A Hidden Reservoir within the Gacheta Formation, Zopilote Field, Llanos Orientales Basin, Colombia*

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Abstract

The Zopilote Field contains two reservoirs, one of them, within the Cretaceous Gacheta Formation, is not easy to identify using standard open-hole logs, gamma ray and resistivity. By-passed oil reservoirs in this formation are therefore expected in other parts of the basin. Operators are called to review relevant data in a similar way that is presented here. A full integration of open-hole logs with well-site-geologist data is extremely important for the identification and delineation of this reservoir. A lithological model based on volume of clay calculations derived from the combination of the density and neutron logs seems to be the most successful tool. Gamma-ray logs are strongly affected by mineralogical composition and do not permit the identification of the reservoir. Image logs are powerful tools to identify this reservoir. Porosity derived from density log has been found to fit very well porosity measurements from core data. None of the known saturation equations has been successful in explaining production behavior even though resistivity of formation water is known. Resistivities are affected by thin laminations and by mineralogical composition. As a consequence, water saturations are not useful for oil-water contact identification, or for net pay calcuations. An old method of log interpretation has been found useful: comparison of Ro (the resistivity of a wet formation) with Rt (the true resistivity of the formation). In this method the only uncertainty is the resistivity of the formation water, as porosity is well defined by density log. Rw in the Ro calculation is modified until it fits Rt in most of the sandstone intervals expected to be water-bearing. Where Rt is higher than Ro, oil saturation is indicated. However, derived Rw does not fit measured Rw, because, as noted, resistivities are anomalously reduced. Oil saturations derived from this method are not reliable as they do not fit production behavior, but they are useful for new oil zone detection and oil-water contact identification. Capillary and relative permeabilities should be used to determine the correct water saturation values for volumetric and other calculations. If an approach like this one is not applied in the evaluation of these reservoirs, conventional petrophysicists, who just apply only the volume of clay, porosity, and water saturation cut-offs in identifying hydrocarbon reservoirs, will fail to identify them, adversely affecting reserves auditing and business development.

Introduction

Perhaps the most important oil discovery in Colombia during 2011, the Zopilote Field in the Central Llanos Orientales Basin (foreland portion; Figure 1) contains two reservoirs, one of which is not easily identified. This reservoir is within the Cretaceous Gacheta Formation. During business development, or reserves auditing, evaluators experience a lot of difficulty trying to delineate the limits of the reservoir, the depth of the oil-water contact (OWC), the net pay, and in general the reservoir characteristics, when they only use open-hole log data. As a consequence, erroneous reserves calculations and misguided recommendations arise, adversely affecting economic evaluations and business appreciation.

It is demonstrated in this article that a non-standard and an integrated approach is required to correctly evaluate these kinds of reservoirs, which have been found to be very common in this basin. It is called the attention of the current and future operators in the basin to review very carefully the Gacheta Formation looking for bypassed oil reserves. It is also an invitation to these operators always to consider the Formation as an additional target that should be drilled.

The Zopilote Field contains two reservoirs, one of Tertiary and other of Cretaceous age. The Tertiary reservoir is known as a Basal C-5 Sandstone, within the arbitrary and informal stratigraphic division of the Carbonera Formation of the Llanos Orientales. Its top and base and the depth of the OWC are very easily identified, based only on standard open-hole logs, mainly gamma ray and resistivity logs.

The other reservoir, known as Middle Gacheta Sandstone, which is the main subject of this article, lies toward the lower half of the Gacheta Formation. It is very closely related to one of the most important marine flooding events in the Llanos Orientales Basin. The marine shale that overlies these sandstones can be traced almost everywhere within the basin.

The Llanos Orientales is a Sub-Andean foreland type basin that although has evolved as such since the Mid-Mesozoic times; yet its present configuration is mostly controlled by the Miocene Andean tectonic events. In the central part of the Llanos, where several fields have been discovered, traps are due to structural closures controlled by the so-called antithetic normal faults (because they dip toward the basin margin). These normal faults strike north to northeast, dip to the east and can be traced for more than 10 km. Typical vertical displacement measured in the wells that cut them is 30 to 150 feet. The sedimentary section in this part of the basin has a thickness of approximately 8500 feet measured between surface (Quaternary sediments) and the top of the Paleozoic sequence (Figure 2), which is normally considered the economic basement of the basin. Paleozoic sediments are normally assigned to the Lower Paleozoic, more specifically to the Cambro-Ordovician. The Cretaceous section with 700 to 800 feet of thickness rests on an important unconformity which separates it from the Paleozoic section. It is subdivided into three formations Ubaque, Gachetá and Guadalupe, from base to top. The upper limit of the Cretaceous is also related to an important unconformity (Oligocene?/Maastrichtian), but its stratigraphic position within the sedimentary pile is not clear. It is arbitrarily placed in the top of a bed of white claystone for which very high radioactivity is measured by the gamma ray tool. However, there is no biostratigraphic data to support the position of this boundary. The lower Ubaque Formation, also named in other parts of the basin as "Areniscas Inferiores" (Lower Sandstones) or Une Formation, is of variable thickness of sandstones (70 to 150 feet), apparently depending on the pre-Cretaceous paleotopography. Its upper limit is defined where the thick, massive sandstones of the Ubaque Formation change upward to a sequence of interbedded sandstones and gray shale. Where this sequence becomes sandy, identification of this boundary is difficult. Although the Gacheta Formation overlying the Ubaque Formation has been considered a shaly sequence, it tends to be sandy in the upper and lower parts. In the middle shaly section commercial hydrocarbon production has been established in this part of the basin. The upper part reflects the beginning of the very well recognized marine regression event of the Late Cretaceous that gave way to the deposition of the thick Guadalupe Formation. Within the middle shaly section, several shale beds can be traced regionally beyond the limits of the block. This section may contain the maximum flooding surface of Cretaceous marine sedimentation in the Llanos Basin. This section is also considered the main hydrocarbon source rock of the basin. The thick Guadalupe Formation is capped by the Carbonera Formation, sometimes by the C-7 informal unit or by the C-5 unit. Some geologists claim that the Mirador Formation is present in this part of the basin, but additional stratigraphic research should be done to clarify the distribution of the different facies of the Tertiary sediments and to establish a formal stratigraphic nomenclature. These basal Tertiary sandstones have demonstrated their production potential in several discovered traps. Farther to the east, younger Tertiary sandstones become hydrocarbon producers, especially the informal C-3 unit. This fluvio-deltaic Tertiary sedimentation began to finish with the regional marine transgression that deposited the Leon Shale during the Miocene. The Guayabo Formation, a very thick fluvial sequence, overlies the Leon Shale and represents the molassic sedimentation that followed the uplift of the Eastern Cordillera.

As pointed out before, the Gacheta Formation is the result of the Cretaceous marine transgressive sedimentation. The reservoir levels that are discussed here were deposited within a marine intertidal sedimentary environment. It is composed of interbedded sandstones and mudstones, with average gross thickness of 50 feet and about 30 feet of potential reservoir sandstones. This Gacheta interval is unusually thick in the Zopilote Field; normally these sandstones are around 10 feet thick. They are very fine-grained sandstones, very well sorted, and are composed of monocrystalline quartz with minor feldspar (plagioclase, orthoclase, and microcline), and sedimentary lithic fragments (<1%), and some diagenetic clays (<3%), especially kaolinite. Carbonaceous material can locally account for 5%. Some traces of quartz overgrowths are noted on the margins of some grains. Fluorapatite and glauconite have also been observed in these units of the Gacheta Formation. Lenticular, undulose and wavy laminations are the main sedimentary structures within this sequence. Cross lamination within sandstones and bioturbation are also very common: *Planolites*, *Thalassinoides*, and *Palaeophycus* have been reported. Reservoir characteristics are excellent; average porosity is around 28%; permeability is several hundred millidarcies. Oil gravity is 17° API, with very low content of gas.

Reservoir Identification

In a standard suite of open-hole logs (resistivity, gamma ray and SP; Figure 3), no reservoir can easily be identified, as it is normally done by most evaluators and by most petrophysicists. However, from the tested interval, as well as the production behavior during the test (Figure 4), there is no doubt that a reservoir is present and with the good properties indicated by the test result. Standard methods of pay identification fail to identify this reservoir. Porosity, volume of clay and water saturation cut-offs do not allow reservoir identification because gamma-ray log measures high levels of radioactivity, and resistivity is anomalously low.

