Geosteering tools and geological modeling applied to HA/HZ well's petrophysical evaluation

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Abstract

Logging high angle and horizontal (HA/HZ) wells is commonplace nowadays, but it presents many challenges for petrophysical data interpretation, especially resistivity measurements. Uncertainties are not only confined to the input data suite but are also inherent to the parameterization of geological and petrophysical models used throughout the characterization effort.

Primary objective of this study was to provide LWD logs reliability by comparing them with wireline data using correlated no HA/HZ wells they are both available. In doing so demonstrate how more common LWD used tools are normally affected by HA/HZ wells and to demonstrate these concepts applied to horizontal wells closely correlated to those vertical and low angle wells.

This methodology suggests using geosteering normally used tools as image resistivity and azymuthal deep resistivities combined with conventional LWD logs and improved geological modeling to validate HA/HZ well's petrophysical evaluation.

Despite obtained results and all involved uncertainties this study aims to bring to discussion LWD petrophysical evaluation of development HA/HZ wells.

Introduction

Despite the widespread use of HA/HZ (high angle/horizontal) wells for offshore Brazil southeast's oil fields exploitation, using LWD (Logging While Drilling) logs as a tool for petrophysical evaluation is not commonly adopted. In spite of nowadays increasing demand for complex well's projects in siliciclastic mature reservoirs, aiming to exploit hydrocarbons in thin layers, field's fringes and thin sections close to gas caps and/or oil/water contacts, it is important to have improved well modeling available and to simulate logs for planning geosteering strategies in the quest for reducing costs and increasing production.

As LWD logs has lately become more and more reliable likewise industry has been developed new technologies for azimuthal and geosteering tools, it allows to estimate the true resistivity (Rt) of a formation and consequently to calculate reservoir's water saturation, even in some wells where the induction resistivities are apparently much affected for a HA/HZ well condition. For results to be valid it is important to have improved geological models and to have sharp quality control to process and interpret available data.

Objective

The aim of this study is to validate a petrophysical evaluation in two horizontal wells (*WELL A* and *WELL B*) drilled through the same siliciclastic reservoir, but with different structural frameworks. Both have the same lately most commonly acquired LWD logs for HA/HZ wells and the purpose is to integrate geosteering tools (azimuthal deep resistivity and resistivity imagery) with improved geological modeling in order to go beyond the main geosteering point by trying them as tools to validate LWD induction resistivities and calculating water saturation in HA/HZ wells.

Method

As this study's main idea is to present an uncommon and new methodology the criterion for choosing a reservoir was to look for a predominantly homogeneous sandstone in order to minimize the effects and anomalies that commonly occur in conventional LWD logs (gamma ray, resistivities, density and neutron) when acquired in HA/HZ wells. Besides the favorable reservoir chosen, it was took into account the availability of correlated vertical wells where there were complete wireline logs available for comparative results, thus providing reliability to the obtained LWD data.

The procedure involves three main steps: [1] to analyze quality of available LWD and wireline data from correlated wells by comparing logs and results with wireline data, [2] to analyze each LWD log from HA/HZ wells and to identify and to characterize anomalies and anisotropy resulting from each high angle well's condition. After steps 1 and 2 and technical features from LWD logs are known, then [3] perform a petrophysical evaluation workflow as similar as used in vertical wells.

It is important to highlight intrinsic features of each LWD tool and main effects observed in each log, especially those that most affect a petrophysical analysis. Due to large differences involved between resistivities and other conventional logs (gamma ray, neutron and density) it is necessary to analyze them separately because resistivities involve greater complexity and more variables. Correct identification of resistivity contrasts (conductive or resistive layers) in a well's vicinity and the geometry of these layers (relative angles to the path) are essential in understanding the behavior of conventional LWD resistivities.

Resistivities: main technical features to note on LWD logs are anisotropy, dielectric effect, adjacent layer effect, polarization horn and eccentricity (it is important to note that, unlike wireline logs, which are processed after their acquisition, LWD resistivities are always raw data.

