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Department of Geology

Comparing Lønøy and Lucia Carbonate Pore System Classifications and Rock-Typing Approaches

Bachelor Thesis

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Anotace: (in Czech)

Přibližně polovina světové produkce ropy a zemního plynu se vyrábí z karbonátových hornin, běžně používaných jako uhlovodíkové rezervoáry, které se nacházejí hlavně na Středním východě. Proto je průzkum a charakterizace těchto nádrží zásadní pro těžbu a průzkum uhlovodíků. Cílem vlastností nádrže bylo poskytnout údaje o prevalenci petrochemických charakteristik, jako je pórovitost, propustnost a nasycení, z pozorovaných dat. Zatímco k tomu dochází, struktura pórů karbonátových hornin významně ovlivňuje jejich vlastnosti, protože nejrozšířenější modely klasifikace typu pórů pro karbonátové rezervoáry jsou konfrontovány se špatně definovanými korelacemi mezi pórovitostí a propustností, což způsobuje, že se chovají rozdílně při různých měřeních resp. geologické nastavení. Vzhledem ke komplikované struktuře pórových systémů v karbonátových horninách může být spojení pórovitosti a propustnosti zcela nepravidelné. Vytvoření modelů fyziky hornin, které berou v úvahu dopady různých odrůd pórů, je proto jednou z nejdůležitějších výzev, které je třeba řešit v mechanice karbonátových hornin a charakterizaci nádrží. Při měření propustnosti vzorku porézního pevného materiálu je třeba zohlednit vliv typu póru, protože každá forma póru ovlivňuje vlastnosti skutečné horniny odlišným způsobem. Tato studie si klade za cíl poskytnout důkladnou znalost prvků, které řídí typy hornin, a přezkoumat novou techniku pro typování hornin, kterou lze použít pro zásoby uhličitanu na Středním východě a po celém světě.

Annotation: (in English)

Around half of the globe's oil and gas output is produced from carbonate rocks, commonly used as hydrocarbon reservoirs, mainly located in Middle East. Therefore, these reservoirs investigation and characterization are crucial for exploiting and exploring hydrocarbons. Giving data on the prevalence of petro-physical characteristics like porosity, permeability and saturation from observed data has been the aim of reservoir properties. While this is happening, the pore structure of carbonate rocks significantly impacts their properties, since the most extensively used pore-type classification models for carbonate reservoirs are confronted by poorly defined correlations between porosity and permeability, it causes them to behave differently under different measurements or geological settings. Because of the complicated structure of the pore systems in carbonate rocks, the porosity-permeability connection may be completely irregular. Therefore, creation of a rock physics models that consider the impacts of various pore varieties is thus one of the most important challenges to be tackled in carbonate rock mechanics and reservoir characterization. When measuring the permeability of a porous solid sample, the impact of pore type must be addressed since each form of pore influences the real rock properties in a distinct manner. This study aims to give a thorough knowledge of the elements that control rock types and review a novel technique for rock-typing that may be used for carbonate reserves inside the Middle East and around the World.

Number of Pages: 42

Declaration

I declare that I have prepared the bachelor's thesis myself and that I have stated all the used information resources in the thesis.

In Olomouc, May 8, 2023 ……………………………………

Ayhan Sardar Fatah

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Here foremost, I would like to thank and appreciate my family for their continuous support throughout my study life. Their sacrifices, wisdom and hard work led me to this moment of success in my life, which I am forever grateful for.

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Table of Contents

Table of Figures

List of Tables

Chapter 1: Introduction

The classification of carbonate reserves necessitates the use of quantitative physical factors like porosity and permeability. The fundamental reason for the unsuitable classifications of carbonate rocks is their diverse characteristics, which has become even more apparent when one seeks to define the petro-physical features at different scales (Janjuhah et al., 2019). Thus, dissolution, precipitation, and cementation actions can modify the basic structure and strength of carbonate rocks, making them more heterogeneous and hence changing seismic characteristics (Sharma, R. & Prasad, M., 2009). The vast divergence in pore type, pore shape, and interconnectivity cause significant uncertainty concerning the petro-physical characteristics of carbonates (Knackstedt et al., 2008). The purpose of reservoir characterization is to define the geographical distribution of petro-physical characteristics such as porosity, permeability and saturation. Wireline logs, core analyses, production data, pressure-buildup data, and tracer tests offer quantitative measures of petro-physical parameters around the well bore. These well bore data must first be combined with a geologic model in order to illustrate the petro-physical parameters in three dimensions. Studies that link rock fabric to pore-size distribution and hence petro-physical features, are critical for numerically quantifying geologic models for use in computer simulators (Lucia, 1995). A new pore-type categorization system has been established based on real-life data, mostly from Europe and the Middle East. The new method incorporates components from previous pore-type classification systems as well as introducing numerous new ones. The new pore-type system consists of 20 pore-type classes with a predictable relationship between porosity and permeability. It merges sedimentologic and diagenetic characteristics with flow-related properties, allowing reservoir-critical parameters to be predicted via sedimentologic and diagenetic models (Lønøy 2006). The new pore-type categorization reviewed here includes rock texture and pore size features, indicating depositional and diagenetic fabrics. As so, it builds on the major contributions of Choquette and Pray (1970) and Lucia (1983, 1995, 1999). Nevertheless, the new classification outperforms previous methods in terms of a better association between matrix-related porosity and permeability, resulting in both porosity cutoff values and permeability estimation (Lønøy 2006).

Chapter 2: Background and Literature Review:

Carbonate deposits represents the most major kind of hydrocarbon reservoirs (Kargarpour, 2020). According to Akbar et al. (2000), carbonate reservoirs contain around 60% of the globe's oil deposits. Carbonate reservoirs are tremendously heterogeneous due to its diverse settings of porosity and permeability. Such heterogeneities are created by the vast range of conditions during which carbonates are deposited, as well as later diagenetic transformation of the parent rocks fabric (Jardine & Wilshart, 1982). Ahr. (2008), stressed the need of assessing the diagenetic modification of the pore system using petrographical thin sections as a measure for diagenesis' contribution to reservoir quality. Pore systems differ between thick, vuggy reservoirs on the reef edge or platform margin's coarse-grained skeletal-rich facies to highly stratified, frequently discontinuous reservoirs on the reef core, platform interior, and nearshore facies (Jardine & Wilshart, 1982). Such heterogeneity complicates the efficient management of carbonate reservoir generation. To efficiently produce from a hydrocarbon reserve, the producing company must have a great set of geology and hydrodynamic data across the reservoir (Kargarpour, 2020). Carbonate rocks contain a diverse variety of pore sizes and an elaborate interconnected network. Porosity and other physical parameters frequently display poor connections with permeability and velocity. Understanding the diagenetic mechanisms that affect porosity is critical for carbonate reservoir evaluation (Wardlaw, 1976). Pore structures are the primary determinants of permeability and elastic characteristics. Different rocks of identical depth and porosity could possess various permeabilities and acoustic velocities (Baechle et al., 2008). Many studies have been conducted to establish the impact of pore structure on the petrophysical characteristics of carbonate rocks.

Archie (1952), initially focused on the link among rock structure and petrophysical parameters to underline the relevance of pore structure in pore type categorization, which he bases on pore type visibility (Table 1) and matrix texture (Table 2).