Several indications of the presence of a reservoir in this interval from the well-site geologist work, mainly geological sample description, and oil and gas shows or hydrocarbon indications during drilling operations. Regarding gas shows, an arithmetic linear scale is strongly recommended, as standard presentations in logarithmic scale sometimes mask them. Figure 5 is an example of a gas show presented in both standard logarithmic and arithmetic scales. The mud-cake development is indicated by the comparison between the caliper log and the bit size, and the drilling rates are also indirect indicators of the presence of a reservoir. When this data is presented together (Figure 6), the presence of the reservoir begins to be suspected.

As noted above, the gamma ray log is not useful for lithology interpretation. It has been found that Vcl (volume of clay in the pore space of the reservoir), derived from the density and neutron logs using the following equation, allows the generation of a lithological model for reasonably accurate reservoir identification:

Vsh = (RhoB-RhoM+PHIN)(RhoM-RhoF)/(RoSh-RhoM+HIsh(RhoM-RhoF))

- HIsh = Hydrogen Index of clay
- RhoF = Density of fluid in the pore space where the density log is reliable
- RhoM = Density of rock matrix
- RhoSh = Density of the clay in the pore space

The parameters for the shale (or the clay), are calculated within the Carbonera C-4 unit after verification of the geological data (that the unit is really composed of mudstone, most commonly of clayey shale, and where average neutron and density values are derived over a section of approximately 200 feet). RhoF is normally assumed to be that of the water as water-base muds are normally used in drilling operations. RhoM is normally 2.65 gm/cc, considering that this reservoir is of quartzarenite composition.

With this Vsh (Vcl) calculation, a simple lithological model (two components) is derived using cut-offs for mudstones and sandstones, and comparing the resulting model with the geological description of the samples. With this operation, the reservoir is thoroughly identified (Figure 7); the top and the base of the reservoir can be picked. It has also been found very useful for reservoir identification and delineation in the observation of the image logs. Figure 8 presents the GR-Resistivity suite of one of the wells of this field only 7 feet of sand were recognized during the 2011 reserves auditing exercise, while in fact it really has over 50 feet, which can be easily identified in the image log.

The gamma ray logs are not useful for reservoir identification and delineation because mineral composition, especially glauconite, phosphates, feldspars, micas and clay minerals, generate high radioactivity levels.

Porosity Determination

The comparison of core-derived porosities with log-derived porosities has shown that density porosity fits core porosity very well. In Figure 9 core porosity is presented with neutron, density, average neutron density, and Vsh corrected average neutron density porosities. Density-derived porosity should be used for log calculations in which porosity is required and in volumetric calculations.

Oil-Water Contact Identification: The Saturation Model

It is very well known that water saturation derived from open-hole logs is the least reliable method of water saturation calculation. Evaluators always prefer capillary and relative permeability measurements to evaluate the distribution of water saturation within a reservoir. Sometimes, when core samples are taken using oil-base muds, laboratory measurements may provide good values of the water saturation at the depth of the core. The Gacheta reservoir is not an exception to this rule. Experience has shown that, even when water saturation calculated from open-hole logs is 100%, production of clean oil or with very low water-cut has occurred. Water saturation from log data should not be used alone in the identification of pay intervals to be tested or to be included within any reserves report. It is very common practice, not only within the Gacheta reservoirs but also within the Carbonera Formation reservoirs, for evaluators to eliminate intervals that do not fulfill cut-off criteria, especially water saturation, even when those intervals have been oil-tested, adversely affecting reserves evaluations and business development.

The Gacheta reservoir is composed of low-resistivity sandstones. It is not completely clear why they are low-resistivity, especially when the water within them is considered fresh (< 200 ppm chloride), and they are normally relatively free of clay matrix and/or clay cements. However, it has been observed that Ro (resistivity of a 100% water-saturated rock), calculated with the resistivity of the produced water, does not fit Rt (true resistivity) measurements (Figure 10). Porosity within the model (which may affect Ro calculation) is not an issue of doubt, as noted before. The clear conclusion is that Rt is affected by something other than fluids. It is suspected that Rt measurements may be affected by mineralogical composition (glauconite and phosphates have been reported), and/or by thin conductive laminations that have been observed to reduce resistivity (Figure 11); with the presence of these thin mudstones or strata rich in mudstone components, resistivity is lower than in zones free of mudstones, containing the same fluids. It is clear that resistivity-derived water saturations do not reveal the true hydrocarbon content of the reservoir. For this reason, water saturation cut-offs should not be applied when computing net pay.

To avoid any misinterpretation and bypassed hydrocarbon zones, an old evaluation method has helped evaluators: the calculation of Ro over the zone to be investigated. There are no concerns regarding porosity, as core data has indicated that density-derived porosity is quite trustworthy. Consequently, the only variable to be determined in the interpretation procedure is water resistivity (Rw). Several water resistivities are anticipated (helped by an apparent water resistivity calculation (Rwa), until a fit between Ro and Rt is found over the zones expected to be wet, most commonly toward the base of the reservoir interval. Where Rt is observed to be higher than Ro, hydrocarbon saturation can be qualitatively identified. The application of this method implies that assigned (and false) water resistivity is affected by mineral composition, thin conductive laminations, etc. This interpretation method has been very successful in selecting intervals for testing and interpretation of the depth of the oil-water contacts. Derived Rw will not match measured Rw, as it is affected by rock characteristics. This approach is illustrated in the right side of the Figure 12, where Ro is fit to Rt in the water zone and the oil zone becomes apparent. On the other hand, in the left side of Figure 12, Ro was calculated using the true resistivity of the formation water. In this case, the resistivity of the water formation is 6.5 ohm m, while the applied water resistivity to identify the oil zone correctly is 1.8 ohm m. This interpretation is greatly supported by core data and testing.

Figure 13 is an example of interpretation where all available data is presented, ensuring consistency between the different pieces of data. Derived water saturations from this method are of course not reliable and should not be used in any interpretation or calculation, especially in the calculation of net pay values. Irreducible water saturations should be obtained from capillary or relative permeability measurements and applied to estimate the initial water saturation a any depth above the oil-water contact or the average water saturation of the reservoir. Production performance, especially-water cuts, is an important clue in deriving the water saturations of these reservoirs.

The location of the oil-water contact in any well, should be considered in the identification of the oil-water contacts in the other wells. The structural cross section of the Figure 14 is very useful in identifying the depths of the oil-water contacts in the wells and ensuring consistency in the interpretation. In this example, the possible oil-water contact indicated close to top of the reservoir in the well D (red arrow), could be anticipated as false, from examination of the core data (available in this well) and examination of the structural cross sections of the field. However, several evaluators actually interpreted an oil-water contact at the depth indicated by the arrow.

Conclusion

The evaluation of more than one hundred wells has allowed the construction of a lithological model that conclusively defines the limits of an important reservoir within the Gacheta Formation (Figure 15). However, before this modeling, the presence of a reservoir should be suspected, using all the information available: the well-site-geologist reports, the hydrocarbon shows during drilling, the rate of penetration, the geometry of the hole (caliper), etc. Density log should be used for porosity calculation, and a modification of the Ro plotting technique in which the resistivity of the water formation is compared and adjusted to resistivity data that can be used to identify pay zones. No water saturation values should be derived from log calculations because it was demonstrated that resistivities are affected by rock composition and fine laminations. Vsh calculation from gamma-ray logs should also be avoided. When standard petrophysical techniques is applied by reserves-auditing consultants or traditional petrophysicists (Vsh, porosity, and water saturation cut-offs), this reservoir becomes bypassed.