Gamma ray, neutron, density: it is important to discretize non azimuthal logs and azimuthal (volumetric) logs to understand theirs behaviors when in a HA/HZ well. Most common features are transition effect and depth difference.

In addition to discussion involving LWD log's characteristics and HA/HZ well's peculiarities, an important key point for petrophysical evaluation in these cases are the deep azimuthal resistivity and resistivity imagery logs for constructing and updating geological reservoir modeling. Initially based on integration of geological and seismic models and resistivity contrasts (mapped in correlaed wells like a resistivity reservoir zoning) a pre drilling model is useful to plan geonavigation strategies and landings operations.

WELL A **and** ***WELL B*** **petrophysical evaluation**

Both HA/HZ wells here presented had real time and post drilling modeling based on same available LWD logs: gamma ray, resistivities (conventional (8 curves); imagery; azimuthal deep), density and neutron.

***WELL A*:** initial model predicted a straight horizontal well (90° inclination) geonavigating near the top of a slightly convex reservoir. Trajectory would descend through stratigraphy till near a lower resistivity layer (LAYER X) and would ascend again. Both syn and post drilling available models (Figs. 1a and 1b) compared to special acquired logs (resistivity imagery and deep azimuthal resistivity) confirmed it (Fig 2).

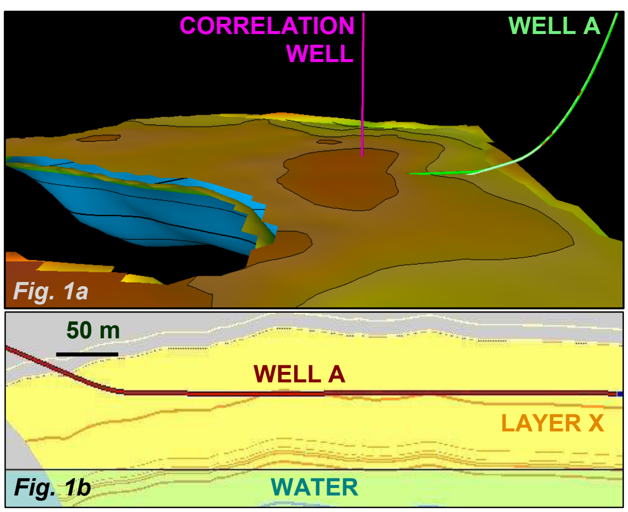

Fig. 1 - *a) WELL A's position through reservoir's top; b) post drilling model (similar to pre drilling model).*

Despite different degrees of interference caused on logs by conductive LAYER X it was necessary to discretize well dividing it into 2 different zonings (Fig 2) which log's processing would be in accordance with uncertainties generated by the HA/HZ well condition. So there were ZONING 1 for interpreting gamma ray, density, neutron and their derived data and ZONING 2 for processing resistivities and their derived data.

