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TÍTULO DO TRABALHO:

Flow units characterization methods in a synthetic carbonate reservoir model

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Abstract

Geologists and petroleum engineers have complex challenges to determine the regions that have analogous features and properties for a proper characterization, porosity–permeability modelling and dynamic reservoir simulation in heterogeneous carbonate reservoirs. Hence, the investigation of reservoir rock properties such as porosity, permeability, and pore throat assists engineers to identify accurate flow units, rock typing, barrier and productive zones performance, and select well placement during field development. Two common rock-typing methods of flow unit identification are considered in this study. Flow units are determined firstly using flow zone indicators (FZI) and secondly using a stratigraphic modified Lorenz plot (SMLP). The main purpose of this research is to describe flow units characterization to identify barriers, baffles, and speed zone units (SZU) or Super_K layers using stratigraphic modified Lorenz plot (SMLP) method and recognize transmissive flow units (TFU) and storage flow units (SFU) based on flow zone indicators (FZI). To reach this goal, synthetic porosity and permeability data are used from three wells (Exploration Well 1, Exploration Well 2 and Wildcat Well) of a carbonate benchmark model named UNISIM-II in a Pre-salt carbonate reservoir in Santos Basin, Brazil. Nine flow units are obtained using FZI method for each well, whereas 7, 8, 10 flow units are gained from Exploration Well 1, Exploration Well 2 and Wildcat Well, respectively based on SMLP method. Furthermore, for the better evaluation of flow units, R35 values (synthetic pore throat radius measured at 35% mercury saturation) by Winland's equation and Dykstra-Parsons coefficient are applied to categorize pore-throats sizes and quantify reservoir heterogeneity, respectively. Finally, we analysed each flow unit according to pore size and facies. Three types of pore-throats sizes are obtained including nonporous, mega-porous and macroporous. The value of Dykstra-Parsons permeability coefficient was 0.76, which indicates that the reservoir is vertically heterogeneous. According to the main goal, the classified permeability and porosity model recognize reservoir barriers and productive zones. Furthermore, the presence of nanoporous zones reduced reservoir quality. Data analyses showed that high-quality flow units mainly consist of Super_K and Megaporous, which are associated with geological facies.

Keywords: flow units, pore types, reservoir characterization, porosity, permeability

Introduction

Geologists and petroleum engineers encounter intricate challenges to determine the regions that have analogous features and properties for a better characterization, modelling and reservoir simulation in heterogeneous carbonate reservoirs. Therefore, since the last few decades, extensive studies have been carried out to advance the reservoir characterization and effective management strategies.

Pre-salt carbonate reservoirs from Santos Basin in Brazil indicate a good opportunity to study and improve reservoir characterization as an important recent oil discovery. One of the main challenges in these reservoirs is a description of rock heterogeneities, facies and flow units distribution, and the existence of high permeability layers (speed zones). Speed zones have a strong effect on the reservoir behaviour, especially for the management of early water breakthrough, which may affect the location of fluid injection or production wells and the assessment of possible drilling of complex wells with accurate completions. Identification of flow units is one of the presented methods that assist to recognize permeable reservoir zones and porosity and permeability relationship even in heterogeneous carbonate reservoirs (Mahjour et al., 2015).

Flow unit is a key and basic unit concerning the fine description of future reservoir (Amaefule, 1993). Reservoir flow units represent lateral and vertical continuity and bedding characteristics, and it can be feasible for a reservoir classification to distinctive zones with similar flow regime. In each flow unit the homogeneity of data is preserved and this homogeneity fades in the borders (Mahjour et al., 2016). Several techniques were applied by several authors to identify flow units in a formation such as flow zone indicators (FZI) and stratigraphic modified Lorenz plot (SMLP) (Amaefule, 1993). Improvement of such flow unit techniques for reservoir zonation leads to the division of reservoir into different zones based on the parameters affecting fluid flow, which is a significant factor in comparison of different zones in terms of reservoir behaviour. Although the porosity-permeability plot exhibits a large scatter in heterogeneous carbonate reservoirs, using data classification based on flow units, a meaningful relation between porosity and permeability can be obtained (Mahjour et al., 2015).