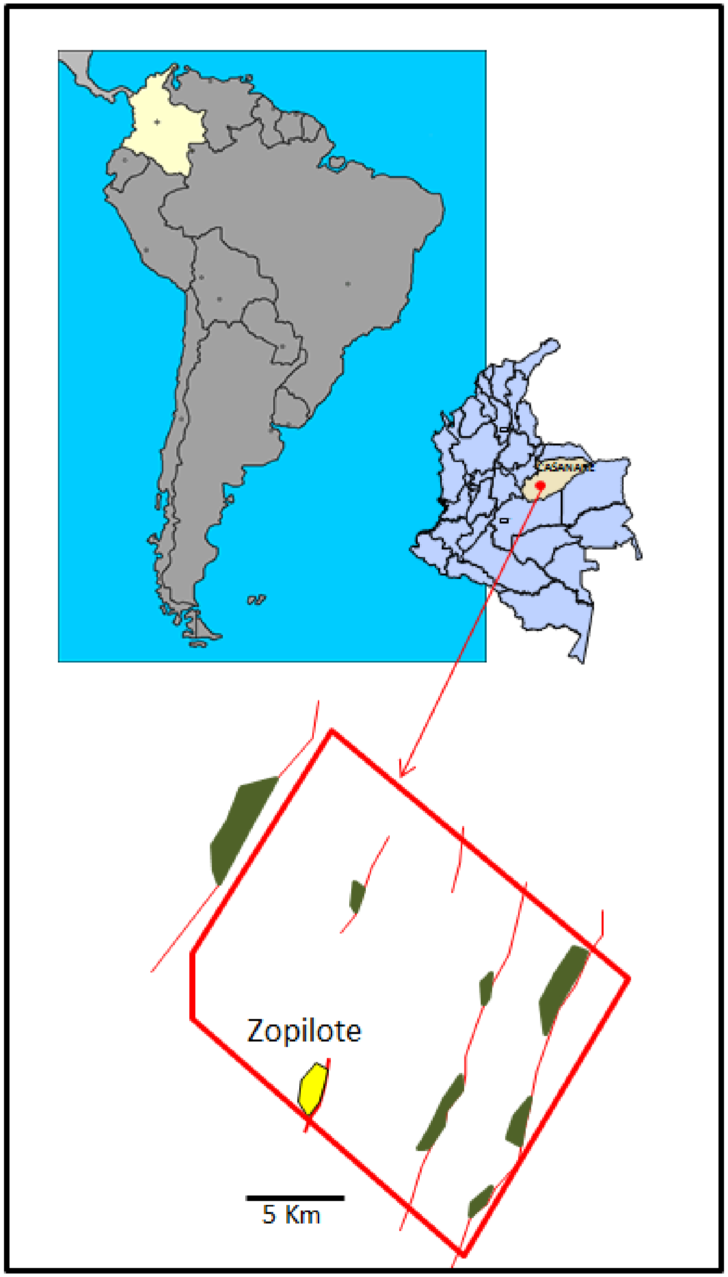

Figure 1. Zopilote Field: Location map.

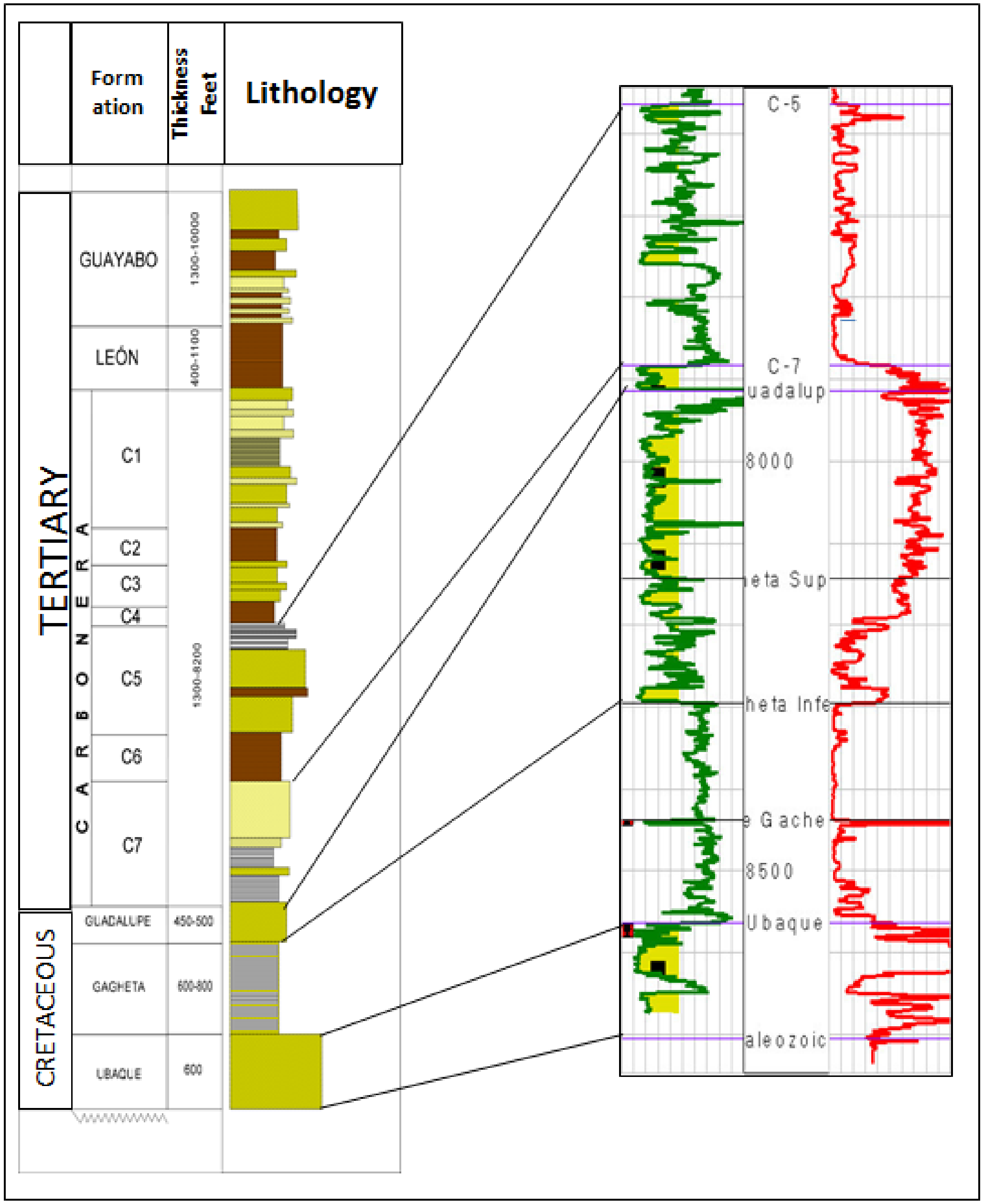

Figure 2. Central Llanos Orientales Basin: Stratigraphy.

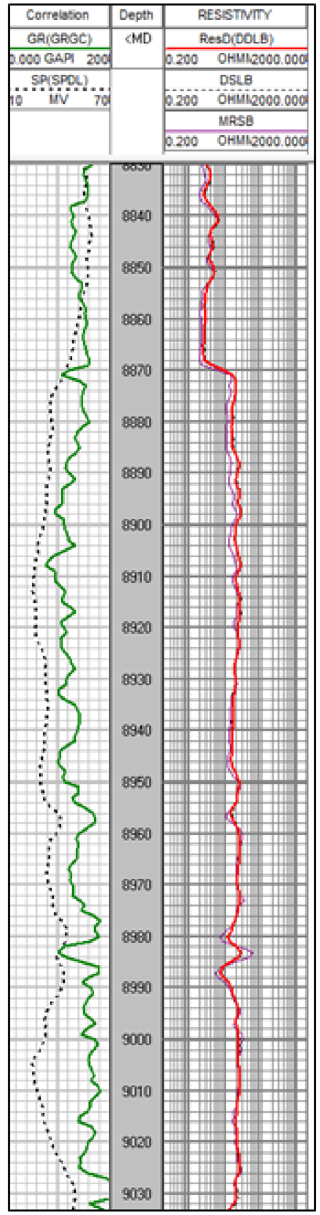

Figure 3. Central Llanos Orientales Basin: Gacheta reservoir. Standard logs.

