# PETROPHYSICAL EVALUATION IN TIGHT GAS FORMATIONS THROUGH CASED HOLE LOGS: CONTINGENCY SOLUTIONS FOR OPEN HOLE LOGS

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In recent decades, the evaluation of tight formations has become a challenge for many petrophysicists. The interpretation of electric logs in these types of unconventional reservoirs becomes difficult because of the low porosity and permeability that they represent.

Quite often, because of drilling problems or simply because of the nature of the reservoir, the well must be cased without the possibility of obtaining open-well records, which are a key requirement to define the correct petrophysical interpretation.

In light of this situation, how difficult does the analysis for this type of formation become when we do not have open hole logs? In other words, how can we evaluate whether or not the zone of interest will produce water when we do not have the critical information?

This paper demonstrates how, through the use of pulsed neutron and complete-wave sonic logging, it is possible to determine the principal characteristics of a tight reservoir. With those logs, the fundamental parameters can be obtained with which to develop the completion of the well (effective porosity, volume of clay, water saturation, VP/VS ratio, and other parameters) to thereby select the “pay” zones to be fractured.

This work presents a concrete solution for the efficient evaluation of tight gas reservoirs, using cased well logging.

## CHARACTERISTICS OF THE FORMATION AND THE RESERVOIR

This work is based on the interpretation of electric logs acquired in the Lajas formation in a well drilled south of the Neuquina basin.

Stratigraphically, the Lajas formation pertains to the Cuyo group, along with the marine sediments of the Molles formation (in the base) and the fluvial sediments of the Challacó, or Punta Rosada, formation, toward the top of the unit (Figure 1) (Vergani et al. 2002).

According to its tectonic evolution, the Cuyo group is divided into two phases. The lower Cuyo Group represents a synrift phase, in which the fill control was fundamentally tectonic, with high subsidence and settling rates. The second instance, or upper Cuyo group, represents a postrift phase, in which the principal accumulation mechanism ceases to be tectonic and begins to become thermal, with lower subsidence rates and a large eustatic influence. In this latter phase, there were large contributions of sediments into the basin. (Gulisano et al., 1984).

The coarse-grained clastic sediments of fluvial-alluvial origin, corresponding to the Challaco or Punta Rosada formation, pertain to the upper Cuyo group and the deltaic and platform deposits that characterize the Lajas formation.

The Lajas formation consists of sands and, to a lesser degree, conglomerates, deposited principally in a marginal marine environment platform, during a large part of the early and middle Jurassic.

The obliteration and worsening of petrophysical conditions, as the result of a complex and varied digenetic history, provide the reasons that this formation is referred to as a “tight reservoir.”

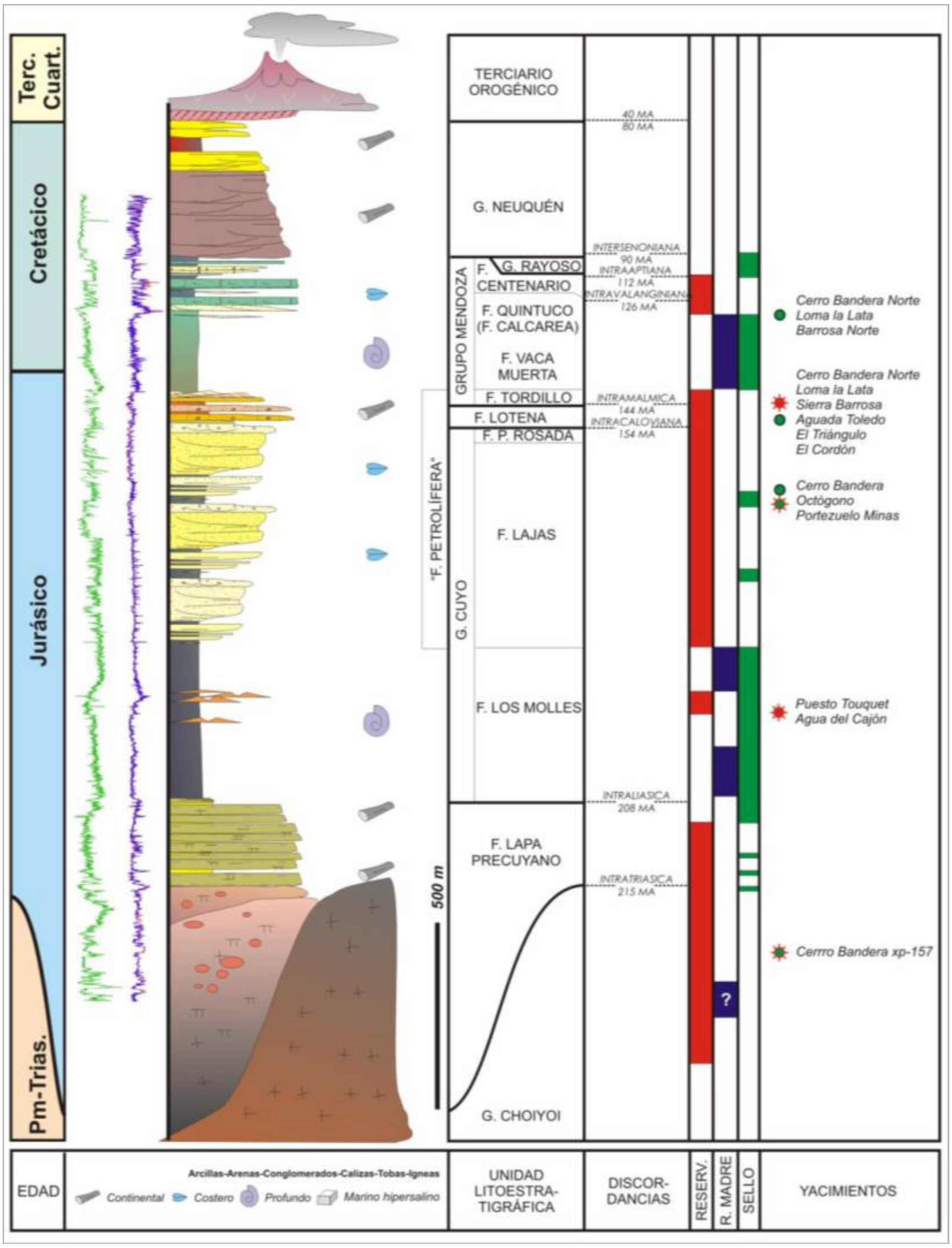


*Figure 1–Synthetic stratigraphic column of the Neuquina basin; Southern and Dorsal Huincul region.*

## DESCRIPTION OF THE CONTINGENCY

To obtain a petrophysical analysis of the Lajas formation, a complete set of open-well logging services was requested in accordance with the following program:

- First run: resistivity, gamma ray, oriented six-arm caliper, and dipolar sonic
- Second run: density, neutron, gamma spectral, mineralogical tool
- Third run: nuclear magnetic resonance

- Fourth run: micro-resistive and acoustic images

During the first logging run, the log reflects significant over-tensioning throughout, affecting the compressional delta-t resistivity curves, as shown in Figure 2.

