Integrating LWD, wire-line and core petrophysical data to improve hydrocarbon evaluation and properties determination from well logs.

Rudolfo Beer, Cristiano Leite Sombra, Paulo Sérgio Denicol, Nuno André Pomar Couto, José Marques Junior PETROBRAS S/A - Brasil

Copyright 2003, SBGf - Sociedade Brasileira de Geofísica

This paper was prepared for presentation at the 8th International Congress of The Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 14-18 September 2003.

Contents of this paper were reviewed by The Technical Committee of The 8th International Congress of The Brazilian Geophysical Society and does not necessarily represents any position of the SBGf, its officers or members. Electronic reproduction, or storage of any part of this paper for commercial purposes without the written consent of The Brazilian Geophysical Society is prohibited.

Abstract

Well logs are used in the oil industry to provide information for hydrocarbon evaluation and petrophysical properties determination. Logs are usually run after the drilling of the different phases of a well and before casing, using a cable device. In horizontal and high angle wells the operational conditions were not adequate for wire-line (WL) operations and therefore logging service companies developed Logging While Drilling (LWD) instruments. LWD logs were also run in some vertical wells, in special those involving high risks, in order to provide an early evaluation of the reservoirs and for geo-steering in exploratory prospects. Resistivity log, one of the most important log run for hydrocarbon saturation calculations, can be strongly affected. A correct understanding of the resistivity device responses is one of the main tasks of the log analyst. All measurements are affected by well-bore environmental conditions, by adjacent beds and by invasion of mud filtrate. Invasion of mud filtrate fluids is conventionally modeled using a cylindrical geometry model. To address other type of geometries one has to run more sophisticated tools and refined modeling algorithms. In theory, LWD logs are less affected by the mud filtrate invasion, once they are acquired right after the drilling of the formation. We will show examples of non-conventional invasion profiles as well as situations where one can misinterpret a resistivity gradient profile with an invasion profile or even a transition zone. Combining LWD and WL logs usually allows insights for the correct interpretation. In other complex situations a more rigorous investigation has to be undertaken, integrating core data such as core descriptions, sieve data analysis, laboratory porosity and permeability data. We also considered variations in hydrocarbon properties showing a coherent correlation between resistivity gradients and variations in the asphalthene content of the hydrocarbon affecting the resistivity log readings. In conclusion, the different aspects reported in this paper may explain the resistivity log behavior and bring valuable insights for a correct hydrocarbon evaluation.

Introduction

Well logs are widely employed by the oil industry in order to provide information for hydrocarbon evaluation and petrophysical properties determination. Logs are usually run immediately after the drilling of the different phases of the well and before casing using a cable device. Recent developed drilling technology allowed the usage of horizontal and high angle wells, which may be the only economic way to produce hydrocarbon in the deep-water scenario. For these wells the operational conditions were not adequate for wire-line operations and therefore the service companies developed instruments for Logging While Drilling (LWD). Nowadays almost all open hole logs could be acquired under LWD conditions. LWD logs were also run in some vertical wells, in special those involving high risks, in order to provide an early evaluation of the reservoirs and for the geo-steering in exploratory prospects.

Both type of measurements, wire-line and LWD, are indirect inferences of the real rock property using some kind of mathematical transform. By this process, for instance, one can estimate the rock porosity from the electronic density measured with a density tool or from the hydrogen content measured with a neutron scattering device or even from the slowness of a sound wave obtained with an acoustic assembly.

One of the most important properties measured with logging tools is the resistivity since it may be directly related to the fluids present in the rock, hence being one of the crucial parameters in the determination of the hydrocarbon content of the reservoirs. Electrical logs were the first devices used for resistivity determination. The evolution of the tools was very significant in the recent years and in the present days one has tools offering different principles of measurements, combination of different number of electrodes or coils, allowing different depths of investigation and vertical resolution, in wire-line as well as in LWD. The correct understanding of the resistivity device responses is one of the main tasks of the log analyst.

The signal may be affected by well-bore environment, by adjacent bed resistivity and by invasion of mud fluids into the formation. These signal correction procedures are modeled by the service companies R&D laboratories and incorporated to the main interpretation software packages available in the market by means of different charts and equation sets.

