Well Correlation by Fuzzy Inference

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Abstract

Well correlation performed using the interpretation of patterns present in wireline logs tries to establish lateral extension and variations in the reservoir parameters from one borehole to another. In the other hand, stratigraphic correlation aims to produce a cross-section of an oil field based on facies recognition using outcrops or cores and the establishment of a temporal sequence of geologic events. Those traditional manual tasks have an important role in geologic modeling of oil reservoir and in the development of production strategies that aim to improve oil recovery. The difficulties in the conversion from well correlation to stratigraphic correlation reside in facies recognition and in the establishment of a stratigraphic sequence in the well logs.

We present a fuzzy inference system able to promote facies recognition by a classifying type fuzzy and fuzzy sequence match to identify a stratigraphic sequence in the layers crossed by a borehole. Thus, well correlation can be performed in non-cored boreholes with all geological applications of stratigraphic correlation

We present this methodology using synthetic well log data and shown an application in two boreholes in the Namorado oil field, Campos's basin, Brazil.

Introduction

Stratigraphic correlation is the study of relationships among rock units or facies from different stratigraphic sections by the identification of a datum or marker bed that can be clearly identified in both sections. Thus, may be demonstrated the equivalency of rock units across an area. Sequences of sedimentary rocks are established on a bed-by-bed basis by thickness of each bed, physical, chemical, and biological characteristics. These data help in to draw up a stratigraphic section for a particular temporal sequence of rocks. A stratigraphic section is a graphical representation of this rock sequence.

A correlation is a hypothesis that units in two separated sequences are equivalent. The time parallel surfaces are considered isochronous, that is, laid down at the same time; and therefore, are important in determining relative time. Key or marker beds are time parallel surfaces that represent any widespread activity that took place in a geological instant.

In some cases, a bed thins progressively in one direction until it pinches out. A pinchout may or may not be accompanied by the increase in thickness of an adjacent unit. In some case, the entire sedimentary section thins in a certain direction.

Well correlation, or the transport of geological information from one borehole to another, is a way to extend laterally the local information produced by wireline logging and permits the definition of lateral continuity and geometric disposition of rock layers that are crossed by different boreholes (cored or non-cored).

The spatial and temporal geological information and its transport from cored wells to non-cored wells are fundamental geological activities to improve the geological model of an oil reservoir. This kind of work is deeply affected by geologist experience and dependent of his interpretative criterions to read and choose the correct log readings to choose appropriated patterns to be correlated.

Usually, the facie identification is obtained from core analysis. The cores are not deformed rock samples and are obtained, in the subsurface, from complex drilling operations. However, just a few boreholes are cored in an oil field, principally for economic reasons. Well logging, in the other hand, is a common technique, applied in all boreholes in an oil field, which measure the physical properties of rocks surrounding the borehole and permits geologists handle with the lack of continuous information in the core data.

The facies recognition using cores is based on geologic features in the rock sample and using well log data, may be realized taking a calibration between rock physical properties and facie information from cores. A common method in formation evaluation to lithologic identification is the M-N plot (Burke et al. 1969), which integrates three physical properties (density, neutron porosity, and acoustic transit time) to enhance the rock composition sensibility of logging tools and avoid the porosity influence in these measures individually.

We present a fuzzy inference system, without defuzzyfication, which is able to reproduce stratigraphic correlation with wireline logs. The fuzzy inference system can be divided in two steps. In the first one, we use the conventional M-N plot to map the facies identification (from core analysis in a reference cored well) in well log readings. This mapping process can be translated in the determination of membership functions of a fuzzy classification process. The second step, a fuzzy sequence match is used to produce the identification of a particular stratigraphic sequence of beds crossed by a borehole that has significance in the reservoir model.

This fuzzy process produces the transport of geological information from a cored borehole to another non-cored borehole. Thus, well correlation can be performed including non-cored boreholes, with all geological benefits of stratigraphic correlation. Our principal intention here is to transform the raw well log data in geological information useful to oil industry.

We show an evaluation of this methodology for one particular shale and sand sequence presents in two cored boreholes in Namorado oil field, Campos basin, Brazil.

