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3D SEISMIC FLOW UNITS AND PETROPHYSICAL PROPERTY MODELLING IN BRAZILIAN PRE-SALT RESERVOIRS

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ABSTRACT. Rock typing into flow units (FU) is a well-known technique for characterizing flow heterogeneities in reservoirs and producing reliable estimations of petrophysical properties. Despite the large availability of methods that correlate a specific pore-throat size to petrophysical attributes, extrapolating FU rock typing from the core and well log scales into the whole reservoir is a major challenge due to the scale differences between data and the lack of correlation with the common-used sedimentological facies. Most 3D generations of flow units and petrophysical property studies available in the literature are merely a geostatistical procedure, without any spatial data constraints in the 3D seismic data. We propose a new approach to discretize flow units in the core and well logs considering the decametric scale characteristics of the seismic data, generating a 3D model of FU facies and calculating porosities and permeabilities that are more accurate than the usual estimation based on sedimentary facies. Despite the complexity of the geological setting and the reduced number of FU, we produced volumes of permeability and porosity that are still capable of obtaining complex reservoir flow characteristics and could be directly considered as variables in lateral interpolation of reservoir parameters, seismic 4D interpretations and seismic-assisted history matching.

Keywords: flow unit, pre-salt reservoir, porosity modelling, permeability modelling.

RESUMO. A tipagem de rochas em unidades de fluxo (FU) é uma técnica conhecida para caracterizar heterogeneidades de fluxo em reservatórios e produzir estimativas confiáveis de propriedades petrofísicas. Apesar da grande disponibilidade de métodos que correlacionam um tamanho específico de garganta de poro a atributos petrofísicos, extrapolar a tipagem de rocha feita em testemunho e/ou perfil de poço para todo o reservatório é um desafio, principalmente devido às diferenças de escala entre os dados e à falta de correlação das FU com fácies sedimentológicas. A maioria dos exemplos de gerações 3D de unidades de fluxo e de propriedades petrofísicas são meramente um procedimento geoestatístico, sem quaisquer restrições de dados espaciais com os dados sísmicos. Propomos uma abordagem para discretizar unidades de fluxo em amostras laterais e nos poços considerando as características da escala decamétrica dos dados sísmicos, gerando um modelo 3D de fácies FU e calculando porosidades e permeabilidades, que são mais precisas do que a estimativa baseada em fácies sedimentares. Apesar da complexidade geológica e do número reduzido de FU, produzimos volumes de permeabilidade e porosidade que são capazes de obter características de fluxo de reservatório complexas e podem ser considerados como variáveis na interpolação lateral de parâmetros de reservatório, interpretações sísmicas 4D e no ajuste de histórico assistido por sísmica.

Palavras-chave: unidade de fluxo, reservatório pré-sal, modelagem de porosidade, modelagem de permeabilidade.

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INTRODUCTION

For any asset team working with complex geological settings, like the Brazilian pre-salt carbonates province, an assertive description of the reservoir heterogeneity and flow behavior in terms of fluid movement is crucial. Considering the amount of effort and investments required to develop any pre-salt oil field, any calculation error present in the porosity and permeability volumes can imply differences of billion dollars in the decision-making process. The Flow Unit (FU) classification can present an advantage when calculating reservoir petrophysical attributes, since it can be more accurate and generate better statical and dynamic models of the reservoir, as discussed by Daraei et al. (2017), Hatampour et al. (2018) and Ghanbarian et al. (2019).

Because of the nature of its classification, flow units rarely show any correlation with lithological facies. Therefore, their incorporation into the building process of 3D static models, in most cases based only on sedimentological premises, can be difficult. To illustrate, one given lithological facies deposited at two high-energy setting in different portions of the basin is grouped in the same sedimentary classification. In the flow unit classification, however, they can be grouped into two distinct FU facies depending on how the differential diagenetic history of both rocks affected their porosity and, consequently, permeability. The mapping and understanding of these heterogeneities are crucial for reservoir management, once their production response can be very different in terms of fluid movement in subsurface. In addition, flow units calculated in core and well log scale (which is the most common workflow) will show poor correlation with seismic data due to scale differences. As a result, most 3D petrophysical models derived from FU are merely a geostatistical extrapolation of well data without any lateral control, often resulting in unrealistic flow models. Examples of lateral extrapolations of FU and their related petrophysical properties considering only well data are found, for example, in Li et al. (2018).

