Electrofacies versus Flow Units in Presalt Carbonate Reservoirs of the Santos Basin: Which is the Best Approach for Estimate Petrophysical Properties?

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Abstract

Presalt carbonates of the Santos Basin represent many challenges in the characterization of their reservoirs. Rock typing into Flow Units (FU) is a well-known method for characterizing flow behaviors in reservoirs and producing reliable estimations of petrophysical properties. We propose the analysis of facies through FU and Electrofacies, in both well-log and seismic scales, of the Barra Velha and Itapema formations based on the estimations of the petrophysical properties such as porosity, permeability, and clay volume of ten exploratory wells of the Santos Basin. In this study, the FU showed more optimistic results when compared to the Electrofacies for considering, indirectly, the effects of diagenesis. The Well presented in this paper shows heterogeneous FU and Electrofacies for both formations but it is more evident in the Barra Velha Formation. After the estimates, we analyze crossplots of effective porosity versus acoustic impedance by FU and by Electrofacies as a way to find the best correlations between porosity and this elastic parameter. We concluded that the relationship between porosity and permeability by the flow units proved to be better than by electrofacies.

Introduction

In Brazil, carbonate reservoirs are responsible for more than 65% of the country's oil production, constituting the main exploratory target. In this context, the Santos Basin plays a prominent role. Located in the southeast of the Brazilian continental margin, this basin is the main producer in the presalt section and it has the coquinas of the Itapema Formation and the shrubs and spherulitites of the Barra Velha Formation as reservoirs (Chopra et al., 2005; Muniz & Bosence, 2015). The carbonate reservoirs present great heterogeneity in their properties due to the complex combination of depositional and diagenetic processes (Dunham, 1962).

Due to the complex depositional environment of presalt carbonates, the division of lithotypes into Electrofacies can assist in the identification of diagenetic and depositional processes that occurred during the life of the reservoir. Understanding both depositional and diagenetic effects in the carbonate settings and their impact on petrophysics properties, such as porosity and permeability, through the FU are the main aims of this paper. Besides, relating the FU to Electrofacies can be essential to facilitate decision making by the asset team.

Reservoir characterization through flow units is well-known as an effective way to simulate production performance within the geological nature (Jennings et al., 2000; Lawrence et al., 2002;). Working with flow units in the carbonate presalt reservoirs is extremely important due to the great diversity of pore types and wide heterogeneity caused by the complex combination of depositional and diagenetic processes such as cementation, silicification, and dissolution (Choquette and Pray 1970; Mazzullo and Harris 1991)

It is important to understand the variability and spatial distribution of petrophysical properties along a reservoir. Understanding these variations of pore geometry in distinct lithofacies is crucial to improve reservoir description and exploration. Different porosity characteristics within a rock type can generate a permeability variation of several orders of magnitude, indicating the existence of multiple flow units (Penna & Lupinacci, 2020). According to Ebanks (1987), a FU represents an elementary volume of total reservoir rock whose geological and petrophysical properties that affect fluid flow rate are internally consistent and predictably different from properties of other rock volumes.

We proposed a workflow to estimate the FU named Flow Facies (FF) from the porosity and permeability curves. In this paper, we considered the number of four main FF as a minimum number to guarantee a better correlation with the seismic data which has a lower vertical resolution. The FF were divided from pre-established cut-off values taken from Penna & Lupinacci (2020) and the Electrofacies were estimated from cut-off values for porosity and clay volume (Vclay) pre-established in this work.

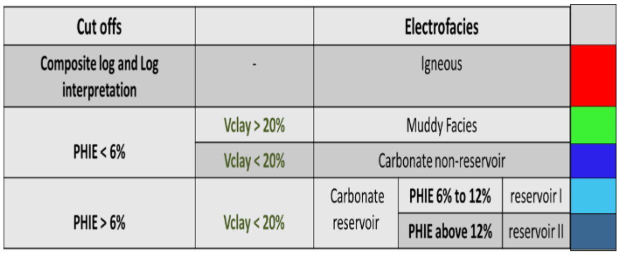
Method

This section describes the procedures used for the evaluation of electrofacies, FF, upscaling, porosity and permeability relations, histograms, and crossplot of effective porosity (PHIE) versus acoustic impedance (IP). It is important to highlight that the data obtained are based on the analysis of ten wells, however, as an example, only the results obtained in one well will be presented. This well was chosen because it is the most heterogeneous and has all five electrofacies and the four FF in its extension.