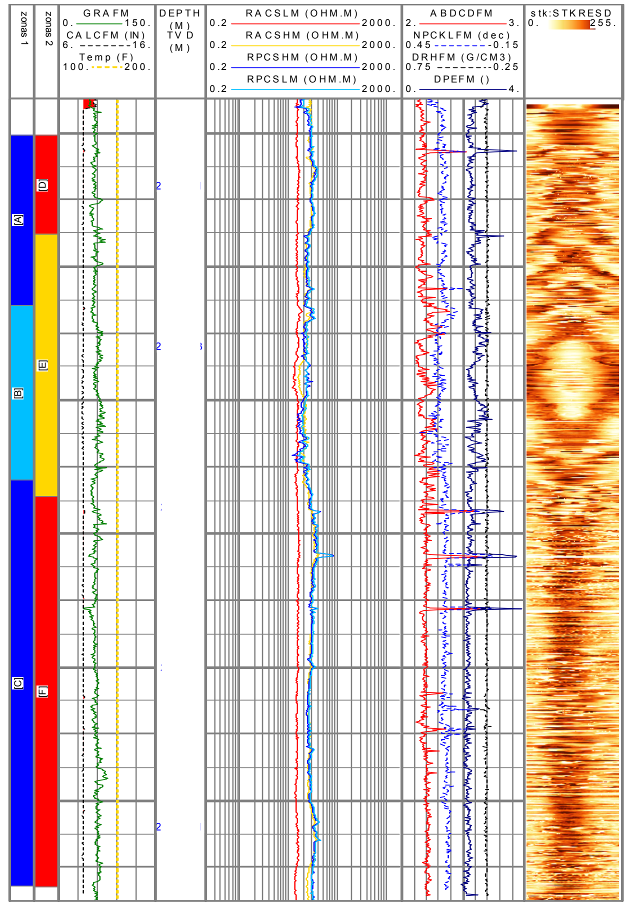

Fig. 2 - *WELL A's acquired logs and their correlated zonings.*

Detailed analysis on eight different conventional resistivity curves showed that most striking aspect was adjacent layer effect sawn on deeper curves near well's edges, specially those curves are relative to frequency attenuation. In the vicinities of clay rich LAYER X shallower curves (phase difference) has lower values and go towards deeper ones, confirming the geological model. Despite expected variations in resistivities readings there are no other significant observed effects like polarization horns or strong anisotropies, indicating a slightly facies variation through the perforated reservoir interval.

***WELL B*:** even *WELL B* refers itself to the same reservoir as *WELL A* crossed through, it presented a series of hard interpreting factors in applying proposed methodology. Despite initial geosteering strategy was planned to be horizontal through its fullest extent (Fig. 3a), *WELL B*'s geonavigation process went through a series of not predicted reservoir's structural odds that strongly affected all conventional acquired logs especially resistivities (Fig. 3b).

Just after starting geonavigation well's trajectory got out of the reservoir through its top. Even though a forced drop off was made to get back in it was necessary to keep a gradual angle decrease while trajectory got in and out twice more till it finally got in the reservoir permanently. To build a reliable post drilling geological model was the critical issue before trying a valid petrophysical evaluation. Considering involved structural geology complexity and how it directly interfered on log acquisition (specially resistivities) whole HA/HZ well was divided into two distinct zonings: [a] ZONING 4 for gamma ray, density and neutron logs and [b] ZONING 3 for resistivities and their derived data (Fig 4).

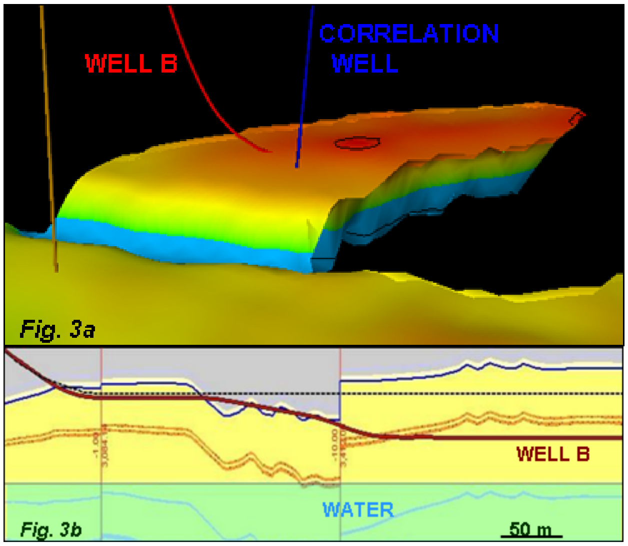

***Fig. 3 -** a) WELL B's position through reservoir's top; b) post drilling model.*

ZONING 3: gamma ray shows transition effect near sandstone/shale boundaries while neutron and density seem affected mainly by carbonate concretions and some transition effect (neutron) and depth difference (density).

