# Identifying a Bypassed Reservoir in Limestone "A" Sequence with Magnetic Resonance While Drilling*

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## Abstract

Petroamazonas EP is the national oil company in Ecuador. It holds most of the oil concessions in the country. As most Ecuadorian operators, they have a common primary formation-producing target present across the country called "Hollin". The need to expand the oil reserves have driven most oil companies, Petroamazonas included, to evaluate some secondary objectives including carbonate sequences believed to contain hydrocarbons.

Attempts to better evaluate the carbonate sequence with a tool able to reflect formation permeability led to a trial run with the Logging While Drilling (LWD) Nuclear Magnetic Resonance (NMR) tool. The choice for LWD was based on the difficult logging conditions (large, heterogeneous interval in a 12 ¼" section) for a conventional cable log. The drilling of this section is a challenge by itself concerning bit and mud selection for covering the whole interval, let alone having good conditions for logging. The LWD tool's static magnetic field geometry was optimized to provide reliable measurements in the hostile LWD environment and to have negligible interference on well-survey instrumentation. For the selected well, Coca K-40, the Bore Hole Assembly (BHA) prioritized quality by placing a 12" stabilizer above the tool to guarantee centralization and minimum lateral motion.

This first run proved to be very valuable providing complementary information to better characterize the secondary objectives. All the expected sands and carbonates were evaluated for lithology independent porosity, permeability and grain distribution. The carbonate section presented very poor porosities and almost no movable fluids, however at the base of formation "Caliza A" a good quality sand body was identified by the MR which was not clearly seen on the triple combo and was not counted on by the expected geological sequence. It presented very good permeability but low resistivity due to a large glauconitic presence. This makes it a potential producer discovery.

Nuclear Magnetic Resonance added precision to rock quality characterization and can identify whether or not the carbonate sequence presents any producible zones in a reliable way. This would allow having solid information to invest in testing those newly identified zones.

## Introduction

Petroamazonas produced in 2015 an average of 350,000 barrels a day with the largest portion destined to be exported and responsible for the generation of a significant income to the country. The main activity among all operators is field development. The reduced exploration activity is generating a concern on future reserves. One option to mitigate this is to better characterize secondary objectives during the development campaign as a way to create some future reserves.

Figure 1 shows (in green) the large number of blocks held by Petroamazonas and on the right side the zoom in showing blocks 7-21 where most of the newest LWD technology is being implemented. The objective is to overcome the drilling and characterization challenges, improve efficiency for a final goal of increasing field production. The well Coca K-40 located in Block 7 is where the new NMR-LWD tool (called ProVISION Plus 8) was run. The main reservoir, from the Cretaceous Era, is located in the oriental part of Ecuador. All of the main producers are sandstones: Hollín, T, U and M1. As secondary objectives, we have the Basal Tena and M2 sands, plus the limestones: A, B, M2 and M1. The main objective of our (NMR) run was to evaluate the main and secondary reservoirs covered behind the 9 5/8" casing generally left with limited information. The section logged included: Basal Tena, U, T sands and Limestone A.

The formations Hollin-Tena-Napo developed in the Aptiano-Albian and were formed as low-level sequences at the base of the sands with a transgressive sequence forming the upper portion of the sands. The low-level had an initial deposition by erosion evolving to a fluvial and stacked fluvial-estuarine environment, later becoming estuarine with tidal influence, ending with platform facies responsible for the generation of the sealing rock.

The Napo U Sandstone has special importance in this study because it was cored giving us the opportunity to validate the acquired data with laboratory measurements. Napo U Sandstone is divided into Upper U and U Main. Upper U Sandstone reservoir consists of quartz-glauconite sand bars encompassed in a clay-calcareous sequence (Figure 2). Sandbars have limited areal distribution and locally may have limited development. The depositional environment of Upper U Sandstone in the OSO and COCA oilfields are clean sandstones interpreted as shore face bars and tend to have less glauconite than the rest of glauconitic shoreface sands.

Napo Lower U from Oso and Coca oilfields are interpreted as clean sandstones tidal channels and bars. They are of limited extent and discontinuous along the OSO Field. They also present muddy areas interpreted as tidal flats. The clean sand areas have a NW-SE orientation. The observed facies distribution suggests a shoreline oriented NE-SW. The log evaluation and production data indicates the zone as an oil producer in the Oso and Coca oilfields. A geological section (Figure 9) indicates local sand distribution in the field. The characterization of these formations from a geological point of view is debatable, the reason being the feeble division between upper and main bodies. This is given basically by electric logs and description from drill cuttings records where glauconite mineralization corresponds to the upper bodies and kaolinite mineralization zones correspond to the lower ones.

Secondary deposits of Napo U Formation in the area of Oso and Coca oilfields represent marginal fields from: the thickness point of view, the lateral extent, and the quality of the deposits. This occurs because the geological reservoir behavior corresponds to transitional and shallow marine environments, which are represented by sandstones channel/bar, presenting discontinuities, as purely stratigraphic traps.

The Napo T Sandstone has also been subdivided into Main T and Upper T Sandstone. The Main Napo T dominant facies to the north of the field are clay from subtidal muddy plains (Figure 5). Sandy plains zones are located southeast of the field and have an orientation W-E. Relatively clean sand bodies are oriented SE-NW with limited extent, possibly representing distal bars with tidal influence. The bar areas deposited in an environment with tidal influence are mainly in the east center of Oso Field, decreasing in size to the west of the field. A deepening of the system westward is observed, with a predominance of muddy facies.

The Upper Napo T in Oso and Coca oilfields is interpreted from cores as being a depositional environment corresponding to shore face environments. Shore face bars are cleaner and tend to have fewer glauconite than the rest of glauconite sands surrounding it (Figure 6). The bars present a NW-SE orientation towards the north of Oso Field and E-W to the center. Apparently, a shale zone divides the bar from the center and north of the Oso Field.

Main Napo "T" Sandstone is composed of a very thin, rounded, moderately sorted and abundant clay matrix quartz sandstone, dark brown, friable fine-grained, while Upper "T" Sandstone has a very fine quartz sandstone in greenish gray, fine-grained friable, well-sorted and rounded, clay matrix, cement and glauconite limestone inclusions.

The log evaluation, the description from cuttings and production data indicate that the Napo "T" Sandstone has a clear pay zone; one example is presented below in the Well Oso A-45 (Figure 7) which to date has an average production of 450 BOPD with a water saturation of 2%. A geological section (Figure 8) shows the distribution of local sandstone in the field.

A geological and petrophysical division of these sands in higher, middle and lower bodies is evident only in the central part of the basin (Sacha -Shushufindi Corridor). For the deposits in the Sub-Andine zone (in Block 7 and the Oso and Coca oilfields), this division is difficult to apply, since their thickness is reduced, which is in the order of less than 20 feet average net per layer or body.

## Drilling Plan

In the drilling plan of the well Coca-40 the main objective was to drill the 77 feet shown in red on the structural section of the field in Figure 5. It is believed to be hydrocarbon bearing, but limited in porosity and permeability. Limestone A is located just above the U sand developing towards the west of the basin, and composed of black micrite shaly limestones, laminated by mudstone, wackstone and packstone. The porosity is normally low (around 3% to 6%) and the permeability very low as well. Sometimes it presents better porosities and/or vugs.

There is only one reported well producing from this formation in the country and only one field producing from the limestone sequence (Puma Field). This formation is believed to bear hydrocarbons but without reliable data to confirm it there will be no motivation to spend on evaluation and production as it may require additional operations for the oil to flow. If run systematically across the fields the LWD-NMR can determine the profile of the limestones and the directions of improved characteristics. This could be considered a semi-exploration activity with low costs estimated in less than 0.5% of the well budget.

## LWD NMR Measurement

Table 1, also from the drilling program, shows all the secondary objectives which are not in the 8 ½” section and will have serious issues to acquire reliable log data. The objective for using the LWD-NMR was to characterize the secondary objectives and explore the potential permeability of the limestone lithology and permeability without the use of radioactive sources. Besides that, it also provides unique measurements on pore geometry and fluid distribution not available from other logs.

The tool works with a time-based Carr-Purcell-Meiboom-Gill (CPMG) sequence with well-defined cycle of echo spacing and wait times. The latest generation tool employs long echo trains and “bursts” composed of a large number of repeated shorter measurements associated with short wait times. The bursts enhance the statistics for the critical early part of the echo decay and are acquired with 0.6 ms echo spacing. A very detailed description of the tool operation can be found in Heaton et al. (2012).

From the programming side of the tool the scan rate defined covered the carbonate section for the best possible accuracy, which is much larger than the limits for the sands. The faster the measurement is, the higher the drilling Rate of Penetration (ROP) that can be applied.

## Bottom Hole Assembly

The proposed BHA (Figure 11) used the first normal flow tool produced worldwide. This was partially an evaluation of this normal flow but with the extensive experience of the previous low flow tool. For that reason, there was a large priority on data quality. The LWD-NMR tool has a very well defined shallow area of investigation represented by the pink area in Figure 10. For this reason, the lateral motion must be kept at a minimum to guarantee the eco measurements are coming from the same polarized volume. The new generation of tool uses a magnet arrangement, which provides a low gradient reducing the effects of lateral motion. Finally, a 12 inch stabilizer was placed above the tool to guarantee centralization. From the initial pre job planning the calculated standard ROP was 60 ft/h, however for an improved quality signal it was reduced to a controlled ROP of 45 ft/h based on a scan rate increase from 30 to 40 secs.

## Log Compared to Core

The log in Figure 12a shows the results of the magnetic resonance LWD for the Coca K-40 well. The log presented includes only the section where the core data was taken for comparison purposes. The log shows on the last track the main T2 distribution from which all other measurements are derived.

For the cored target sand "U", at depth 9879’ we have the logs showing a medium to low quality sand indicated by the gamma ray (track 1) and by the neutron density modest crossover compared to what is normally expected for a clean sand (track 3). In more detail, we can see the results of the MR that shows the pores distribution in a colored scale on track 4. The green color represents coarser grains and the brown the finest. The green area in the "U" sand is reduced while the red component is wider. That is another evidence of poorer quality rock. This confirms the core findings shown lower “U” sand in Figure 13 D at this depth. On that core, we find the presence of flasher and ripple laminations with cross stratifications and mud drapes. It was classified as regular quality in the sedimentological study.

The upper “U” sand, here represented by the core in Figure 13 C, is described as a poor glauconitic sand with fine bedding. This sand is seen on the log with a poorer quality than the lower sand. On the grain distribution log we have no presence of the green or the red areas confirming the fine grains.