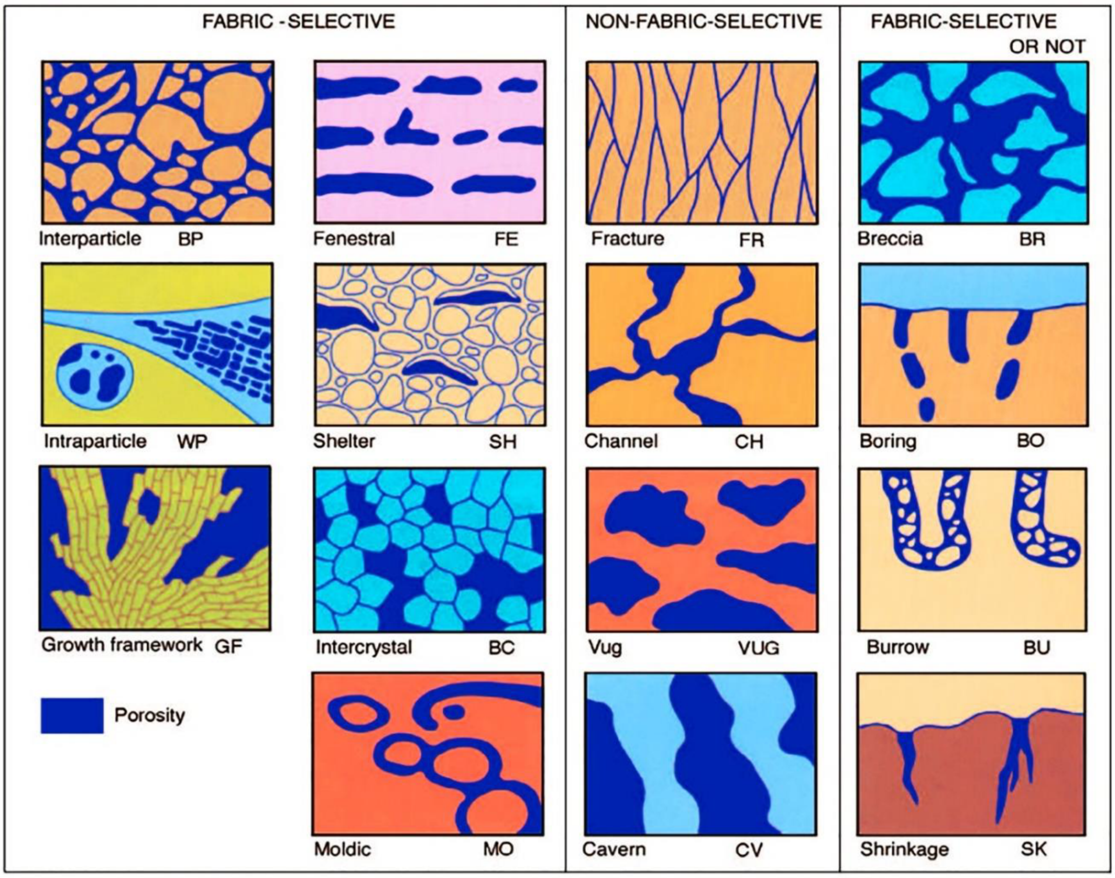
Table 1 Visible pore size classification of carbonate rocks (Archie, 1952)

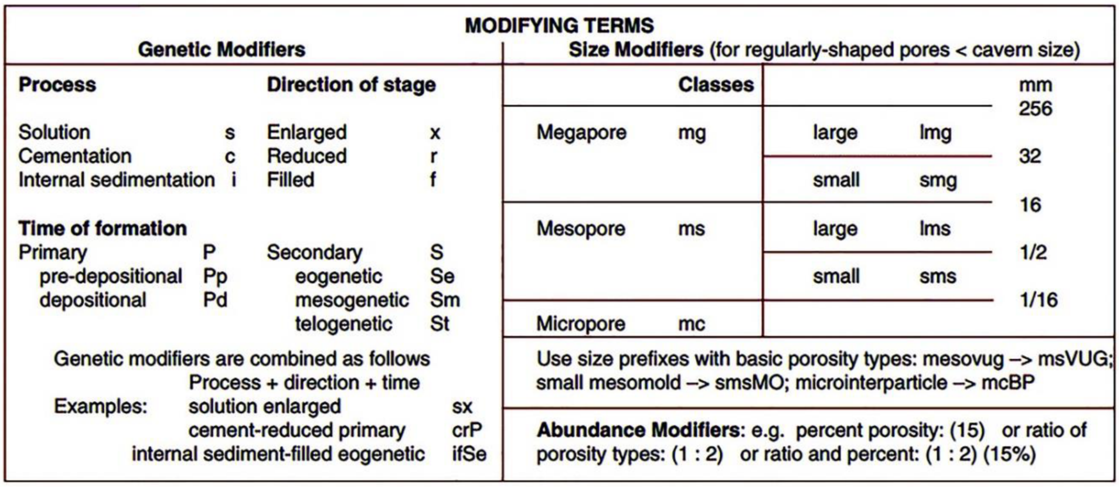
Class	Description
Class A	No visible porosity under about 10^x resolution microscope or where pore size is less than about 0.01 mm in diameter.
Class B	Visible porosity, greater than 0.0l but less than 0.1 mm.
Class C	Visible porosity, greater than 0.1 mm but less than size of cuttings
Class D	Visible porosity, as evidenced by secondary crystal growth on faces of cuttings or '"weathered-appearing" faces showing evidence of fracturing or solution channels; where pore size is greater than size of cutting.

Table 2 Micrite texture classification of carbonate rocks (Archie, 1952)

Matrix Texture	Hand Sample Appearance	Microscopic Appearance
Type-I Compact Crystalline	Hard, dense, crystalline, sharp edges and smooth faces	Matrix made up of crystals lightly interlocking allowing no visible pore spaces between crystals, commonly producing "feather edges" on breaking due to fracturing of clusters of crystals in thin flank.
Type-II Chalk	Dull, chalky, crystalline, appearance absent because small crystals are less tightly interlocked, thus reflecting light in different directions, or made up of extremely fine granules	Crystals, less effectively interlocking than the foregoing, joining at different angles. Extremely fine texture may still appear "chalky"' under this power, but other may begin to appear crystalline.
Type-III Granular	Sugary appearance (Sucrose). Size of crystals classed as: Very fine = 0.5mm, Fine = O.lmm, Medium = 0.2mm, Coarse = 0.4mnL	Crystals interlocking at different angles, generally allowing space for considerable porosity between crystals. Oolitic and other textures fall in this class

Choquette & Pray (1970), developed a specific description system that included all key forms of carbonate pores and was extensively recognized and utilized in the industrial and academic fields. The genetic categories of this system are broken down into primary and secondary pore networks. Primary porosity appears as intergranular pores that are also seen in terrigenous sand (clastic deposits). Due to the enormous diversity and nature of the carbonate grains and the texture of the sediments, along with its powerful diagenetic potential, this is the sole a likeness between the carbonate pore systems with terrigenous sand (clastic deposits) (Choquette & Pray, 1970). Most carbonate pores, though are formed by secondary processes. The suggested categorization aims to improve the geological understanding and description of pore structures and associated carbonate source rocks (Choquette & Pray, 1970). The basis of this classification depends on the genetic formation in which it is possible to predict how the porosity was formed, in which the key element of this system is to determine if the porosity is fabric selective or not. (Fig 1) shows the principles of Choquette & Pray, (1970) classification, from fabric selective seven common forms of fabric selective (intraparticle, interparticle, shelter, fenestral and growth framework) being from primary porosity and (intercrystalline, moldic) being from secondary porosity types. Non-fabric selective porosities being (fracture, channel, vug and cavern) in which all non-fabric selective types are of secondary porosity and finally (breccia, boring, burrow and shrinkage) are considered as fabric selective or non-fabric selective depending on how the rock is viewed.