ZONING 4: low frequency attenuation curves are most affected and show strong adjacent layer effect while high frequency attenuation seem to be slightly affected by dielectric effect. Looking at all four phase difference curves they seem to be quite consistent and have no significant anomalies or anisotropy. Resistivities behavior through last well's half indicate a gradual increase in resistivity and validating these curves depended on image interpretation and understanding azimuthal deep resistivity. Taking into account that formation's exposure time is normally low when acquiring LWD logs it means an advantage because drilling fluid invasion was not able to affect shallower curves.

There were three major difficulties while evaluating WELL B: [a] supposed shale/sandstone interchange during geonavigation's beginning (Fig. 4), [b] a large number of variegated carbonate concretions inside whole reservoir (Fig. 5), [c] a fault zone across geonavigation's half and end (Fig. 6). Resistive imagery and azimuthal deep resistivity substantially helped in understanding how layers close to the trajectory affected logs (or not) and to estimate concretion's influenced logs and reservoir's permo-porosity.

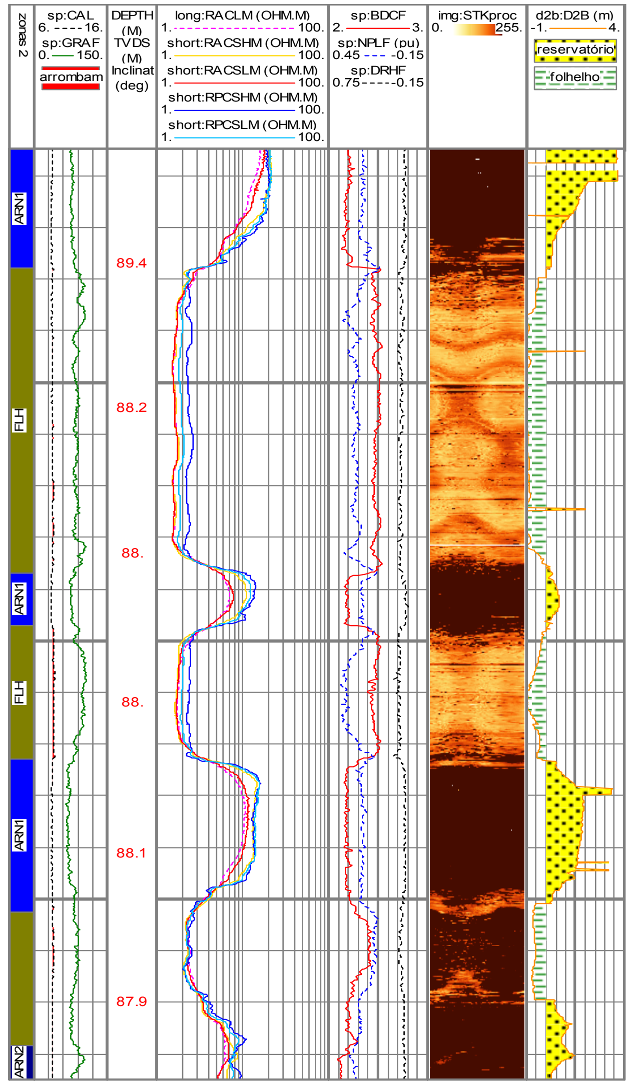

***Fig. 4 -** a) shale/sand interchange imagery combined with azimuthal deep resistivity showing trajectory going out and in across reservoir's top.*