Electrofacies Classification

The lithologies were divided into four distinct electrofacies which are: igneous, carbonate reservoir (subdividing into reservoir I and reservoir II), carbonate non-reservoir (or tight carbonate), and muddy facies as shown in Table 1. These criteria were established by taking into account the curves of Nuclear Magnetic Resonance effective porosity (PHIE_NMR) and the clay volume (Vclay) by the Larionov method for ancient rocks (Larionov, 1969). In carbonates of the Brazilian presalt, the porosity of 6% is considered relatively good, so this number was established as the first parameter of cut-off and the second parameter was the value above or under 20% of Vclay.

Table 1: Cut-off values of porosity and Vclay curves used to define the electrofacies.



Cut offs		Electrofacies			
Composite log and Log interpretation	-	Igneous			🟥
PHIE < 6%	Vclay > 20%	Muddy Facies			🟩
	Vclay < 20%	Carbonate non-reservoir			🟦
PHIE > 6%	Vclay < 20%	Carbonate reservoir	PHIE 6% to 12%	reservoir I	🟦
			PHIE above 12%	reservoir II	🟦

FU Classification

Amaefule & Altunbay (1993) introduced the flow zone indicator (FZI) concept derived from the Carman-Kozeny equations (Kozeny, 1927; Carman, 1937). FZI is widely used to classify rocks with similar characteristics and behavior and FZI is considered a robust method of permeability estimation and reservoir prediction in terms of flow heterogeneities, due to petrophysical correlations between permeability and flow units (Emami Niri & Lumley.,2016 and Iravani et al., 2018). Studies developed so far have shown that the estimation of flow units through the FZI method correlates with many petrophysical properties. Also, it is seen as a more accurate method than lithological or sedimentary facies (Aggoun et al. 2006; Pritchard et al. 2010; Emami Niri and Lumley 2016; Iravani et al. 2018). Thus, the first step to calculate the reservoir-quality index (RQI) is defined as:

$$\mathrm{RQI} = 0.0314\sqrt{\frac{\mathrm{k}}{\varphi_{\mathrm{e}}}}, \tag{1}$$

where φ_{e} and k are respectively the effective porosity and permeability of the NMR logs. After that, the FZI is calculated as:

$$\mathrm{FZI} = \frac{\mathrm{RQI}}{\varphi_{\mathrm{z}}}, \tag{2}$$

with φ_{z}:

$$\varphi_{\mathrm{z}} = \frac{\varphi_{\mathrm{e}}}{1-\varphi_{\mathrm{e}}}. \tag{3}$$

The Ln (FZI) was calculated and separated according to the cut-off values present in Table 2.

Table 2: FF and Ln(FZI) cut-offs from Penna & Lupinacci (2020)

FF	Ln (FZI) cutoffs values	
FF1	below -0.5	FF1
FF2	-0.5 to 0.67	FF2
FF3	0.67 to 1.49	FF3
FF4	above 1.49	FF4

FF1 is considered a barrier or baffle zone and corresponds to the initial flat segment of the curve with near-zero permeability. FF2 relates with reduced but considerable flow capacity. FF3 corresponds to an increase in porosity and permeability. This could represent a reservoir rock with greater permeability and good flow performance. Lastly, FF4 corresponds to the better flow characteristics.

Upscale

This step comprises the upscale method used in the PHIE, permeability (KTIM), IP, Vclay, FF, and electrofacies curves, using the suffix _UPS to highlight the curves in seismic domain. The upscale was performed using the Backus Average (Backus, 1962; Tiwary et al., 2019), with a frequency of 100Hz and a sampling rate of 5 meters.

PHIE x K relations

A semi-log graph, which was adjusted to empirical models, of porosity vs. permeability was constructed from well-log data from 10 wells in the area of study with regressions only per FF because the regression per electrofacies showed low correlation.

Histograms and PHIE x IP crossplots

The histograms were made with the frequency of occurrence of the IP curve per FF and electrofacies. In addition, PHIE vs IP crossplots were produced both on the well-log scale and on the seismic-scale by FF and by electrofacies.