MODIFYING TERMS

Genetic Modifiers

Process		**Direction of stage**	
Solution	s	Enlarged	x
Cementation	c	Reduced	r
Internal sedimentation	i	Filled	f

Time of formation			
Primary	P	Secondary	S
pre-depositional	Pp	eogenetic	Se
depositional	Pd	mesogenetic	Sm
		telogenetic	St

Genetic modifiers are combined as follows
Process + direction + time
Examples: solution enlarged sx
cement-reduced primary crP
internal sediment-filled eogenetic ifSe

Size Modifiers (for regularly-shaped pores < cavern size)

Classes				mm
				256
Megapore	mg	large	lmg	
				32
		small	smg	
				16
Mesopore	ms	large	lms	
				1/2
		small	sms	
				1/16
Micropore	mc			

Use size prefixes with basic porosity types: mesovug –> msVUG; small mesomold –> smsMO; microinterparticle –> mcBP

Abundance Modifiers: e.g. percent porosity: (15) or ratio of porosity types: (1 : 2) or ratio and percent: (1 : 2) (15%)

Figure 1 Choquette & Pray rock fabric classification. Modified after Choquette & Pray (1970)

Lucia (1983, 1995) applied the Dunham texture classification (Dunham, 1962) and the Choquette and Pray taxonomy. (1970), to adjust the essential geological factors, which may minimize the uncertainty in estimating petrophysical parameters in carbonate geological systems. Lucia (1983) categorization is based on two major classes: interparticle pores and vuggy pores (Fig 2, 3). Lucia. (1995), praised Archie. (1952), work and remarked that while the categorization is still relevant for evaluating petrophysical features in the case of a basic geological model, it falls short of giving accurate data on depositional and diagenetic processes. According to Lucia. (1995), both the Dunham. (1962), and the Choquette and Pray taxonomy. (1970), categories are commonly used, but none provides a clear relationship to the quantitative reservoir properties that are indicative of the borehole environment. Lucia. (1995), sought to close the gap by presenting a method for determining significant mappable geological characteristics for petrophysical quantification of geological reservoir systems. According to Lucia. (1995), the pore size distribution influences permeability and saturation and is connected to rocky tissue. The rock fabric consists of texture (inspired by Dunham. 1962), grain size, pore kinds, and distribution. Relatively, the texture is broken down into three components: grain-dominated, muddy grain-dominated, and mud-dominated. The pore system's categorization is simplified by defining three pore size classes: intraparticle, separate vugs, and touching vugs. (Lucia, 1995).

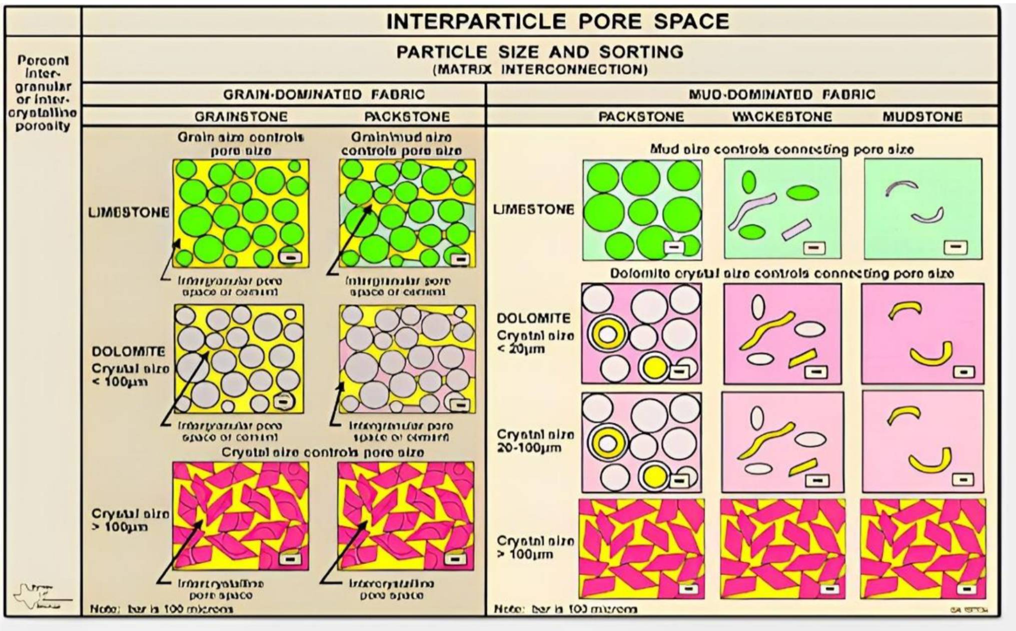


Figure 2 Classification of interparticle carbonate pore spaces based on grain size and sorting of grains and crystals. Modified after Lucia (1995)

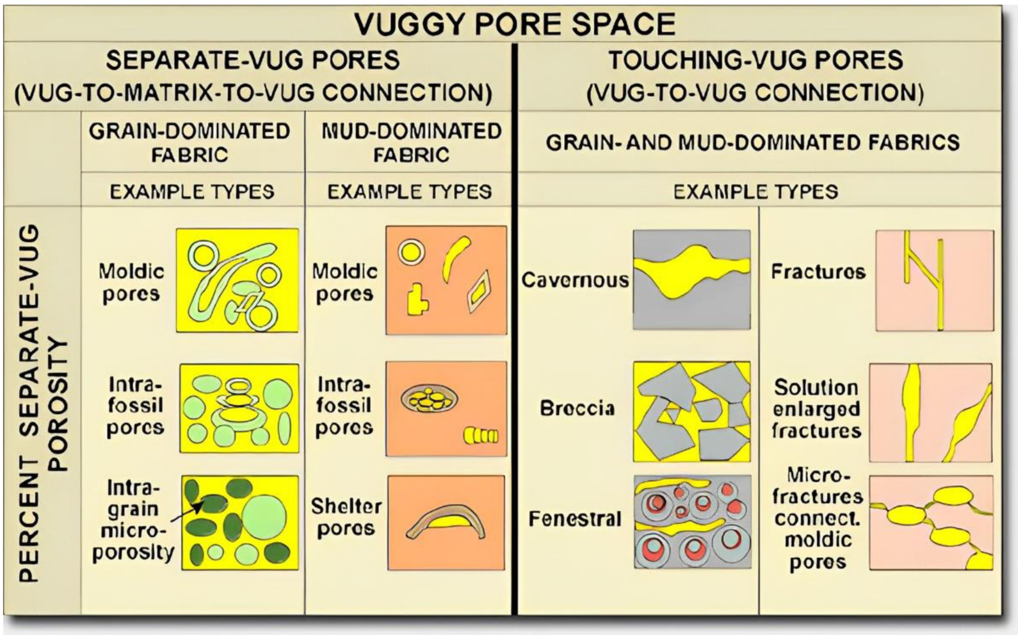


Figure 3 Geological and petrophysical classification of vuggy pore spaces based on vugs interconnection. Modified after Lucia (1995)

Lønøy. (2006), suggested a new pore space categorization based on Lucia. (1995), and Choquette & Pray. (1970), descriptive taxonomy. Lønøy. (2006), defined a group of 20 pore types (Table 3). His categorization allows good access to sedimentological and diagenetic features. Lønøy. (2006), noted that his categorization is based on pore size rather than grain size, as Lucia. (1995). Lønøy. (2006), describes that the link between porosity and permeability is not well defined, which is a limitation for the pore-type classification methods that are currently the most extensively used during carbonate reservoirs. These systems limitations result from carbonate reservoirs having high porosity. In many instances, the current categorization methods for porosity-permeability statistics do not adequately incorporate diagenesis, sedimentology and flow-rated features, which may be problematic during the data analysis period. Because of this, it's challenging to develop prediction models for such dispersion of reservoir quality throughout many carbonate reservoirs, which results in a large amount of ambiguity in the estimations of hydrocarbon reserves.