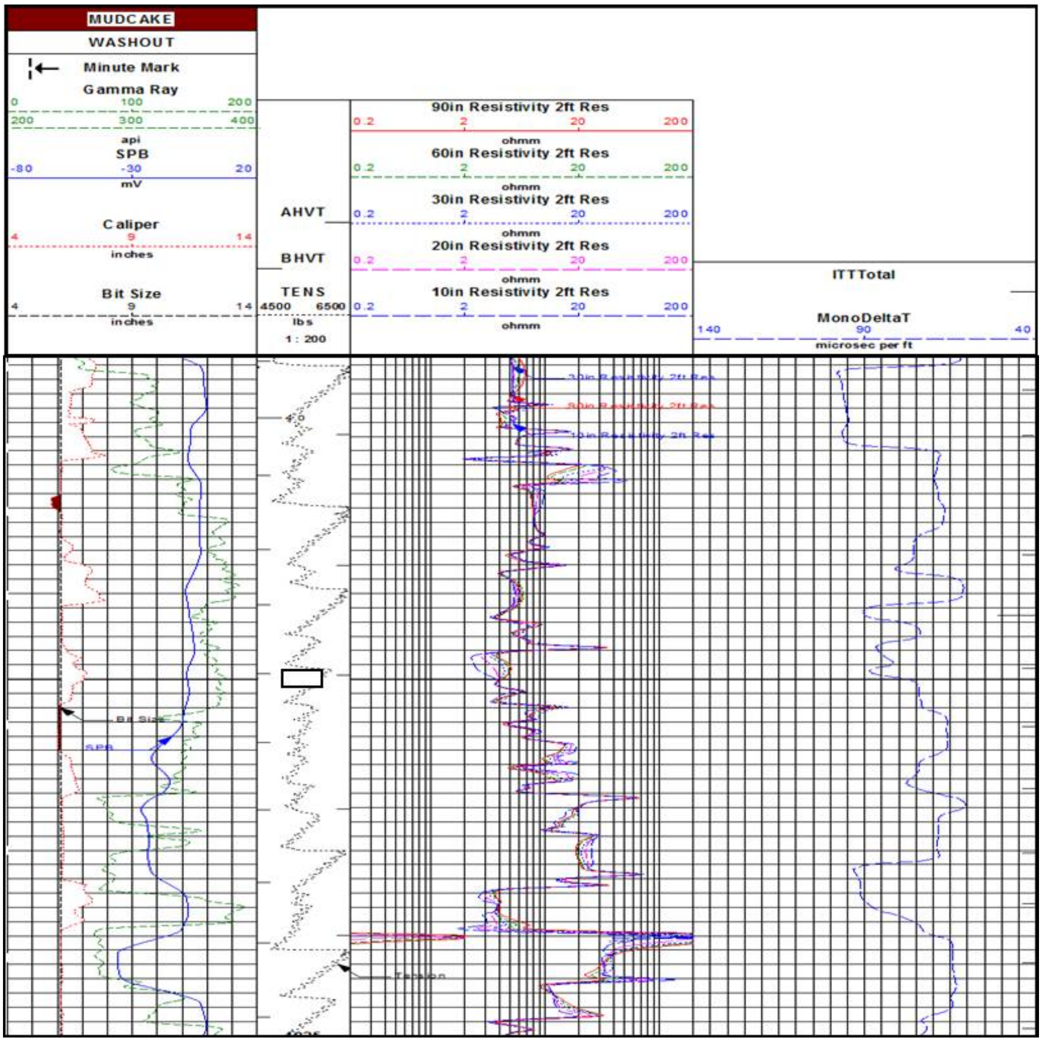



*Figure 2–First run: gamma ray, induction, and sonic record; the depth track clearly shows over-tensioning.*

To provide a better visualization of the well geometry, 3D caliper images were performed. Figure 3 reveals the possible causes of the over-tensioning.