For geophysicists and reservoir characterization, flow units are rarely a considered technique for quantitative seismic interpretation (QSI). The main publications related to QSI (Avseth et al., 2005; Simm & Bacon, 2014; and Vernik, 2016) do not mention any definition or workflow to identify and map the FU from elastic seismic attributes. Some recent works do correlate flow units with multiple seismic attributes, producing constrained tridimensional petrophysical properties of porosity and permeability (e.g. Iravani et al., 2018; Hatampour et al., 2018). However, most of the studies are simply an extrapolation of FU classification based on core and well log data into the seismic resolution, regardless of the scale difference between data types.

We propose a methodology for calculating better seismic derived petrophysical volumes, characterizing large-scale flow characteristics of the reservoir considering flow units as constraints. Using percentiles and a cumulative S-curve in permeability and porosity core measurements from the Mero Field, a Brazilian pre-salt carbonate reservoir (Fig. 1), we calculated a small and significant number of flow units that correlate with seismic elastic attributes and respond for the large-scale flow characteristics in the reservoir, maintaining part of the local flow complexity (Penna and Lupinacci, 2020). Within each FU, we establish petrophysical relations that calculate more accurate seismic derived 3D volumes of porosity and permeability which are then compared to volumes calculated using sedimentological k- ϕ relations.

Rock Typing for Seismic Flow Units

Given the amount of core porosity and permeability analysis available in the area (500m of core analysis, 1700 conventional porosity and permeability measurements in both Barra Velha and Itapema Formations), we performed the well log FU discretization preferentially through two methods: flow zone indicator (FZI - Amaefule and Altunbay, 1993) and Gunter et al. (1997) stratigraphic modified Lorenz plot (SMLP). Both approximate a given pore-throat size radius for each FU through k/ϕ based relations.

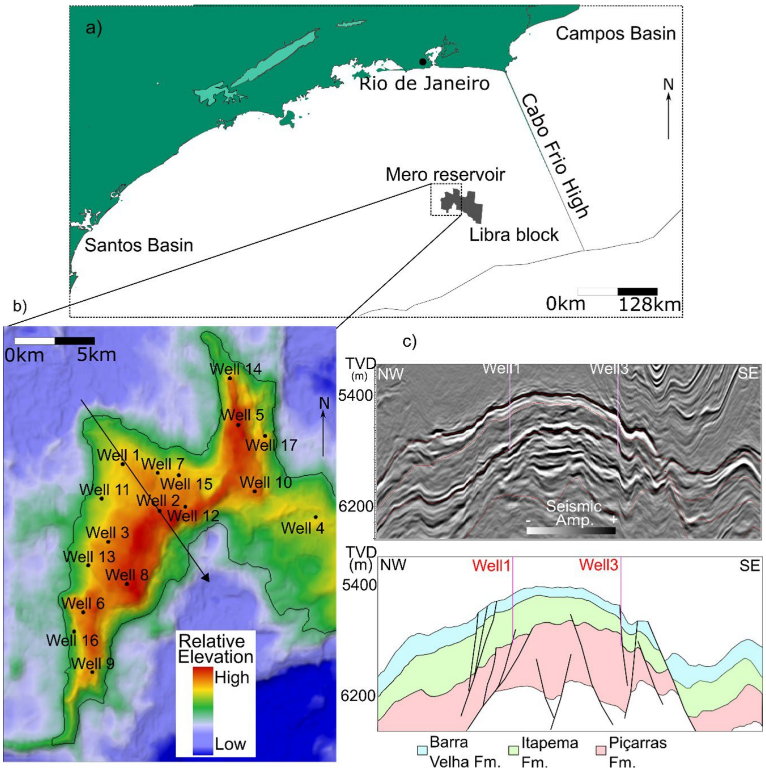

Figure 1 - (a) Mero Field is located on the northeastern portion of the Santos Basin, southeast Brazil. (b) Base of salt horizon (top of the Barra Velha Formation). (c) NW-SE seismic section and interpretation of the main reservoir stratigraphy (the black peak corresponds to an increasing impedance interface, the white trough to a decreasing impedance interface). After Penna and Lupinacci, 2021.