Invasion of mud filtrate fluids is conventionally modeled using the cylindrical geometry model, considering a mud ring around the tool, a mud-cake ring in the interface between mud and the well-bore wall, an invaded zone ring containing mud filtrate and residual or irreducible formation fluids and a virgin zone ring containing the original formation fluid of the rock. To address other type of geometries one has to run more sophisticated tools and refined modeling algorithms. Theoretically, LWD logs are less affected by the mud filtrate invasion, once they are acquired right after the drilling of the formation.

In this paper we will show several examples of non-conventional invasion profiles as well as other situations in which one can misinterpret a resistivity gradient profile with an invasion profile or even a transition zone.

The combination of LWD and wire-line logs allowed the correct interpretation in some of these situations, to obtain a reliable value of resistivity for water saturation calculation purposes.

In those complex situations that could be misinterpreted as asymmetrical invasion profiles, a more rigorous investigation has to be undertaken. Integration of core data such as core description, sieve data analysis, laboratory porosity and permeability data provided a good means of understanding the resistivity gradient profile.

Hydrocarbon varying properties may also play a role in the correct determination of the resistivity value. Recent geo-chemical analysis shows a coherent correlation between a resistivity gradient similar to an unconventional invasion profile and the variation in the asphalthene content of the hydrocarbon. As we demonstrate bellow, due to the increase in the asphalthene content, the hydrocarbon polarity also increases, seeming to affect the resistivity log and may be one of the causes of these gradients.

Case # 1: The mud filtrate invasion problem

Figure 01 shows a good example of the problems caused by the invasion of mud filtrate in the resistivity log.

In the first track we have the GR log in blue indicating two sandy intervals at 3249/3257m and 3264/3269m. The different resistivity logs are shown in the track 02. The curves RESA and RESB are, respectively, the shallow and deep LWD resistivities. The curves RLA5 and RLA2 are the corresponding deep and shallow WL logs. Neutron (Nphi_EnvCorr) and density (RHOZ_EnvCorr) logs are plotted on track 03, the shaded yellow area highlights the sand intervals.

The upper interval has a fining upward bell shape. Cores taken in adjacent wells showing similar GR behavior indicate that these are laminated sand shale sequences. A resistivity gradient is formed due to these layers. The lower resistivities indicate a greater amount of laminations.

Corrections in these situations involve a great amount of uncertainty since almost all correction procedures cannot recover the real resistivity values. The tools have not sufficient vertical resolution to do that. Sophisticated techniques using higher resolution image logs or the modern induction multi-component tool could help in some cases. In this example mud filtrate invasion lowered the WL resistivity comparing to the LWD resistivities.

The lower sand presents a box shape, indicating a minor or none amount of shale laminations and a cemented portion around 3367m. This cemented interval is well defined in the neutron and density logs.

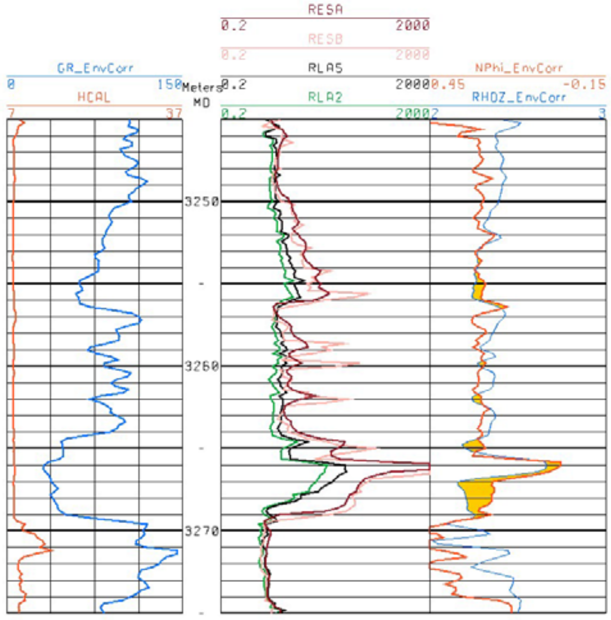

Figure 01: LWD x WL logs showing invasion effect.

Observing only the wire-line logs a common sense interpretation could be the presence of a narrow resistivity gradient below the cemented layer, indicating a possible oil/water contact at 3268m. Invasion could also be inferred since the deep and shallow curves show different resistivity values, in special at the 3266/3268m interval. In this case an asymmetrical invasion profile ([1]) could be claimed.