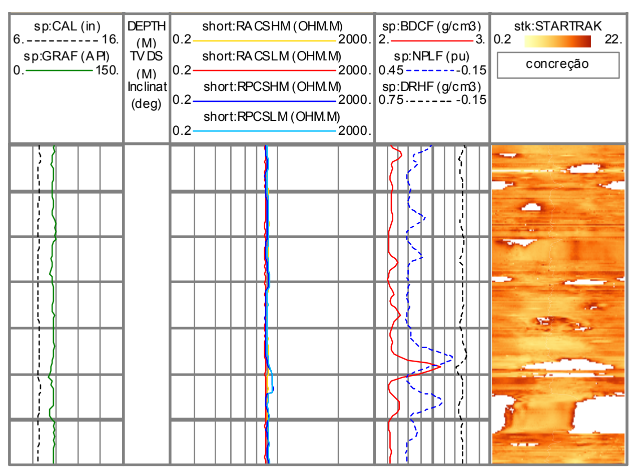

***Fig. 5 -** widespread and not connected carbonate concretions inside reservoir.*

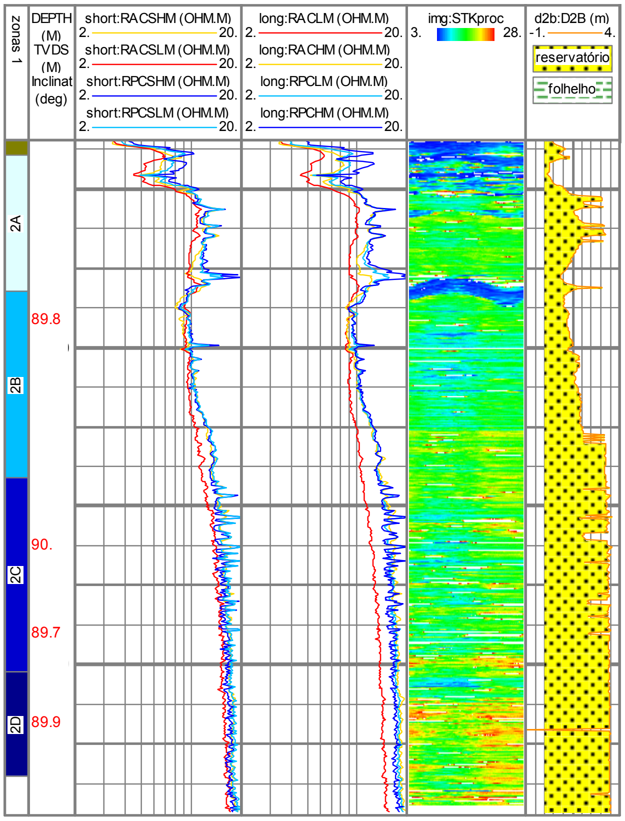

***Fig. 6** - resistive imagery and color contrasts used to distinguish faults (track 5) and resistive increase towards well's end (tracks 3, 4 and 5).*

Results

Although normally best LWD resistivity for water saturation's estimative would be a low frequency phase difference curve (RACLM) which is theoretically less affected by HA/HZ condition, developed quality control showed that high frequency phase difference (RACSHM) which offers better resolution was minimally or none affected in both wells (Figures 7 and 8). Adopting Archie parameters obtained from correlated wells and extrapolating them to *WELL A* and *WELL B* after showed criterous quality control achieved reliable results that seemed similar and coherent to those were expected according correlated wells (see Table 1).

Conclusions

Considering primary objectives and achieved results the methodology was effective and able to be better developed. HA/HZ evaluation were close to those obtained from correlated wells and gave good results even in those intervals where uncertainty apparently prevailed.

Structural differences involving *WELL A* and *WELL B* and consequent different degree of difficulties for interpreting resistivities demonstrated how important is to build a reliable geological model.

Developed methodology showed the importance of data quality control before trying an unconventional evaluation and how geosteering tools can be usable for this process.

Acknowledgments

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Table 1 - comparison results.

