PSPore Type Characterization and Classification in Carbonate Reservoirs*

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Abstract

Pore space geometry affects permeability and water saturation, becoming an important aspect of reservoir characterization. Existing pore space classifications for carbonate reservoirs include some genetic, geometrical and petrophysical aspects, but the influence of diagenesis in the pore system is poorly described. The purpose of this study is to develop a new pore classification applied to carbonate rocks that encompasses pore geometry, pore connectivity and the influence of diagenesis in the pore system by generating a quantitative result in order to identify and map reservoir flow units and diagenetic trends. This new classification is based on features observed in thin sections and hand samples, being a fast and less expensive method to evaluate porosity characteristics. Pore geometry data come from image analysis of scanned thin sections. Area, perimeter, maximum elongation and minimum width of the pores are measured. These data are used as input in an equation, and a numerical result gives information about the pore complexity and roughness. Pore connectivity data come from the definition of pore types, pore size distribution, patchiness (spatial distribution of pores), and characteristics of cementation, dolomitization and dissolution processes. Giving values for each of these textural characteristics, a numerical result also is generated through an equation, which gives information about pore connectivity. The influence of diagenesis in the pore system is evaluated through the analysis of pore types, cement textures, characteristics of dissolution (if fabric selective or not), and dolomitization, combined with the intensity of each of these processes. The diagenetic parameter is calculated similarly to the connectivity parameter, but the numerical value for each textural characteristic is different, so it gives information about diagenesis instead of connectivity. The result is a two-axis graph (pore geometry versus pore connectivity) with diagenetic data superimposed in color. This graph shows, for each sample, if the pores have simple or complex geometry, low or high connectivity, and their degree of diagenetic influence. This information helps to define petrophysical rock types and evaluate the role of diagenesis in enhancing or reducing reservoir quality. It can also be displayed as maps, so variations in the pore system geometry can be visualized in space and lateral diagenetic trends can be defined.

Pore type characterization and classification in carbonate reservoirs

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Introduction

Porosity is the proportion of pore space in any rock, expressed as a ratio or percentage, independent of geometry. The geometry of a pore space depends on its genesis. In sedimentary rocks it starts with the depositional rock fabric, and proceeds through the subsequent diagenetic alteration of the rock. In sedimentary carbonate rocks the pore system can be very complex because of the great diversity of possible depositional rock fabrics (carbonates can be clastic, chemical or biogenic in origin), and the great susceptibility to diagenetic alteration due to its mineralogy. Carbonate minerals can undergo rapid dissolution, cementation, recrystallization, and replacement at ambient conditions in a variety of diagenetic environments.

Definition of the problem

Pore space geometry affects permeability and water saturation, becoming an important aspect of reservoir characterization. Existing pore space classifications encompass some genetic, geometrical and petrophysical aspects, but the influence of diagenesis in the pore system is poorly described. Pore classification in carbonates were developed by Archie (1952), Choquette and Pray (1970), Lucia (1983, 1995), Ahr and Hammel (1999) / Ahr et al. (2005), and Lonoy (2006). The idea for a new pore characterization emerged from the desire to turn diagenetic information a quantitative data and combines it with pore geometry and connectivity data. The new pore characterization method is easy and uses only information from thin-sections, being a cheap and quick data resource to help in the evaluation of a reservoir. The new pore characterization method presents three coefficients: geometry, connectivity and diagenesis. Each coefficient value ranges from 1 to 10. To constrain the equations we analyzed 91 thin sections, which represent several types of carbonate facies and pore characteristics.

Results

Geometry coefficient

Pore geometry data come from image analysis of scanned thin sections, so it is a two-dimensional evaluation of a 3D pore system. Area, perimeter, maximum and minimum diameter of the pores are measured. These data are used as input in an equation, and a numerical result, the geometry coefficient gives information about the pore roughness and elongation (Equation 1).

$$\textbf{Geometry coefficient} = (P / A)*(8/700) + (Max\ D / Min\ D)*(2/6) \qquad \text{Equation 1}$$

Where: P = perimeter, A = area, Max D = maximum diameter, Min D = minimum diameter

The image analyses were done using the software Image-Pro Premier®. Each pore was recognized as an object by the software. Each thin section contains from 1,000 to 236,000 pores. Roughness (perimeter over area) and elongation (maximum diameter over minimum diameter) of each pore was calculated, along with the average for each thin section. Geometry data from micropores was not considered, since each micropore corresponds generally to one pixel size and the area equals zero. Macropores and mesopores have also the most influence on the effective porosity and the permeability, so it is reasonable to consider their geometry representative of the pore system.