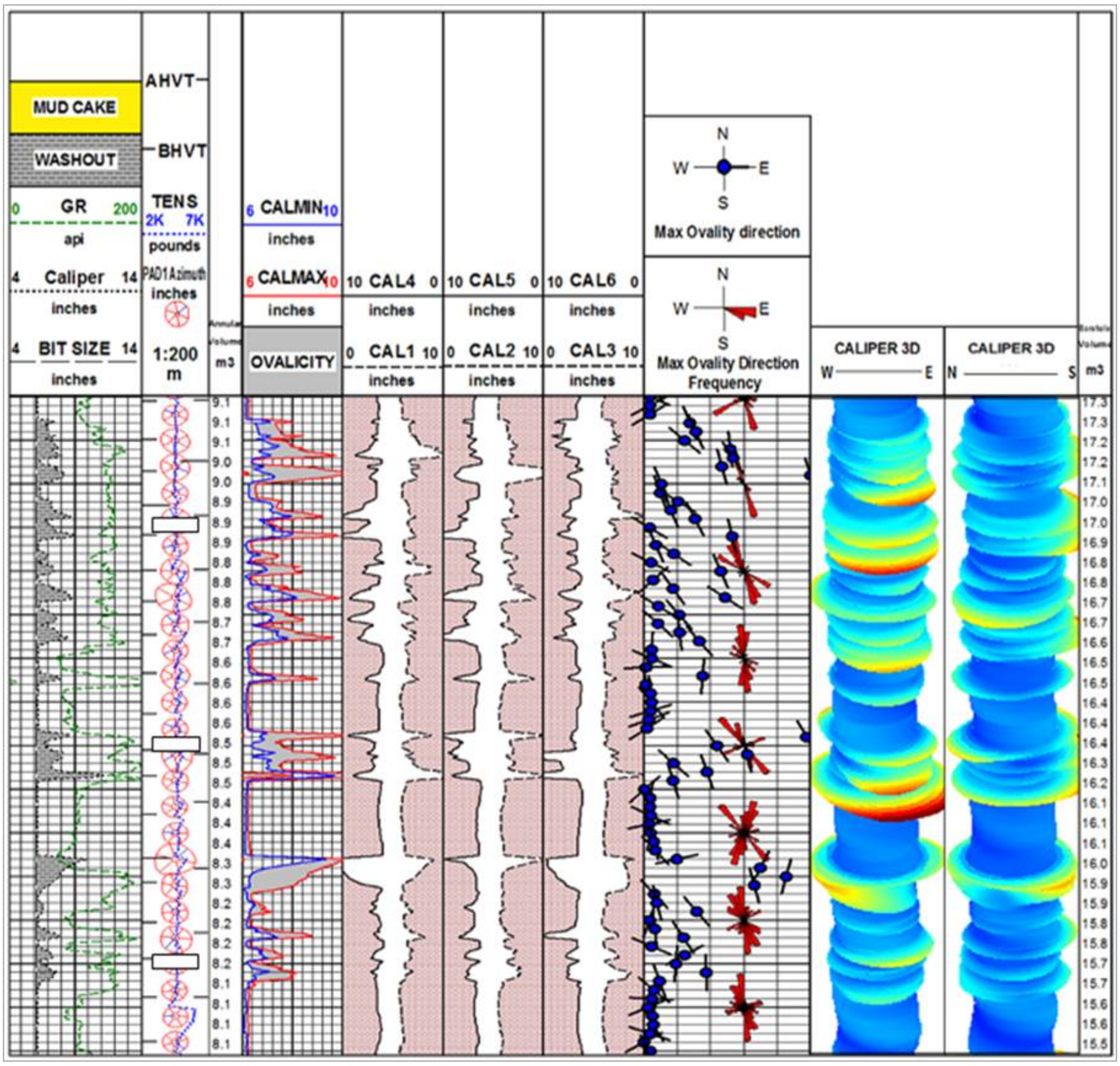



*Figure 3–6-arm caliper log, 3D images.*

Because of the well conditions, it was decided to calibrate the well before continuing with the established logging program.

After beginning the second programmed run, only the first 100 meters of the Lajas formation could be logged without problems; after the first 100 meters, however, over-tensioning of the cable began to occur again (Figure 4).

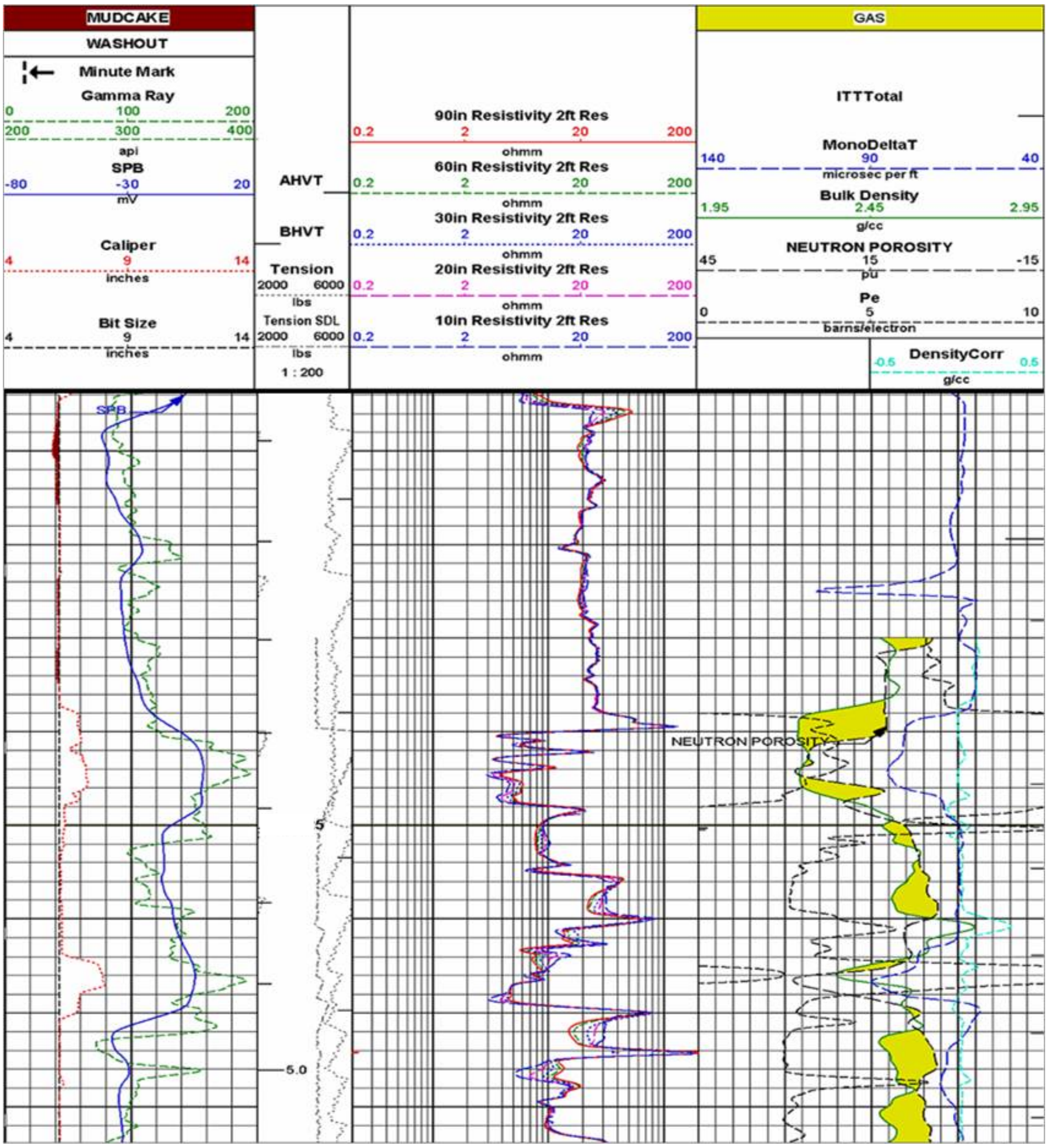



*Figure 4–Second run: induction, density, and neutron.*

The condition of the well affected the responses of the density and neutron tools. The operator decided to completely suspend the logging operation and to case the well.