Limestone A, one of the secondary targets and expected to display some porosity, did not present any on the MR log as seen around 9815’ on the log (Figure 12a and Figure 12b). The core photo in Figure 13 A is taken from this same interval. The Limestone areas are not purely carbonate, having a mixture of clay and limestone, therefore the density/neutron porosity are more affected than the lithology independent magnetic resonance. The MR is consistently showing a porosity close to zero. Limestone A is believed to be hydrocarbon bearing, finding the presence of porosity/permeability across the field in this formation with MR would unmistakably identifying potential new production zones.

The largest contribution obtained in this well section was around 9825’ where a very good quality sand shows up unexpectedly below Limestone A. In the sedimentology study it is interpreted as upper “U” sand, however the upper “U” is generally poorer. This sand is considered in the Petroamazonas geology department as not being part of the normal geological sequence for this field. Thus, it is considered a reservoir discovery. To become a productive reservoir it requires additional evaluations on pressure, extent, and continuity.

This “new” sand presents good porosity and permeability, matching the core results. The grain size calculated by the MR is slightly better than the best portion of the target sand “U”. This sand was identified by sedimentological studies as being poor due to the presence of calcareous calcifications, which collides with what we see on the log. Finally, clarified by the laboratory measurements, it presented the same good porosity and permeability as seen on the log. The core of this section is shown in Figure 13 B. It displays a clean uniform structure with coarse-grained pore size.

In the “U” sand we see some slight differences in porosity between the MR log and the core. This has two possible reasons: the plugs taken from the core are usually taken away from laminations to avoid ruptures in the plug over estimating porosity, and the LWD MR tool in very low T2 signals may reduce slightly the total porosity in the bound water range. The second can be corrected for by processing by FaRE (Fast Relaxation Enhancement) on the T2 distribution or by the advanced combined T1 and T2 processing.

Five samples were submitted to the MR in the laboratory. They can be seen in Table 2. The average porosity is around 17% for the three sand samples. The T2 cut offs from the laboratory measurements display variations associated with the larger presence of laminations or not. A T2 cutoff of between 26.56 ms and 33.52 ms, usually presented in a log scale, does not represent a significantly large difference. Only Sample #19 is considered to have a lower T2 cutoff value.

Both Sample #9 and Sample #22 have below 5 pu of irreducible water. The upper “U” sample #19 (Figure 15) however has a larger irreducible water more likely associated with the larger presence of thin mud and organic material laminations. The free fluid located in a lower T2 contributes to the lower cutoff and indicates a free fluid confinement in smaller pores.

We see on all three graphics that the irreducible water drops between 20 to 30 ms on the T2 axis. For the computation, we used a value of 26 ms. The laboratory cutoff is calculated strictly using the cumulative distribution. The point at which the maximum amplitude of the SWIRR cumulative distribution meets the SW1 cumulative distribution is where the cutoff value is derived from.

Sample #19 is more compatible with the core seen on Figure 13 B while sample #22 displays much better quality comparable to the sand below the carbonate. As mentioned previously it may not be a good representation of the "U" sand as the plug must have been taken to avoid the laminations and over estimating the average interval quality. For a better differentiation, it is recommended to run LWD resistive image logs for lamination identification.

## Advanced Factor Analysis

The latest processing available today is the factor analysis. It provides the decomposition of T2 distributions over a depth interval into the underlying poro-fluid constituents. Poro-fluid signatures are shown in the factor plots (Figure 17) non-weighted and weighted (weighted by cumulative volume over the depth interval). If we compare the 26 ms T2 cutoffs from the sand core analysis with the computed 21 ms cutoff from the factor analysis we get a very close match.

The signatures are used to invert for the respective volumes which are then analyzed for spatial patterns or poro-fluid facies (Figure 18). Facies are characterized by sorting NMR and other petrophysical information. Thus, sorted results show the variance of petrophysical information by facie (Figure 19).

One can further characterize each facie by the mean value and deviation of all petrophysical information. Mean of T2 distribution is then transformed into saturation pseudo-capillary pressure functions using standard transforms. Unfortunately this information is not available from the field for validation.

## Conclusions

The application of NMR LWD in the 12 ¼" drilling sections in Ecuador has proven to be an efficient method to uncover secondary objectives generally hidden by the limited access of loging tools, well condition, the lithology effects on basic measurements, and the additional information it brings for the reservoir characterization. This is applicable not only locally but wherever secondary reserves are expected with the advantage of having solid information to back up a plan to test or produce those zones. NMR LWD reflects not only petrophysical parameters but also producibility parameters like permeability estimation with a more in-depth understanding of the rock. This method can also uncover new reserves, taking advantage of the regular development activity in a "semi-exploratory" activity at a low cost as compared to regular exploratory initiative.

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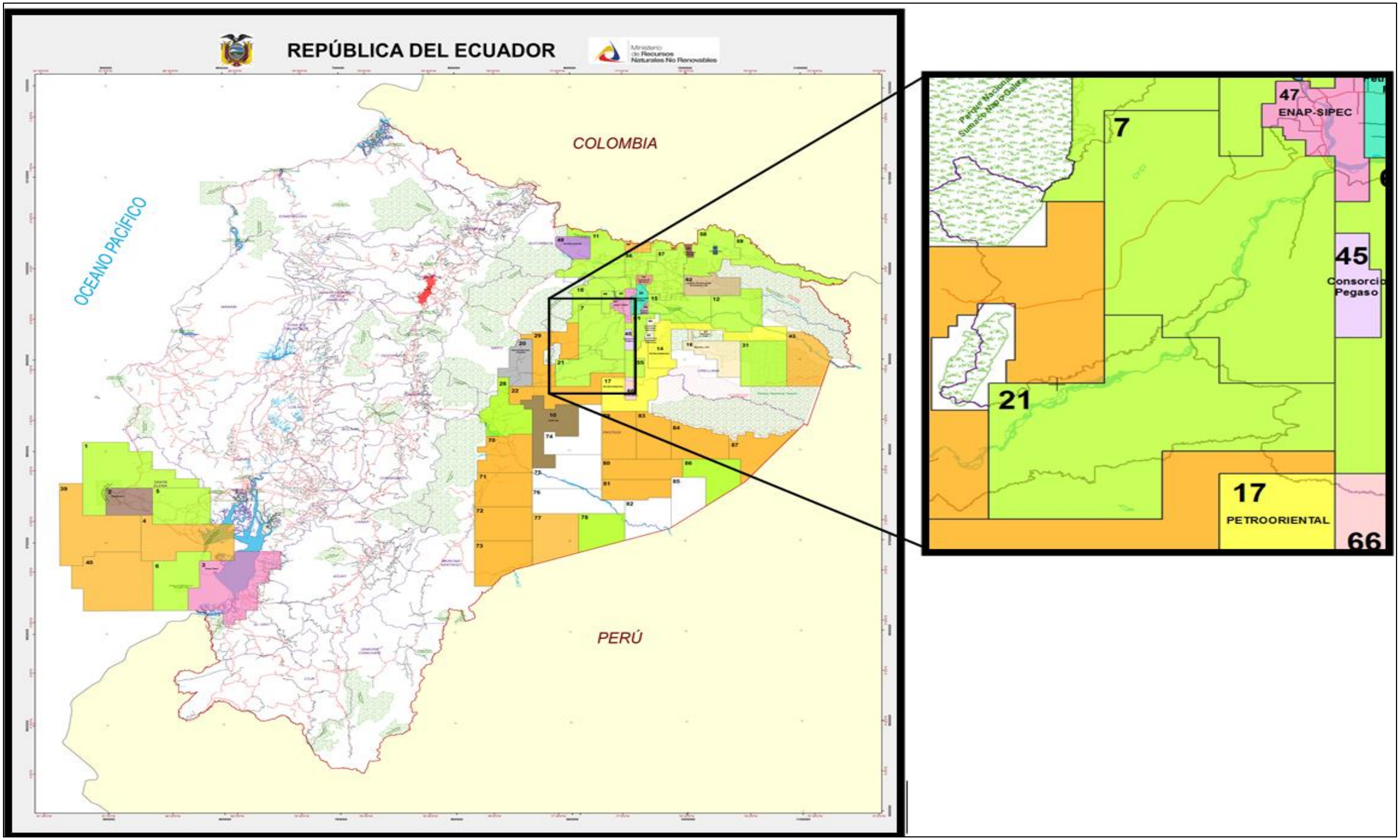



Figure 1. Petroamazonas blocks and location of 7-21 block.