Results and Discussion

The results of the electrofacies and the FF in one well in the study area are presented in Figure 1. The Itapema Fm. has FF1 as the main FF of the formation, both on the well-log and seismic scales. The FF1 represents the worst FF in permo-porous conditions terms and they are found, precisely, in the intervals where there is a high content of Si and Vclay, low porosities and permeabilities values, and predominance of muddy facies. We identified a cyclicality in the behavior of the curves, which ends up affecting the FF performance. Going from the base to the top of the formation, there is a transition from the cleanest to the dirtiest intervals, and it happens five times in this formation. The cleaner intervals are generally associates with good porosity and permeability, as well as low Si content, low Vclay, and low IP. The electrofacies associated with these intervals, in this case, are mainly carbonate reservoirs I and II (Table 1), as well as FF2 and FF3 (Table 2). Also, the description of sidewall core samples contained in the reports indicated the presence of locally collected coquinas. This behavior can be identified in both well-log and seismic domains. In the dirtier intervals, on the other hand, we can see the opposite. The porosity and permeability values decrease significantly, the Si content raises, as well as the clay volume. So, the electrofacies associated with these intervals, in this case, are mainly muddy facies, as well as FF1, which corroborates with the samples that indicate the presence of mudstones and laminite. This behavior can be identified in both well-log and seismic domains. In this formation, there is no evidence of FF4.

The Barra Velha Fm. shows more heterogeneous behavior with intervals associated with the FF3 and FF4 (Table 2), being related to clean carbonates zones. Two intervals are important to be highlighted, the first is in the intermediate interval of the formation, where it is observed the increase in Si content, higher values of Vclay, and a decrease in PHIE and KTIM. This interval shows a predominance of FF2 both in well-log and seismic domain, which may be associated with the presence of carbonates with low porosity associated with the presence of fine grains or silica-cemented. This can be evidenced by the electrofacies where there is a predominance of muddy facies with intercalations and carbonate reservoir I. It is important to understand that FU are a more robust method of analyzing fluid performance from petrophysical properties when comparing with the electrofacies classification because it considers the effects of diagenesis, such as cementation, silicification, obstruction of the radius of the pore throat, among others. Therefore, in some cases, we can find FF2 associated with facies carbonate reservoir I. The second interval is located right above the first one and it is characterized by an increase in porosity and permeability, a considerable decrease in Vclay and Si, and there are FF3 and FF4, as well as electrofacies carbonate reservoir I, which denotes the presence of an interval with better permo-porous conditions. Some local areas with a decrease in porosity and permeability associated with peaks in Si and Vclay content are related to FF2. Finally, the range in which the igneous rock is found is characterized by FF1 and is characterized as an interval with low porosity and permeability (close to zero), high IP, and low Vclay.

In the seismic domain, the thin layers of FF1 and FF2 found in the well-domain give space for FF3 at the base of the formation. In the middle of the formation, the thin layers of FF3 seen on the well-scale disappear, as well as the FF1 and the FF2 becomes the predominant FU. The identified upscale electrofacies (ELTs) are muddy facies and reservoir carbonate I. Finally, near the base of the igneous, at the top of the formation, it is noted that FF1 is predominant in both the well and the seismic scales, as well as the ELTs identified as igneous and non-reservoir carbonate. Therefore, in this well, the worst FU are found at zones with carbonates with low porosity, muddy carbonates with high silica content, and igneous bodies.