## PROPOSED SOLUTION

In view of this contingency, a cased well solution was proposed to enable a correct evaluation of the Lajas formation. The proposal was based on performing pulsed neutron logging, followed by a complete wave sonic and neutron logging run. With the information logged, the three following analyses would be presented to provide the petrophysical interpretation of the reservoir:

- Neural Net analysis: Because it was possible to log the base of the Lajas formation (100 meters) without problems, it will also be possible to train the neuronal networks in this zone, to predict the resistivity and density curves in the remainder of the interval of interest. The training consists of constructing an architectural network that relates the open well curves with the pulsed neutron logs. After the desired results are obtained, a resistivity curve will be computed that will be used to correct the values affected by the over-tensioning of the first run and a density curve. The density/neutron crossover—the latter in a cased well—will be an indicator of gas and used to determine the pay zones.

- Sigma saturation analysis: This model is used to obtain the saturation value of hydrocarbons through pulsed neutron technology.
- Complete-wave sonic analysis: Sonic porosity will be used as an input for the Sigma saturation analysis. In addition, by obtaining the velocities of the P and S waves, the Vp/Vs ratio will be available as an indicator of gas.

The following sections describe the complete-wave sonic and pulsed neutron technologies to provide a better understanding of the principles of the solution proposed.

**Sonic Tool**

The Halliburton sonic tool includes two mono-polar transmitters and a vertical array of five piezoelectric receptors. This configuration enables higher quality acoustic measurements to be obtained than those provided by previous designs because the information logged by all the receptors combines to obtain a single log of the complete wave (Figure 5).

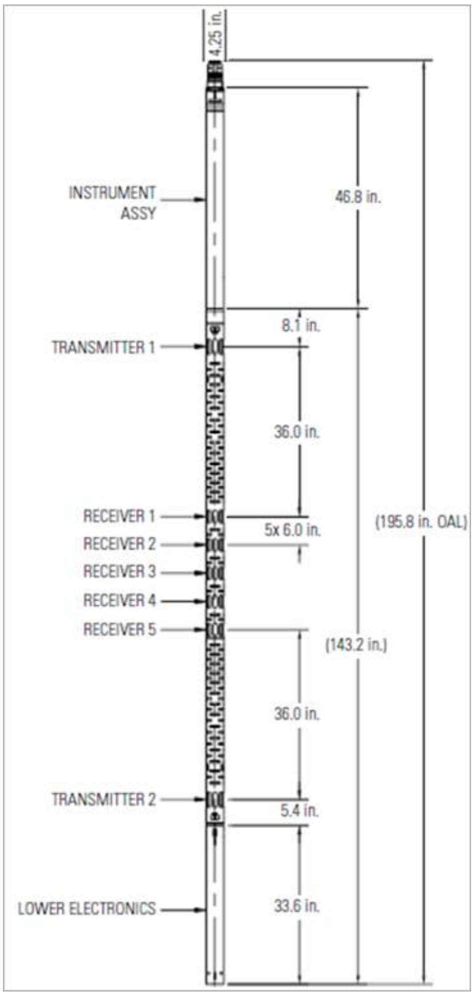



*Figure 5–Configuration of the sonic tool.*

In rapid formations (in which the velocity of the shear wave is greater than that of the fluid), in addition to the compressional wave (P) and the Stoneley wave (S), the velocity of the refracted shear wave may also be measured (Figure 6).

When data on compressional and transverse waves are available, the Vp/Vs velocity ratio is useful for identifying the properties of the fluids and lithology. It is also an important parameter in the advanced modeling of rock mechanics to evaluate the stability of the drill hole, the stimulation design, and the optimization of well completion.

Because shear waves are not transmitted through fluids, the velocity with which the transverse waves (S) move in the formation depends principally on the matrix. Conversely, the velocity of the longitudinal waves depends as much on the matrix as on the properties of the fluids that occupy the porous spaces, and moves more slowly when the fluid is less dense. Because of this, the velocity ratio (VP/VS) can be calibrated to provide a very good indication of the presence of gas in the formation.

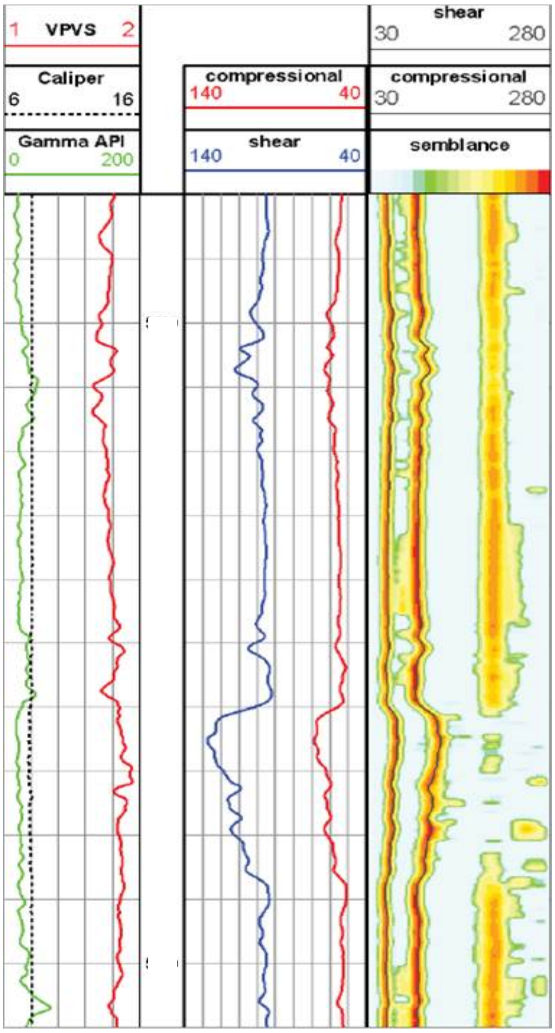


*Figure 6–Shear and Stoneley compressional waves.*

**Pulsed Neutron Tool**

The pulsed neutron tool (Figure 7) uses induced gamma ray spectroscopy and the measurement of decay time to calculate the saturation of fluids in reservoirs through the logging of cased wells.

The diameter of the tool is 2-1/8 in., which enables logging in casings of 2-7/8 in or larger. The selection of a diameter of 2-1/8-in. made it possible to use two bismuth germanate detectors of a greater diameter (1.4 in.). The use of these high density detectors enabled an improvement in the detection of the counts proceeding from the capture gamma rays, thereby obtaining a resolution two or three times greater than other systems on the market. At the same time, this improvement in resolution made logging in low porosity formations viable, whereas other tools can accomplish this only by means of stationary logging.