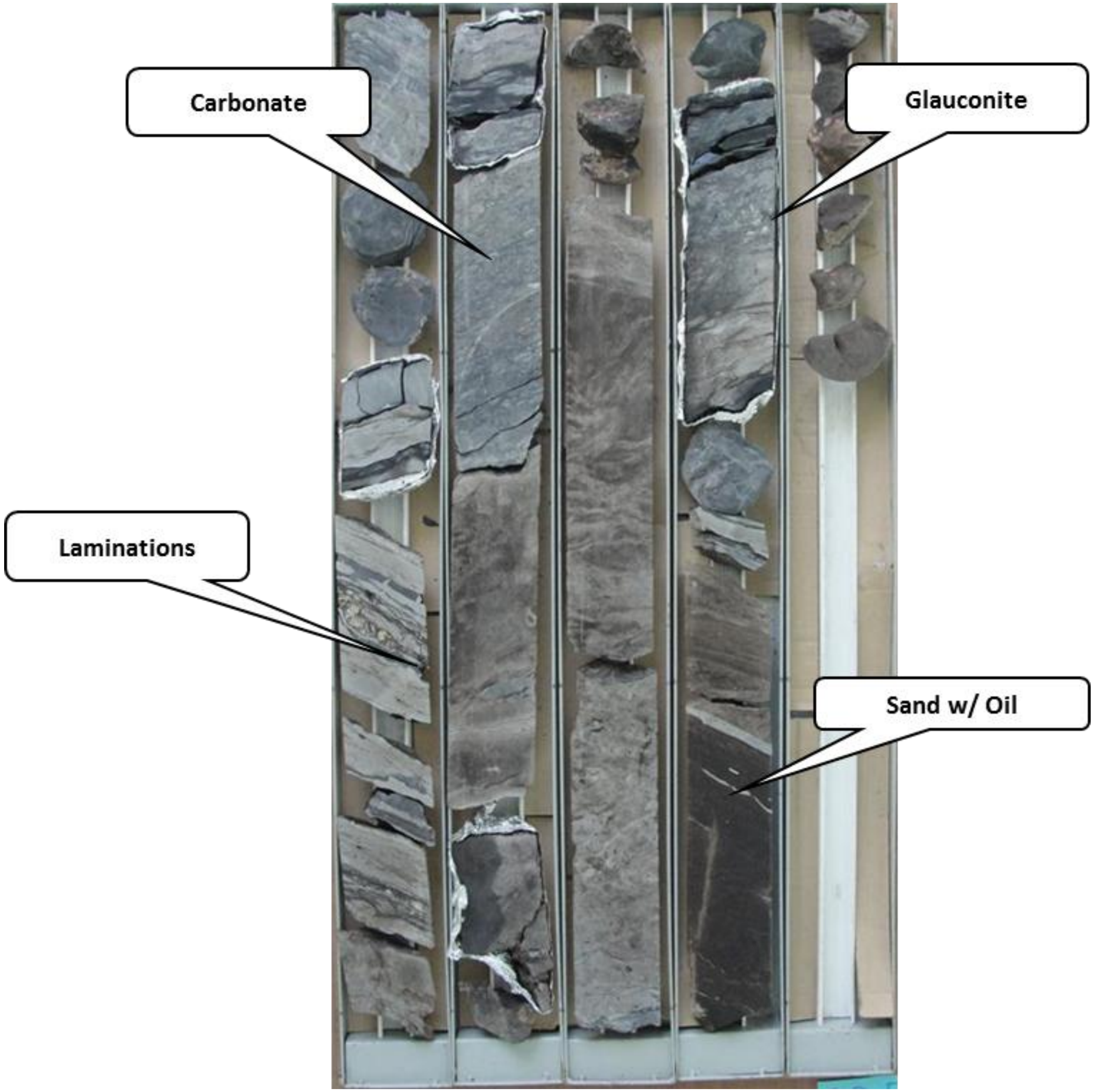
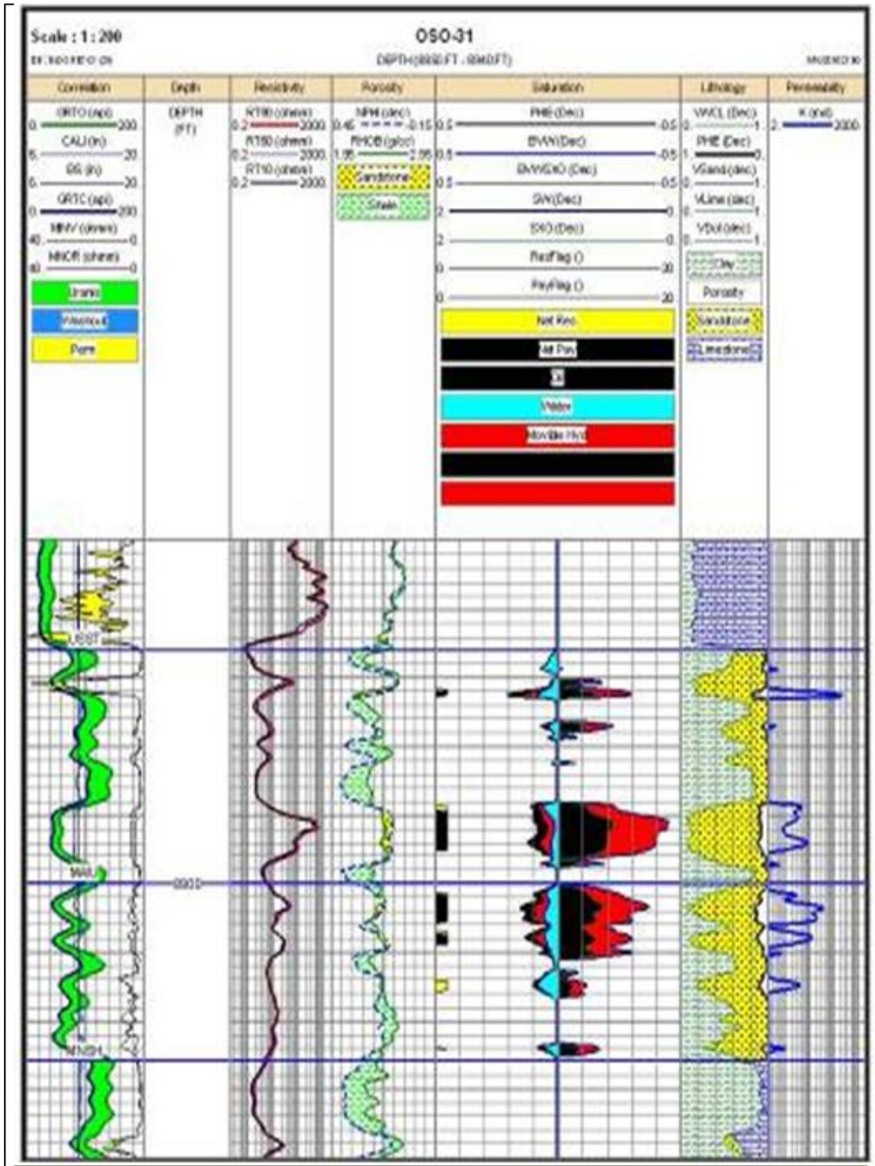



Figure 2. Napo U Superior Coca K-40.




**Parámetros Petrofísicos OSO - 31**

| Reservorio | Tope | Base | Gross | Net Res | Net Pay | Phi Res | Phi Pay | Sw Res | Sw Pay | Vcl Res | Vcl Pay |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | MD | MD | MD | TVD | TVD | % | % | % | % | % | % |
| USST | 8,866 | 8,900 | 34 | 8 | 7 | 10 | 11 | 29 | 25 | 14 | 12 |
| MAIU | 8,900 | 8,926 | 26 | 8 | 6 | 11 | 12 | 47 | 38 | 20 | 18 |

Figure 3. Petrophysical interpretation of Napo U in the Oso B-31 well with the oil pay indicated by black and red areas.

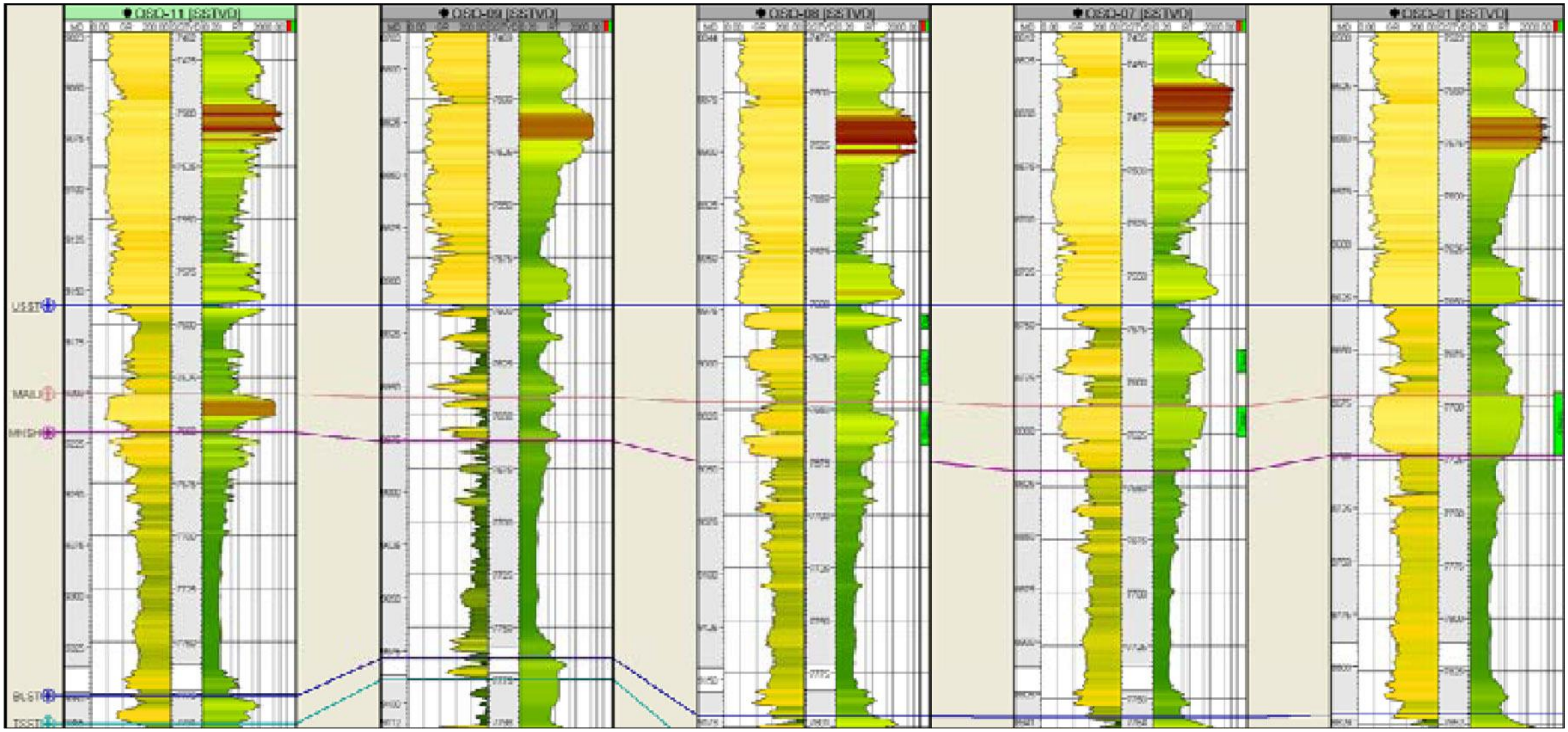


Figure 4. North-south structural cross section of Napo U Reservoir in Oso Field.

