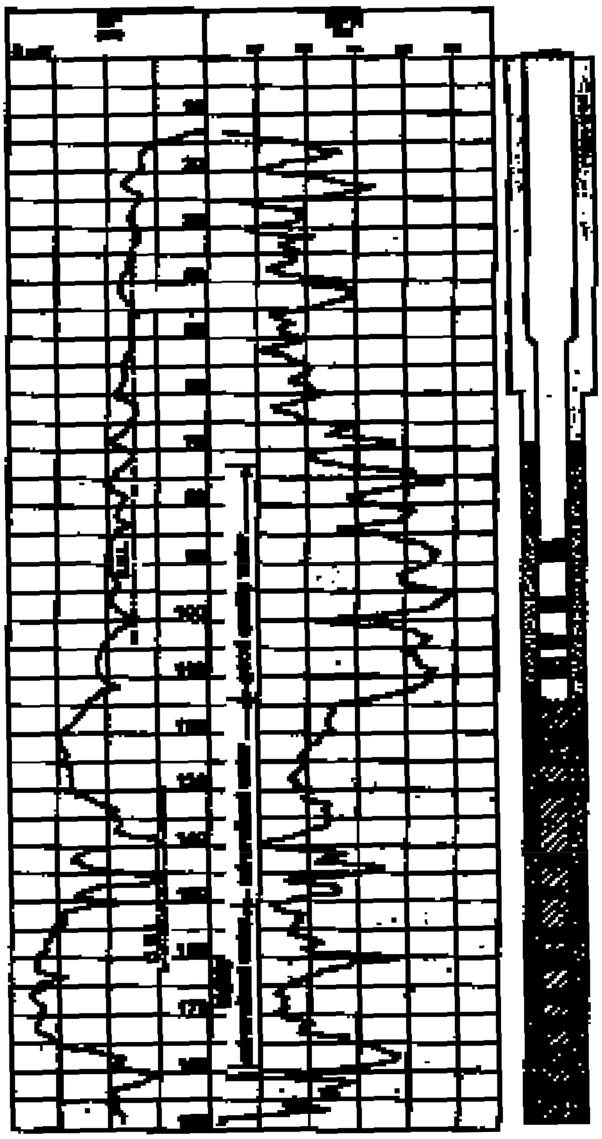

Figure 6 – SP and SPR logs from a deeper older well, located near the well represented in figure 2.

piezometric differences among different aquifer layers and local inhomogeneity in mud density), data must be carefully interpreted. Final results must only be considered in a semi-quantitative basis, unless total control is exerted during drilling and logging (including probe calibrations).

Nevertheless, confirming the facts that were previously pointed out, more examples can be found in the area, even with upper mineralised aquifer beds than the main Cretaceous aquifer set. In some areas, values ranging from 250 to 300 mg L^{-1} Cl^- can be found, against 25 to 30 mg L^{-1} Cl^-, if only the main Cretaceous aquifer set is exploited. Sometimes, when screens are located beyond the main Cretaceous aquifer set, serious water quality problems have to be solved, often with well cementations carried out later. Another important factor to a successful logging interpretation in this type of environments, is the geological and hydrogeological knowledge about the area, specially the guide-layers, since even the drilling process itself leads to difficulties in reconstructing lithology only through drilling cuttings.

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