The tool includes a neutron generator and, unlike other nuclear tools, does not have a radioactive source, which increases its safety and reliability in all eventualities.

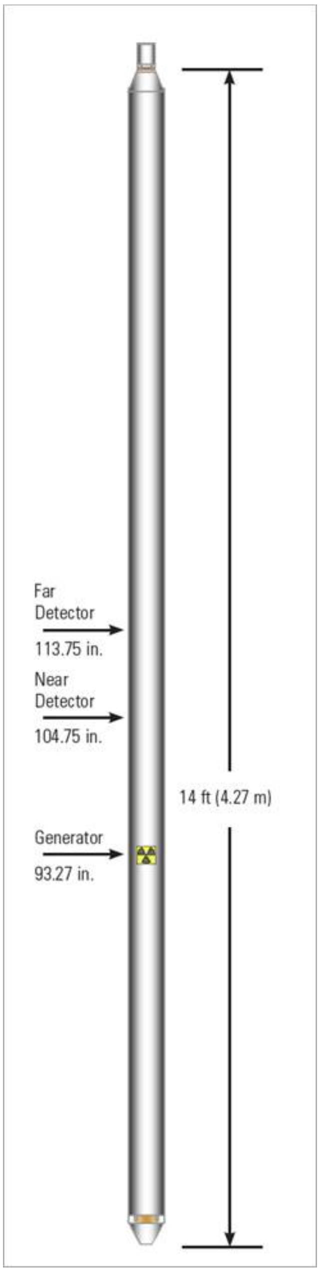



*Figure 7–Pulsed neutron tool.*

**Capture Mode**

The logging mode in the well under study is known as capture mode, and its ultimate purpose is to determine the water saturation of the reservoir by means of the "*sigma*" of the formation.

**What is Sigma (Σ)?**

The pulsed neutron tool emits high-energy neutrons (14 MeV) and measures the time required for a certain fraction of these neutrons to be absorbed by the formation. Chloride is one of the elements with a greater capacity for absorption. In clean formations, the response of the tool is principally determined by the chloride present in the formation water. Consequently, the tool can be used to quantitatively measure water saturation.

In a homogeneous medium, the decay of the thermal neutrons is theoretically an exponential function of time:

$$n = n_0 e^{-t/\tau}$$

in which $n_0$ is the number of thermal neutrons at time $t_0$ after the emission of neutrons, $n$ is the number of thermal neutrons at a time $t$, as measured from $t_0$, and $\tau$ is the time of thermal decay. The time required for a number of neutrons to decrease to the fraction 1/e is defined as $\tau$.

$\Sigma$(sigma) and $\tau$ are related by the following equation:

$$\Sigma = 4.55/\tau$$

To summarize, sigma refers to the capacity of the formation to capture neutrons in a thermal state and emit gamma rays. These capture gamma rays are read by the detectors of the tool and used to analyze the saturation.

Figure 8 shows that the decay of the formation depends upon the fluid contained in the rock.

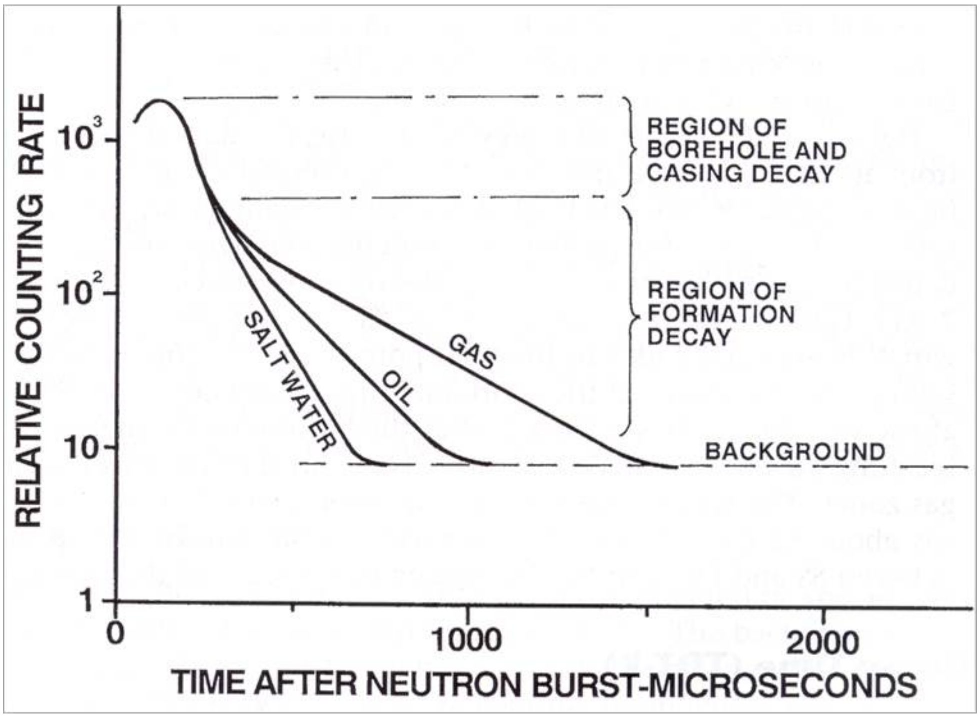



*Figure 8–Typical fluid decay response (from Halliburton laboratory tests).*

In addition, with spectroscopy, the capture mode resolves the calcium (Ca), silicon {Si), iron (Fe), sulfur (S), chlorine (Cl), potassium (K), hydrogen (H), and magnesium (Mg) elements, which can be used for mineralogy analyses.

One of the advantages of this modality is the speed of the logging. It is sufficient to perform a single logging run at a velocity of 3 meters/minute to obtain the necessary information, whereas the inelastic mode (carbon-oxygen saturation) requires a minimum of three runs at a velocity of approximately 1 meter/minute.