Looking to the LWD logs we see the RESA and RESB curves running close together at higher resistivity values. The narrow gradient almost disappeared and no oil/water contact may be assumed in this case.

Both measures, LWD and WL, reconcile in non-reservoir portions of the well. The difference between them can be used as an indication of permeable sandy intervals not clearly identified in the GR and neutron/density logs in the 3257/3264m interval. Mud filtrate invasion seems to induce this difference.

For evaluation and volumetric calculation purposes the LWD curves provide the best resistivity, allowing the calculation of more realistic water saturations and the correct identification of the hydrocarbon bearing intervals. Integrating LWD and WL information was fundamental to interpret this well.

Case # 2: A real transition zone example

In some reservoirs we can observe a resistivity gradient between the oil zone at irreducible water saturation and the water leg, named the transition zone. In this interval the water saturation increases continuously in the down-hole direction to the oil/water contact.

Transition zones form in rocks due to capillarity effects in the pore space. It depends also on some hydrocarbon properties like viscosity. The high of this zone depends on the porosity/permeability relation of the rocks and its fluid content characteristics.

The logs presented in Figure 02 illustrate a typical transition zone. GR in blue and CALIper in black are plotted in track 01. Induction resistivity (ILD in black) stays in track 02, density (RHOB in blue), neutron (NPHI in red) and acoustic (DT in green) are in track 03.

The porosity of this carbonate reservoir decreases in the down-hole direction as can be seen in the porosity logs, in special on the acoustic log. Core measurements indicate that the permeability also decreases with the porosity.

We observe a constant resistivity level in the 1885/1925m interval indicating an irreducible water saturation zone. The resistivity decreases continuously from 1925m until the water zone below 2060m. A clear oil/water contact could not be marked due to this continuity.

Wire-line logs are sufficient to correctly characterize this kind of situations and water saturations calculated with them could be considered reliable.

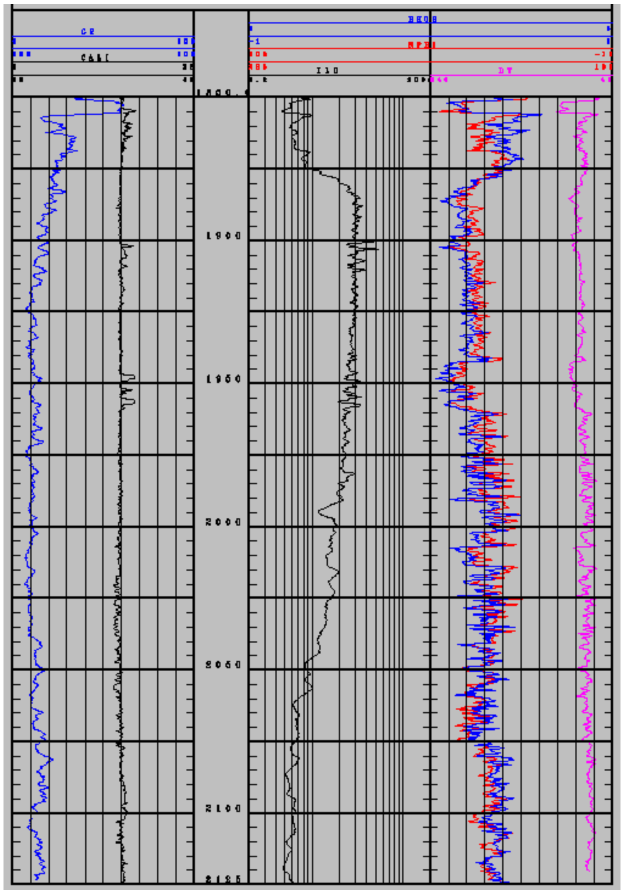

Figure 02: Example of transition zone.

Case # 3: Mixing invasion and transition zone

A more complex situation is presented in Figure 03. In this example we present the GR in blue and HCAL in red in track 01, LWD deep resistivity (SEDP) and shallow resistivity (SEXP) curves in track 02, density (blue RHOZ) and neutron (red NPHI) in track 03. The yellow shaded intervals indicate unconsolidated highly porous and permeable sandstones.