First, the SMLP was used as a qualitative display to analyze the flow units and fluid movement variation in the reservoir at different scales of observation, similar to sequence stratigraphy studies in which high order (and high frequency) events can be distinguished from low order (and low frequency) events. The plot in Figure 2 demonstrates how four decametric flow fluid heterogeneities are visible at lower, decametric scale, as well as higher scale variations related to metric flow fluid characteristics. In the plot, as described by Gunter et al. (1997), the X axis is the cumulative storage capacity (product of porosity and thickness) and the Y axis is the cumulative flow capacity (product of permeability and thickness). Flat segments of the curve correspond to flow barriers, and steep segments are better permoporous carbonates.

The SMLP discretization for FU is usually made well-by-well. After each individual analysis, the FU results from one well are laterally correlated to the results from another one, generating a volumetric model. Although this qualitative approach is not adequate for our purpose, the usage of cumulative porosity and permeability plots proved to be a powerful tool to analyze the scale-dependance of porosity and permeability. Considering this, and that the FZI method provides a more robust method of classification, we constructed a cumulative permeability versus log (FZI) value, visualizing the contribution of each pore throat radius (the FZI value) for the fluid movement capacity of the reservoir. The plot in Figure 3 shows how this discretization can be made using the core data, and analyzing the main changes in the slope of the curve (the derivative plot in Fig. 3) as threshold values for the rock typing, similar to the SMLP analysis for flat and steep segments of the curve. This allows identifying, in terms of flow movement in subsurface, four FZI flow units.

FZI1 is the first segment of the curve parallel to the X axis and close to zero accumulated permeability (Fig. 3). This is the worst facies in terms of permoporous characteristics with lower

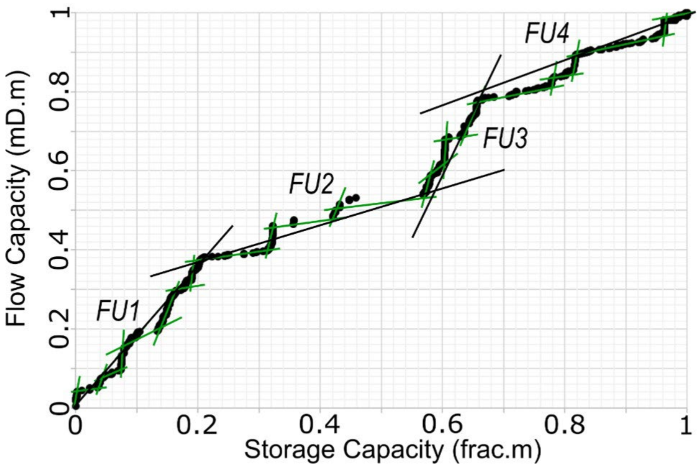

Figure 2 - SMLP and the expression of different FU in two observation scale. The black line shows how the flow behaves in a decametric scale, while the green line shows the same in a higher scale (after Penna and Lupinacci, 2021).

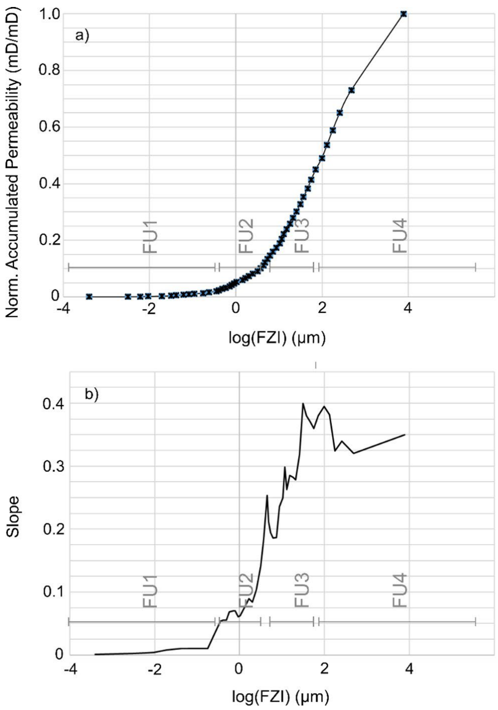

Figure 3 - (a) Cumulative curve of permeability versus log(FZI). (b) Derivative of the cumulative curve. Note how the four main variations shown in the SMLP also appear here as lower orders of variation.

porosities and little or none permeability contribution. The second, FZI2, is defined where the curve starts to detach from the X axis. This facies still presents reduced porosity and permeability capacity, but its detection can be interesting for reservoir pressure maintenance, for instance. FZI3 shows better permoporous conditions, as well as FZI4, the best one. FZI3 and FZI4 are the main reservoir facies for fluid production, and their mapping and detection are crucial for the reservoir management.