## METHODOLOGY

Before performing the work, an analysis must be performed to determine whether or not the capture mode is a reliable method with which to obtain the water saturation data for the reservoir in question (Figure 9 and Figure 10). For this purpose, the average porosity value of the reservoir and the salinity of the formation water must be known. With this data, the calculation shown in Figure 9 can be performed.

| Porosity (PU) * Salinity (kppm) = X | |
|---|---|
| **Si X <500** | Logging is not possible |
| **Si 500 < X < 1000** | Zone of uncertainty ("gray") |
| **Si X > 1000** | Logging is possible |

*Figure 9–Verification of applicability of the tool.*

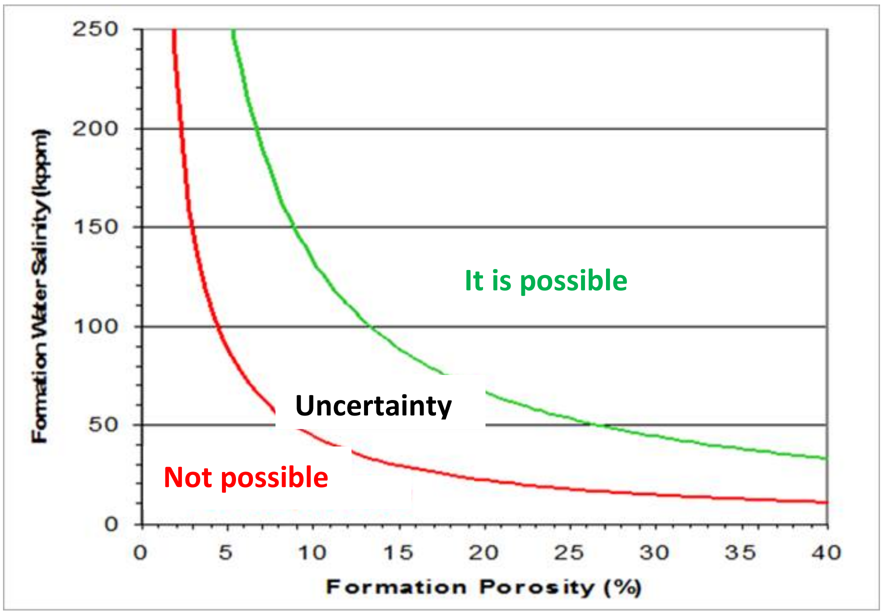



*Figure 10–Measurement certainty ratio, according to porosity-salinity (from Halliburton laboratory tests).*

The average porosity values of the section of the Lajas formation under study ranges from 8 to 12%. The salinity of the formation water obtained in production tests is approximately 100 kppm:

100 * 10 = 1000 → It is posible

The sigma measured by the tool is based on the elements constituting the formation. For a clean formation containing water and petroleum, it can be expressed in the following manner:

$$\Sigma_{LOG} = (1-\Phi)\Sigma_{ma} + \Phi S_w \Sigma_w + \Phi (1-S_w)\Sigma_h$$

In which:
**$\Sigma_{LOG}$** = Total sigma read by the tool
**$\Sigma_{ma}$** = Matrix sigma
**$\Sigma_w$** = Water sigma
**$\Sigma_h$** = Hydrocarbon sigma
**$\Phi$** = Porosity of the formation
**$S_w$** = Water saturation

Resolving the equation:

$$S_w = [(\Sigma_{LOG} - \Sigma_{ma}) - \Phi (\Sigma_h - \Sigma_{ma})] / \Phi (\Sigma_w - \Sigma_h)$$

The processing consists of selecting the correct sigma value for each term of the equation. The porosity data is obtained from the sonic log.

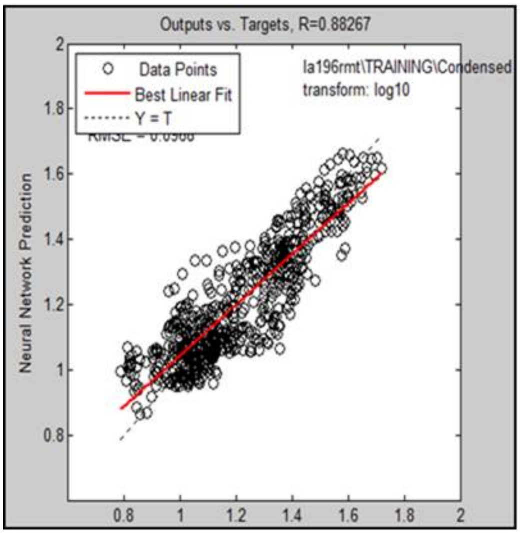
Figure 11 shows a generic table of sigma values for different minerals, as well as various rocks and fluids.

| Mineral | Σa 20º C, |
|---|---|
| Quartz ($SiO_2$) | 4.36 |
| Calcite ($CaCO_3$) | 7.48 |
| Dolomite ($CaCO_3$ $MgCO_3$) | 4.78 |
| Anhydrite ($CaSO_4$) | 12.3 |
| Gypsum ($CaSO_4$ $2H_2O$) | 19.4 |
| Anthracite Coal ($C_4$) | 1.08 |
| Bituminous Coal ($C_4$) | 1.54 |
| Halite (NaCL) | 762 |
| Iron (Fe) | 215 |
| Water ($H_2O$)(Distilled) | 22.2 |
| Boron (B) | 760 |
| Sandstone | 7-16 (10) |
| Limestone | 7-15 (12) |
| Dolomite | 8-12 (9) |
| Shales | 20-50 |
| Oil | 16-22 (20) |
| **Gas** | 2-15 |
| **Fresh Water** | 22 |
| **Salt Water (120 kppm)** | 59 |
| **Salt Water (240 kppm)** | 119 |

*Figure 11–Capture sigma for pure minerals and types of fluids (from Halliburton laboratory tests)*

**Neural Net Analysis: Training Results**

The following figures show a very good correlation between the open well curves (RT90_OH and RHOB_OH), as compared to those obtained through the neuronal network training (RT90_TRAIN and RHOB_TRAIN).