Palabiran et al. (2016), States the dynamic and static reservoir models for a simulation project may be built with the aid of rock characterization. Reservoirs characterization allows for more accurate estimates of reservoir reserves and forecast of its performance. Several specialist have produced many models of rock typing approaches, however, these models often fail to consistently classify rock types depending on geological or technical properties in carbonate reservoirs. Thus, we demand research on the reliability and applicability of a rock-typing approach in a given setting. To accurately characterize oil and gas reservoirs, one must collect data. Log information's gathered from wells has to be compared to the results of analysis of core samples. Rocks may be categorized (typed) using core data, often according to petrophysical (prototyping) or geological (lithotyping) characteristics. A reservoirs dynamic and static modelling benefits greatly from rock classification on core samples (Palabiran et al., 2016). If we characterize the reservoir first, we can make better-informed estimates of the reserves and predictions about the reservoirs performance. Several different models of rock typing systems have been created, yet, they all differ in their ability to designate types of rocks according to the geological and technical properties of carbonate reservoirs. That calls for research on the reliability and applicability of rock-typing techniques in a given environment. Attempting to type a variety of carbonate rocks may be difficult since their diagenesis mostly determines their composition. As a result, it is important to evaluate the most effective rock typing techniques currently in use for carbonate rock characterization

Rosid. (2019), explained in his research that the depositional facies have far greater influence on the degree of heterogeneity inside a carbonate reservoir than in a crustal reservoir. That is due to the increased intensity of diagenesis and facies fluctuations vertically and laterally. Consequently, the carbonate reservoirs permeability and rock type posed the greatest difficulties in characterization. The rock-typing technique was developed to estimate rock type and rock permeability. In environments with a wide variety of diagenesis and facies, like a carbonate reservoir, such a technique has shown to be the most effective. Optimal output from carbonate reservoirs may be predicted based on their petrophysical characteristics, which can be relied upon. Basic data is rare to find and usually prohibitively costly.

Chapter 3: Methodology

The reviewed study's technique included the assessment of thin sections as well as the addition of standard core analysis data. The study's permeability was computed and compared to observed values after pore categorization using each technique. Routine core analysis data from c.430 reservoir interval core plugs were fed into a porosity-permeability cross plot to enable quality control of the dataset exempting fractured specimens. A total of 50 rock samples were petrographically investigated and categorized using both Lucia's and Lonoy's methods. In the study, porosity was also measured in terms of points per pore type. Porosity-permeability Cross-plots were created for each scheme. Finally, each scheme's permeability was computed and compared to the observed permeability.

Nevertheless, this study also aims to review and compare both existing carbonate pore system classifications of Lucia. (1995, 1999) and Lønøy. (2006), in order to understand how each classification describes and categorizes the various types of pores found in carbonate rocks. We'll look at the ideas and criteria that each classification method uses to detect and distinguish between distinct pore types, such as interparticle, intraparticle, and moldic pores. We will also analyze the benefits and drawbacks of each categorization system, such as simplicity of use, application to various carbonate rocks, and the kind of information supplied by each system. Finally, with the reviewed data sets, we will be able to obtain a better knowledge of the differences and similarities between these two categories by comparing them, which will assist us in selecting the most appropriate classification system for a certain reservoir or application.

Chapter 4: Results and Discussion

4.1 Lucia (1995, 1999) Scheme

There are three kinds of rock fabrics depending on sorting and grain size in addition to petrophysical information (interparticle porosity). While interparticle porosity determines the pore-size distributions and permeability inside the fields, sorting and grain size determine the three permeability areas these rock materials maps. According to Lucia. (1995, 1999), pore space among crystals or grains (interparticle) and every other pore space represents the most practical separation of pore varieties for petrophysical reasons (vuggy). Separate-vug (fabric-selective, pores joined by a matrix) and touching-vug are two kinds of vuggy porosity that Lucia. (1995, 1999), recognized (non-fabric selective, forms an interconnected pore network of significant extent)

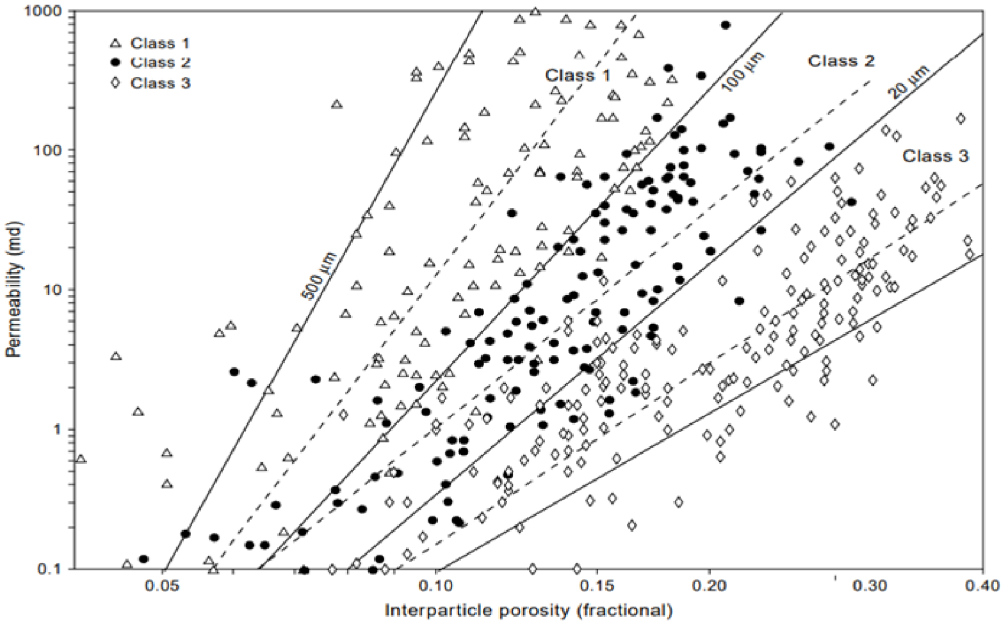


Figure 4 porosity-permeability cross plot illustrating trends exhibited by each of the 3 rock fabric classes Lucia. (1995, 1999)