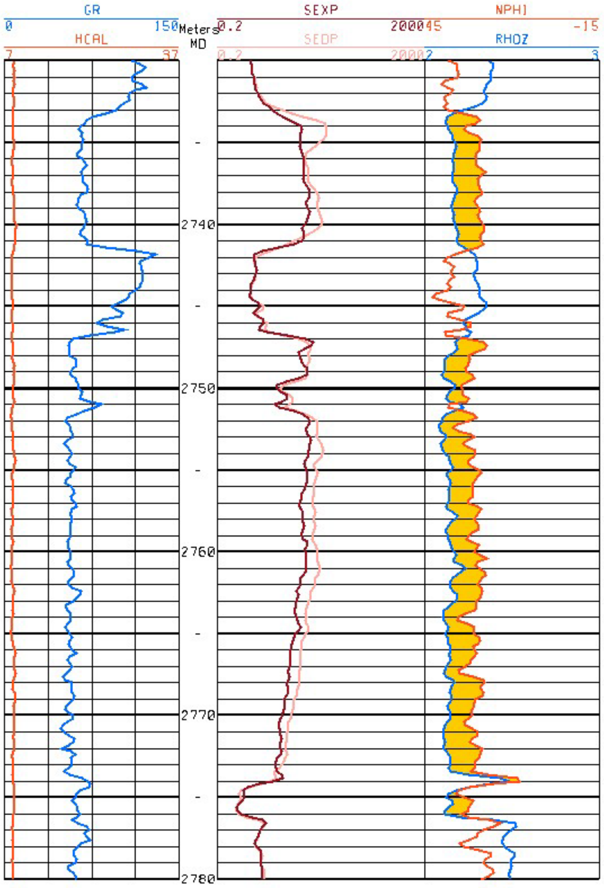

Figure 03: LWD resistivity log showing asymmetrical invasion profile.

The upper sandstone interval shows characteristics of mud filtrate invasion when comparing the deep resistivity with the shallow one in the interval 2733/2736m and 2738/2741m.

The lower sandstone interval also shows some influence of the mud filtrate invasion in the 2752/2772m interval. The most peculiar feature in this sandstone unit is, however, the resistivity gradient starting at 2751m, decreasing slightly until 2774m.

The oil/water contact seems to be masked by a thinly cemented layer at 2774m but we can assume that this is a sharp contact and that there is a huge difference, almost one logarithmic decade, between the oil zone and the water leg.

The question that immediately arises is: Are we really dealing with a transition zone like the one of the previous example?

Porosity logs show a constant behavior along all this section, indicating that we do have the same porous and permeable conditions. This is not a characteristic of transition zones, where we expect to have a decrease in porosity towards the oil/water contact. The step between oil and water is also unusual in transition zones. We will come back to this problem later in this paper.

To solve the invasion problem we should take a look in the wire-line logs of this well in Figure 04. Deep laterolog (dark blue HLLD) and shallow laterolog (green HLLS) resistivities were superimposed over the LWD logs in track 02.