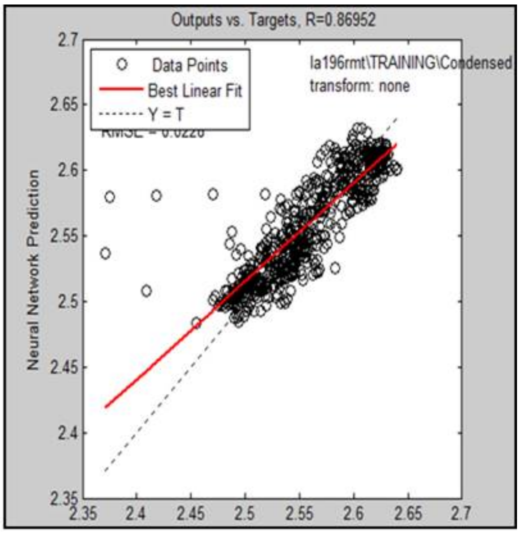




*Figure 12–Crossplot RT90_OH vs. RT90_TRAIN.* *Figure 13–Crossplot RHOB_OH vs. RHOB_TRAIN.*

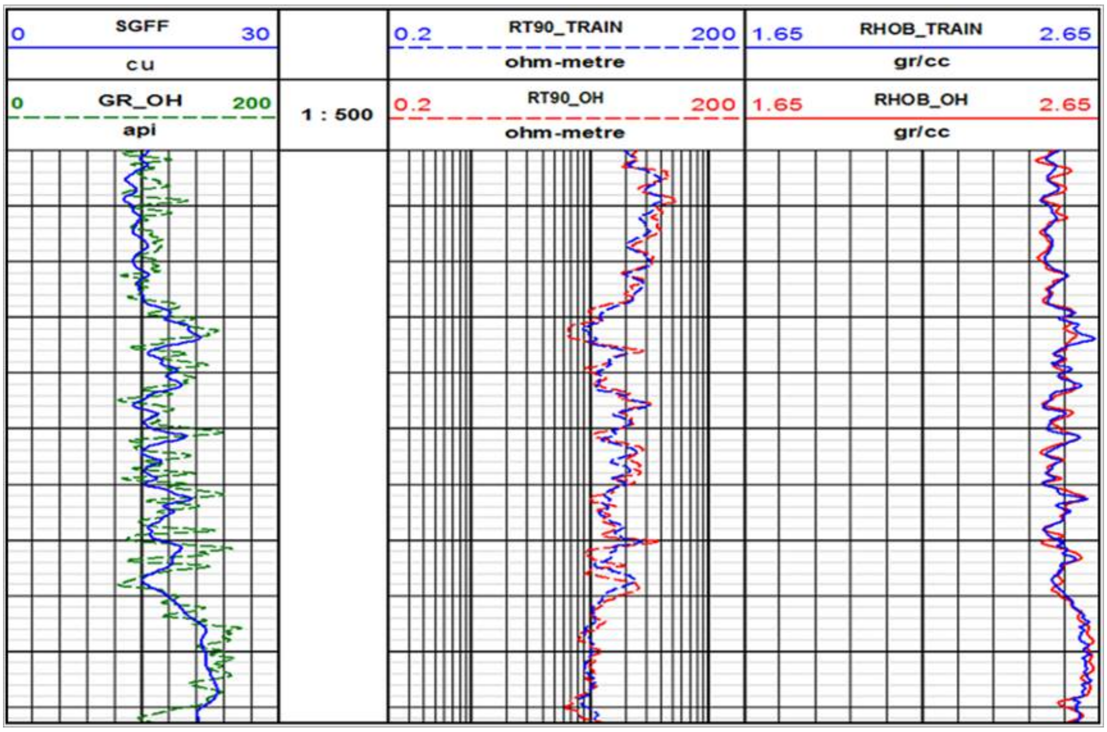



*Figure 14–Open hole curves vs. curves derived from the training of neuronal networks.*

## INTEGRATION OF RESULTS

Figures 15 through17 show the final results corresponding to the three analyses previously discussed. These results were compared to production logs to validate the methodology implemented. The following list describes the contents of each track:

- Track 1: Volume of clay and effective porosity
- Track 2: Depth track
- Track 3: Correlation curves – formation sigma and gamma ray
- Track 4: Resistivity resulting from the application of neuronal networks
- Track 5: Sigma saturation analysis
- Track 6: Sigma saturation analysis – calculation of volume, water saturation
- Track 7: Gas indicators: Vp/Vs ratio and density/neutron crossover