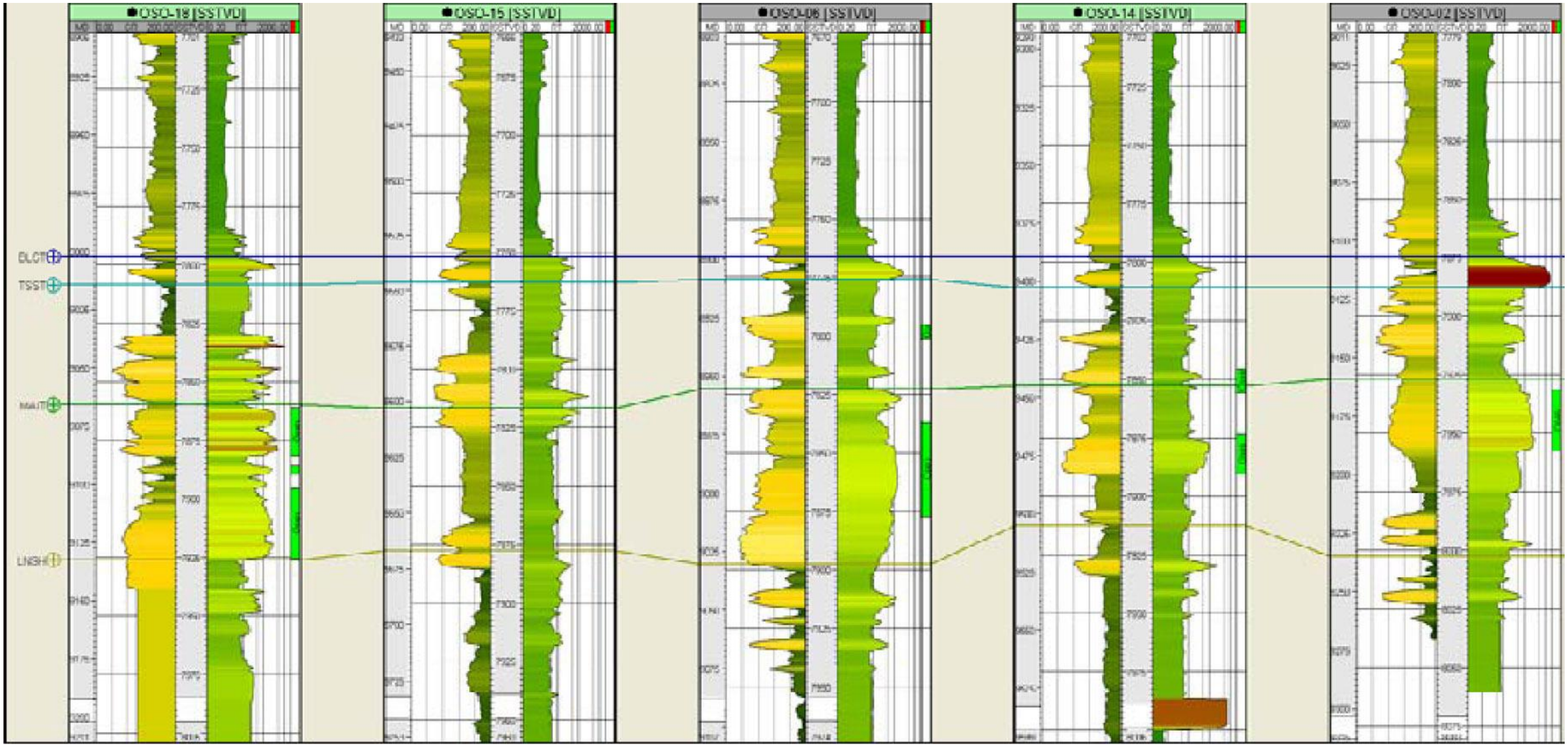



Figure 5. North-south structural cross section of Napo T Reservoir in Oso Field.

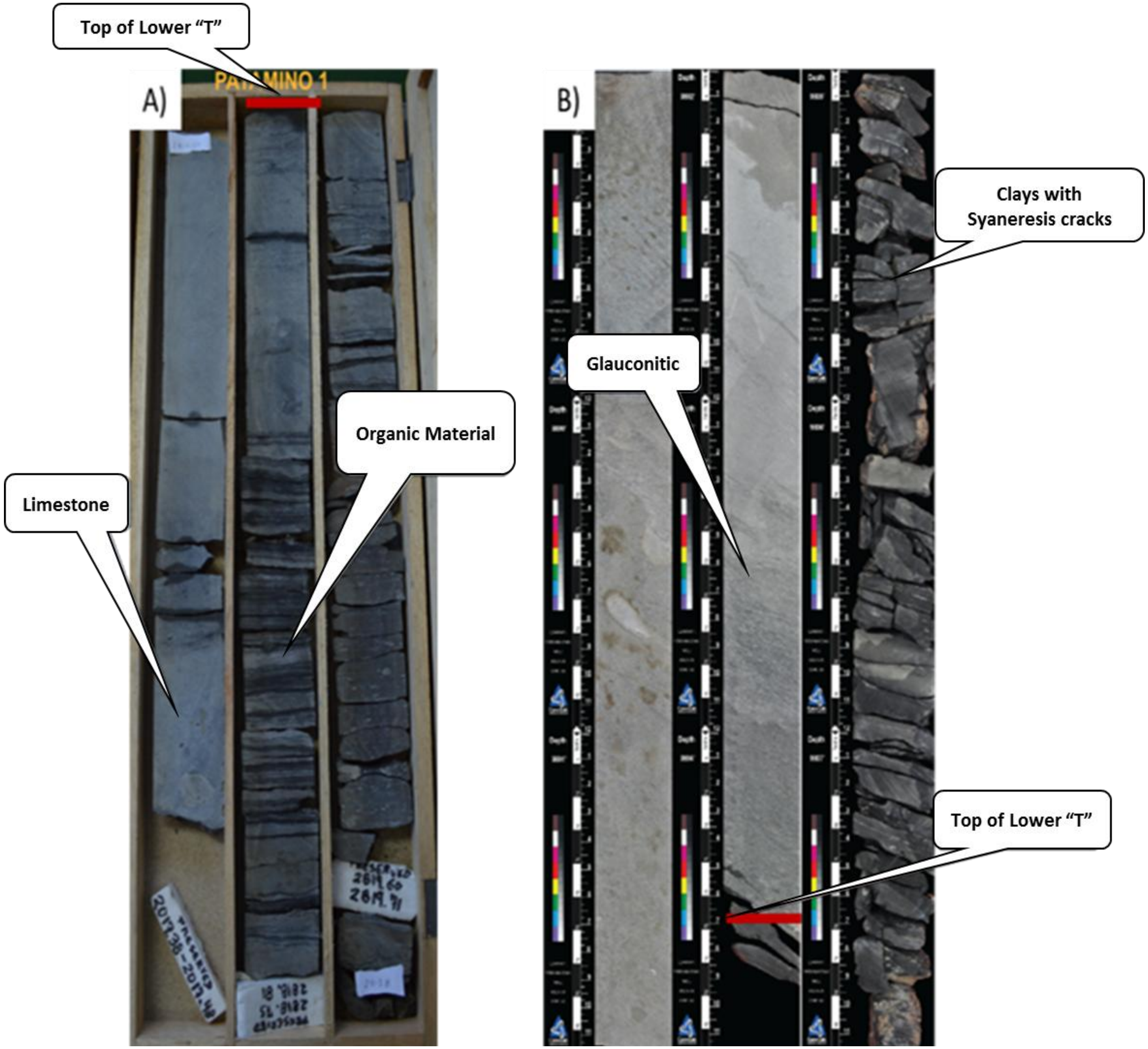



Figure 6. Lower Napo in wells Payamino A1 and Oso A79.

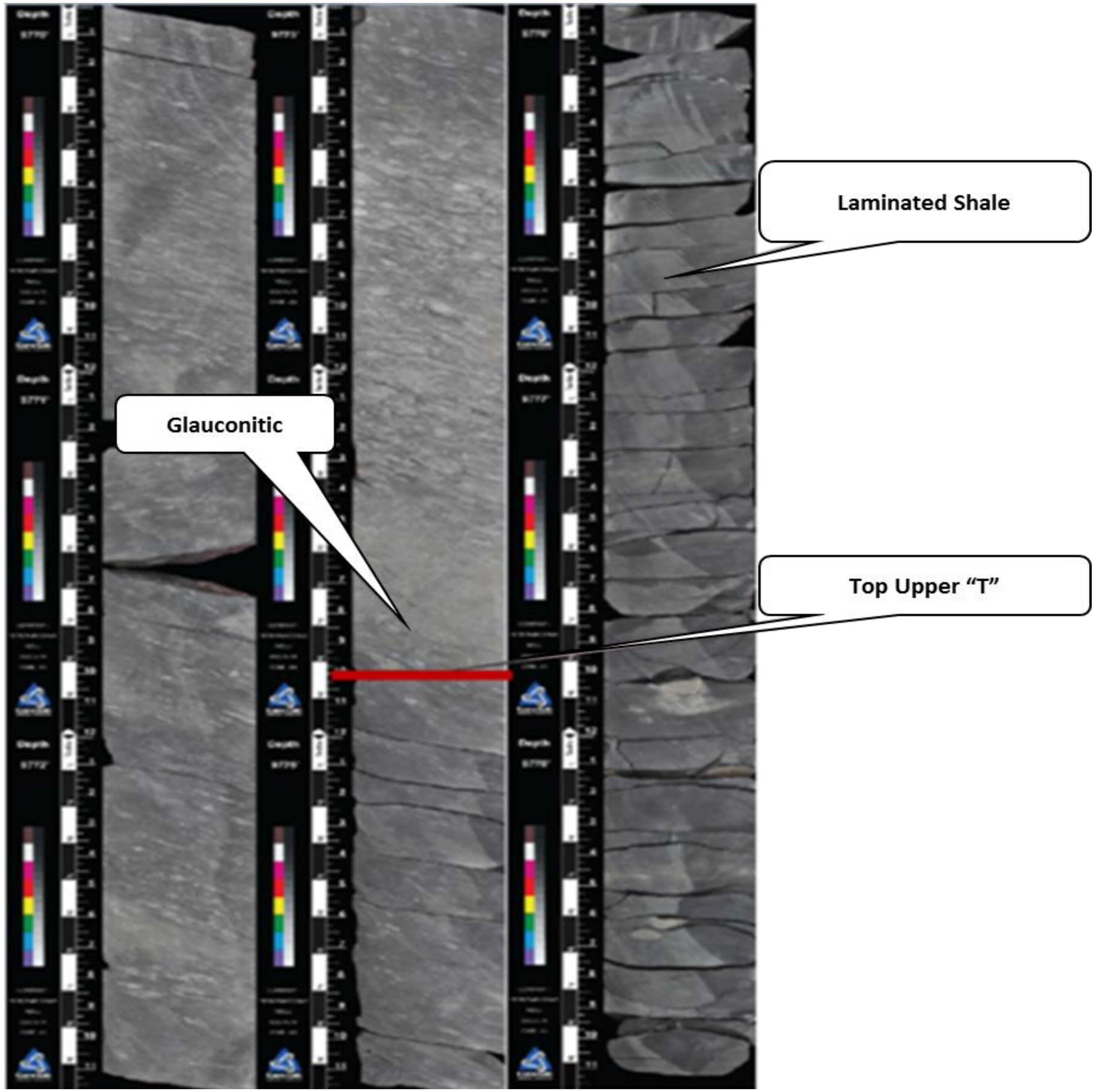
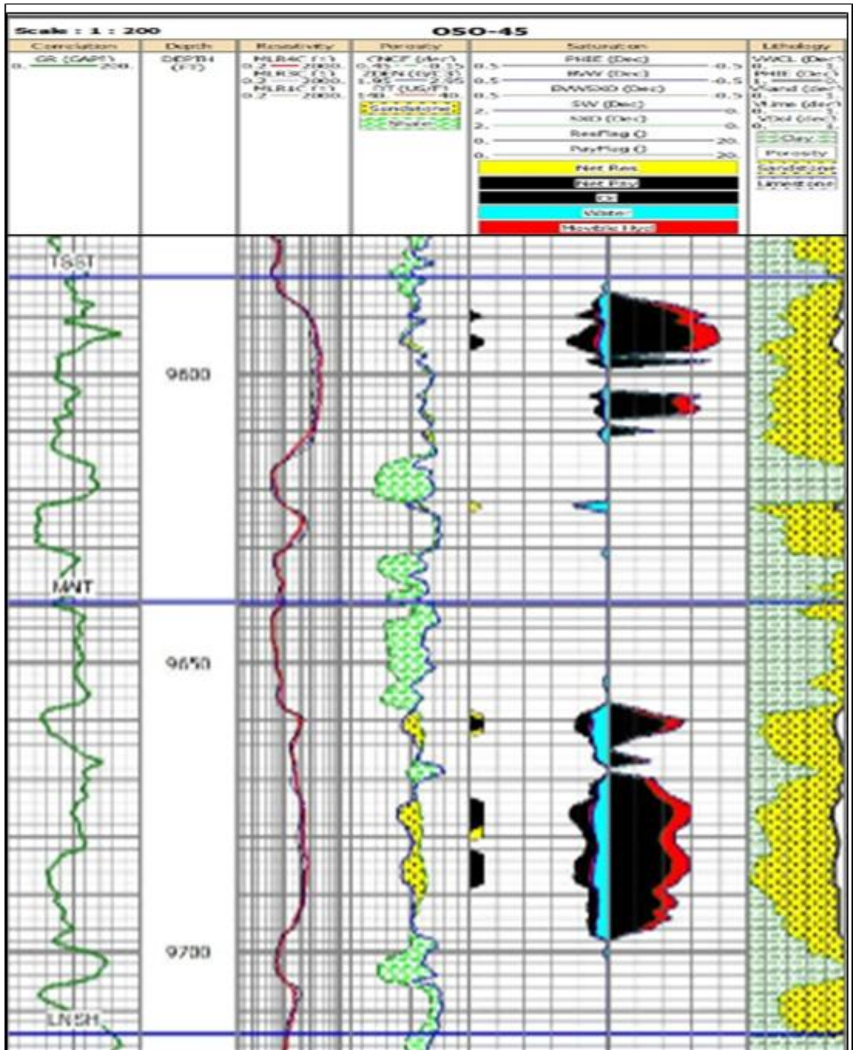