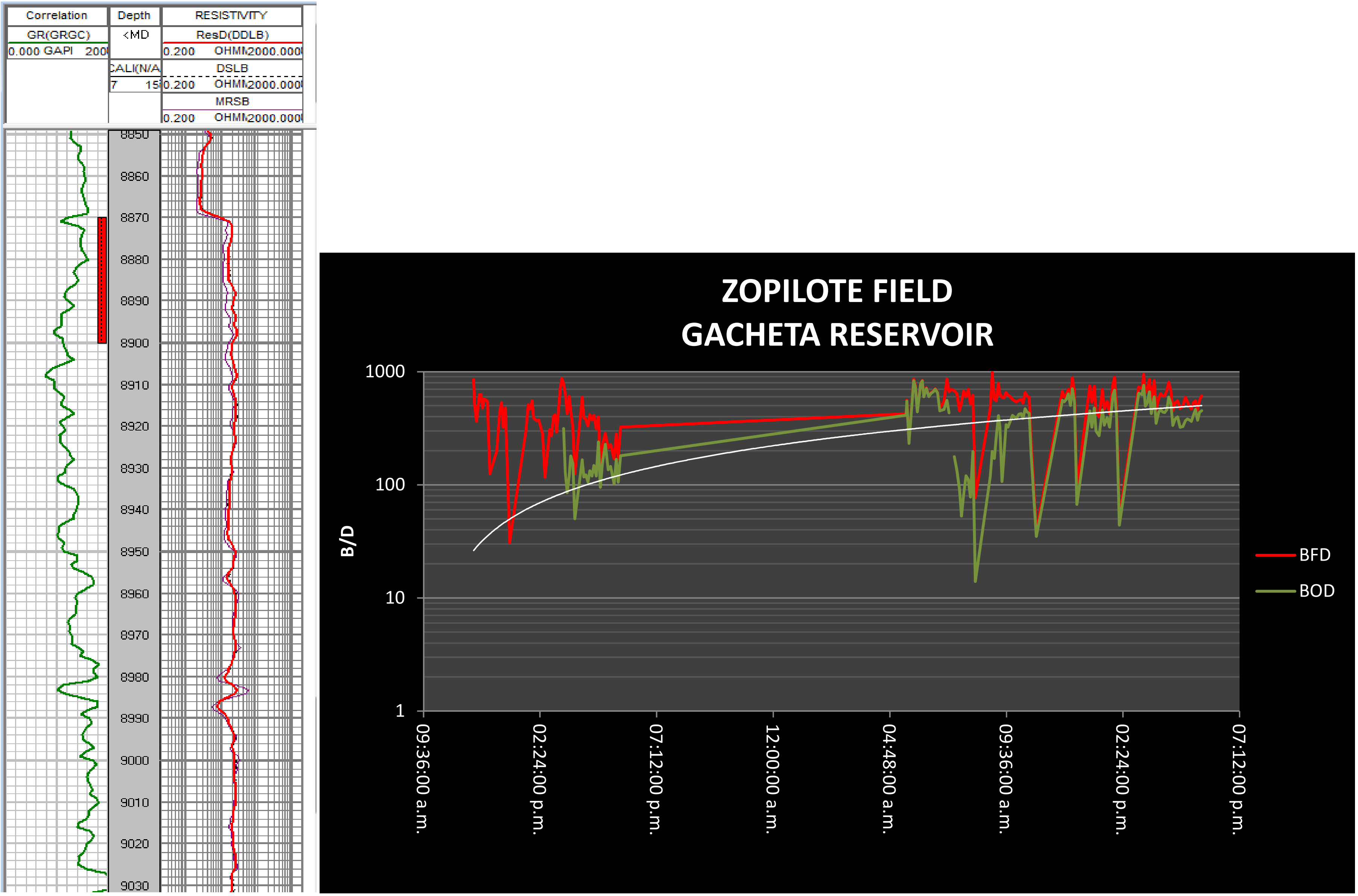

Figure 4. Central Llanos Orientales Basin. Same well as in Figure 3, with the tested interval and production test indicated.

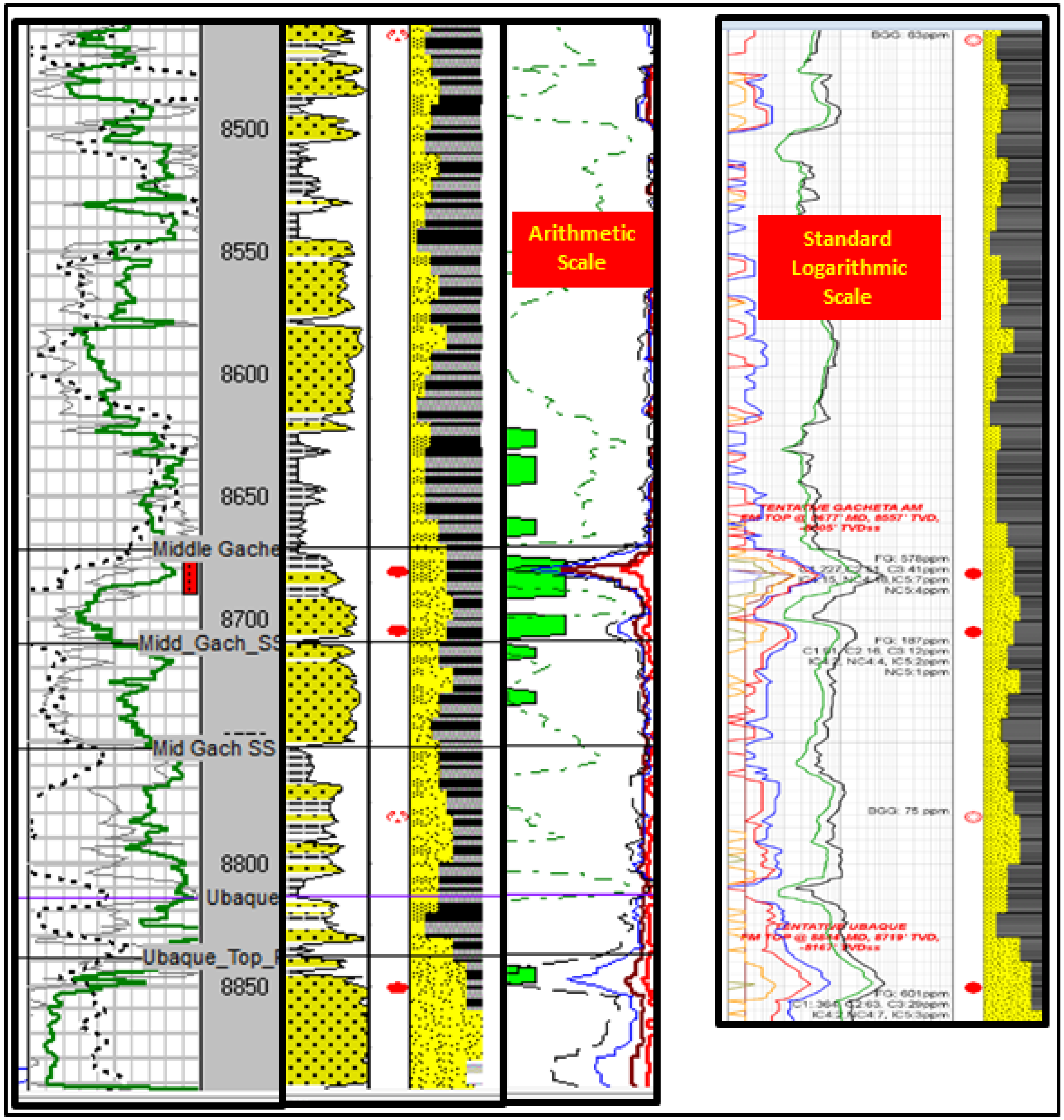

Figure 5. Central Llanos Orientales Basin: Gas shows presented in logarithmic and arithmetic scales. Note that the gas show can be identified more easily using arithmetic scale.

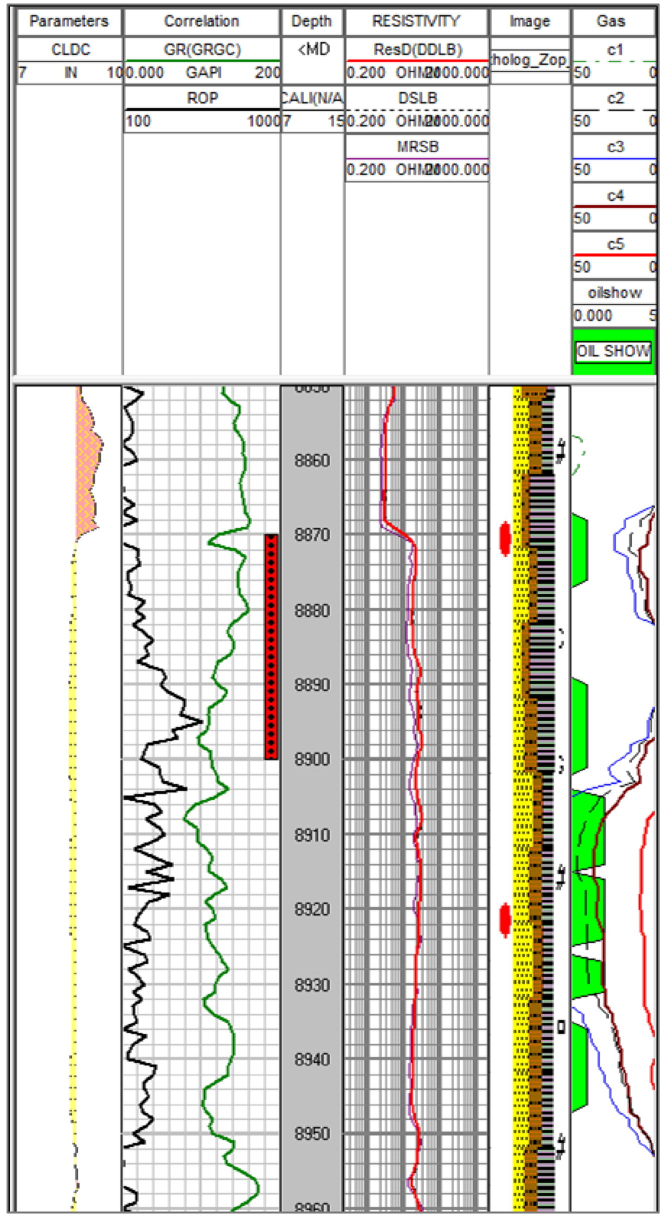

Figure 6. Central Llanos Orientales Basin: Identification of the reservoir: CLDC=Caliper; GR=Gamma ray; ROP=Rate of penetration.