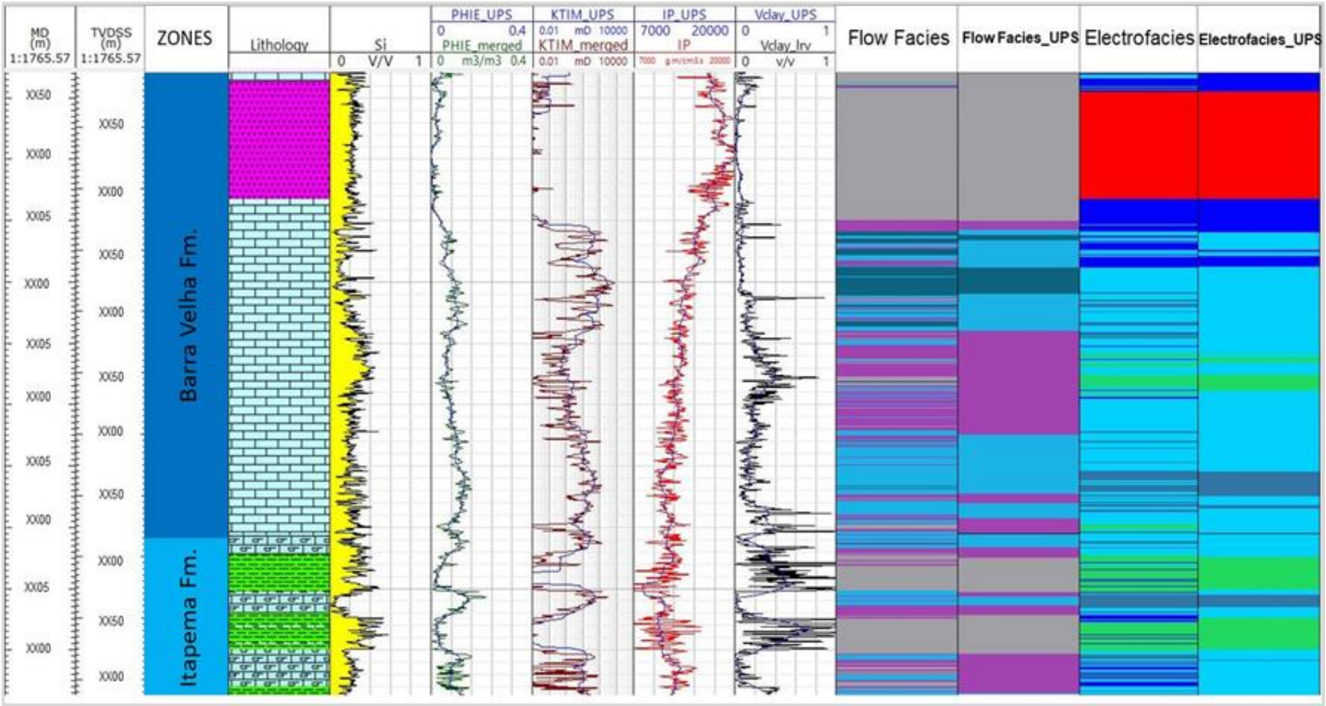


Figure 1: Layout with the main logs used to estimate the FF and Electrofacies in Well 01 in both log and seismic domain (blue curves).

An example of how difficult it is to incorporate FF into geological models is because each FF shows a wide variety of sedimentological facies, with no relationship between FF and carbonate facies. For example, the same FF can have different geological facies and different FF can have the same geological facies grouped.

Because of this, we made a porosity vs. permeability semi-log plot from ten wells to demonstrate that the scattering around each FU regression line is more evident than using regression lines of lithological descriptions which are not easy to be identified. Figure 2 shows that it was only possible to plot the regression curves per FF.

Fig. 2a shows each regression per FF that makes it possible to reproduce the porosity and permeability characteristics. There is a scatter around each FF regression line. The regressions per FF present good results having the most optimistic adjustment of the equation for the FF3 and FF2 that present themselves in a more behaved way, showing R^2 values of 0.76 and 0.62, respectively. On the other hand, the FF that presented the worst adjustment was the FF4 with R^2 = 0.28, having more disperse points and behaving in a more heterogeneous way.

Finding a good permo-porous correlation per lithology is difficult as it can be seen in Figure 2b. Muddy facies, igneous facies, and tight carbonates are mixed, making it difficult to separate and identify them. Also, the igneous facies are scattered over low and intermediate porosity values. The highest R^2 value found in the porosity and permeability regressions per eletrofacies was 0.25 and represented the carbonate reservoir I. Due to the low values of R^2, we decided not to show the regressions in Figure 2.b.

This happens due to a large amount of scattered and mixed points and because the lithological descriptions neglect diagenetic effects that occur differently in later stages of geological history. However, those effects are indirectly estimated using FU (Penna & Lupinacci, 2020).

In addition to the analysis of the curves, the distribution of the acoustic impedance (IP) curve using the FF and the electrofacies as parameters were generated. Figure 3 shows the histograms of the IP curve to the Well 1. The letters a) and b) show the IP histogram for the electrofacies and FF on the well-scale, respectively. It is possible to observe that FF1 is associated with electrofacies identified as igneous and largely with non-reservoir carbonates, in addition to presenting the highest IP values. FF3 and FF4 are associated with electrofacies identified as reservoir carbonate I and II and have lower IP values. FF1 and FF2 are associated with muddy facies, which in turn are more spread out, without a certain trend, sometimes with low IP values, sometimes with high values. It is worth noting that electrofacies carbonate reservoir I is, sometimes, related to FF2, sometimes to FF3, as previously seen. The arithmetic IP average for this well is 13.597 (gm.m/cm3.s).