The main purpose of this research is to describe flow unit characterization to identify barrier (seals), baffle (zones control fluid flow) and speed zones (Super_K) using stratigraphic modified Lorenz plot (SMLP) method and recognize transmissive flow units (TFU) and storage flow units (SFU) based on flow zone indicators (FZI). To achieve this goal porosity and permeability data are used from three wells (Exploration Well 1, Exploration Well 2, and Wildcat Well) of a carbonate benchmark model named UNISIM-II in a Pre-salt carbonate reservoir in Santos Basin, Brazil. The benchmark model is based on a combination of Pre-salt characteristics and Ghawar field information according to its diagenetic events and flow features similar to Pre-salt (Correia et al., 2015). This study also quantifies reservoir heterogeneity using Dykstra-Parsons permeability coefficient, porosity-permeability regression, and pore-throats sizes based on R35 values (pore throat radius measured at 35% mercury saturation) using Winland's equation (Pittman, 1992).

Methodology

The data acquired for this study is based on synthetic porosity and permeability data for three wells (Exploration well 1, Exploration well 2 and Wildcat well) from a benchmark case (UNISIM-II) that includes a simulation model with geological trends and rock/fluid data with dynamic characteristics from Brazilian Pre-salt reservoirs (Correia et al., 2015). Due to the lack of geologic information, the reservoir model involves a combination of Pre-salt reservoirs and Ghawar field data in Brazil and Saudi Arabia, respectively. Synthetic porosity and permeability data are examined for heterogeneity measures using Dykstra Parson Coefficient, flow units identification via two statistical methodologies including flow zone indicator values (FZI), and stratigraphic modified Lorenz plot (SMLP) methods and calculation of pore size using Winland's equation. These methods are detailed below.

Quantification of heterogeneity level using Dykstra-Parsons Coefficient (V_{dp})

Comparing to sandstone reservoirs, carbonates exploration are commonly more challenging because of inherent heterogeneities. Heterogeneity in carbonates can be related to different lithology, mineralogy, pore types, pore connectivity, and sedimentary facies. Permeability and porosity heterogeneity are quantified using Dykstra and Parsons Coefficient (V_{dp}). In this method, the calculation of V_{dp}, data should be ranked in order of decreasing magnitude and indicated on a chart of log probability scale.

Dykstra- Parsons coefficient (V_{dp}), is obtained as follows:

$$V_{dp} = (k_{50} - k_{84.1})/k_{50} \quad (1)$$

where K50 is median reservoir permeability and K84.1 is permeability at 84.1 percentile

Jensen et al. (2000) proposed that lower values of VDP (0 – 0.5) represent small heterogeneities (zero being homogeneous), while larger values (0.7–1) show large to extremely large heterogeneities. Most reservoirs have V_{dp} values between 0.5 and 0.9 for permeability data.

Hydraulic flow unit determination using flow zone indicator (FZI)

Rock typing based on reservoir quality index (RQI) and flow zone indicator (FZI) was applied using Kozenye-Carman equation for the determination and classification of hydraulic flow units (HFU) (Nooruddin et al.,2011). Each of HFU has a unique FZI value (Al-Ajmi and Holditch, 2000). From dividing sides of Kozenye-Carman formula by porosity and taking the square root of both sides, Equation (2) will be obtained:

$$\sqrt{\frac{K}{\emptyset}} = \frac{1}{S_{Vgr}\ K_T}\ \left(\frac{\emptyset_e}{1-\emptyset_e}\right) \qquad (2)$$

where (k) is the permeability in μm^2, (Ø) is the total porosity in fraction, (K_T) is Kozeny constant and usually has values of between 5 and 100 in most reservoir rocks, (S_{Vgr}) is the surface area per unit grain volume in μm^{-1} and ($\emptyset_e$) is the effective porosity in fraction.

If permeability and porosity are respectively represented in millidarcy (mD) and fraction, then:

$$RQI = 0.0314\sqrt{\frac{k}{\emptyset_e}} \qquad (3)$$

where the constant 0.0314 is the permeability conversion factor from μm^2 to mD and RQI is rock quality index (µm).

Input data for this equation include core porosity ($\emptyset_e$) (Tiab and Donaldson, 2004).Furthermore, porosity must be converted to normalize one as shown below:

$$\emptyset_Z = \frac{\emptyset_e}{1-\emptyset_e} \qquad (4)$$

where; $\emptyset_Z$ (normalized porosity) represents ratio the of pore space volume to the grain volume.