LITHOLOGICAL MODEL

Vsh = (RhoB-RhoM+PHIN)(RhoM-RhoF)/(RoSh-RhoM+HIsh(RhoM-RhoF))

- **HIsh = 0.46 (Hydrogen Index of clay)**
- **RhoF = 1.0 gr/cc.**
- **RhoM = 2.65 gr/cc.**
- **RhoSh = 2.43 gr/cc.**

(HIsh and RhoSh calculated in Carbonera C-4 unit)

Vs > 0.5 Mudstone
Vsh < 0.5 Sandstone

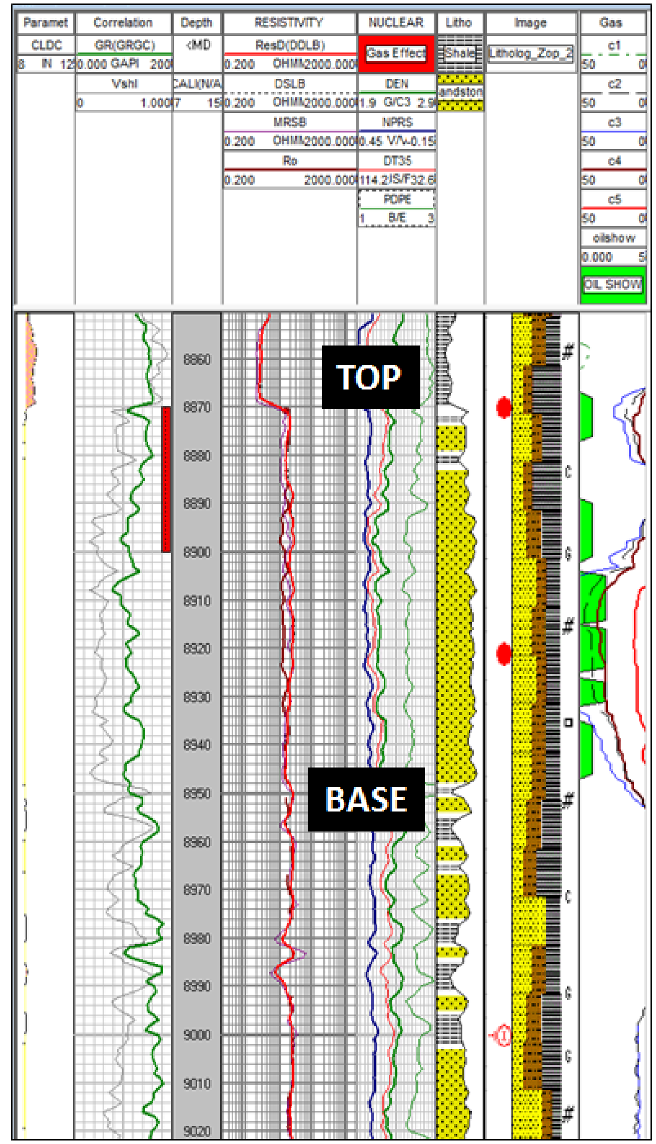

Figure 7. Central Llanos Orientales Basin: Lithological model. Vsh calculation using density and neutron logs and the integration with other data (caliper, hydrocarbon shows, geological description of cutting samples, etc.), permits the identification of the reservoir, its top, and its base.

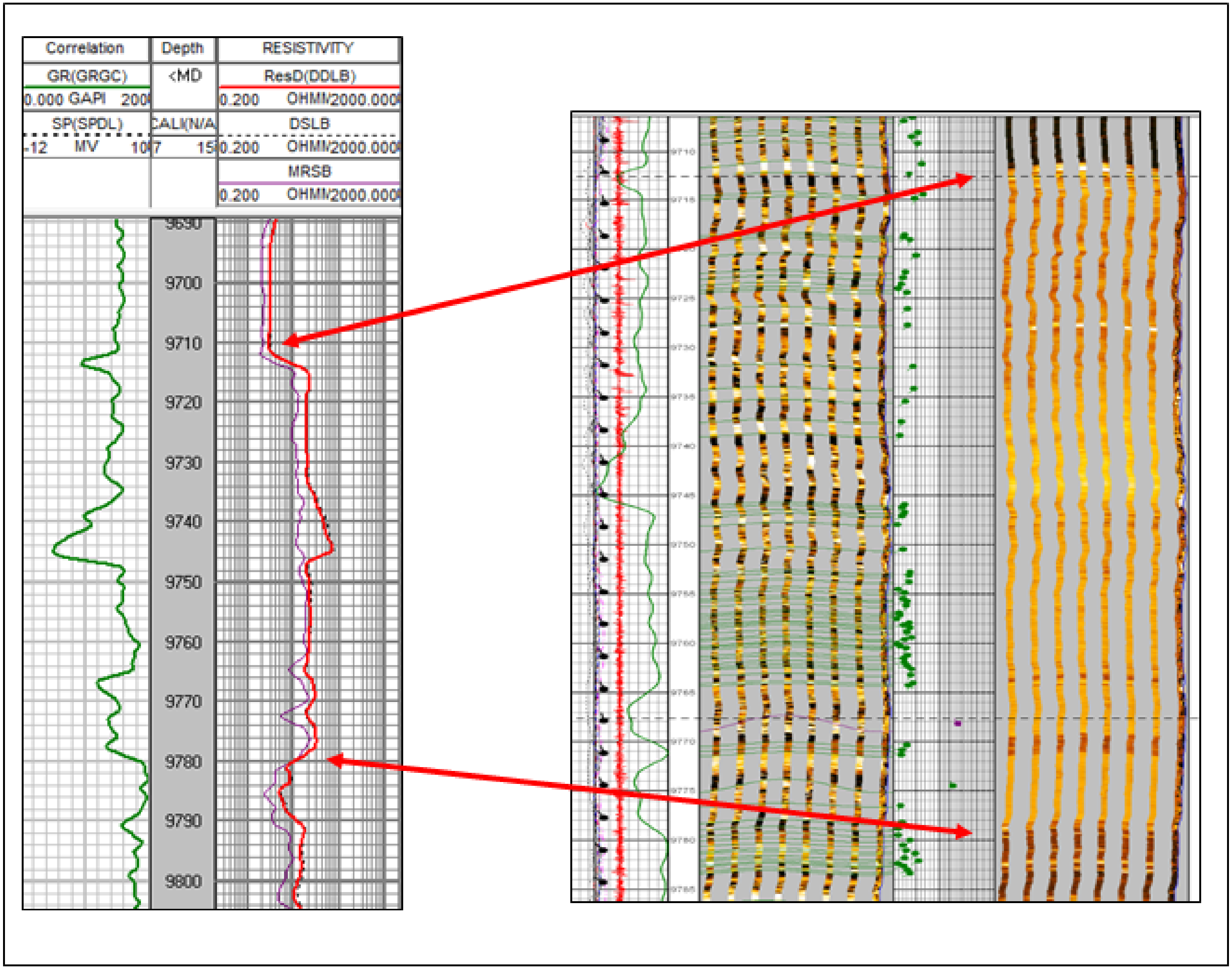

Figure 8. Central Llanos Orientales Basin: Image logs are useful for reservoir identification and delineation.