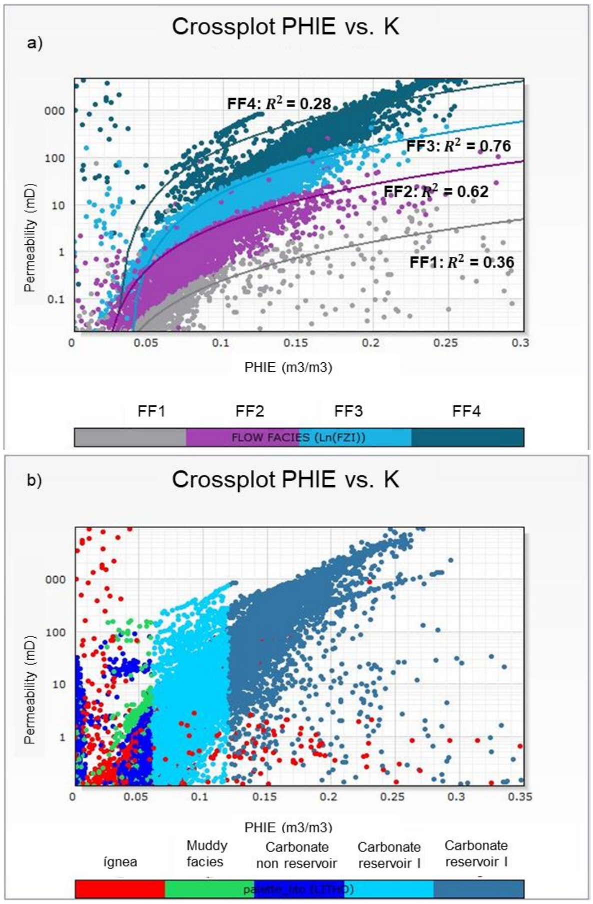


Figure 1: (a) Porosity vs. permeability regressions per FU according to the discretization proposed in Table 1. (b) Porosity vs. permeability regressions per electrofacies.

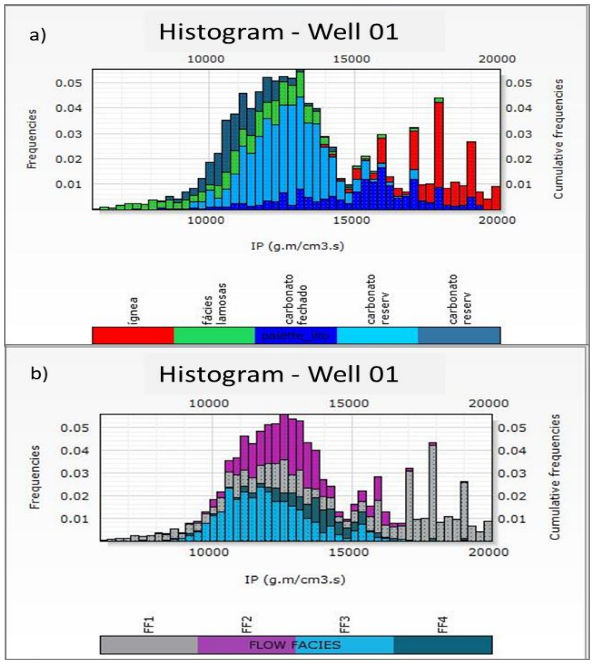


Figure 3: Histograms with the frequency of occurrence of the IP curves. (a) IP by Electrofacies on the well-scale; (b) IP by FF on the well-scale.

Figure 4 shows four different PHIE vs. IP crossplots. Note that in Figure 4.a the carbonate reservoir facies I and II have higher PHIE values and low to intermediate values of IP. This shows a good correlation between these two curves, while the IP decreases, the PHIE increases, and vice-versa. Also, igneous electrofacies and carbonate non-reservoir present low porosity values and high IP values, corroborating the trend previously described. On the other hand, the muddy facies have a peculiar behavior, presenting low porosities but low to medium IP values. In Figure 4.c, the FF are distributed in a very similar way to the electrofacies. It can be seen that the best FF (FF3 and FF4) are distributed in high porosity values and low IP. FF2 is more widespread with low to intermediate PHIE values and intermediate to high IP values. And finally, FF1, which in this work are associated with electrofacies with worse permo-porous conditions, such as igneous, muddy facies, and non-reservoir carbonate, are distributed along low PHIE values associated with low IP values (resembling the behavior of muddy facies), and also at low PHIE values and high IP values (igneous electrofacies).