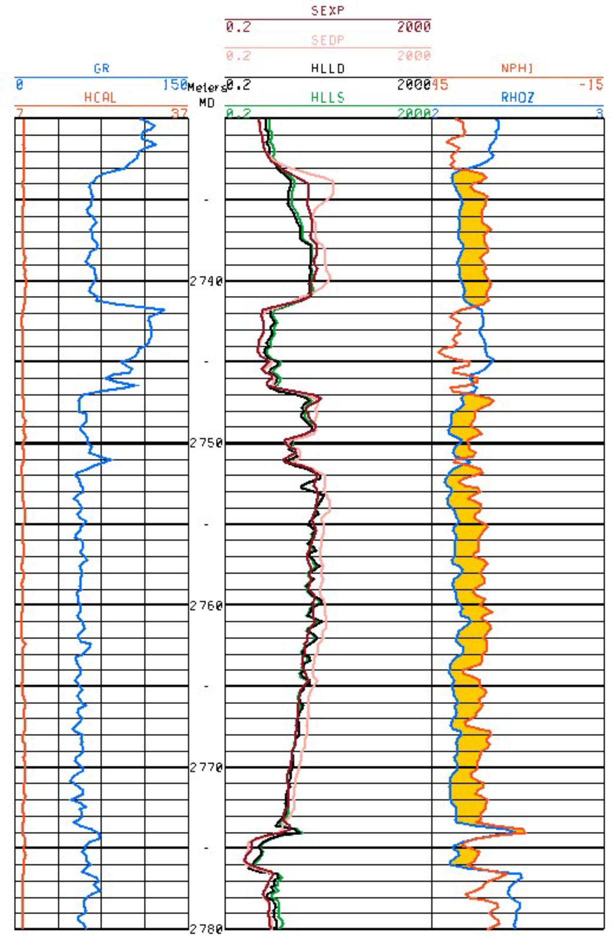

Figure 04: Previous well showing WL and LWD resistivity logs.

Invasion of mud filtrate resulted in an asymmetrical invasion profile in the top of the upper reservoir, slowing down the WL resistivities. All the remaining section seems to be only slightly affected by invasion, which could not be responsible for the resistivity gradient formation.

In this example the deep LWD resistivity SEDP should be used for water saturation calculations and hydrocarbon content definition. If the interpreter would have only the wire-line logs available he could easily misinterpret the upper portion of the pay zone as a thinly laminated sandstone sequence.

Case # 4: Oil biodegradation and resistivity gradients

As was mentioned in the previous example, the resistivity gradient observed on that logs could hardly be associated to a transition zone. Variations in rock grain size could affect resistivity measurements leading to the formation of gradients. In this case finer sands usually have lower resistivities than coarser sands due to the increase of irreducible water in the finer ones. Density logs often show a similar gradient effect with the finer sands having lower densities than the coarser ones.

Figure 05 illustrates a resistivity gradient similar to that of the previous case. In this composite log we show the WL GR in track 01 (black RG), laboratory grain size distributions in tracks 02 and 03, density (red) and neutron (light blue) WL in track 04, WL induction resistivity (black) in track 05, log porosity (black) and core porosity (blue dot) in track 06, core permeability in track 07 and log calculated SW in track 08.

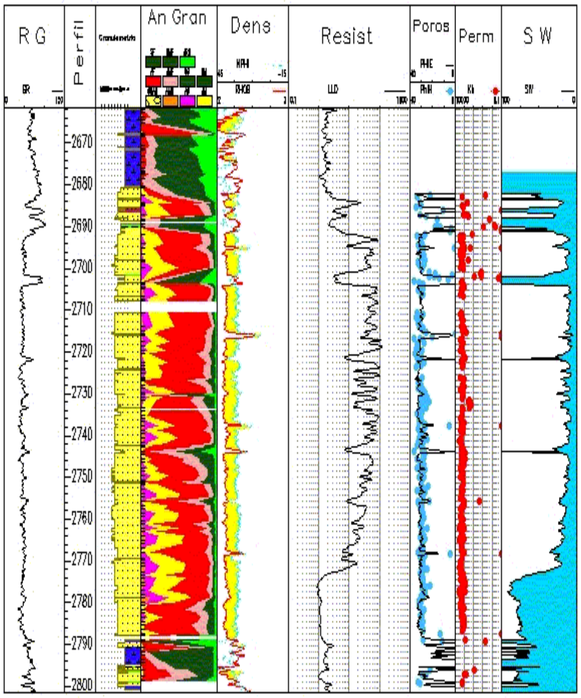

Figure 05: Composite logs integrating core and WL data.

The resisitivity log shows a gradient starting at 2736m and a sharp step at 2770m separating the oil and the water zones. The reflection of this gradient over the calculated water saturation can be seen in track 08. The irreducible water saturation is of the order of 15% but the mean water saturation of this pseudo-transition zone is around 22%.

This reservoir, like the one of the previous case, is an unconsolidated, high porosity (25-31%) and high permeability (1200-3100 mD) sandstone (^{2}). Porosity and permeability are very constant over the entire gradient zone as can be seen in the tracks 06 and 07. These permo/porous characteristics usually don't allow the formation of extensive true transition zones between oil and water intervals like the one present in this well, reaching a thickness close to 40m. Production data also do not support this interpretation.

The grain size distribution shows a coarsening of the sand to the bottom of the 2736/2780m interval (track 03), contradicting the normal grain size/resistivity relationship. A grain size originated resistivity gradient could not be evocated in this situation.