Figure 7. Upper Napo in wells Payamino A1 and Oso A79.




**Parámetros Petrofisicos OSO-045**

| Reservorio | Tope | Base | Gross | Net Res | Net Pay | Phi Res | Phi Pay | Sw Res | Sw Pay | Vcl Res | Vcl Pay |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | MD | MD | MD | TVD | TVD | % | % | % | % | % | % |
| T SST | 9,583 | 9,639 | 56 | 4 | 3 | 13 | 13 | 42 | 23 | 20 | 26 |
| MAIT | 9,639 | 9,714 | 75 | 16 | 12 | 11 | 11 | 46 | 43 | 13 | 12 |

Figure 8. Petrophysical interpretation of Napo T in well Oso A-45 with the oil pay indicated by black and red areas.

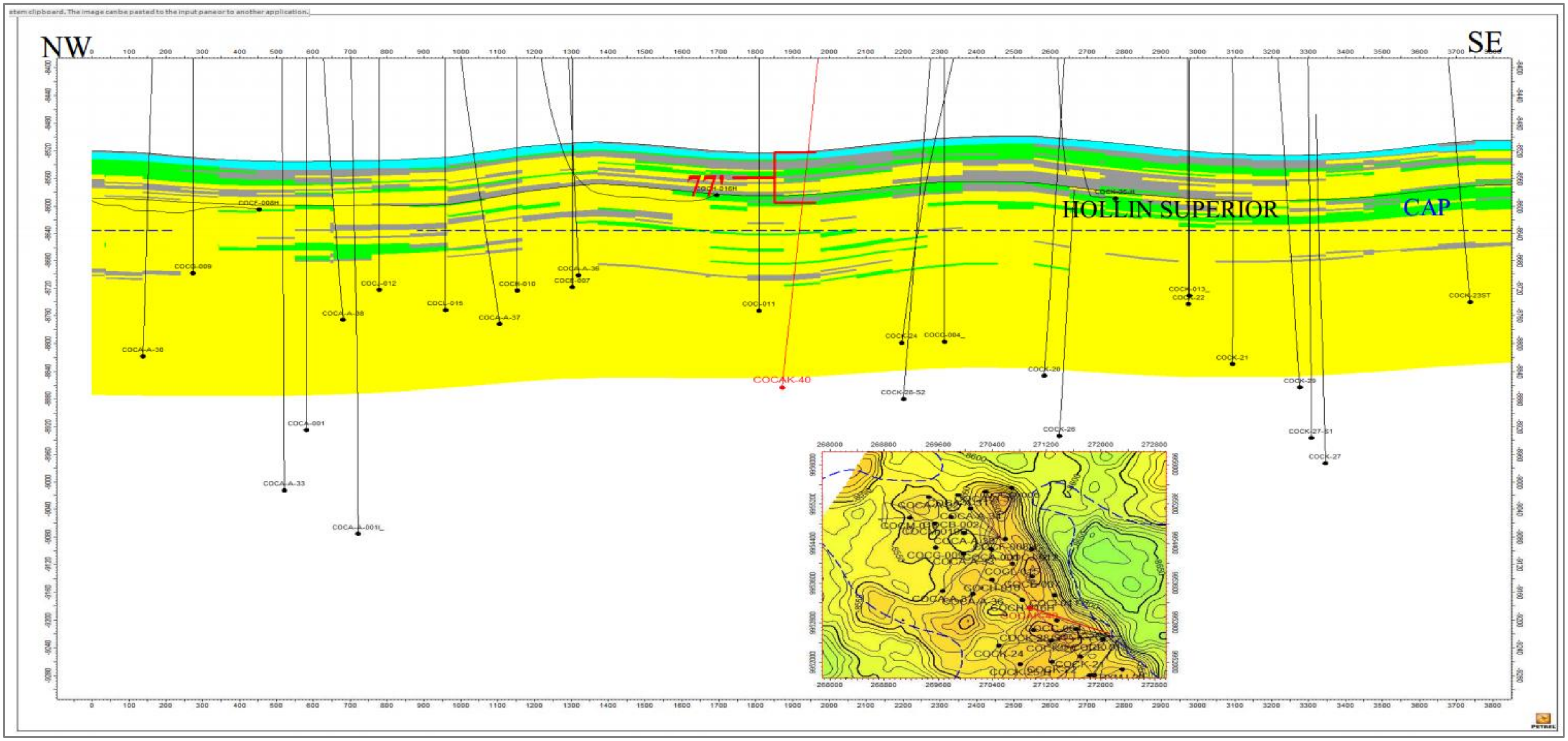



Figure 9. Structural cross section of Coca Field with planned well in red showing an expected 77’ of pay in the main reservoir.

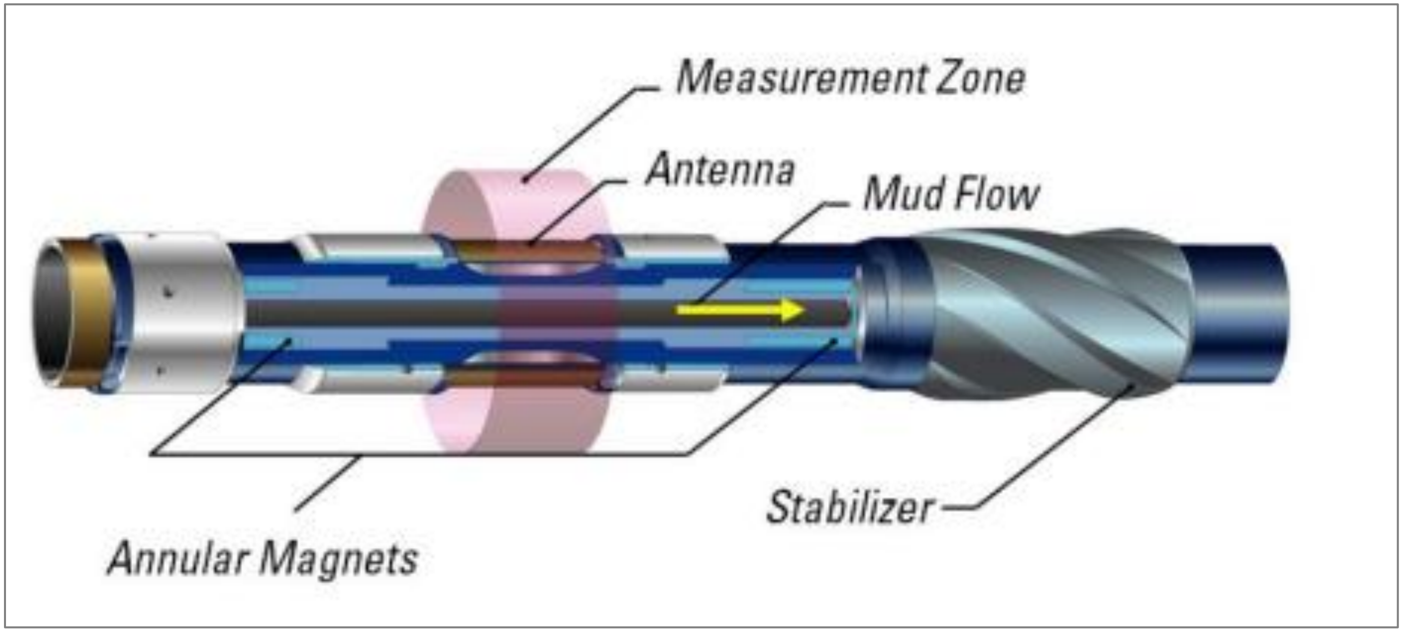



Figure 10. Schematic of LWD NMR tool design.

Figure 11. Bottom Hole Assembly composition with LWD NMR tool.