In the crossplots on the right (Figure 4.b and 4.d), the relations of IP and PHIE are in the seismic domain. Due to the smoothing applied and the higher sampling rate, the number of data points decreases, but it is possible to observe the same trend when compared to crossplots in the well-domain. In Figure 4.b, it is noted that the electrofacies carbonate reservoir I and II have higher porosity values as well as lower IP values. The igneous electrofacies correspond to the lowest PHIE values and the highest IP values (inversely proportional relation). The muddy facies, as seen previously, assume a peculiar position when presenting both low PHIE values and low to intermediate IP values. Figure 4.d has the same trend, with the best FF (FF3 and FF4) with high PHIE values and low IP values, FF2 are in the middle, presenting medium to low PHIE values and intermediate values of IP. Finally, FF1 with low PHIE and high IP are associated with igneous electrofacies, and FF1 with low porosity and low acoustic impedance to muddy facies.

Conclusions

The analyzed wells showed great heterogeneity of electrofacies and flow facies (FF). It was possible to identify, on the one hand, a certain similarity between the electrofacies and FF, for example, igneous in Well 01, identified as permeability barriers, present themselves as FF1, as well as muddy facies. On the other hand, the electrofacies defined as reservoir carbonate will not always show FF3 or FF4 as we saw in Well 01 that they were, sometimes, associated with FF2. The upscale showed that the proportions of electrofacies and FF were maintained, with just occasional changes. Furthermore, with the upscale, the thin layers of FF and electrofacies tend to disappear. Finally, the flow units correlate better with the porosity and permeability than the electrofacies. Therefore, it is the most indictable method to build correlations between PHIE and K. Finally, it is still complex to use the relation between PHIE and IP as a constrain to determine electrofacies or flow units. This ends up being a problem for 3D characterization.

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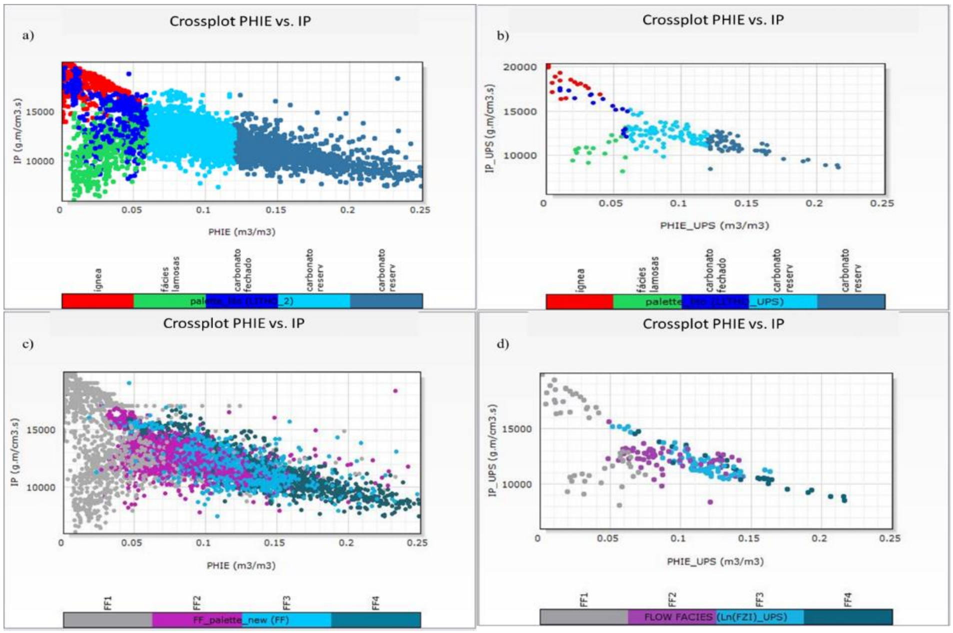

Figure 4: PHIE x IP crossplots for the two wells by electrofacies and FU. (a) PHIE x IP by electrofacies on the well scale; (b) PHIE_UPS x IP_UPS by electrofacies on the seismic scale); (c) PHIE x IP by FF on the well scale; (d) PHIE_UPS x IP_UPS by FF on the seismic-scale

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