A flow zone indicator (FZI) value is a function of mineralogy and texture; FZI value is defined by the following equation:

$$FZI = RQI/\emptyset_Z \qquad (5)$$

Each hydraulic flow unit must be indicated by one FZI (Abbaszadeh et al., 1995). The points with analogous FZI are placed in the same flow unit. There are several practical methods to identify hydraulic flow units using FZI, including histogram analysis, normal probability diagram, and analytic classification algorithm. In this paper, we used normal probability plot. The method is explained below. A normal distribution makes a distinct straight line on a probability plot. Therefore, the number of straight lines in the probability plot of the logarithm of FZI is used to indicate the number of hydraulic flow units in the reservoir (Mahjour et al., 2016).

Flow unit determination using a stratigraphic modified Lorenz plot (SMLP)

Gunter et al. (1997) applied the stratigraphic modified Lorenz plot (SMLP) to evaluate the minimum number of flow units in a reservoir based on cumulative storage capacity (cumulative %KØ) versus cumulative flow capacity (cumulative %Kh). To construct the SMLP, continuous (ft-by-ft) core porosity and permeability data and the respective K/Ø ratios are ordered in the stratigraphic sequence of the reservoir (Gomes et al., 2008). The equation for calculating a single value of cumulative flow capacity is as follows:

$$(\mathrm{Kh})_{\mathrm{cum}} = \mathrm{K}(\mathrm{h}_1 - \mathrm{h}_0) + \mathrm{K}(\mathrm{h}_2 - \mathrm{h}_1) + \cdots \mathrm{K}_\mathrm{i}(\mathrm{h}_\mathrm{i} - \mathrm{h}_{\mathrm{i}-1}) \quad (6)$$

where K is permeability (mD), and h is the thickness of the sample interval.

A similar equation can be used to determine a single value of cumulative storage capacity:

$$(\emptyset\mathrm{h})_{\mathrm{cum}} = \emptyset_1(\mathrm{h}_1 - \mathrm{h}_0) + \emptyset_2(\mathrm{h}_2 - \mathrm{h}_1) + \cdots \emptyset_\mathrm{i}(\mathrm{h}_\mathrm{i} - \mathrm{h}_{\mathrm{i}-1}) \quad (7)$$

where Ø is fractional porosity.

The slope of the segments on this plot demonstrates the main flow units in their correct stratigraphic position. Flow units (speed zones, baffle zones and barrier zones) are determined by selecting changes in slope or inflection points. Steeper slopes have a greater percentage of flow capacity compare to storage capacity, and by the definition, have a high reservoir process speed. They are known “speed zones” (Gomes et al., 2008) or sometimes as “hydraulic units”. Segments with lower gradients have storage capacity but little flow capacity and are typically reservoir baffles. Segments with neither flow nor storage capacity are seals or barriers, if laterally extensive. The shape of the curve can be classified into three sections: 1- Speed Zone Unit (SZU), with high Øh % and Kh% values, 2- Baffles with high Øh % but low Kh% values, and 3- Barriers with low Øh % and Kh% values.

Winland pore throat prediction method

H. D. Winland used mercury injection capillary pressure curves and multiple regression analysis to develop an empirical equation using porosity, air permeability, and the pore aperture corresponding to a mercury saturation of 35% from over 300 sandstone and limestone samples. The Winland equation was used and published by Kolodzie (1980). The winland equation is:

$$\mathrm{Log\ R35} = 0.732 + 0.588 \log \mathrm{K} - 0.846 \log \emptyset \quad (8)$$

where R35 is the pore aperture radius (in microns) at 35 % mercury saturation in a mercury porosimetry test, K is core permeability (in millidarcy), and Ø is the core porosity (in percent). Pore systems may be classified into “pore types” using pore throat radius or pore size (Pittman, 1992). Table 1 illustrates the five petrophysical pore types with distinctive reservoir performances.