Recent geo-chemical studies performed on oil samples of this sequence showed that oil biodegradation starts on almost the same point that the resistivity gradient. These results are illustrated below.

In Figure 06 we have a composite plot of the above well with the same logs as previously defined in tracks 01, 02, 03 and 05. The track 04 represents the geo-chemical results, the amount of asphaltene components being colored in blue.

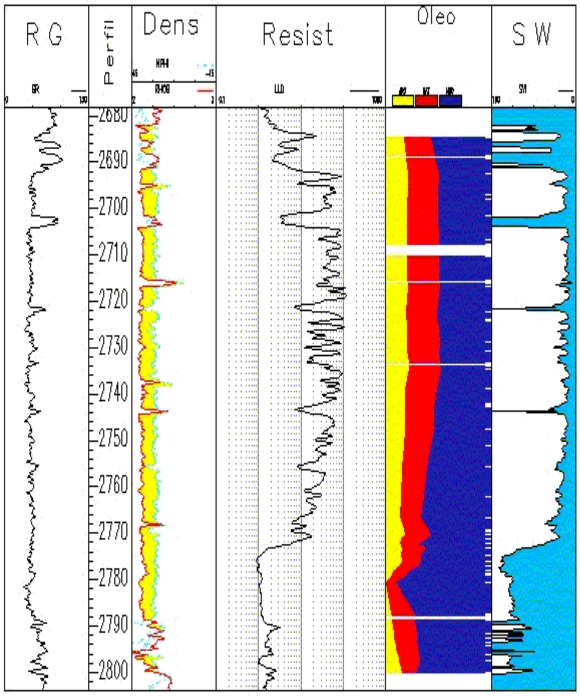

Figure 06: Composite logs showing geo-chemical data.

The amount of asphaltene components remains constant in the uppermost part of the reservoir, starting to increase at the depth close to 2736m, reflecting the biodegradation of the oil. The API degree also decreases in the same direction. Biodegradation can be so severe causing the formation of a tar mat as in the depth of 2780m, which constitutes an effective flow barrier ([3]).

The increase in asphaltene components changes the electrical behavior of the hydrocarbon. Asphaltene rich oils present bipolarity and, under extreme conditions, one can even invert the rock wettability. In our example there is a possibility that the oil bipolarity allows oil particles to retain a minor amount of water molecules, creating a favorable condition for electrical conduction ([4]).

This would provide a sounding explanation for the formation of resistivity gradients in these peculiar reservoirs, resulting in a profile similar to that found in a real transition zone. Water saturations calculated using these logs could be considered reliable. As in the previous #3 case, asymmetrical mud filtrate invasion seems to account for a minor contribution to the gradient.

Conclusions

Combining LWD and WL log information is a useful technique to understand and interpret asymmetrical invasion profiles.

Core data and petrophysical laboratory measurements are important complimentary tools for the correct evaluation of complex resistivity gradients.

Variations in hydrocarbon properties may produce some peculiar log responses and need to be accounted for the correct evaluation of hydrocarbon bearing rocks.

Acknowledgments

The authors express their gratitude to PETROBRAS for the permission to publish this paper.

References

(1) Allen, David et all. – Invasion Revisited. Oilfield Review, p 10 – 23, julho de 1991.

(2) Bruhn, Carlos Henrique Lima, et all. – Estratigrafia de alta resolução, heterogeneidades de reservatório e modelagem geológica tridimensional do reservatório do Campo de Marlim, Bacia de Campos. In: Anais do I Seminário de Reservas e Reservatórios, setembro de 1996. Seminário Interno PETROBRAS, Rio de Janeiro – RJ.

(3) Sombra, Cristiano Leite, et all. – Camada basal de petróleo viscoso em reservatórios da Bacia de Campos – Caracterização petrográfica, geoquímica e reconhecimento em perfis. In: Anais do Seminário de Reservatórios 2002, novembro de 2002. Seminário Interno PETROBRAS. Angra dos Reis – RJ.

(4) Beer, Rudolfo, et all. – Gradientes de resistividade e seu impacto na quantificação de reservas de hidrocarbonetos. In: Anais do Seminário de Reservatórios 2002, novembro de 2002. Seminário Interno PETROBRAS. Angra dos Reis – RJ.