Roughness values from the thin sections analyzed varied from 98 to 662 mm-1, so the maximum value for roughness considered in the equation is 700 mm-1. Elongation values from the thin sections analyzed varied from 3 to 5.7, so the maximum value for elongation considered in the equation is 6. The maximum roughness and elongation values could change according to the database used. In the geometry coefficient equation it was given 80% weight for the roughness and 20% weight for the elongation, as the variation in the roughness is larger and it better reflects the variation in the pore geometry. The lower geometry coefficient value is 1 and it corresponds to simple pore geometry, whereas the higher geometry coefficient value is 10 and it corresponds to a very complex pore geometry.

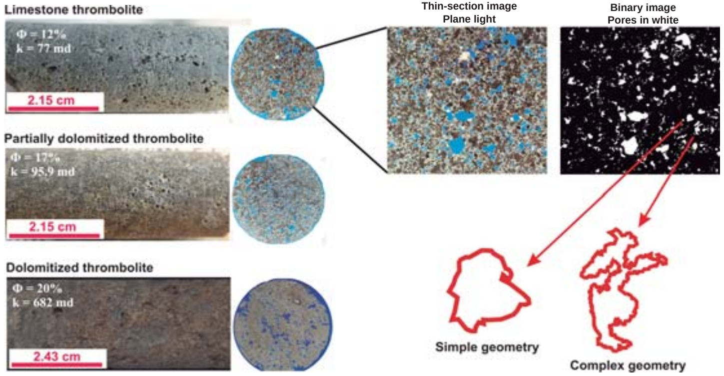

Figure 1: Pictures of plugs with their corresponding thin section - left portion of the picture. Plug measurements of porosity and permeability are shown. On the right portion of the picture a detailed image of one of the thin-sections with the correspondent binary image. Two pores with distinct geometry were highlighted. Thrombolite unit, Little Cedar Creek Field, Alabama.

Connectivity coefficient

Pore connectivity data come from porosity, pore size distribution, pore types, and characteristics of cementation and dissolution. Giving values for each of these textural characteristics, according to its influence on enhancing or reducing connectivity, a numerical result also is generated through an equation, which gives information about pore connectivity (Equation 2).

$$\begin{aligned}\textbf{Connectivity coefficient} = {} & \text{Porosity} * \text{Macroporosity (in fraction)} * \\ & * \text{Pore type combination} * \text{Dissolution intensity} * \text{Cement type (s)} * \\ & * \text{Cementation intensity} * (9/62.4) + 1\end{aligned} \qquad \text{Equation 2}$$

Porosity and pore size distribution come from the image analysis, where the software calculated the area corresponding to the pores, which are filled with blue epoxy, and recognized each pore as an object, measuring its maximum diameter. In the dataset used the maximum porosity value measured was 32%, so this is considered the maximum value for porosity in the equation. The maximum porosity value could change according to the database used. Percentage of the porosity corresponding to micropores (< 50 μm), mesopores (50 – 100 μm), and macropores (> 100 μm) was measured. Pore types were divided in two groups: “low connectivity” and “high connectivity”. The combination of the two dominant pore types, pore type 1 and pore type 2 provides a value for the equation according to its impact on the connectivity characteristics of the rock (Figure 2A). Pore type 2, when present, should correspond to at least 20% of the porosity. Dissolution intensity data comes from the percentage of secondary porosity generated by dissolution. If this secondary porosity is more than 15% it is considered high, between 5 and 15% is moderate, and less than 5% is low. Each dissolution intensity level provides the equation a value according to its impact on the connectivity.

Cementation intensity corresponds to the percentage of the original (primary) porosity that is cemented. If more than 50% of the primary porosity is cemented, the cementation intensity is high, between 20 and 50% is moderate, and less than 20% is low. The type of cement also impacts the connectivity. Two types of cement were considered: rimming / meniscus cement and non-rimming cement. The rimming / meniscus cement impacts connectivity more because it blocks the pore throats, significantly reducing permeability. Each of the cementation intensity levels and type provides the equation a a value according to its impact on the connectivity.