Table 1) Pore types (Pitman, 1992)

Pore type	Size range (μm)
Megaporous	>10
Macroporous	2-10
Mesoporous	0.5-2
Microporous	0.1-0.5
Nanoporous	<0.1

Results

Level of heterogeneity

Permeability and porosity heterogeneity are quantified via Dykstra-Parsons coefficient and the results showed that permeability and porosity data for three wells are heterogeneous. The heterogeneity value of permeability data for Exploitation Well 1, Exploration Well 2 and Wildcat Well are 0.70, 074 and 0.85 respectively, whereas for porosity data are 0.48, 0.53 and 0.70. Due to space restriction, we have just shown the figures for Wildcat Well in this article. Figure 1 shows the chart of log normal probability scale to obtain Dykstra-Parsons coefficient for Wildcat Well.

Flow zone indicator (FZI)

Probability plot of logFZI for each well represented nine hydraulic flow units by visual inspection and a straight line drawn through it. Figure 2 indicates probability plot of logFZI for Wildcat Well.

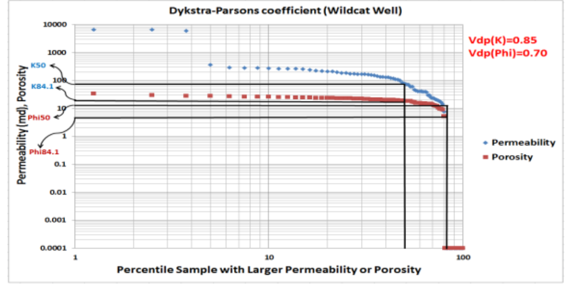

Fig. 1) Lognormal permeability and porosity distribution (Wildcat Well)

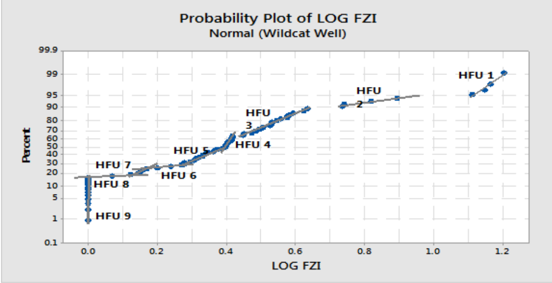

Fig. 2) Probability plot of logFZI for Wildcat Well

Identification of hydraulic flow units, which have an important role in flow transmissibility and storage, can be used in secondary recovery and additional production of the reservoir. According to the obtained hydraulic flow units from probability plots, transmissive flow units (THU) and storage flow units (SHU) are defined using Lorenz plot for porosity and permeability data (Corbett et al., 2001). THU and SHU are distinguished in the intersection of tangent and unit slope to Lorenz plot if data of each flow unit is marked on Lorenz plot.

The HFU-coded Lorenz plot indicated that around 40 % of the total flow in Exploration well 1 is corresponding to HFU1. Around 72% and 78% of the total flow in Exploration Well 2 and Wildcat Well respectively, are related to HFU 1 as well. On the other hand, the contribution of HFU 1 for storing the fluid in Exploration Well 1, Exploration Well 2 and Wildcat Well is 0.2 %, 6%, and 8%, respectively. Figure 3 shows Lorenz plot for Wildcat Well.

Stratigraphic modified Lorenz plot (SMLP)

7, 8, and 10 flow units are obtained from Exploration Well 1, Exploration Well 2 and Wildcat Well, respectively using SMLP method. Determining baffles, barriers, and speed zone units (SZU) or Super_K using SMLP method showed that baffle zones are dominant in three wells. Figure 4 shows that Wildcat Well includes 10 flow units. In this well, flow units 1, 2, 4, 6, 8, and 10 are baffles and flow units 3, 5, 7, and 9 are speed zones. Baffles, barriers, and speed zone units for other wells are illustrated in Table 2.