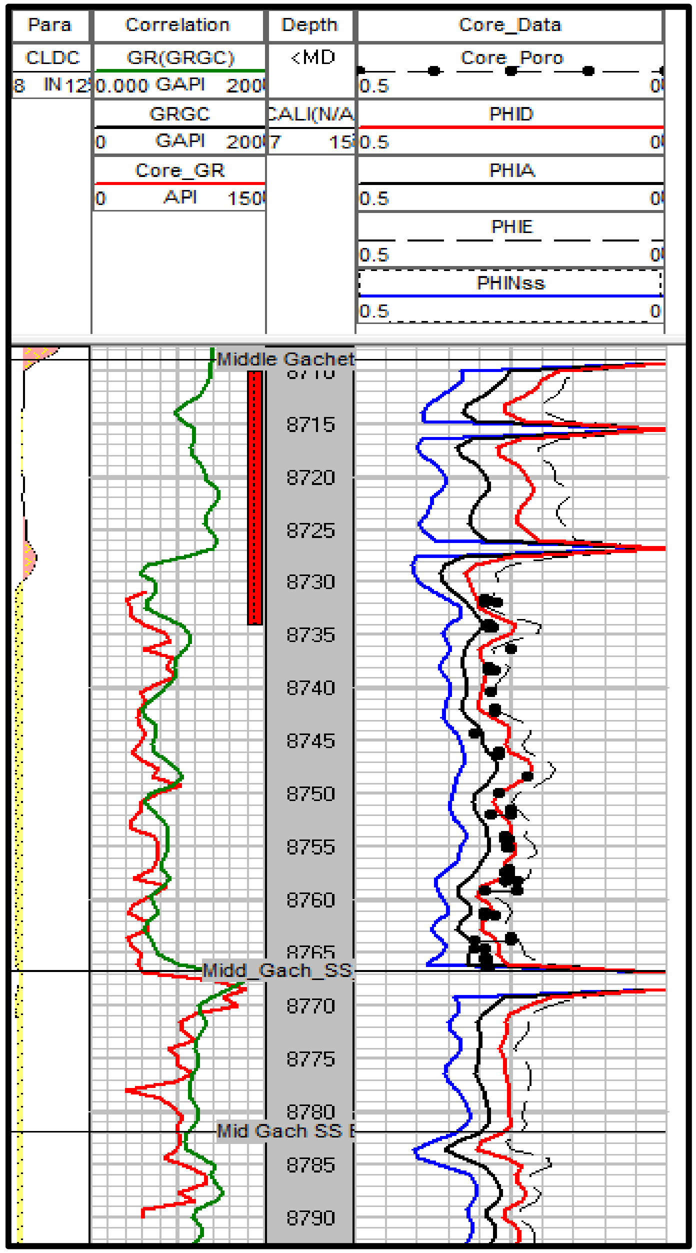

Figure 9. Central Llanos Orientales Basin: Correlation between measured core porosity (core pore) and density (PHID)- and neutron (PHINss)-derived porosities, density-neutron average porosity (PHIA), and Vsh corrected average porosity (PHIE).

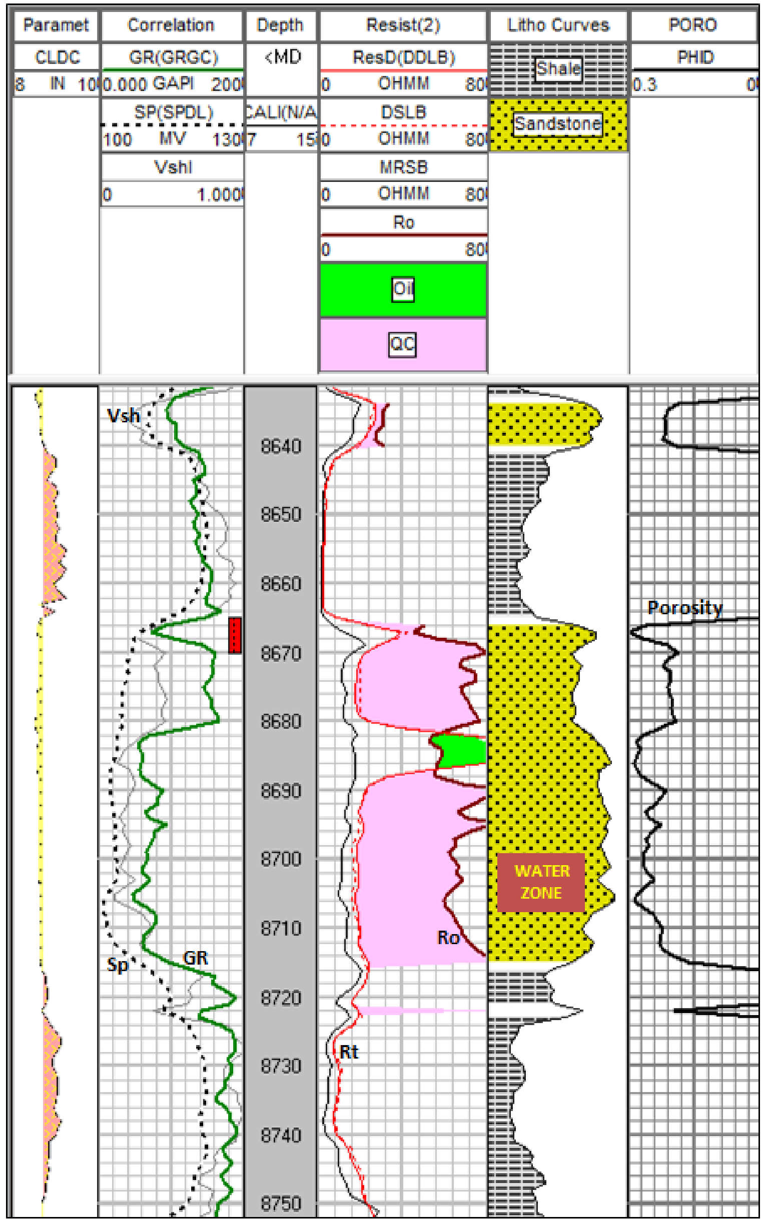

Figure 10. Central Llanos Orientales Basin: Comparison between Ro (the resistivity of a rock with 100% water saturation calculated with the resistivity of the produced water), with the measured resistivity of the rock. Rw in this well is 5.5 ohm m at reservoir conditions.