Diagenesis coefficient

The influence of diagenesis on the pore system is evaluated through the analysis of pore types, intensity of cementation and/or dissolution, and dolomitization or recrystallization (if it is associated with intercrystalline porosity). The diagenetic parameter is calculated similarly to the connectivity parameter, but the numerical value for each textural characteristic is different, so it gives information about diagenetic or depositional origin, instead of connectivity (Equation 3). Pore types were divided in two groups: “depositional” and “diagenetic”. The combination of the two dominant pore types, pore type 1 and pore type 2 provides the equation a value according to the degree of diagenetic influence. Pore type 2, if present, should correspond to at least 20% of the total porosity.

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Diagenesis coefficient = Pore type combination * Dissolution intensity * * Cementation intensity * Dolomitization / recrystallization intensity Equation 3

Dissolution intensity data comes from the percentage of secondary porosity generated by dissolution. If the secondary porosity is more than 15% it is considered high, between 5 and 15% is moderate, and less than 5% is low. Each dissolution intensity level provides the equation a value according to the diagenetic influence in the rock.

Cementation intensity corresponds to the percentage of the original (primary) porosity that is cemented. If more than 50% of the primary porosity is cemented, the cementation intensity is high, between 20 and 50% is moderate, and less than 20% is low. The cementation intensity levels provides the equation a value according to the diagenetic influence in the rock.

Dolomitization and recrystallization are diagenetic modifications to the rock, but they have impact on the pore system only if intercrystalline pore types are created during these processes. Dolomitization / recrystallization is considered high if it affects more than 30% of the rock, moderate if it affects between 10 and 30%, and low if it affects less than 10%. The dolomitization / recrystallization intensity levels provide the equation a value according to the its influence on the pore system.

Connectivity coefficient - how to get the values to use in the equation

1) Identify the major and the minor pore types.The minor pore type should correspond to 20% or more of the porosity. Check if they are related to high or low connectivity.

Pore types	
Intergranular Intercrystalline Connected vugs Connected growth framework Fractures Breccia	High connectivity
Intragranular Intracrystalline Isolated vugs Isolated growth framework Moldic Microporosity	Low connectivity

2) Make a combination of major and minor pore types. Use the related number in the equation.

Major pore type	Minor pore type	
Low connectivity	Less than 20% or absent	0.5
	Low connectivity	0.5
	High connectivity	0.75
High connectivity	Low connectivity	1
	High connectivity	1.5
	Less than 20% or absent	1.5

3) Identify the cement (s) and classify it (them) in rimming, meniscus or not-rimming. Determine the intensity of the cementation. Use the related numbers in the equation.

Cement type	
Not-rimming	0.9
Rimming / Meniscus	0.7
Rimming / Meniscus + Not-rimming	0.5

Cementation intensity	
Low	1
Moderate	0.9
High	0.8

4) Define the dissolution intensity.
Use the related number in the equation.

Dissolution intensity	
Low	1.1
Moderate	1.2
High	1.3

Diagenesis coefficient - how to get the values to use in the equation

1) Identify the major and the minor pore types. The minor pore type should correspond to 20% or more of the porosity. Check if they are depositional or diagenetic in origin.

Pore types	
Intergranular Intragranular (Intraskeletal) Growth framework Constructed void (vug) Microporosity	Depositional
Intragranular (by dissolution) Intercrystalline Intracrystalline Vug (by dissolution) Moldic Fracture Microporosity (by dissolution)	Diagenetic

2) Make a combination of major and minor pore types. Use the related number in the equation.

Major pore type	Minor pore type	
Depositional	Less than 20% or absent	1
	Depositional	1
	Diagenetic	2.2
Diagenetic	Depositional	3.4
	Diagenetic	4.6
	Less than 20% or absent	4.6

3) Identify the cement (s) and determine the intensity of the cementation.
Use the related numbers in the equation.

Cementation intensity	
Low	1.1
Moderate	1.2
High	1.3

4) Define the dissolution intensity.
Use the related number in the equation.

Dissolution intensity	
Low	1.1
Moderate	1.2
High	1.3

5) Identify if there is dolomitization or recrystallization, and if intercrystalline porosity created by one of these processes is present.
Use the related number in the equation.