WELL A's CORRELATED (wireline)									
interval	***H***	***gross***	***net***	***net/gross***	***PHI av.***	***Vcl***	***Sw av.***	***H*PHI***	***H*PHI*So***
oil (top)	*10,00*	*9,90*	*9,82*	*0,99*	*0,24*	*0,05*	*0,15*	*2,37*	*2,03*
oil (botton)	*20,43*	*20,43*	*19,75*	*0,97*	*0,25*	*0,04*	*0,19*	*4,91*	*3,99*
total	***97,54***	***97,54***	***29,57***	***0,30***	***0,25***	***0,05***	***0,17***	***7,28***	***6,01***
WELL A's CORRELATED (LWD)									
interval	***H***	***gross***	***net***	***net/gross***	***PHI av.***	***Vcl***	***Sw av.***	***H*PHI***	***H*PHI*So***
oil (top)	*9,90*	*9,90*	*9,67*	*0,98*	*0,25*	*0,05*	*0,16*	*2,34*	*1,98*
oil (botton)	*20,43*	*20,43*	*19,44*	*0,95*	*0,26*	*0,04*	*0,21*	*4,84*	*3,81*
total	***97,54***	***97,54***	***29,11***	***0,30***	***0,25***	***0,05***	***0,20***	***7,17***	***5,79***
WELL B's CORRELATED (wireline)									
interval	***H***	***gross***	***net***	***net/gross***	***PHI av.***	***Vcl***	***Sw av.***	***H*PHI***	***H*PHI*So***
oil (top)	*10,05*	*10,05*	*9,59*	*0,96*	*0,26*	*0,06*	*0,15*	*2,46*	*2,09*
oil (botton)	*15,80*	*15,80*	*14,33*	*0,91*	*0,26*	*0,05*	*0,20*	*3,76*	*3,00*
total	***67,17***	***67,17***	***23,93***	***0,36***	***0,27***	***0,05***	***0,18***	***6,22***	***5,08***
WELL B's CORRELATED (LWD)									
interval	***H***	***gross***	***net***	***net/gross***	***PHI av.***	***Vcl***	***Sw av.***	***H*PHI***	***H*PHI*So***
oil (top)	*10,05*	*10,05*	*9,56*	*0,95*	*0,25*	*0,06*	*0,15*	*2,36*	*2,01*
oil (botton)	*15,80*	*15,80*	*14,48*	*0,92*	*0,25*	*0,05*	*0,20*	*3,62*	*2,89*
total	***67,17***	***67,17***	***24,04***	***0,36***	***0,25***	***0,05***	***0,18***	***5,97***	***4,90***

WELL A									
interval	***EPH***	***gross***	***net***	***net/gross***	***PHI av.***	***Vcl***	***Sw av.***	***EPH*PHI***	***EPH*PHI*So***
[D]	*74,37*	*74,37*	*73,91*	*0,99*	*0,28*	*0,06*	*0,14*	*21,24*	*18,16*
[E]	*196,14*	*196,14*	*196,14*	*1,00*	*0,27*	*0,11*	*0,17*	*54,8*	*45,39*
[F]	*292,15*	*292,15*	*288,49*	*0,99*	*0,27*	*0,06*	*0,15*	*79,67*	*67,61*
total	***562,66***	***562,66***	***558,55***	***0,99***	***0,27***	***0,08***	***0,16***	***155,71***	***131,16***

WELL B									
interval	***EPH***	***gross***	***net***	***net/gross***	***PHI av.***	***Vcl***	***Sw av.***	***EPH*PHI***	***EPH*PHI*So***
1A	*127,56*	*127,56*	*127,48*	*1,00*	*0,25*	*0,07*	*0,17*	*31,99*	*26,69*
1B	*10,21*	*10,21*	*10,13*	*0,99*	*0,25*	*0,08*	*0,21*	*2,52*	*2,00*
1C	*29,57*	*29,57*	*28,04*	*0,95*	*0,25*	*0,07*	*0,22*	*7,05*	*5,51*
2A	*85,8*	*85,80*	*85,80*	*1,00*	*0,27*	*0,08*	*0,20*	*22,85*	*18,20*
2B	*117,65*	*117,65*	*117,65*	*1,00*	*0,28*	*0,05*	*0,19*	*32,64*	*26,42*
2C	*121,92*	*121,92*	*121,92*	*1,00*	*0,28*	*0,04*	*0,16*	*33,82*	*28,35*
2D	*65,84*	*65,84*	*65,84*	*1,00*	*0,27*	*0,05*	*0,16*	*17,92*	*15,12*
total	***558,55***	***558,55***	***556,87***	***1,00***	***0,27***	***0,06***	***0,18***	***148,79***	***122,28***