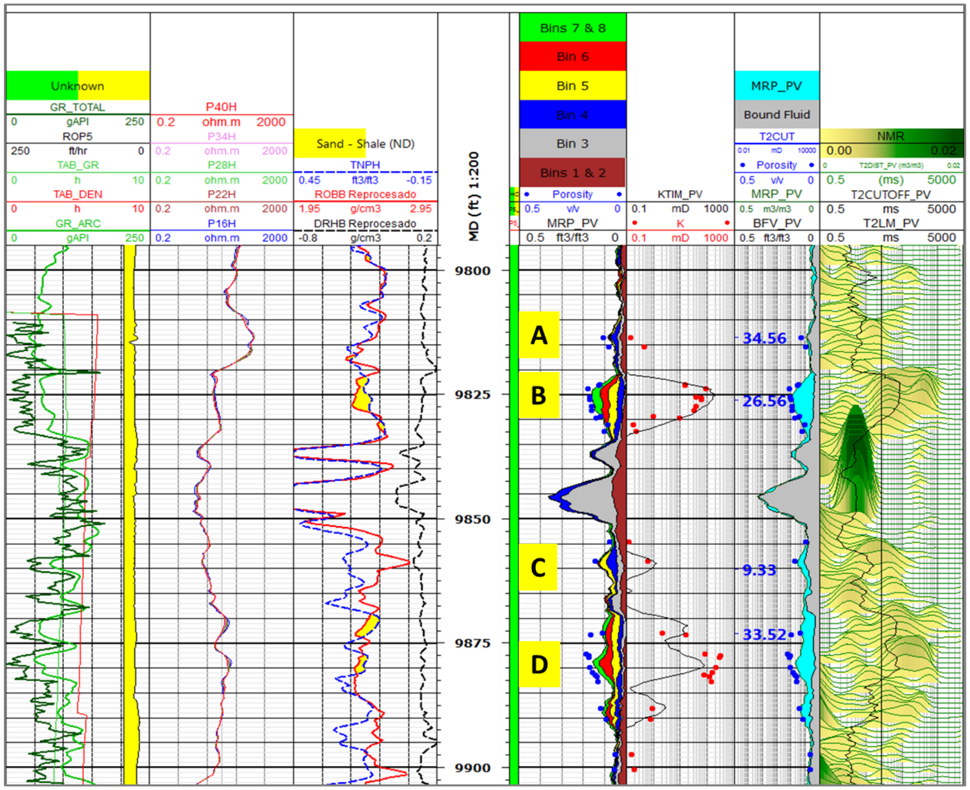



Figure 12a. Magnetic resonance log and core results.

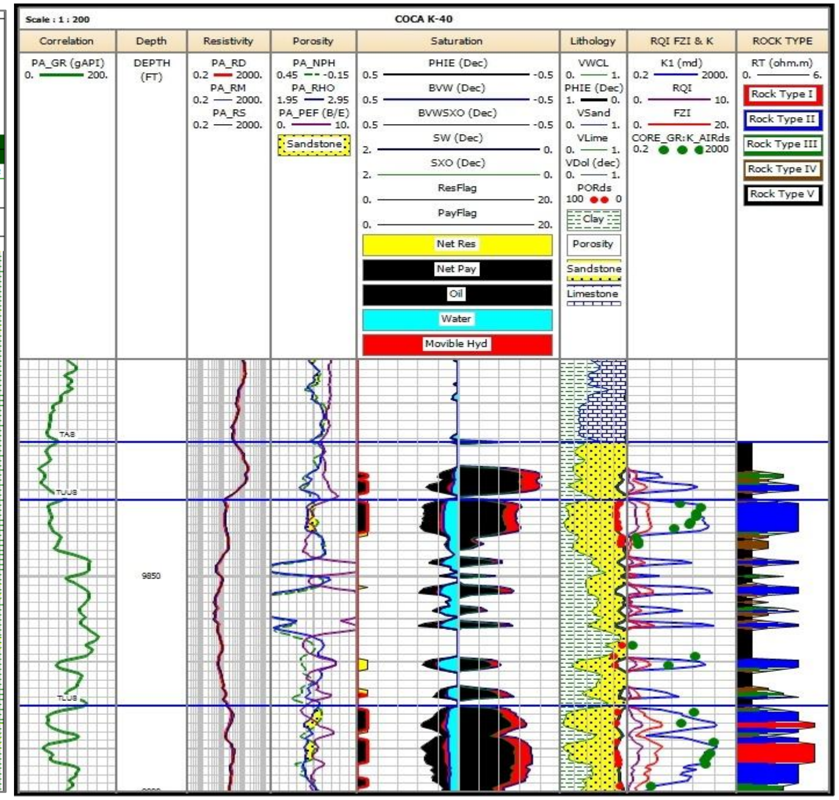



Figure 12b. Petrophysical evaluation of Coca K-40.

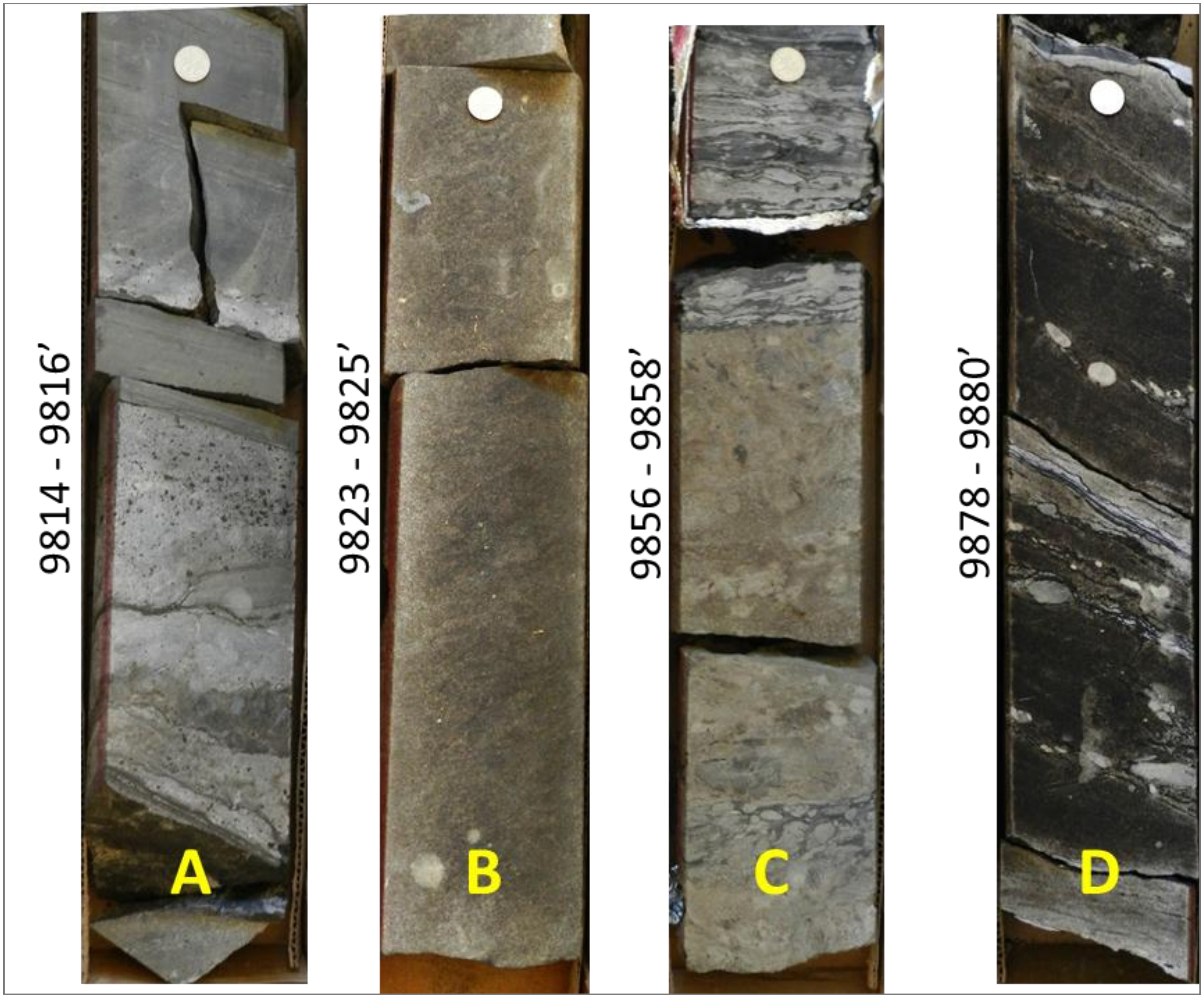



Figure 13. Core comparison in four key intervals.

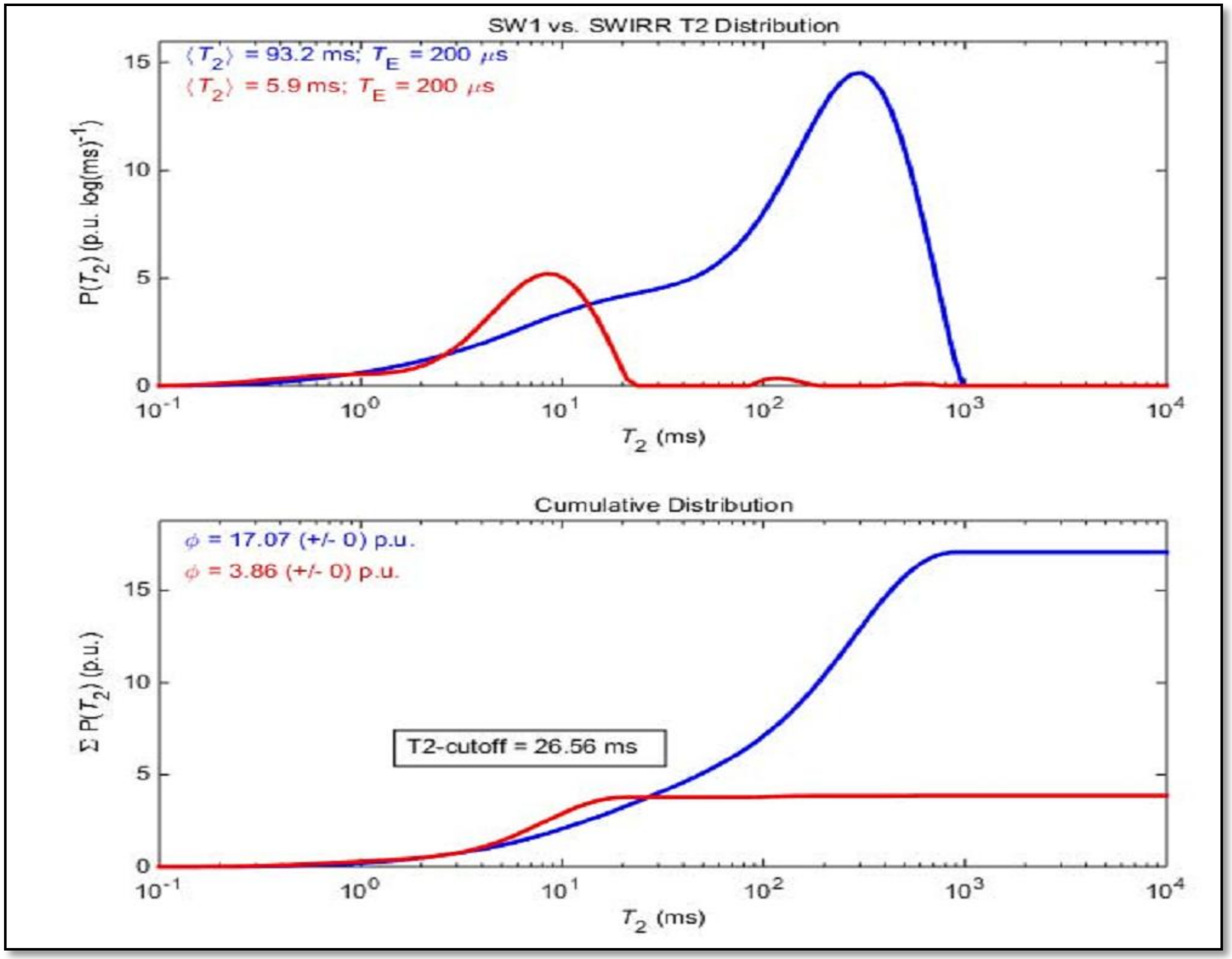



Figure 14. Irreducible T2 vs. 100% Brine T2 sample #9.