After the FZI core analysis, we transposed the cut-off values to the well log data, using the magnetic resonance porosity and Schlumberger-Doll-Research permeability (Al-Ajmi and Holditch, 2000). Figure 4 shows an example of the FZI cut-off discretization in Well 7, as well as some relevant well logs for comparison. Note how the diagenesis effect is qualitatively seen on the flow unit classification, even though this causality between flow units and diagenesis is very hard to correlate directly. Carbonates with no or little presence of clay and reduced amount of silicon usually correspond to better permoporous facies (FU3 and FU4). This type of quantification is not possible using the classical seismic sedimentological classification.

It is important to note that the currently flow unit classification, made with cumulative curves and using cut-off values relative to large changes in the FZI and permeability values, is related to decametric scales of the reservoir. Considering the nature of the vertical resolution of the seismic data, and our intention to use it as constraints for the 3D estimation of petrophysical attributes, this type of discretization is fit for the purpose.

Flow Units and Seismic Feasibility

To verify how the discretization of decametre flow units behaves in the elastic domain in terms of P-impedance and S-impedance, we performed a 1D feasibility study using time-filtered versions of well logs. The crossplot and histogram from Figure 5 show how each flow unit separates in the filtered elastic domain, considering the P- and S-impedance values within each decametre FZI unit previously determined. FU1 tends to present higher values of impedances, while FU4 corresponds to lower values. This is an expected behavior, considering that FU1 and FU2 are mostly comprised of low porosity and silicon cemented carbonates, while FU3 and FU4 correspond to higher porosity and calcium-pure carbonates, for both Barra Velha and Itapema formations. Carbonates with moderate diagenetic features will fall between FU3 and FU2, sometimes leading to miscalculations.

Although the plot in Figure 5 shows only the Barra Velha Formation behavior, the samples for Itapema Formation show similar distribution in the elastic domain. This is expected, considering that Mero carbonates are considerably harder to separate in terms of stratigraphy and even fluid content, compared to other pre-salt areas (Penna et al., 2019). This is mainly due to higher dry rock bulk modulus values in this area.

It is clear that the flow units show a considerable amount of superimposed areas in the elastic domain, as seen in the crossplot and histograms in Figure 5. Although this is problematic for seismic facies classification purposes, this scenario is quite common in quantitative interpretation studies using P-impedance, S-impedance, Poisson ratio and other elastic attributes. This is problematic for deterministic facies classification, and we recommend a probabilistic approach to account for uncertainties in the classification.

One of the main advantages of working with flow units is obtaining better estimations of petrophysical properties, such as porosity and permeability. This is partially evidenced in Figure 6, where the porosity estimation through impedance correlation, considering flow units as templates, is more accurate than using the conventional seismic sedimentological classification. For this, we are using the classical P-impedance versus porosity relationship that is explored by several authors working with quantitative interpretation of seismic data (Avseth et al., 2005).

Figure 7 illustrates both estimations of permeability through porosity correlation, considering both flow units and lithologic facies as constraints. It is noted that FU provides a much better estimation of permeability. Both Itapema and Barra Velha formations have similar behavior. For both porosity and permeability estimations, the dispersion around the regressions is high. This is because we are considering a seismic correlation and working with a limited amount of flow units for the constraint. For example, more flow units would improve the permeability estimate around FU2 (Fig. 7).