Dolomitization / recrystallization intensity	
Low	1.1
Moderate	1.2
High	1.3

Results

The final result is a two axis graph (pore geometry vs pore connectivity) with diagenetic data superimposed in color or a three axis graph (Figures 11 and 12). These graphs show, for each sample, if the pores have simple or complex geometry (in average), low or high connectivity, and the degree of diagenetic influence on the pore system. This information helps to define petrophysical rock types and evaluate the role of diagenesis in enhancing or reducing reservoir quality. It can also be displayed as maps (Figures 5, 6 and 7), so variations in the pore system geometry can be visualized in space and lateral diagenetic trends can be defined.

Case of study: Upper Jurassic Smackover Formation thrombolite unit at Little Cedar Creek Field, southwestern Alabama

The thrombolite reservoir facies in Little Cedar Creek Field is approximately 42 km (26 mi) long, 5 to 11 km (3 to 7 mi) wide and from 9 to 21 m (30 to 70 ft) thick, oriented along a NE-SW trend (Figure 2). The thrombolite has a clotted, mottled and nodular texture, with rare domal and branching structures. The thrombolite includes abundant peloids, with minor amounts of skeletal fragments of benthic foraminifera and ostracods. Dolomite can compose as much as 30% of the bioherm and its occurrence gradually decreases from south to north, being absent from near the center to the northeast portion of the field (Figure 8). The pore types in the thrombolite are primary growth framework vugs and intergranular, and secondary diagenetic vugs (primary growth framework vugs enlarged by late dissolution), intercrystalline porosity (when calcite cement crystals or dolomite crystals have pore space between them) and microfractures.

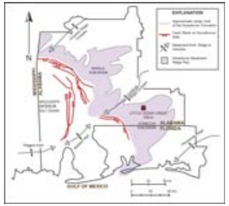

Figure 2: Location map of Little Cedar Creek Field,southwestern Alabama, U.S.A. (modified from Mancini et al. 2008)

The new pore characterization was applied to 34 thin-sections of Little Cedar Creek Field, simulating a situation where the only material available to evaluate the quality of a reservoir are some thin-sections. Three maps were generated: a pore geometry distribution map (Figure 5), a pore connectivity map (Figure 6), and a map of the degree of the diagenetic influence in the pore system (Figure 7). These maps were compared with other maps generated in previous detailed study on this field (Tonietto and Pope, 2013), to test applicability the new pore classification. In this previous study permeability data from hundreds of plugs were used to construct the permeability map (Figure 4), detailed petrography and cathodoluminescence of 153 thin sections were used to construct a dolomite distribution map (Figure 8) and a cement distribution map (Figure 9). Pore size was described in cores from 32 wells and a map of the lateral distribution of pore sizes was produced (Figure 10).

Comparing the connectivity map with the permeability map it was noticed that they have the same trend. The diagensis map resulted from a mixture of dolomitization, cementation, and dissolution trends of the reservoir. The pore geometry map indicates that in the southern portion of the reservoir, where dolomitization occurs, the pore geometry is simpler.

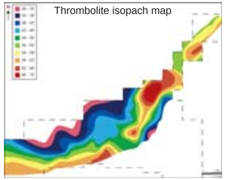

Figure 3: Thrombolite unit isopach map in Little Cedar Creek Field (Tonietto and Pope, 2013).

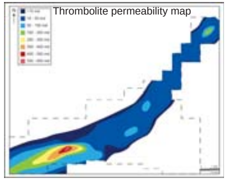

Figure 4: Permeability map of the thrombolite unit (Tonietto and Pope, 2013).

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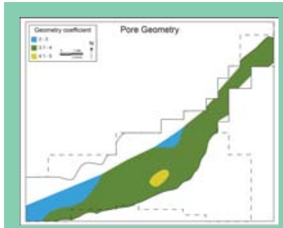

Figure 5: Lateral variation of the calculated geometry coefficient in the thrombolite unit.

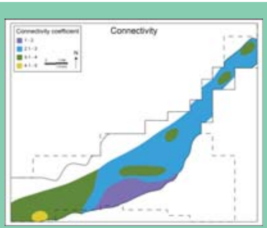

Figure 6: Lateral variation of the calculated connectivity coefficient in the thrombolite unit.