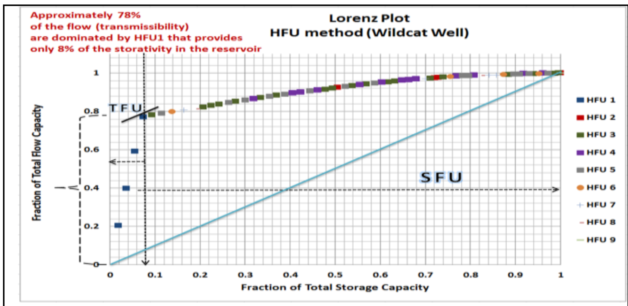

Fig. 3) Lorenz Plot for Wildcat Well

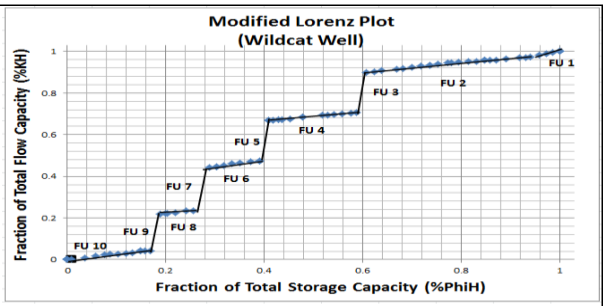

Fig. 4) Stratigraphic modified Lorenz plot for Wildcat Well

Table 2) Identification of baffles, barriers and speed zone units (SZU) for Exploration Well 1 and 2 using SMLP plot

Well	FU1	FU2	FU3	FU4	FU5	FU6	FU7	FU8
Exploration Well 1	Baffle	Baffle	Barrier	Baffle	Speed zone	Baffle	Baffle	Speed zone
Exploration Well 2	Baffle	Baffle	Speed zone	Baffle	Speed zone	Baffle	Speed zone	Baffle

Winland pore throat

Determining pore throat size (R35) from porosity and permeability data for the reservoir units provided the best basis for defining reservoir flow units. In this study, three types of pore throat sizes are obtained: macroporous, megaporous, and nanoporous. Macroporous was dominant for three wells (around 77%).

Matching of flow units

Through Petrel software, well sections of three wells are generated (Figure 5 for Wildcat Well). The facies log data is used to compare with flow units and pore types. Note that there is a good boundary matching among FZI method, pore size and facies in high and low permeable zones whereas this agreement was faded for SMLP method. The presence of nanoporous zones reduced reservoir quality. Data analyses showed that high quality flow units mainly consist of Super_K and megaporous, which are associated with geological facies. Furthermore, the value of logFZI and R35 are greater in high permeable flow units.

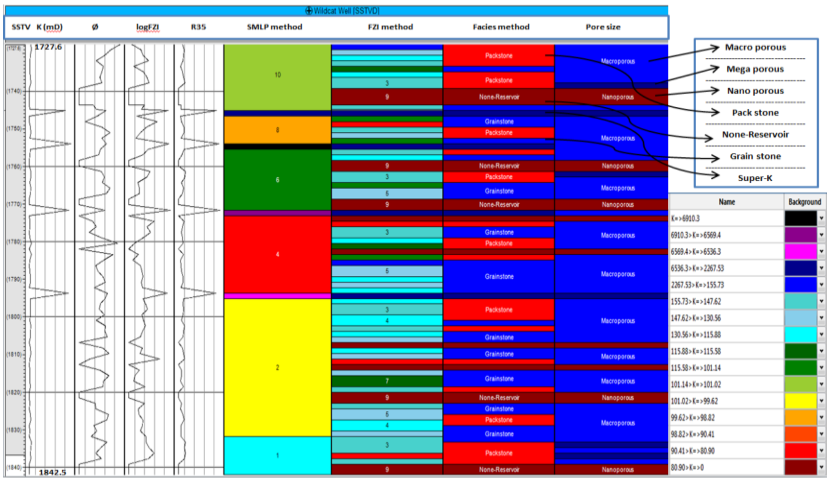

Fig 5) Well section for Wildcat Well

Conclusions

Flow zone indicator (FZI), stratigraphic modified Lorenz plot (SMLP), and Winland R35 method are applied in this research. The following conclusions are drawn from the current study.

- FZI analysis showed that there are nine flow units for each well, whereas 7, 8 and 10 flow units are obtained from Exploration Well 1, Exploration Well 2 and Wildcat Well, respectively using SMLP method.
- Among hydraulic flow units; HFU 1 is one of the most important reservoir subunits in the flow transmissibility. On the other hand, baffles, barriers, and speed zone units (SZU) are achieved using SMLP method for each well.
- The concept of flow unit is integrated with the pore size data to investigate the rock physical characteristics, providing a good basis for simulation purposes.
- In this study, three types of pore throat sizes are obtained: megaporous, macroporous, and nanoporous. Macroporous was dominant in three wells.
- In general, there is a good boundary agreement between good quality HFU and pore types with reservoir facies and vice versa.

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