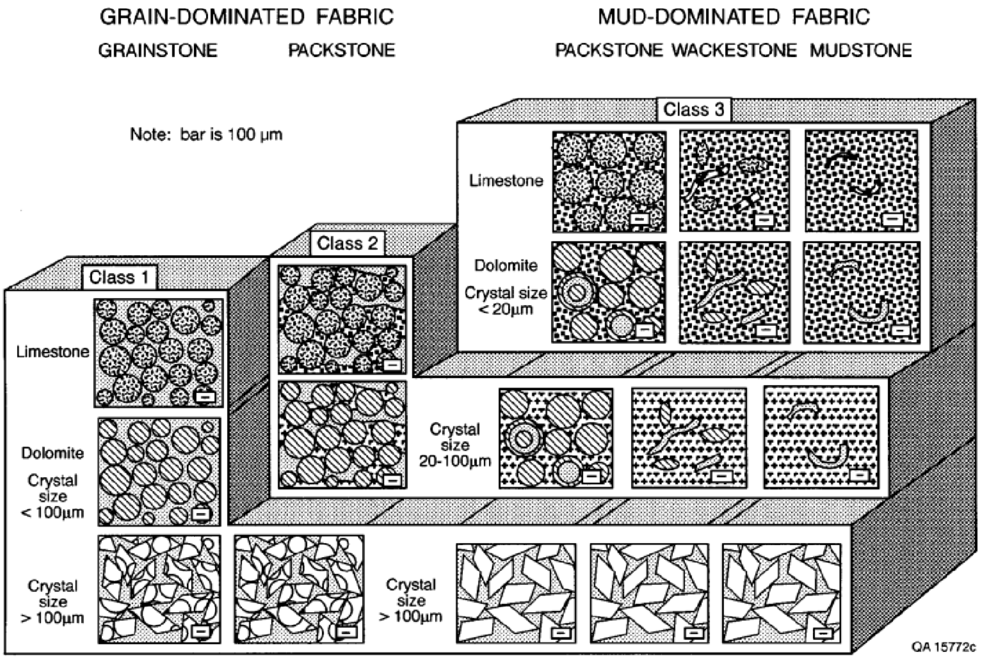


Figure 5 petrophysical and rock fabric classes based on similar capillary properties and interparticle porosity/permeability transforms Lucia. (1995, 1999).

In Lucia. (1995, 1999), scheme, classes 1, 2, or 3 specimens usually don't plot inside the corresponding permeability area, indicating no apparent difference between them (Fig 6). Class 1 specimens are absent from the class 1 field. They, therefore, are concentrated inside the level 2 permeability area, with a few instances in the class 3 field. Most class 2 samples are outside of the 1st class permeability area and inside it. In contrast, a small number of examples are in the class 2 field. In contrast to the class 1 field, all three fields' class 3 specimens showed a minimal trend. Using Lucia. (1995, 1999), transformation, permeability estimates are dramatically overstated for higher permeabilities or understated for lower permeabilities. The contrast indicates a relatively low R2 level (0.16), suggesting inaccurate permeability prediction. A large number of samples do not fall inside the class 1 field, indicating that inter particulate porosity is not considered.

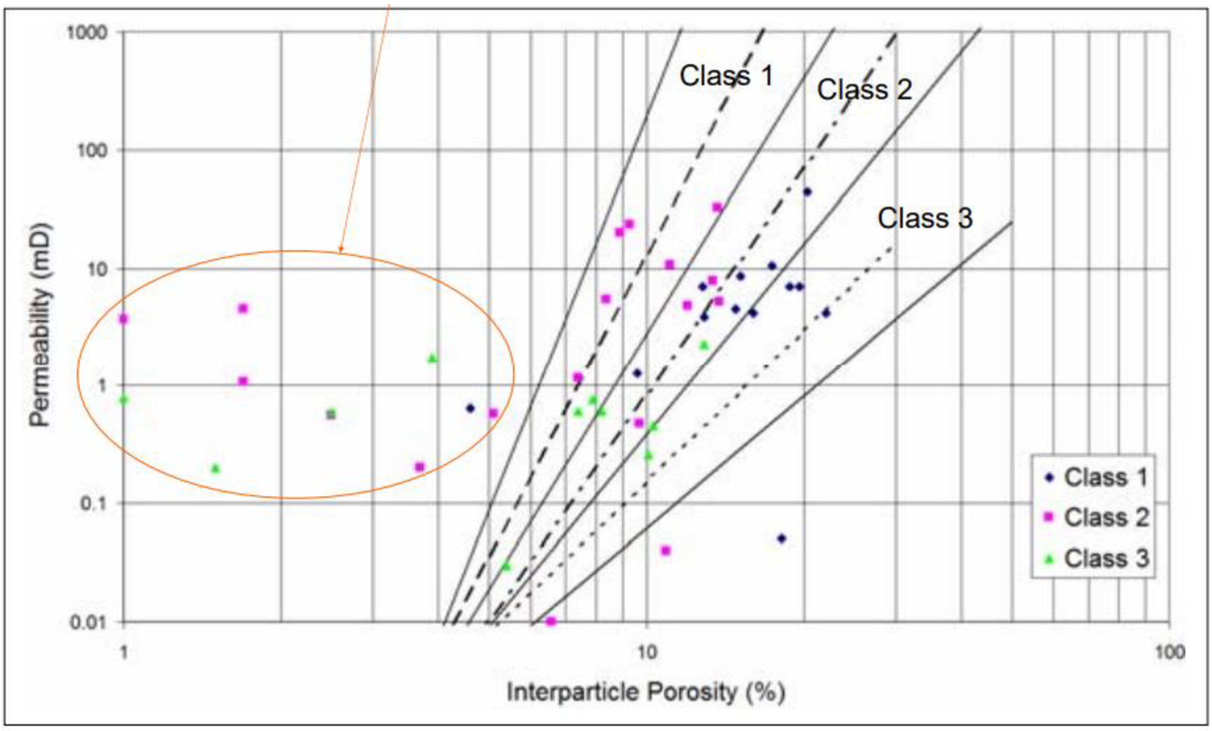


Figure 6 porosity-permeability cross-plot of data divided by Lucia (1995, 1999) class (Johnson, 2010).

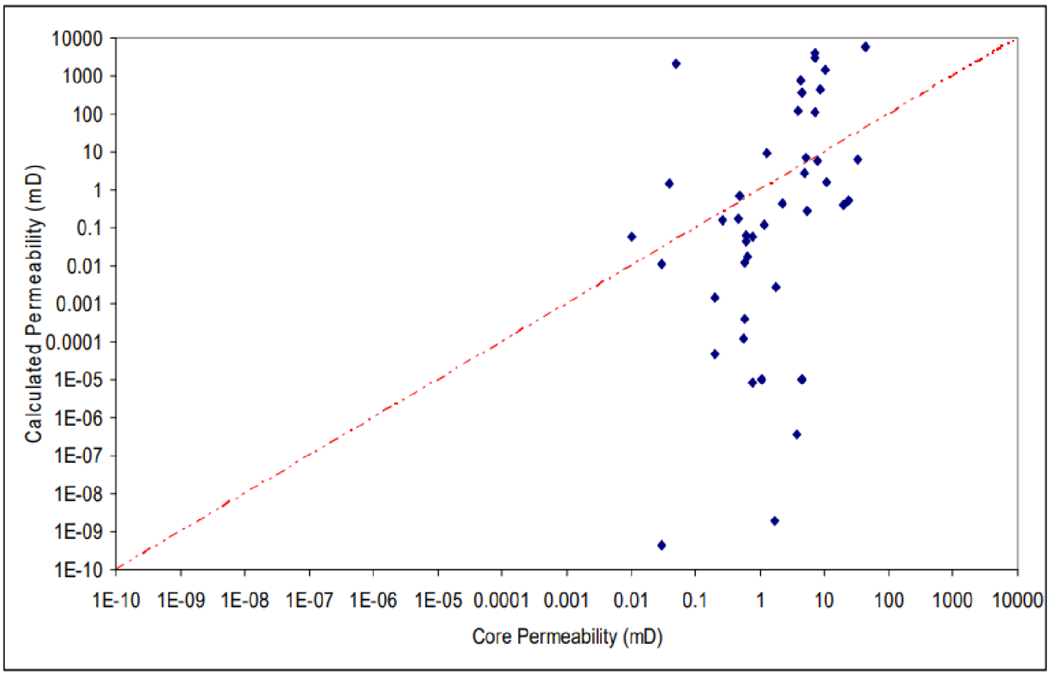


Figure 7 cross-plot to show comparison between measured and calculated permeability using Lucia (1995, 1999) calculation (Johnson, 2010).