Namorado oil field

The Namorado oil field is located in the central part of Campos basin (Figure 1) and composed by a sequence of clastics and carbonates rocks (conglomerates, sandstones, shales, marls and diamictites) of transgressive characteristic (Guardado et al., 1990).

As a function of its particular low energy depositional environment and occurrence in a large area inside the basin, the shales are a natural reference of the ancient topography and a good correlation datum, with high probability to be crossed by different wells in an oil field.

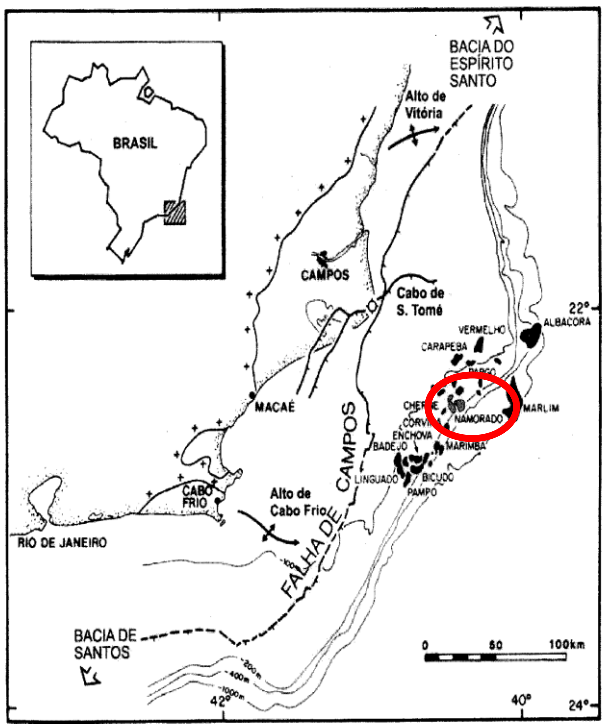

Figure 1- Campos basin map. The Namorado oil field location is highlighted by a red circle.

Method

Well correlation, usually, is performed taking two or more well logs, natural gamma ray log, and resistivity log are of common use (Luthi, 2001). Here, we the M and N parameters from porosity logs.

We present an automatic well correlation performed by a fuzzy inference system, without defuzzyfication, which is able to reproduce stratigraphic correlation with wireline logs. The fuzzy inference system can be divided in two steps: The fuzzy classification realizes the facies identification and produces the zonation of a non-cored borehole. In the second step, a fuzzy sequence match is used to produce the identification of a particular stratigraphic sequence

The M-N plot

The M-N plot (Burke et al., 1969) uses a combination of sonic, density and neutron porosity logs and attempts to remove the effect of porosity on these measurements. A combination of the sonic and density measurements is used to define the M parameter, which is the slope of the curve for each particular lithology in the sonic-density crossplot that varies slightly among the three common lithologies of reservoir rocks due the matrix endpoints. The slope of neutron-density crossplot is designated as N. Thus, each one rock forming mineral produces a slightly different value of N and M. Porosity variations affect both the numerators as well as the denominators of M and N, making them almost independent of porosity (Luthi, 2001).

The M and N parameters can be expressed in metric units as

$$M = \frac{\Delta t_w - \Delta t_m}{\rho_m - \rho_w} 0.003 \qquad (1)$$

$$N = \frac{\phi_{\mathrm{Nw}} - \phi_{Nm}}{\rho_m - \rho_w} \qquad (2)$$

In equations (1) and (2), Δt_w represents the transit time for fresh water; Δt_m, the matrix transit time; ρ_m, the matrix density; ρ_w, the fresh water density; ϕ_{Nw}, the water neutron porosity and ϕ_{Nm}, the matrix neutron porosity. The M and N values can be obtained with log readings by replacing the matrix values in the respective equations by the appropriate log readings (Crain, 1986).

Some common minerals have well-defined values of M and N, some of which are listed in Table 1. Those points are plotted in the M-N plot as fixed points or matrix reference points, as shown in Figure 2. If a pair of M and N calculated with log readings in a particular depth of a borehole are plotted on the overlay of the M-N plot, the intersection of those M and N defines a depth point in the M-N plot. The location of depth point with relation to fixed points may permit simplified lithology identification.

Table 1 – M and N values for common minerals.