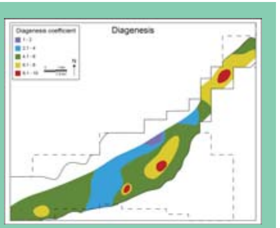

Figure 7: Lateral variation of the calculated diagenesis coefficient in the thrombolite unit.

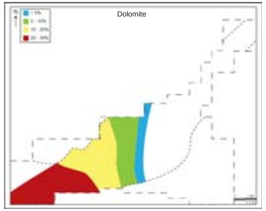

Figure 8: Lateral variation in dolomite content in the thrombolite unit (Tonietto and Pope, 2013).

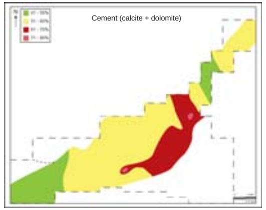

Figure 9: Lateral variation in cement content (calcite and dolomite) in the thrombolite unit (Tonietto and Pope, 2013).

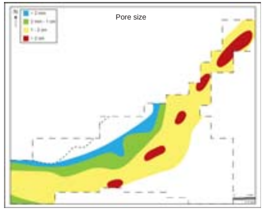

Figure 10: Lateral pore size variation in the thrombolite unit (Tonietto and Pope, 2013).

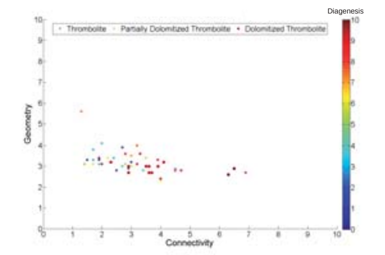

Figure 11: Crossplot of connectivity coefficient versus geometry coefficient where diagenesis coefficient values are superimposed in color.

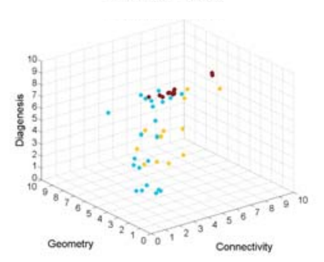

Figure 12: three-dimensional crossplot between connectivity coefficient, geometry coefficient, and diagenesis coefficient. Each facies presents a different color.

Applicability

Pore geometry characterization can be useful as a complementary method to understand petrophysical behavior of carbonates. For example, carbonate samples with large simple pores and a small amount of microporosity display higher acoustic velocity at a given porosity than samples with small, complicated pores (Weger et al., 2009). Another study reveals that in carbonate rocks, both pore structure and the absolute number of pores (and pore connections) seem more important in controlling the electrical resistivity, instead of the size of the pore throats (Verwer et al., 2011).

Defining porosity, pore type (s), cementation, and dissolution in a sample provides useful information about connectivity. Pore connectivity characterization can have reasonable results through thin-section analysis, although it is not a permeability value. It is a value that on a relative scale suggest the expected permeability value for that rock is high or low.

Diagenesis is an aspect of the rock that can be described only though thin-section analysis, being the main component of this new pore characterization. By characterizing the impact of diagenesis in the pore system, enhancing or reducing permeability, it is possible to map diagenetic trends and predict reservoir quality.The new pore characterization proposed here combines information about pore geometry, connectivity, and the influence of diagenesis in the pore system using only thin-sections. Therefore this is a cheap method that helps to quickly evaluate reservoir quality and map connectivity and diagenetic trends.

Conclusions

There are very efficient methods to study a three-dimensional pore systems in detail. Measuring porosity, permeability, and capillary pressure in plugs or hole-core samples can provide information about porosity and permeability, and computed microtomography of small fragments of the rock can precisely characterize the pore system geometry. However these methods are very expensive and time consuming compared to the simple thin-section analysis described here. Although the 3D measurements are more accurate, none of them provide information about the influence of diagenesis within the pore system. The new pore characterization proposed here is a cheap and quick method to characterize pore geometry and connectivity through the analysis of thin sections; although it is not as accurate as some of the 3D methods it provides diagenesis information. The new pore characterization was tested in one field so far, but the results were encouraging. The connectivity trends matched with the permeability map, the pore geometry characterization showed lower values where dolomitization occurs in the field, and the diagenesis map have good correlation with the dolomitization, cementation, and dissolution maps.

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