3D Bayesian Flow Units Classification

Considering IP and IS seismic inversion volumes calculated through a sparse-spike prestack seismic inversion from seven partial angle stacks derived from the RTM data (Penna et al., 2019), and the probability density functions of the FUs in the elastic domain (Fig. 4), we performed a Bayesian classification of the volumetric occurrence probability of each flow unit. This methodology, as described by Penna and Lupinacci (2021), outputs five volumes: one discrete, called most probable

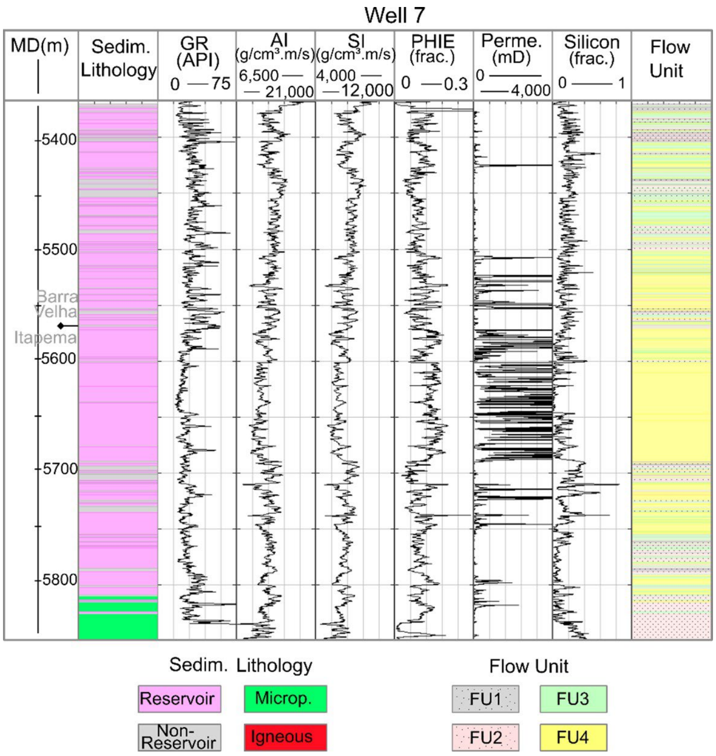

Figure 4 - Flow Unit classification in Well 7 though FZI discretization. The conventional seismic sedimentological classification is displayed on the left, while the flow unit classification is on the right.

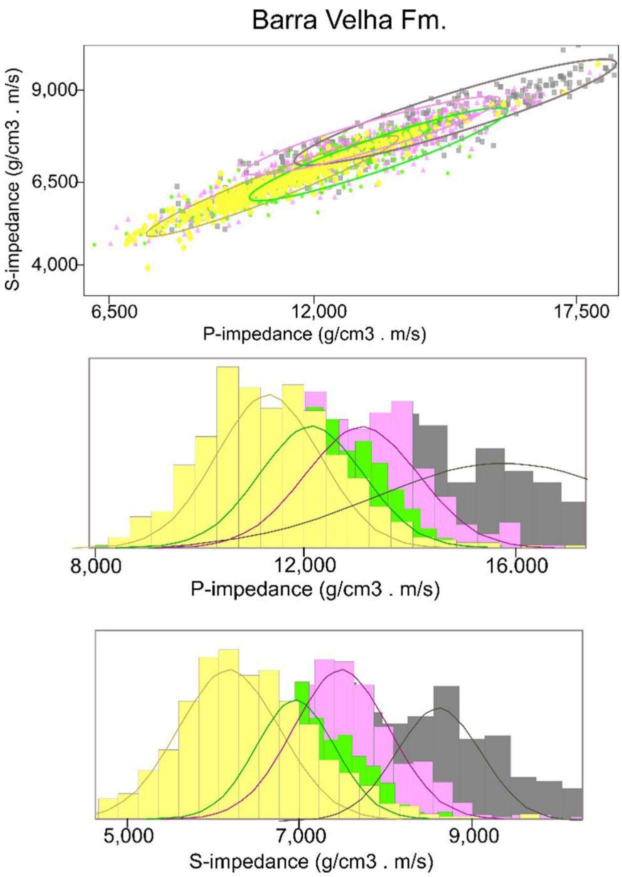

Figure 5 - Distribution of P- and S-Impedance values for each FU defined in Figure 3 for the Barra Velha Fm (the Itapema Fm. shows similar distribution pattern).