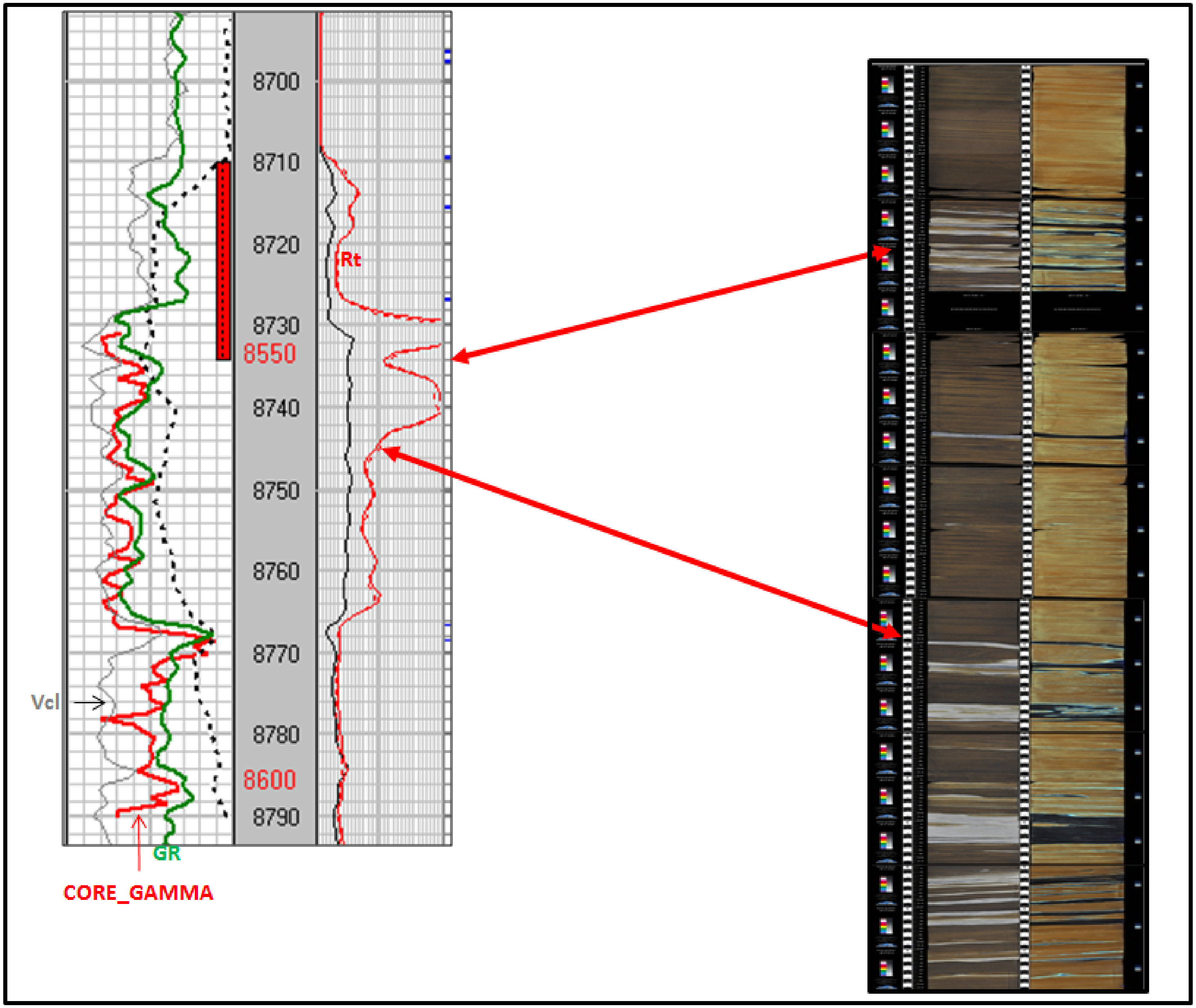

Figure 11. Central Llanos Orientales Basin: Effect of thin mudstone laminations on resistivity.

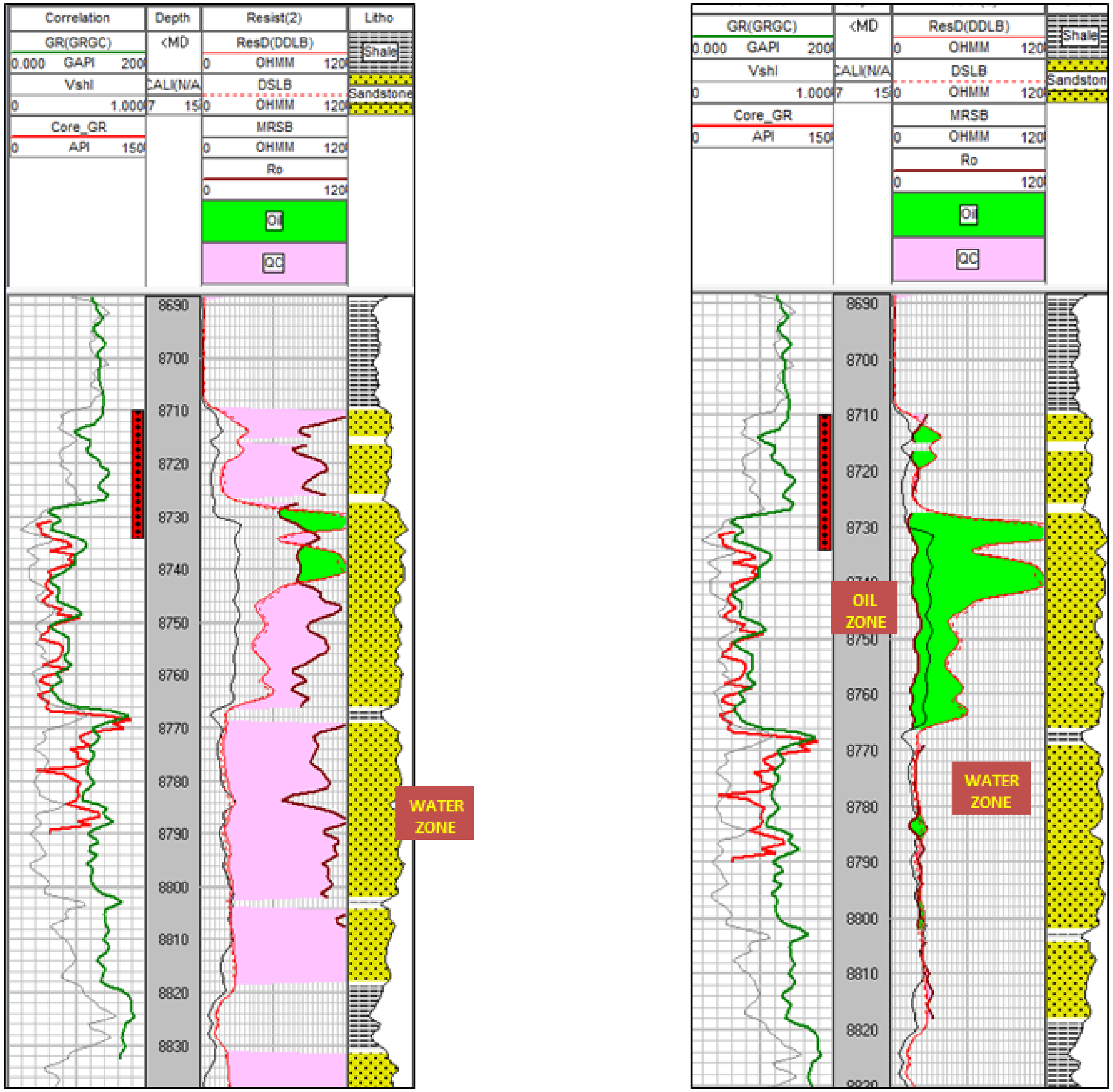

Figure 12. Central Llanos Orientales Basin: On the right, Ro (the resistivity of the wet formation) is matched with the measured resistivity in the water zone; the oil zone can be identified where Rt measured resistivity) is greater than Ro. The same procedure is applied on the left but using the resistivity of the produced water; a lot of oil is bypassed.