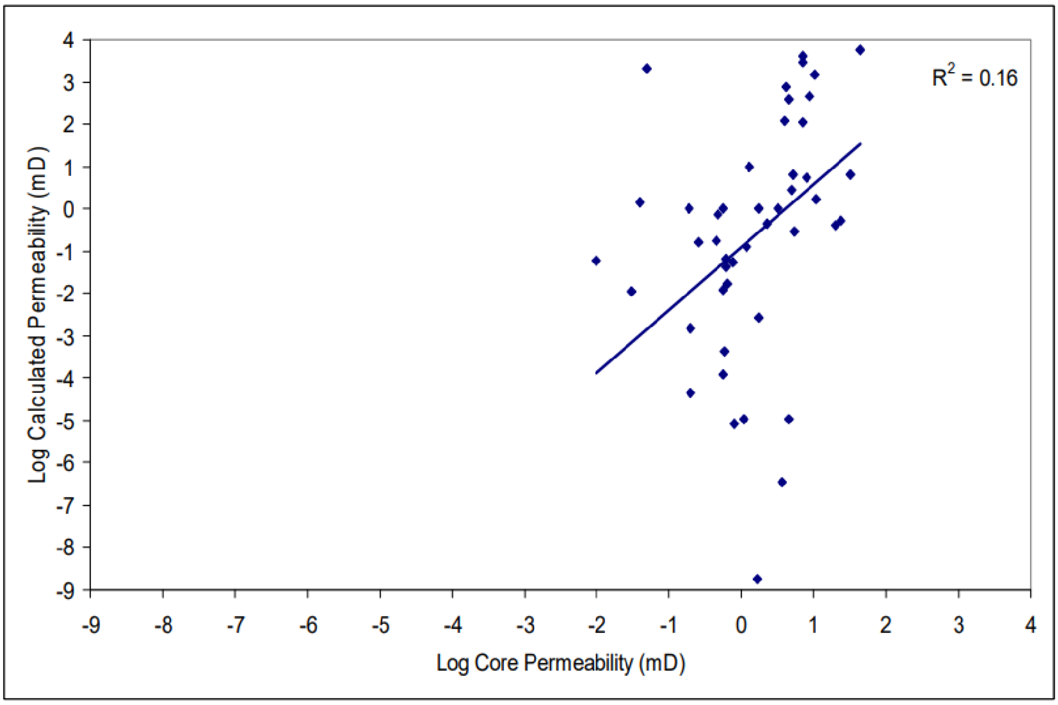


Figure 8 cross-plot logarithm permeability to show comparison between measured and calculated permeability using Lucia (1995, 1999) calculation (Johnson, 2010).

4.2 Lønøy. (2006) Scheme

Lønøy. (2006), classified that depending on pore size, type, and distribution, there are 20 kinds of pores (Table 3). Pore-size difference from Lucia. (1995, 1999), is included in the scheme, which was texturally developed by Choquette & Pray. (1970).

Table 3 New porosity classification of carbonate rocks proposed by Lønøy. (2006)

Pore Type	**Pore Size**	**Pore Distribution**	**Pore Fabric**	**R2**
Interparticle	Micropores (10-50 um)	Uniform	Interparticle, uniform micropores	0.88
		Patchy	Interparticle, patchy micropores	0.79
	Mesopores (50-100 um)	Uniform	Interparticle, uniform mesopores	0.86
		Patchy	Interparticle, patchy mesopores	0.85
	Macropores (> 100 um)	Uniform	Interparticle, uniform macropores	0.88
		Patchy	Interparticle, patchy macropores	0.87
Intercrystalline	Micropores (10-20 um)	Uniform	Intercrystalline, uniform micropores	0.92
		Patchy	Intercrystalline, patchy micropores	0.79
	Mesopores (20-60 um)	Uniform	Intercrystalline, uniform mesopores	0.94
		Patchy	Intercrystalline, patchy mesopores	0.92
	Macropores (>60 um)	Uniform	Intercrystalline, uniform macropores	0.80
		Patchy	Intercrystalline, patchy macropores	
Intraparticle			Intraparticle	0.86
Moldic	Micropores (<10-20 um)		Moldic micropores	0.86
	Macropores (>20-30 um)		Moldic macropores	0.90
Vuggy			Vuggy	0.50
Mudstone microporosity	Micropores (<10 um)		Tertiary chalk	0.80
			Cretaceous chalk	0.81
		Uniform	Chalky micropores, uniform	0.96
		Patchy	Chalky micropores, patchy	

As per the Lønøy. (2006), Scheme, because not all 20 pore-type categories were included in the dataset, it was impossible to evaluate them all, except for intercrystalline homogeneous macropores, achieving significant R2 values was challenging. Estimated permeability was often overestimated as well as a lower R2 value (0.22) in the contrast of estimated and observed permeability indicates inadequate permeability estimation.

Table 4 R2 comparison (Johnson, 2010).

Pore-type class	R2: this study	R2: Lonoy (2006)
Chalky microporosity, uniform	0.03	0.96
Intercrystalline uniform macropores	0.86	0.80
Moldic micropores	0.45	0.86
Interparticle uniform mesopores	0.75	0.86
Interparticle, uniform macropores	0.02	0.86

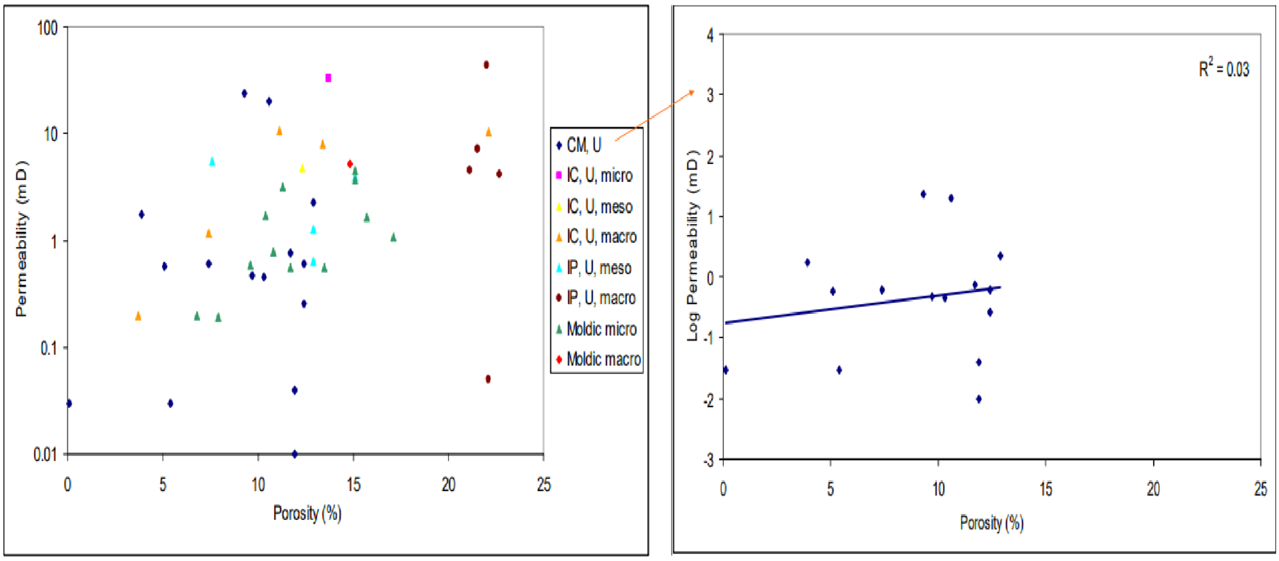


Figure 9 Porosity-permeability cross-plot of data provided by Lonoy (2006) Class (CM, U =Chalky micropores,IC, U = Intercrystalline, Uniform Macropores,IP, U = Interparticle, Uniform Mesopores), compared to Porosity permeability cross plot for Uniform Chalky Micropores