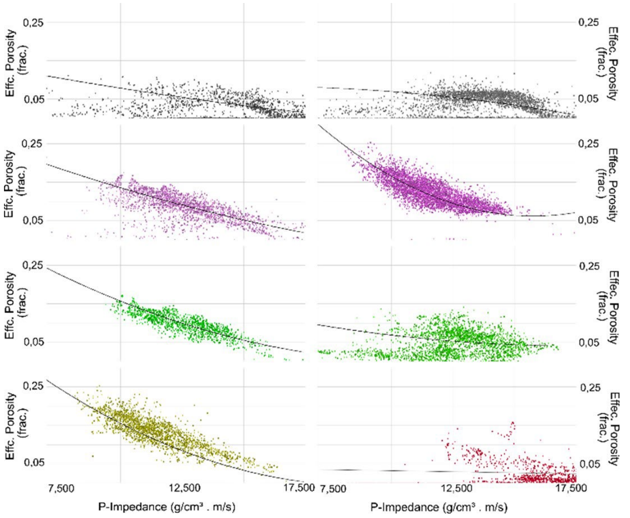

Figure 6 - P-Impedance versus porosity (above) regressions considering both flow units and lithology facies as constraints.

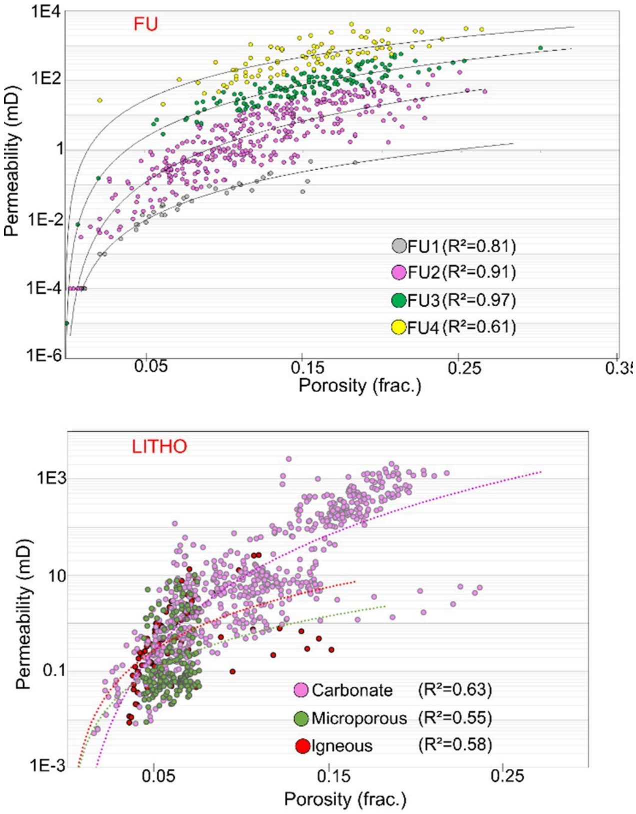

Figure 7 - P-Impedance versus porosity (above) regressions considering both flow units and lithology facies as constraints.

FU, and four different occurrence probability volumes for each decametre flow unit. The most probable volume consists of the corresponding discrete data with the higher occurrence probability for a given sample. Each occurrence probability volume varies from zero to one, and the sum of all the probabilities for a given sample is always one.

Figure 8 illustrates an average of occurrence probability of a given flow unit in the upper Itapema Formation, as well as the corresponding porosity and permeability (estimated using the regressions shown in Fig. 6 and Fig. 7). The results of both k and ϕ estimations using the FU constraints are much more refined in terms of layer definition and