Mineral	***Composition***	***M***	***N***
Quartz	SiO_2	0.81	0.64
Calcite	$CaCO_3$	0.83	0.59
Dolomite	$CaMg(CO_3)_2$	0.78	0.49
Anhydrite	$CaSO_4$	0.70	0.50
Gypsum	$CaSO_4.2H_2O$	1.01	0.30
Clay Minerals			
	Illite	0.6	0.49
	Kaolinite	0.6	0.45
	Smectite	0.6	0.50

If characteristics of actual fluid approximate the fluid properties used in the M-N plot construction and there is no evidence of secondary porosity in the reservoir rock, the location of any depth point in the M-N plot depends primarily on the matrix characteristics.

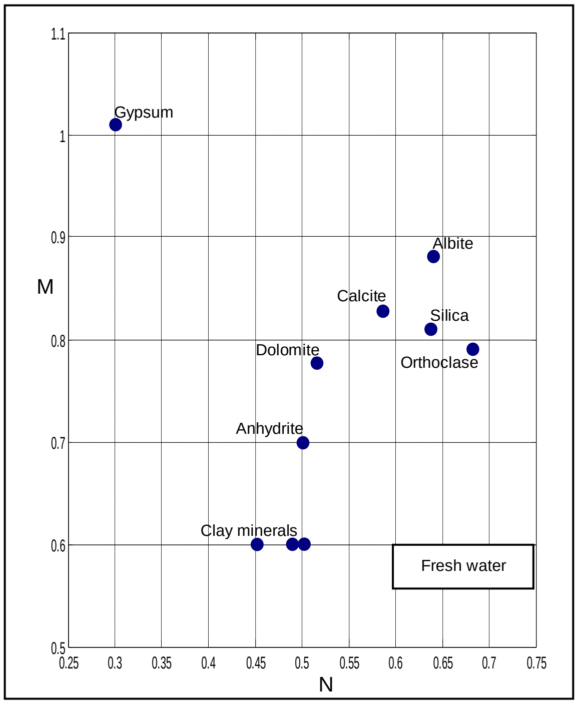

Figure 2 – The M-N plot.

Fuzzy Inference

Fuzzification is a function from a discrete value, in a domain of discourse, to a fuzzy dimension. This process creates a fuzzy value from a crisp value. The fuzzification process may encode both the concepts of uncertainty and relative membership. Uncertainty of input is encoded by having high membership of other possible input element. In general, an input element close to the received input element is mapped to in the fuzzy dimension in the same way, but not necessarily. Relative membership is the concept that if an element has degree of membership $\boldsymbol{X}$, then elements close to it should have a degree of membership close to $\boldsymbol{X}$.

Fuzzy inference is performed over a set of rules (logical sentences upon which a derivation can be performed), with the same domain of discourse, to produce a single consequence. There are two forms of inference, the first one is to derive the consequent from each rule, and apply a fuzzy operator (T-norm) to the set of consequences to obtain a single consequent. The second approach of fuzzy inference is to combine the rules into a one composed rule to derive a single consequent.

The antecedent of a fuzzy rule is a multi-dimensional fuzzy set. An antecedent attribute is a single fuzzy dimension (domain of discourse) of the multi-dimensional antecedent fuzzy set. An applicable rule has a consequent as a subset of the set of all inputs in a fuzzy-multidimensional space that has the same domain of discourse as the antecedent of. A classic fuzzy rule can be started as (Ros, 1995)

IF $\boldsymbol{A}$ THEN $\boldsymbol{B}$

where $\boldsymbol{A}$ is an antecedent and $\boldsymbol{B}$ is a consequent.

In fuzzy logic, the result of a fuzzy inference is of use in the real domain, so a defuzzification function from the consequent fuzzy set to a single element in the domain of discourse is required. This is a function from a fuzzy set to a single discrete ('crisp') value.

Fuzzy Sequence Pattern Match

Sequence pattern matching problem aims to find a particular pattern P in a pattern set S. The classic example is to find a particular word in a text; in this case, the rule is to search an exact sequence of letters (pattern P) in the whole text (pattern set S). In real applications, some of events in the searching pattern are non-existent in the sequence data. A classic example is in biological data where two proteins with similar functional properties may have similarity in their DNA sequences. (Gusfield, 1997)

The inference rule for sequence pattern mach can be started as

IF sequence $(\boldsymbol{P_1}, \boldsymbol{P_2} \ldots)$
THEN pattern $\boldsymbol{T}$ exist with degree $\boldsymbol{d}$

Where $\boldsymbol{d}$ = T-norm $[\mu(\boldsymbol{P_i})]$ and $\boldsymbol{P_i}$ is a consequent of a fuzzy rule that consider the order of occurrence or position in the sequence vector that represents the pattern P.