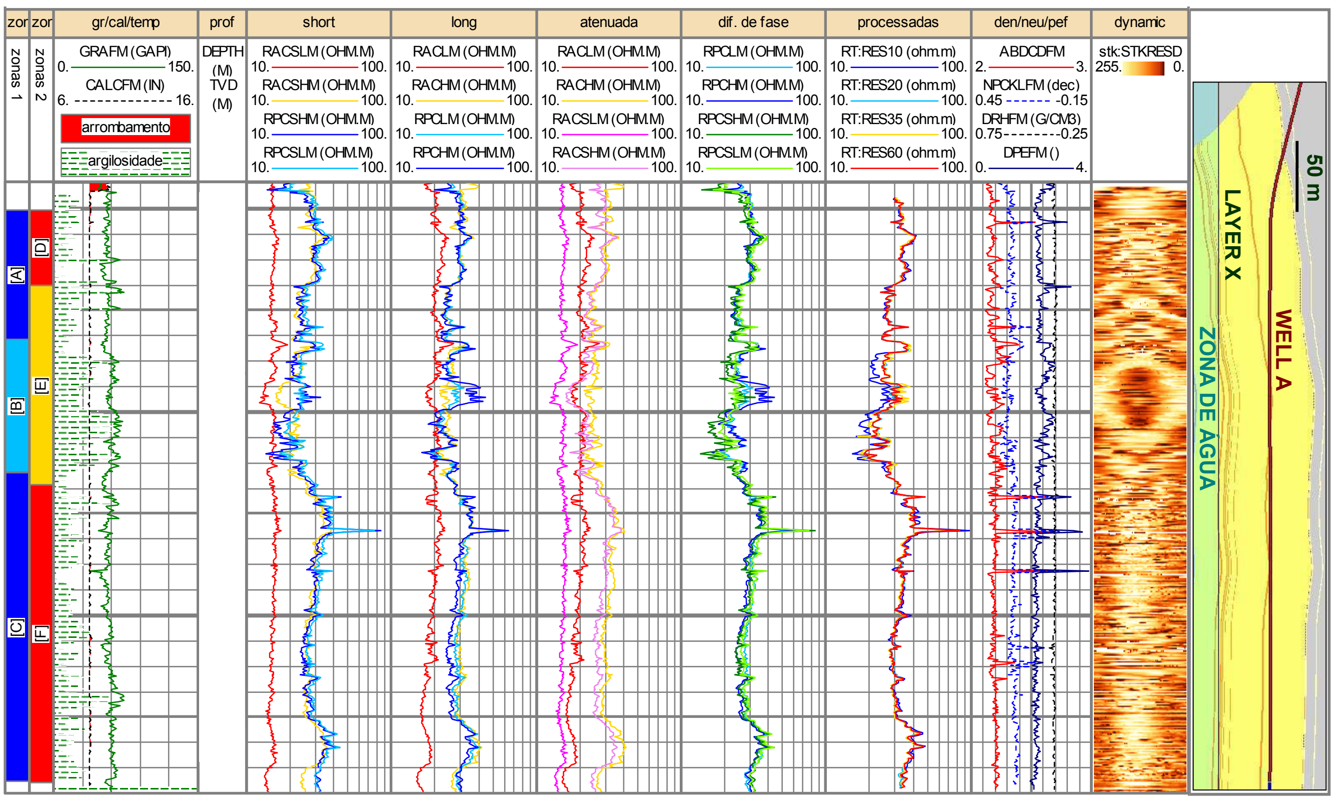

***Fig. 7 -** WELL A's data integration.