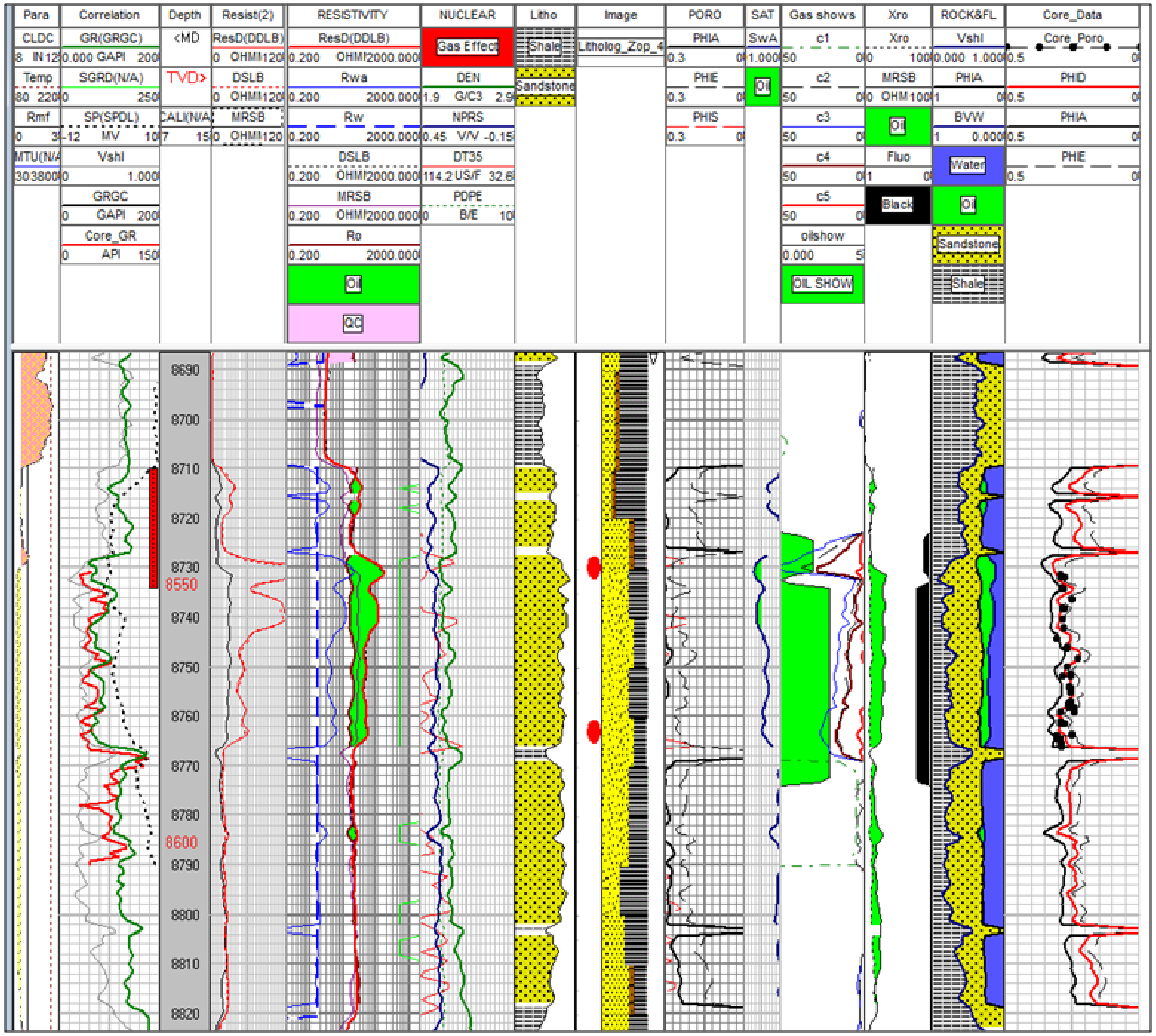

Figure 13. Central Llanos Orientales Basin: Ro calculation and the integration of the available data are useful for the identification of the reservoir, its limits, its fluid content, and the oil water contact.

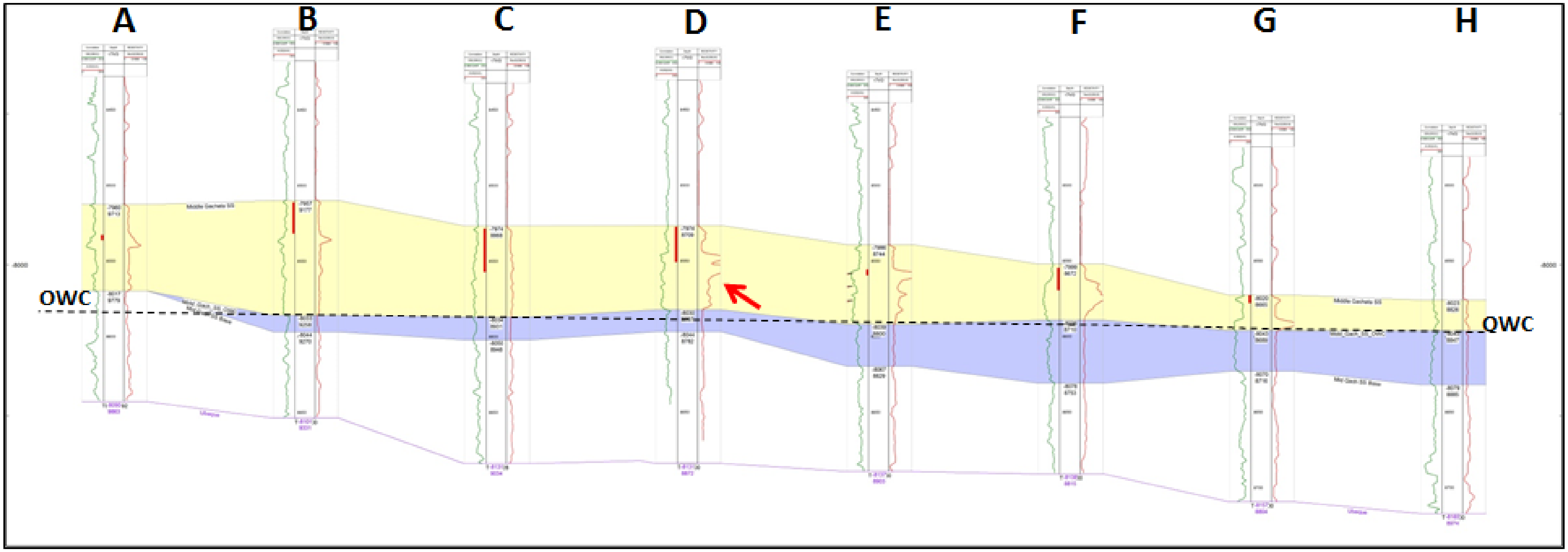

Figure 14. Central Llanos Orientales Basin: Structural cross section with fluid distribution indicated. Red arrow points to a depth in well D in which a false oil water contact has been identified by several evaluators.

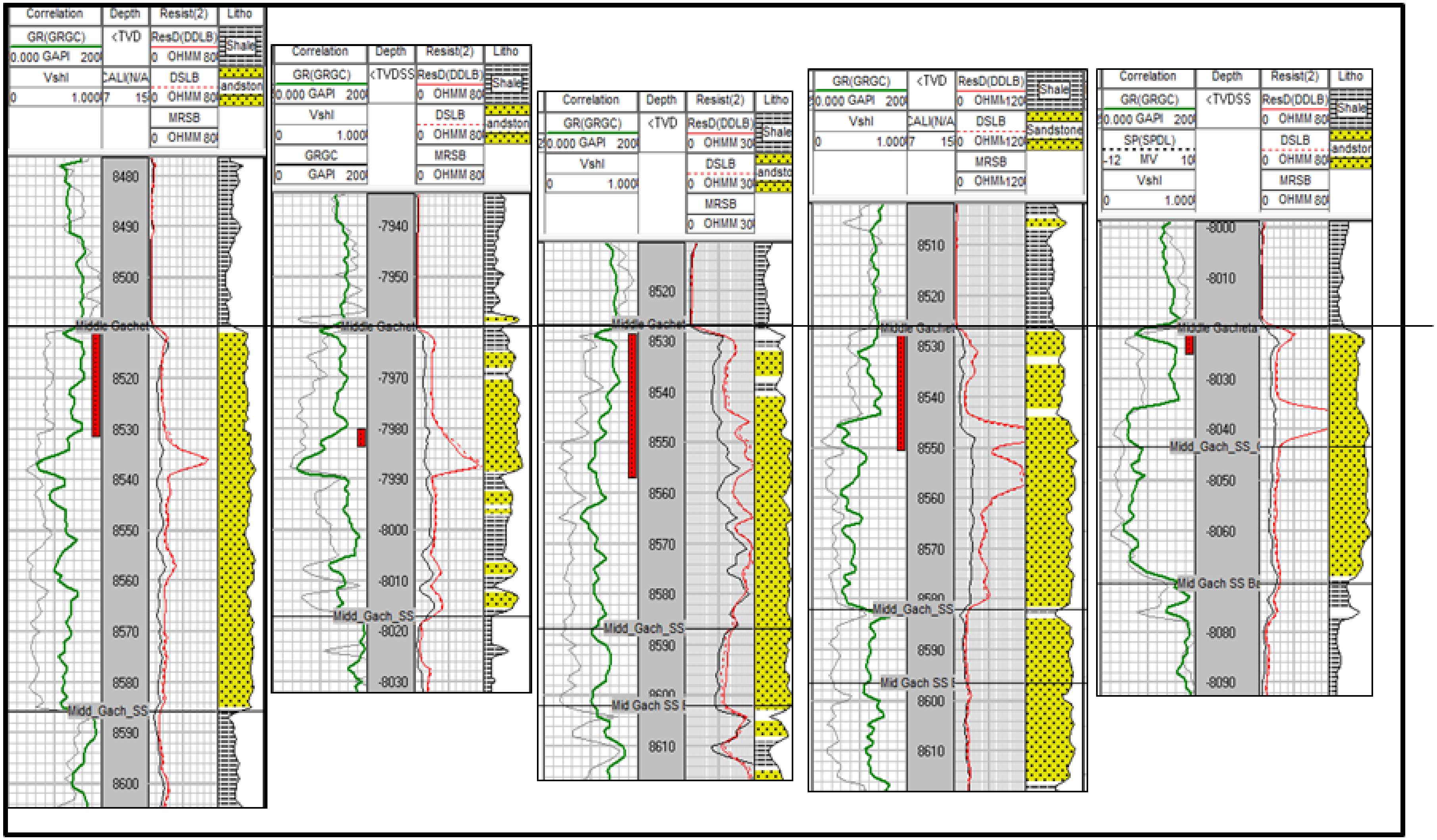

Figure 15. Central Llanos Orientales Basin: Gacheta reservoir identification with the lithological model.