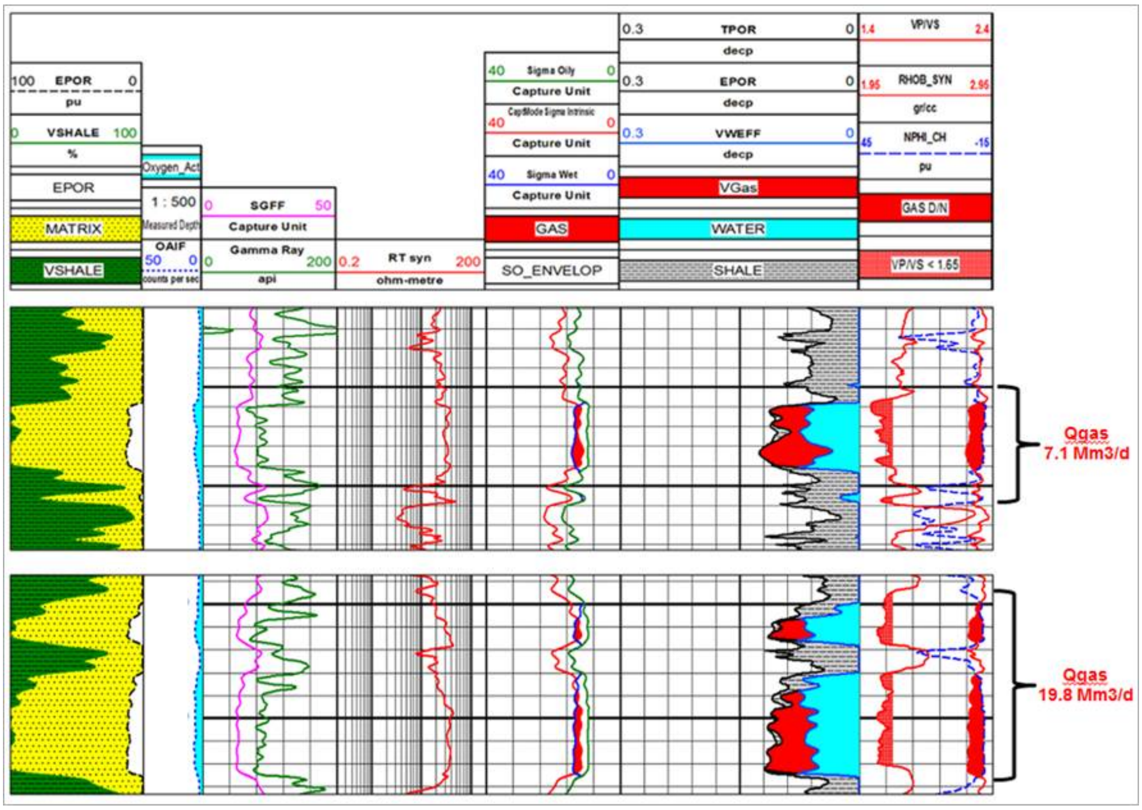



*Figure 15–Cased well analysis and petrophysical interpretation.*

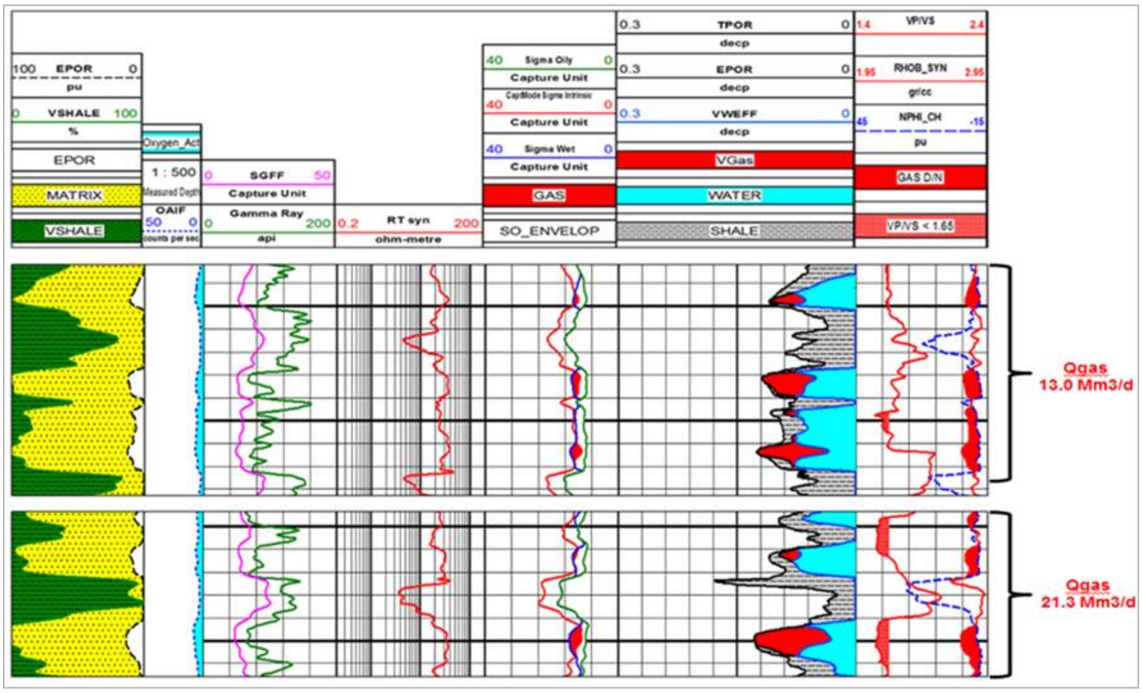



*Figure 16–Cased well analysis and petrophysical interpretation.*

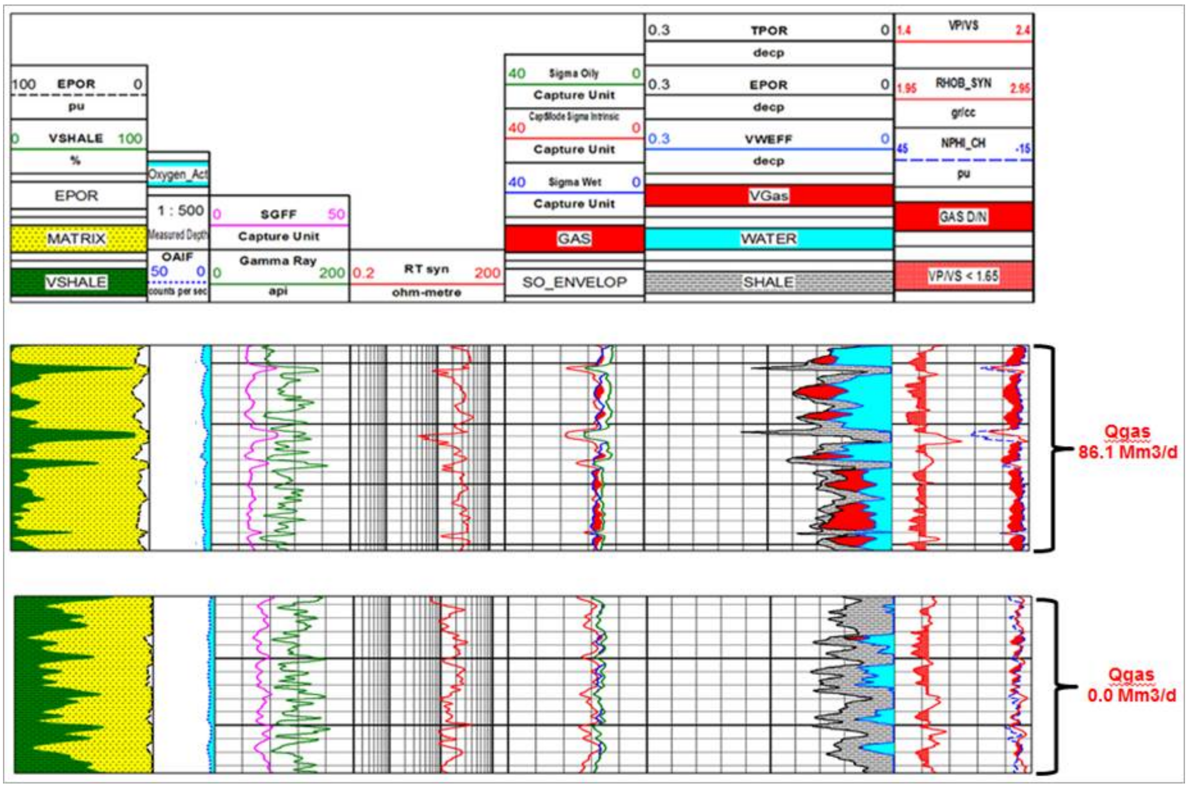



*Figure 17–Cased well analysis and petrophysical interpretation.*

## CONCLUSIONS

The results of this work show that, after canceling the request for the logging of an open well, it was possible to complete the well by using precise data gathered from logging of the cased well.

The inconclusive resistivity, which occurred because of the condition of the well in the first run, was successfully replaced, and the density curve was obtained through neuronal networks.

The results provided by the Sigma saturation analysis coincides with the PLT tests. This correlation can also be observed with the known density/neutron crossover, in addition to the Vp/Vs gas indicator.

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