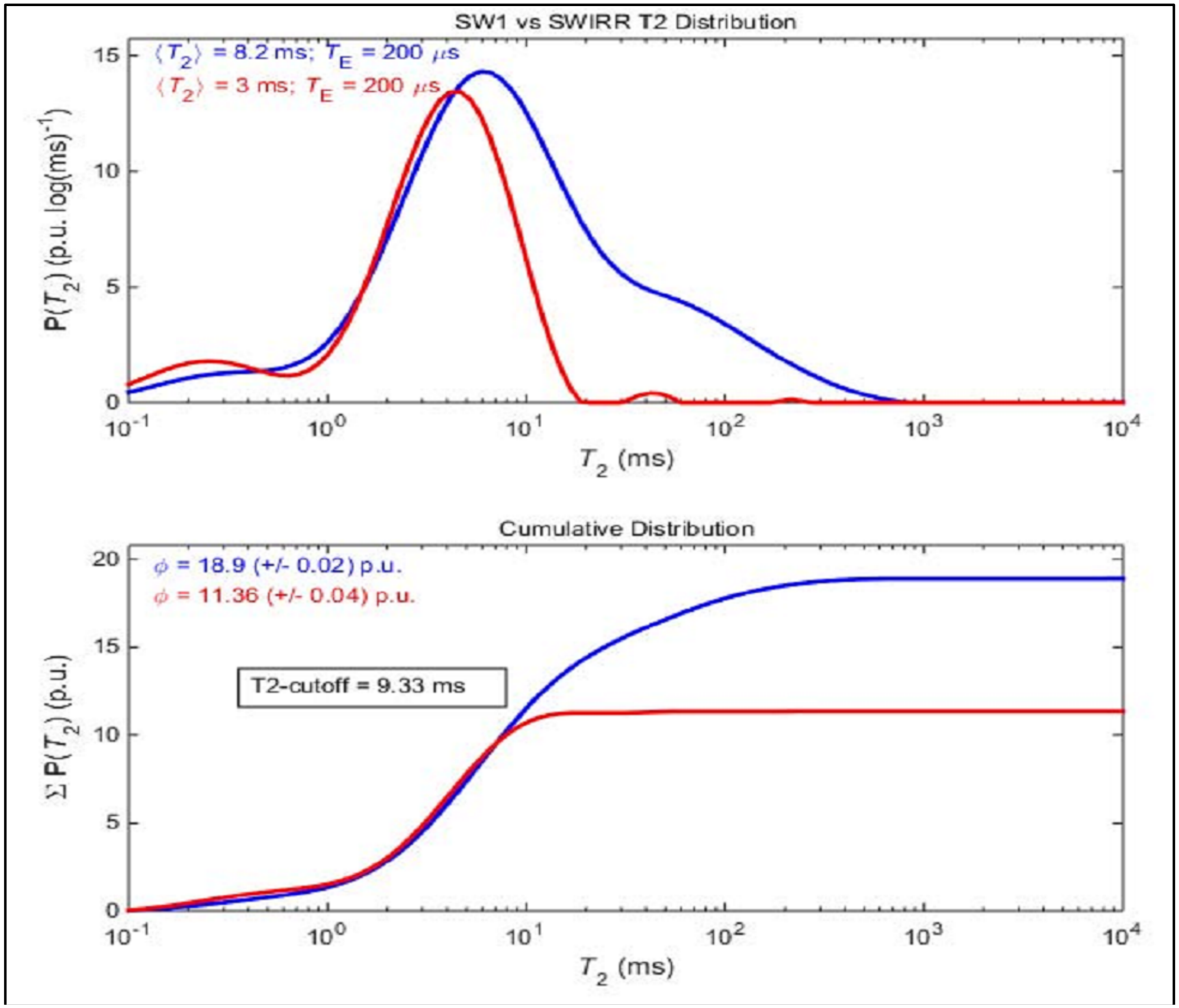



Figure 15. Irreducible T2 vs. 100% Brine T2 sample #19.

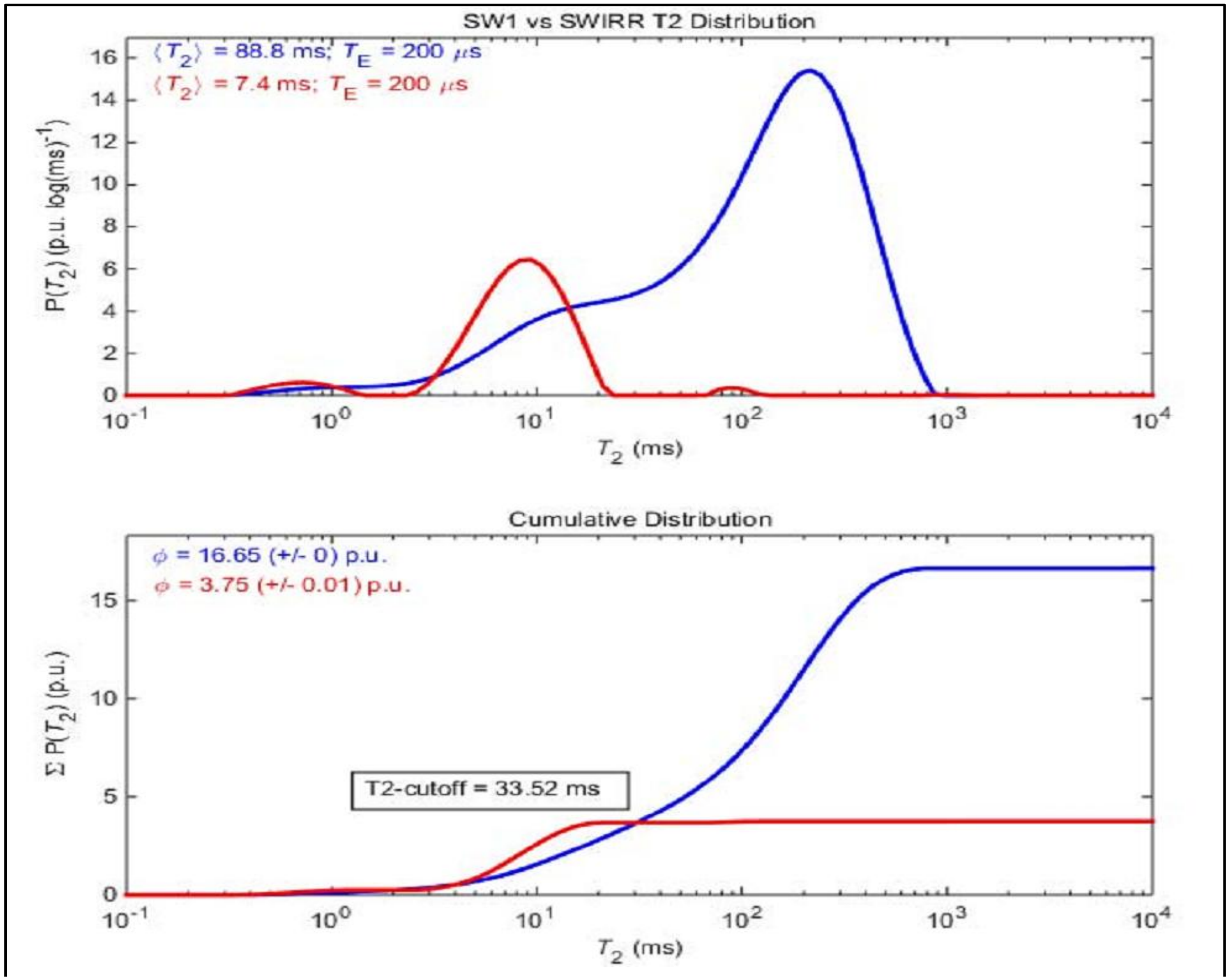



Figure 16. Irreducible T2 vs. 100% Brine T2 sample #22.

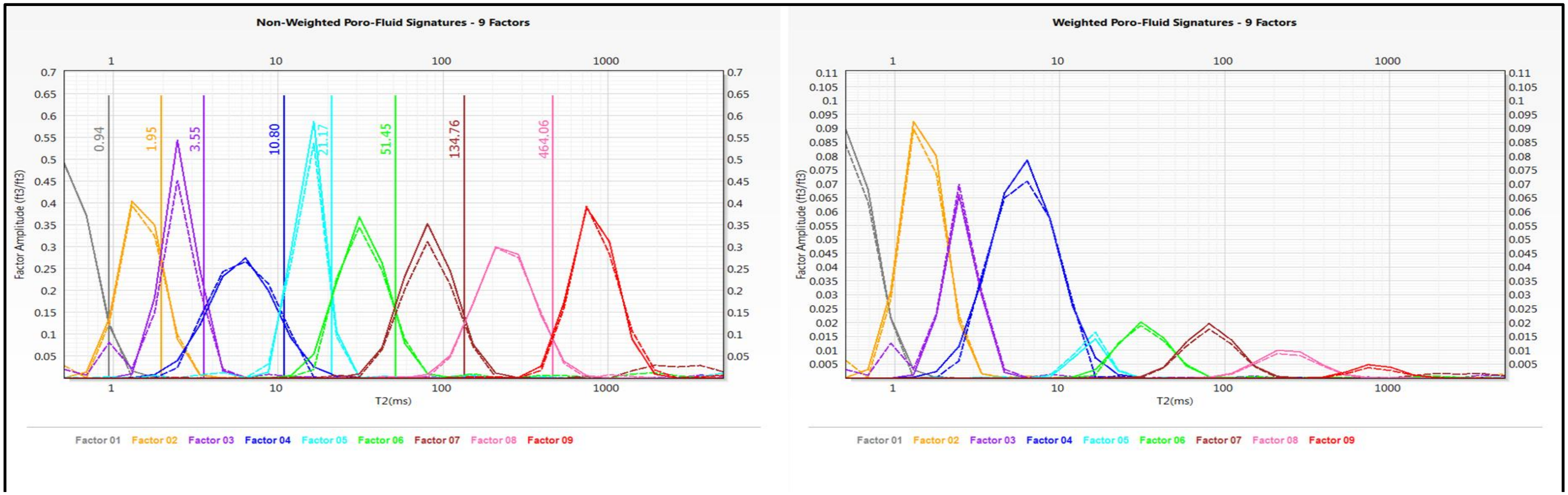



Figure 17. Factor analysis results.