In a more general case, ASCII representation of an event may be not efficient, as in the case of a representation of a sequence of facies in a stratigraphic section. In this case, a linguistic representation may be an effective choice.

Example

We present well correlation by fuzzy inference with synthetic data using a modified shaly rock model, including the shale in the matrix constitution to simulate the conventional porosity logs as

$$p = \phi p_w + V_{sh} p_{sh} + (1 - \phi - V_{sh}) p_m \qquad (3)$$

In equation 3, p can be the neutron porosity, density, or sonic log reading, V_{sh} is the shale volume and ϕ is the porosity. p_{sh} and p_m are porosity parameters for shale and matrix, respectively.

The natural gamma ray log is modeled in function of shale volume, considering the following equation

$$GR = V_{sh}(GR_{max} - GR_{min}) + GR_{min} \qquad (4)$$

GR_{max} and GR_{min} represent the assumed maximum and minimum values for natural gamma ray log readings.

This rock model considers the shale properties in the reservoir as equal the properties of neighbor shale layers. In this appoach, the visual interpretation of porosity logs, as shale cut-off and porosity cut-off are eliminated, with M and N values calculated with raw logging readings.

Figure 3 shows the synthetic natural gamma ray log measured in the reference cored borehole and the reference stratigraphic sequence to be correlated.

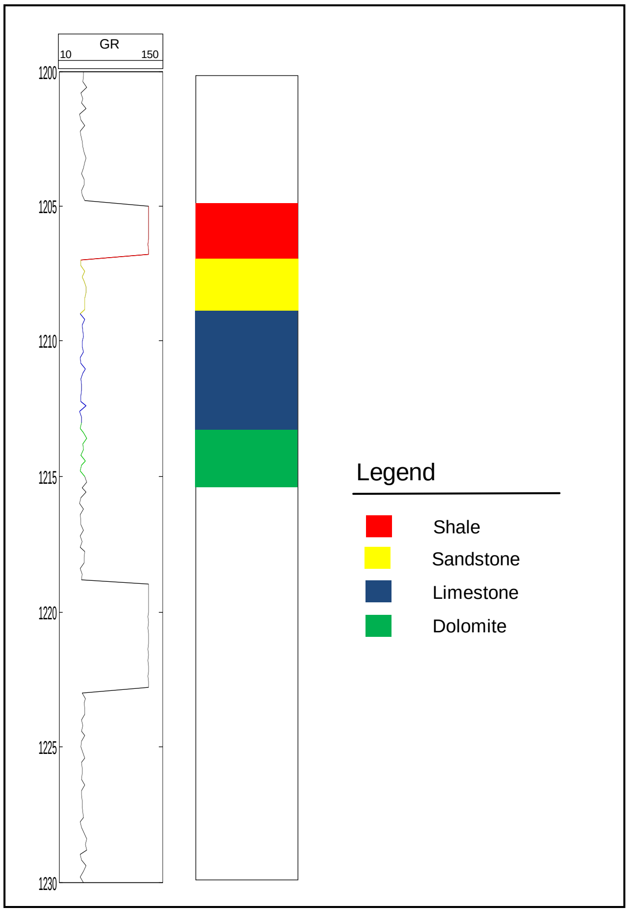

Figure 3 – Synthetic data. Natural gamma ray log and reference stratigraphic sequence.

The first step in the fuzzy inference system for well correlation is the calibration of facies, as identified in core analysis, with porosity log readings represented in M-N plot. This calibration is the base for fuzzy classification or the identification of those reference facies in the others boreholes. The fuzzy classification starts with determination of membership functions in the M and N domain of discourse for each one facie identified in the reference borehole. For both M and N parameters was adopted a Gaussian membership function with parameters defined in function of the spread of M and N values from log readings in the M-N plot.