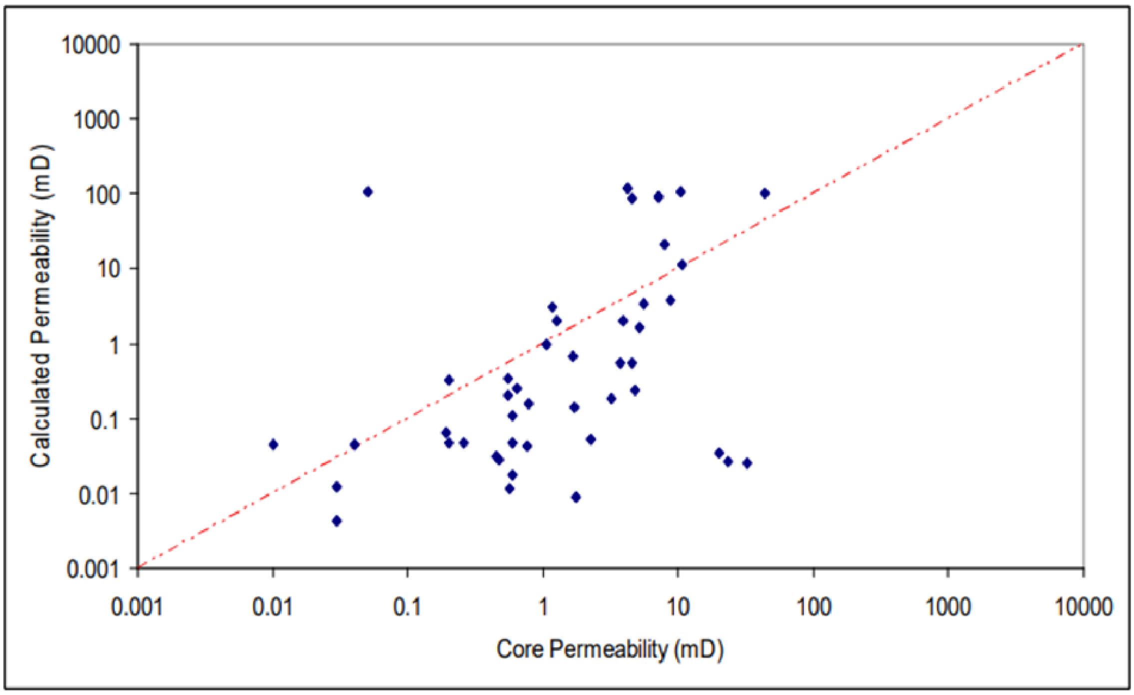


Figure 10 Cross-plot to show comparison between measured and calculated permeability using Lonoy (2006) scheme (Johnson, 2010).

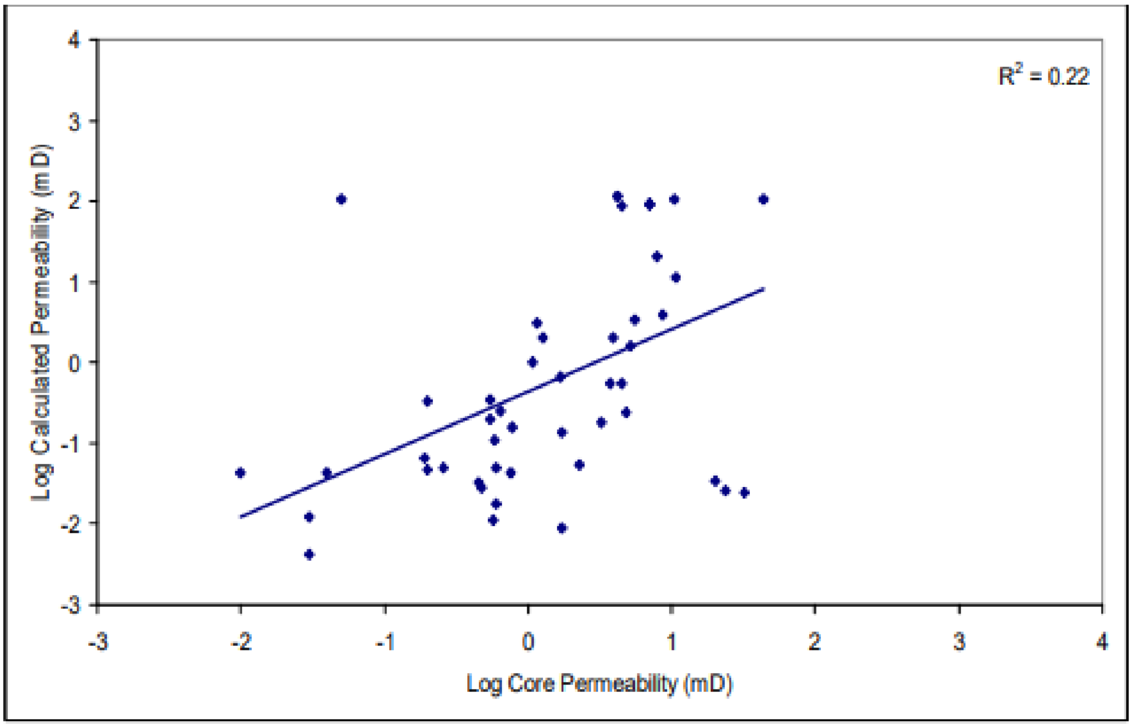


Figure 11 Cross-plot of logarithm permeability to show comparison between measured and calculated permeability using Lonoy (1995, 1999) scheme (Johnson, 2010).

For the Lucia (1995, 1999) Scheme, numerous samples fail to fall below the class 1 permeability range, indicating that interparticle porosity is underrated. Interparticulate porosity is determined by reducing separate-vug porosity from total porosity, according to Lucia. (1995, 1999):

“Interparticle porosity = Total porosity – Separate-vug porosity”

Assuming overall point-counted porosity equals observed porosity to properly point-count inter particulate porosity. A cross-plot of such two possible values reveals that the estimated porosity is 1–10% higher than the point-counted total porosity. That occurs because point-counting is not possible for samples with microporosity. In samples with greater estimated porosity versus point-counted porosity, intraparticle microporosity predominates. It is impossible to precisely point-count such sort of pore. Point-counting Intraparticle microporosity precision issues might result in an overstatement of this pore kind and an inaccurate computation of inter-particulate porosity. A suggestion is that datasets with lower separate-vug porosity are most suited for using Lucia. (1995, 1999) categorization.