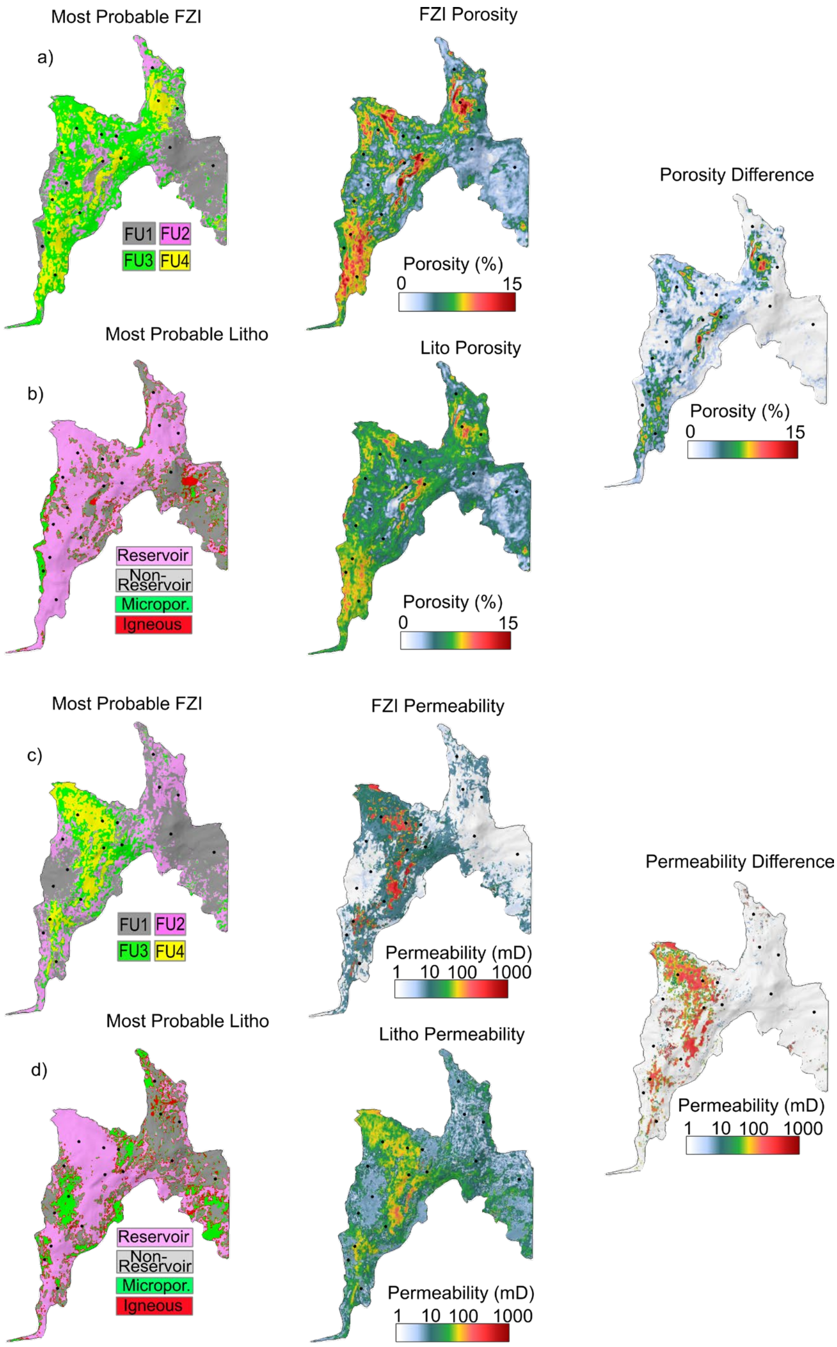

Figure 8 - P-Impedance versus porosity (above) regressions considering both flow units and lithology facies as constraints.

accuracy, considering the comparison between the seismic lithology facies as constraint.

Estimation errors between the well log data compared to the estimated ϕ and k through seismic volumes are found in Penna and Lupinacci (2021). We can see errors, when using lithologies, up to 0.10 of porosity and 1000 mD of permeability. Although this probably will not substantially impact the VOIP (because Mero mean reservoir porosity is around 10%), this amount of errors can be very considerable in terms of injection efficiency prediction, well placement for production, seismic assisted history matching and reservoir management in general, considering the size of the Mero structure.

CONCLUSIONS

The use of decametric flow units as a constraint to estimate petrophysical properties at seismic inversion scale produces better results than using the lithology classification. We consider that the accurate mapping and comprehension of the flow behavior at decametric scale is the first step to build the dynamic knowledge of the reservoir at smaller scales, especially considering all the concerns and difficulties to incorporate FU into geologic models built essentially on analogs, sedimentary facies and conceptual premises. Our methodology provides ways to generate a minimum amount of FU that calculates porosity and permeability with acceptable accuracy and is correlatable with elastic attributes on seismic inversion scale.

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