Figure 4 shows M-N plot with reference facies sequence in the cored borehole showed in Figure 3. The red crosses represent the shale layer, in the top of sequence, followed by the sandstone facie, as yellow crosses. Blue crosses represent the limestone layer deposited after the dolomite layer represented by green crosses in the bottom of reference sequence.

In the M-N plot is defined the membership functions for each reference facie. Figure 5 shows the membership functions for the reference facies for the M parameter.

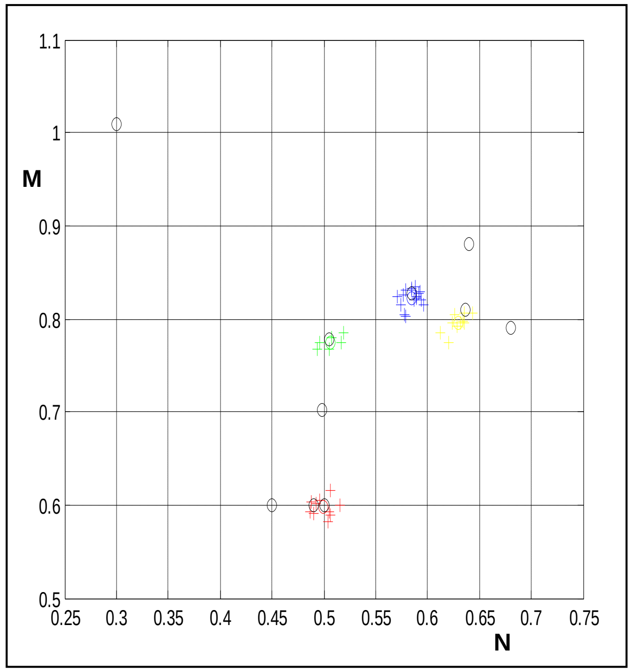

Figure 4 – M-N Plot. Reference facies in the reference well.

Figure 6 shows the membership functions for the reference facies for the N parameter. In Figures 5 and 6 is kept unchanged the legend of colors for the reference sequence of facies in the reference well.

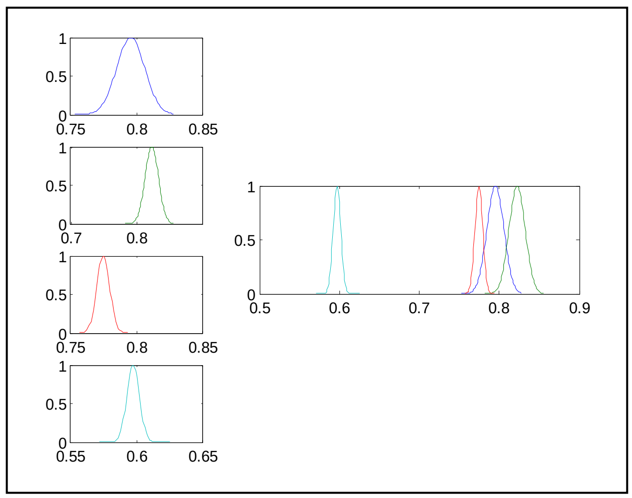

Figure 5 – Membership functions for the reference facies in the M parameter.

The fuzzy classification proceeds with the evaluation of the membership degree for each pair of M and N values in a non-cored well. The net result of this process is the zoning of non-cored well in function of facies identified in the reference borehole.

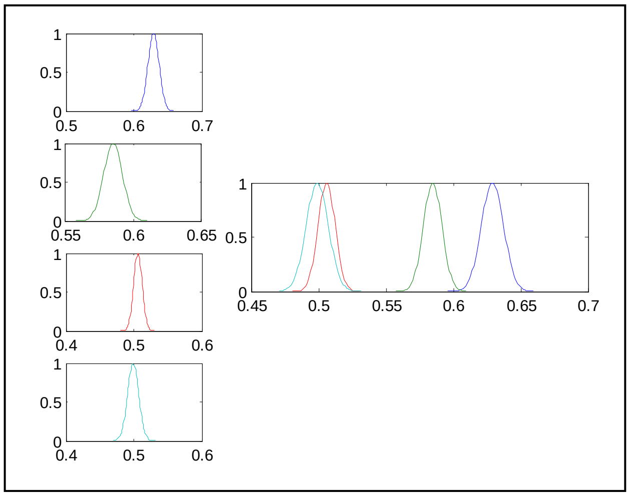

Figure 6 – Membership functions for the reference facies in the N parameter.