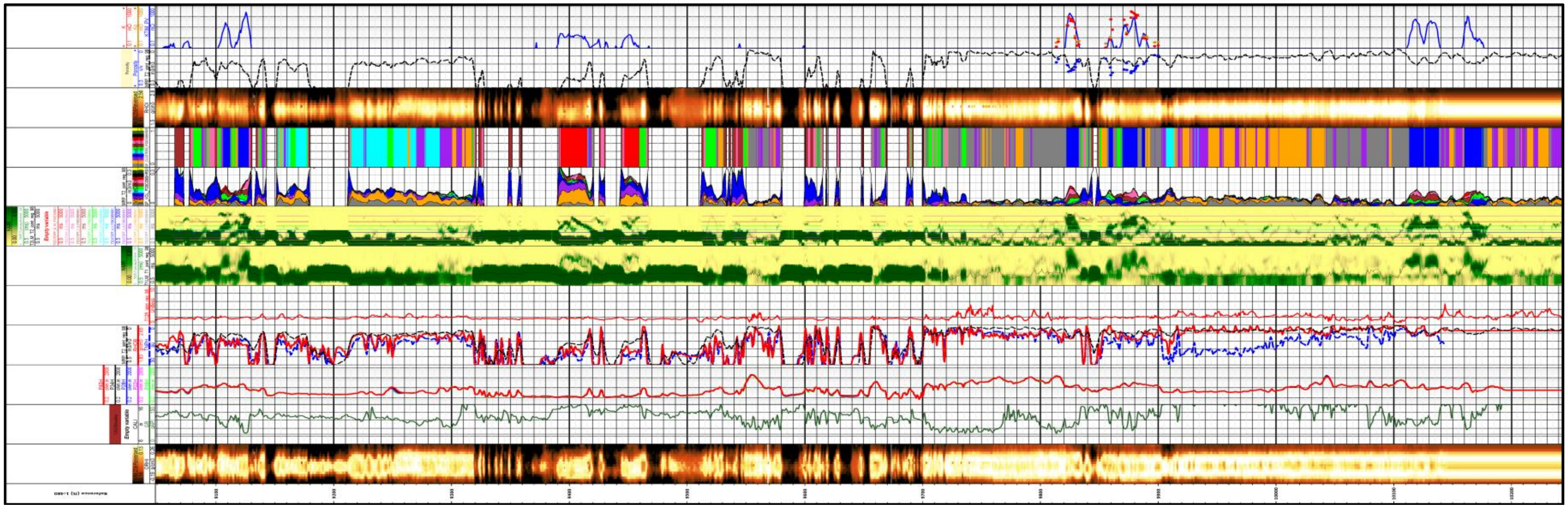


Figure 18. Factor analysis results after bad hole facies removal.

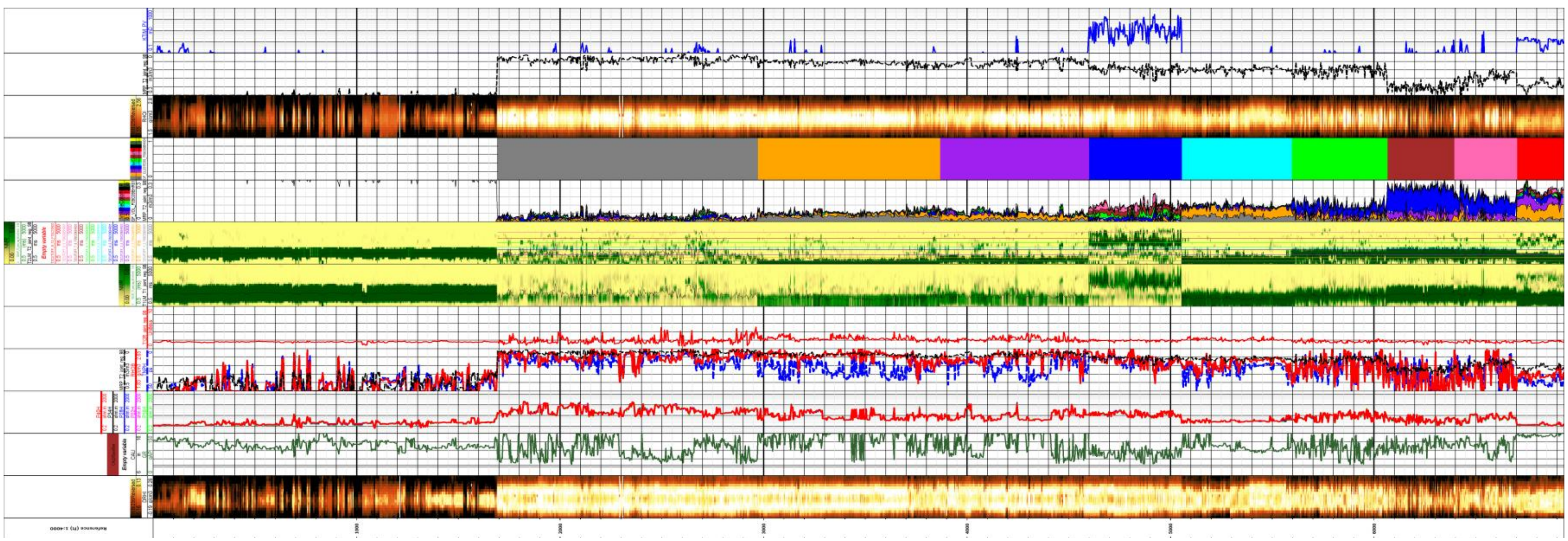


Figure 19. Sorted factor analysis results after bad hole facies removal.

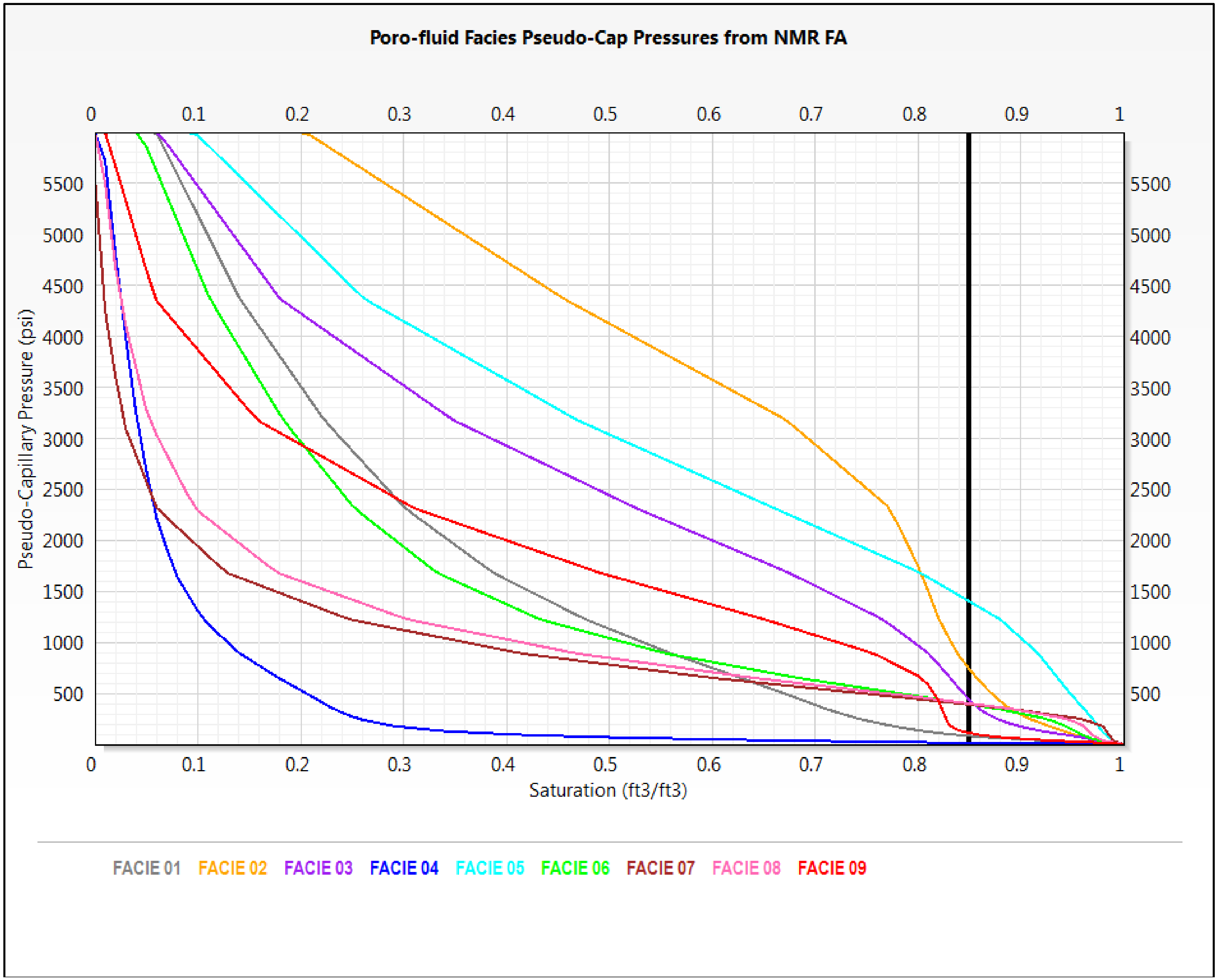



Figure 20. T2 distribution transformed into saturation pseudo-capillary pressure functions.

| | | |
|---|---|---|
| 9 5/8" | ORTEGUAZA | |
| | TIYUYACU | |
| | SHALE TENA | |
| | BASAL TENA SAND | Secondary Objective |
| | SHALE NAPO | |
| | LIMESTONE M1 | |
| | LIMESTONE M2 | |
| | LIMESTONE A | |
| | NAPO UPPER U SAND | |
| | NAPO MAIN U SAND | Secondary Objective |
| | SHALE NAPO | |
| | LIMESTONE B | |
| | UPPER T SAND | |
| | LOWER T SAND | Secondary Objective |
| | SHALE NAPO | |
| 8 1/2" | HOLLIN SAND | Primary Objective |

Table 1. Secondary objectives list in the 9 5/8” section.

| Sample ID | Lithology | Depth | Porosity | T2-Cutoff |
|---|---|---|---|---|
| **1** | Limestone | 9811.60 | 11.09 | 34.56 |
| **2** | Limestone | 9813.50 | 8.37 | 42.29 |
| **9** | Sand | 9824.20 | 17.07 | 26.56 |
| **19** | Sand | 9859.00 | 18.90 | 9.33 |
| **22** | Sand | 9871.00 | 16.65 | 33.52 |

Table 2. MR core results for Coca K-40 well.