*

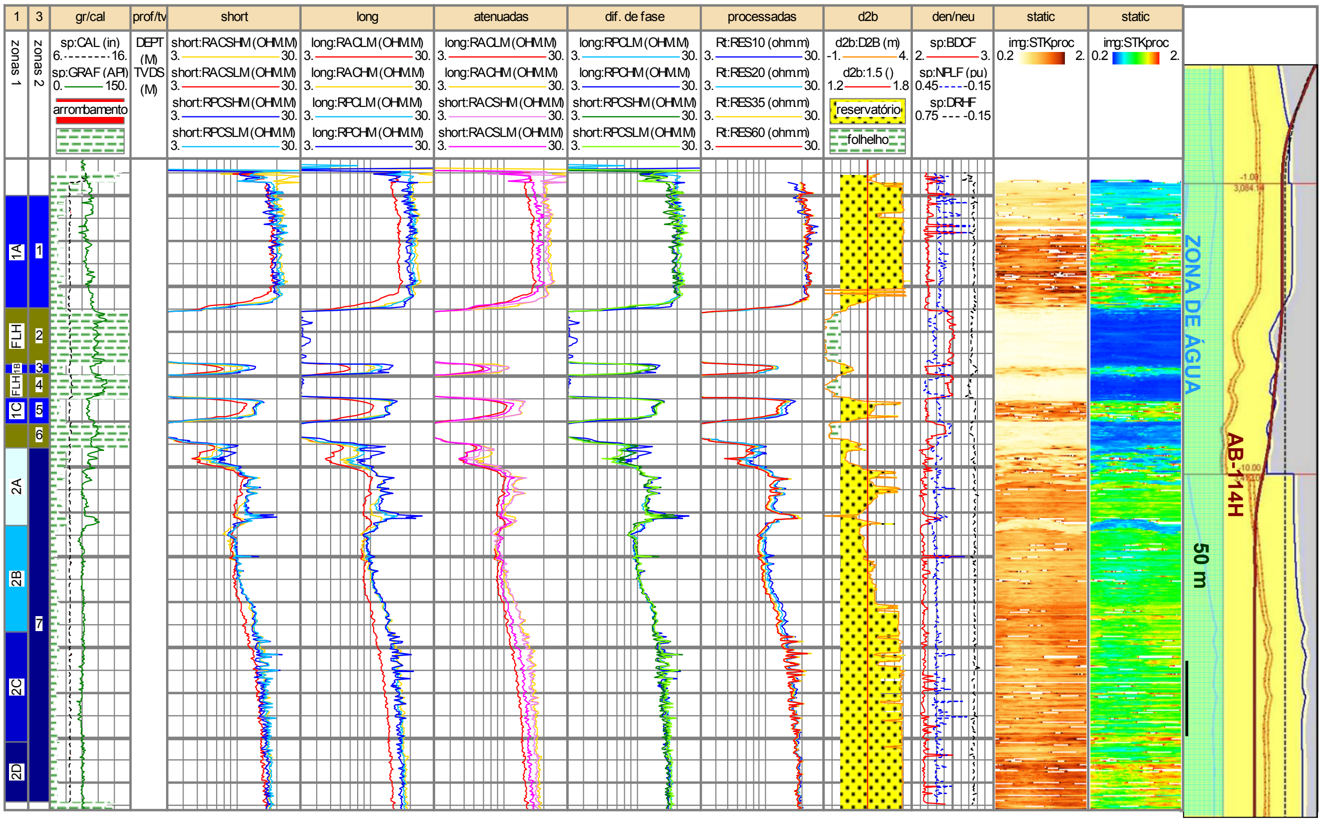

Fig. 8 - *WELL B's data integration.*