Figure 7 shows the results of fuzzy classification and the zoning of non-core borehole showed over the natural gamma ray log. Figure 7 also shows the synthetic stratigraphic section as identified by the fuzzy inference.. In this time, each identified facie receives a linguistic term, which will represent this facie in the stratigraphic section.

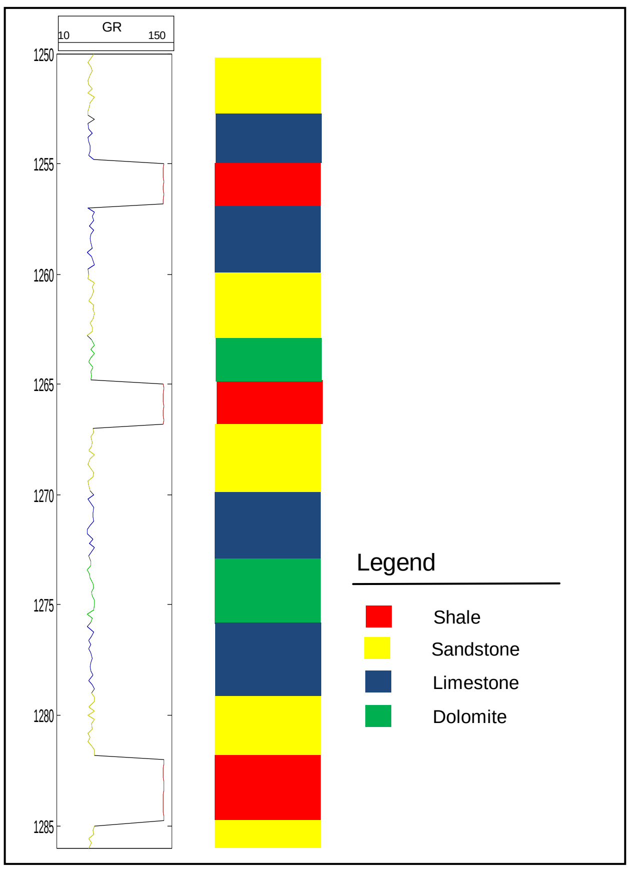

Figure 7 – Test borehole. Zoning using natural gamma ray log.

In the real world, just facies identification in a non-cored borehole is necessary, but it is not sufficient to support the well correlation. The time depositional scale is not considered by well log data. In the geological observations proceeded during the core analysis may be possible estimate the time sequence of successive cores. This information can be transported to non-cores boreholes in support to well correlation.

The fuzzy sequence pattern match take as input the linguistic terms associated with the facies identified by the zoning in the non-cored borehole. This process can be understand as to find a substring of linguistic terms representing the facies sequence in a string represented by the zoning of non-cored borehole.

The reference sequence is formed by shale, sandstone, limestone, and dolomite from the younger to oldest facie in the reference interval.

Figure 8 shows the well correlation over the natural gamma ray logs established between the cored and the non-cored boreholes.

In Figure 8, we show only the correlation of reference facies and notice that the full correlation can be established following those correlations lines. We notice that is impossible the crossover of correlations lines to honor the depositional time scale.

If one considers only the facie identification, could be a hard problem to decide which shale layer in non-cored borehole correlated with shale in the reference interval.

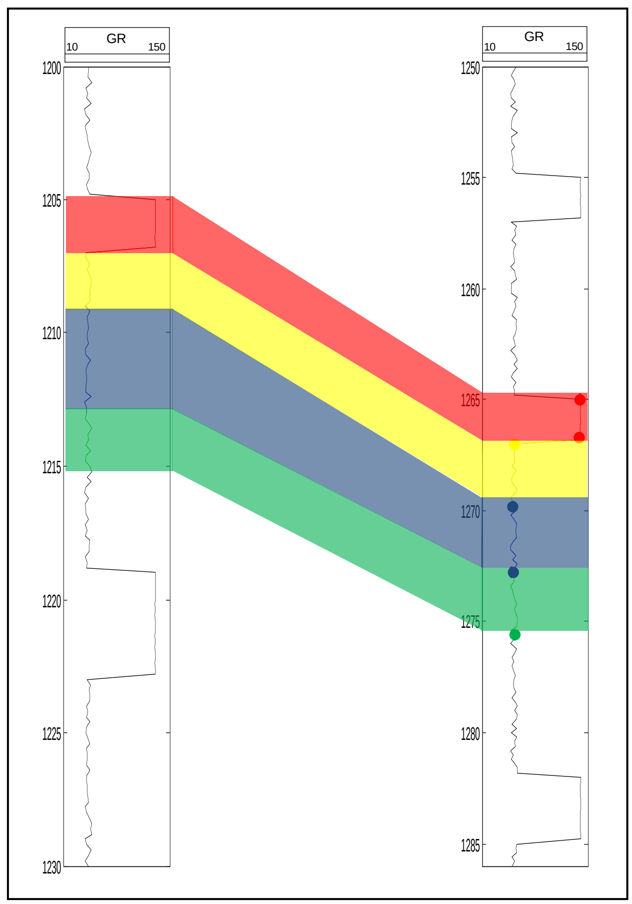

Figure 8 – Synthetic data. Well correlation of reference facies sequence.

Results

The evaluation of the method for well correlation by fuzzy inference is performed using two cored boreholes in Namorado oil field.

We choose a reference facies sequence composed by one tick shale (fine mixture including marl and silt) in the depth interval from 2975 to 2987 meters and a sandstone layer (well cemented and well selected) in the depth interval from 2990 to 3001 meters in borehole A.

This reference facies sequence determines the facies identification, the zoning of borehole B and the determination of the correlation lines liking the boreholes A and B.

We notice the agreement between the zoning performed by the fuzzy inference and the facies description of cores from well B

Figure 9 shows de natural gamma ray logs from the boreholes A and B. For clarity in the figure, we only represent the correlations lines link the reference facies.

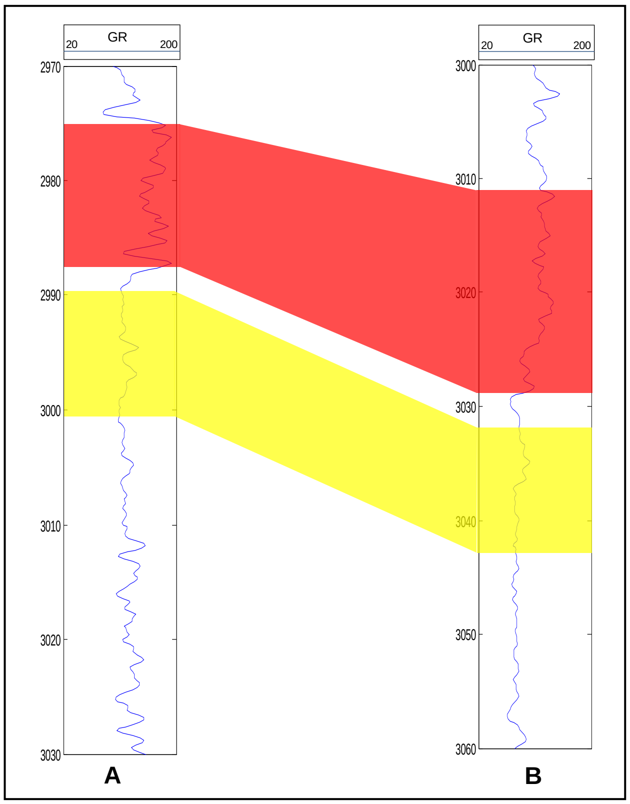

Figure 9 – Actual data. Well correlation of reference facies sequence

Conclusions

The solutions of actual problems in oil reservoir characterization appear in the sense of a larger integration among information produced by the several different areas of petroleum industry.

In this work, we present an efficient method that integrates facies information from core analysis and well log readings; making possible the transport of relevant information from one core borehole to other non-cored wells, generating valuable subsidies for the definition of lateral continuity of oil reservoirs.

An accurate model of the oil reservoir is a crucial input to complete field development planning process. Without it, costly decisions like the placement of wells and future predictions about production volumes, using reservoir simulation, will be wrong.

Acknowledgments

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