For Lønøy. (2006), scheme, although Lønøy’s categorization is predicated on dominant pore structure, most samples hold various pore types. Because each specimen has a variety of pore types, data points along porosity-permeability trend lines tend to be dispersed. Although not always, re-plotting pore kinds with pore-type specific porosity often raised the R2 value. As a result, this isn't the only explanation for the low R2 values, but it helps to explain why the R2 values in this research are lower than those predicted by Lønøy. (2006). Low R2 values might be explained by the wide variation of pore diameters in each sample. Intercrystalline homogeneous macropores represent the only category that exhibits the anticipated trends, perhaps due to dolomite’s relatively predictable impact on porosity. Data may not be well restricted around projected trend lines due to the scaling mismatch between the core plug and thin section.

As a result, neither approach produces the intended outcomes for the dataset in this investigation. Lønøy. (2006), categorization outperformed Lucia. (1995, 1999), classification in terms of permeability prediction. Because of pore-type variability, both the Lucia. (1995, 1999) and Lønøy. (2006), approaches fail to appropriately characterize porosity-permeability interactions. There were issues with determining interparticle porosity with significant quantities of intraparticle porosity (separate-vug) present in Lucia. (1995, 1999), approach. There were issues with pore type and size variability in Lønøy. (2006), design. The scale differential among thin sections and core plugs presented issues while point-counting pore types due to core-plug heterogeneity. The sample size was the study's principal drawback. It is suggested that the study be repeated with a much bigger dataset to allow for better assessment of porosity-permeability connections and examination of more of Lønøy's pore-type classifications.

As previously stated, the new pore-type categorization method presented by Lønøy. (2006), is based on the Choquette and Pray. (1970), approach but mainly integrates components from the Lucia. (1983, 1995, 1999), system. The new methodology, however, includes additional features that are crucial for estimating reservoir parameters.
The following are the primary differences between the new carbonate pore system and that of Choquette and Pray. (1970) and Lucia. (1983, 1995, 1999):

- The distribution of porosity is a significant new element in the classification.
- The newly developed classification method incorporates Lucia's subdivision of interparticle porosity, but it now relies on pore size rather than grain size and sorting.
- The three interparticle pore-type classes of Lucia, as well as the interparticle and intercrystalline porosity types of Choquette and Pray, have been separated into 12 different types (6 interparticle and 6 intercrystalline).
- Micromoldic and macromoldic pores have been separated.
- Mudstone microporosity is an entirely new pore type class with four pore types.

Porosity-permeability crossplots for data sets utilized in Lønøy. (2006), generate considerably higher coefficients of determination (R2) with the newly developed classification method than with Choquette and Pray. (1970), and Lucia. (1983, 1995, 1999), systems of classification (Tables 3, 5).

Table 5 Porosity-Permeability Coefficients of Determination

Pore Type	R2
Lucia (1983, 1995, 1999) Classification System	
Interparticle, class 3	0.68
Interparticle, class 2	0.62
Interparticle, class 1	0.79
Vuggy, separate	0.86
Vuggy, touching	0.45
Choquette and Pray (1970) Classification System	
Interparticle	0.70
Intercrystalline	0.50
Moldic	0.88
Intraparticle	0.86
Vuggy	0.50

Sedimentologic and diagenetic traits are combined with flow-related qualities in the new classification framework, and reservoir-critical parameters may therefore be predicted using sedimentologic and diagenetic models. The Lønøy. (2006) scheme is built around three key components: pore type, pore size, and pore distribution. However, some of the mudstone micropore classes are affected by age.

4.3 Pore type

Interparticle, intercrystalline, vuggy, intraparticle, moldic, and mudstone microporosity are the six major pore types found (Table 3). The initially described five pore types are remarkably similar to those outlined by Choquette and Pray. (1970), while the sixth is new. Although Choquette and Pray defined ten more pore types that are relevant for considering. These pore types were left out in Lønøy. (2006), classification due to a lack of data for fenestral, shelter, boring, burrow, and shrinkage porosity and analytical considerations for fracture, channel, cavern, growth framework, and breccia porosity. Due to a lack of data, it is likely that pore patterns are of limited importance in the reservoirs that the classification has included and studied thus far. The majority of analytical issues are connected to a high pore/plug size ratio, i.e., plug sizes are too tiny to accurately represent the pore network.

4.4 Pore size

Lucia. (1983, 1995, 1999), discovered that the distribution of pore sizes governs permeability and is connected to rock fabric. As a result, he employed average particle size and sorting to distinguish between several interparticle pore-type classes. The word "particle" was applied to both grains (multicrystalline particles) and crystals (single-crystal particles) (Lucia, 1983). The data set in Lønøy. (2006), demonstrates a pretty strong connection between intercrystalline pore size and crystal size. Nevertheless, as Lucia (1995, 1999) points out, the relationship between intergrain pore size and particle size is occasionally insufficient, which is due in part to poor sorting. Allochem size and interparticle mud can influence pore diameters in packstones, leading to a wide variety of pore sizes. Pore size at the same average particle size is governed by interparticle mud (pores between mud particles) in some circumstances and bigger grains (pores between allochems) in others. Typical particle size is similarly difficult to quantify because it might be determined by volume or by grain count. Sorting in relation to mud infilling of interparticle pore space was studied by Lucia. (1995, 1999). by distinguishing between grainstone, mud-lean packstones (graindominated packstones), and mud-rich packstones (muddominated packstones). Lønøy. (2006), however, ignores the significant impact that allochem sorting has on pore size. Grain sizes in moderately to badly sorted grainstones and mud-lean packstones vary greatly, regardless of the same grain-size class, resulting in tighter grain packing and smaller pore diameters. Cement is another key influence on pore size that has not been addressed by the Lucia (1983, 1995, 1999), classification scheme. Interparticle cement has little effect on particle size or sorting, however it does lower pore size and pore throats. With respect to the cement volume and morphology, samples that share similar particle size and sorting might display a significant variation in pore size and permeability-porosity relationship. Lucia. (1983, 1995, 1999), categorization scheme, which argues that pore-size distribution influences permeability and is connected to rock fabric, is therefore lacking a crucial component. In accordance with these concerns, the new pore-type classification technique of Lønøy. (2006), use pore size rather than particle size. Pore-size differentiation outperformed particle-size differentiation in terms of coefficient of determination (R2) in the porosity-permeability crossplots. Pore-size disparity was carried out by visual inspection of thin sections and was employed for interparticle, intercrystalline, and moldic pore types (Table 3). Moldic pores are optically divided into micro-, meso-, and macropores, whilst interparticle and intercrystalline pores have been visually separated into micro- and macropores. Pore diameters vary according to pore type (Table 3) and do not depend upon other published definitions. The interparticle pore diameters and size distributions of the samples used for reference portrayed in Figures (13-16) were taken into account. Micropores dominate with pore diameters ranging from 10 to 60 mm (70% of the pores). Mesopores have a major pore diameter of 40-100 mm, with around 30% of the pores being in the 100-300-mm range. Macropores have a diameter greater than 100 mm (about 75% of the pores). Pore-size groups of interparticles can thus be defined as 10-50 (micropores), 50-100 (mesopores), and larger than 100 mm (macropores). Mudstone microporosity is defined as porosity with prominent pore sizes smaller than 10 mm. Intercrystalline micropores are typically 10 - 20 mm in diameter, however, mesopore sizes are often 20 -60 mm. Intercrystalline macropores are greater than 60 mm in diameter. Moldic micropore widths are normally less than 10-20 mm, however they can be greater on occasion. Moldic macropores are greater than 20-30 mm in diameter.

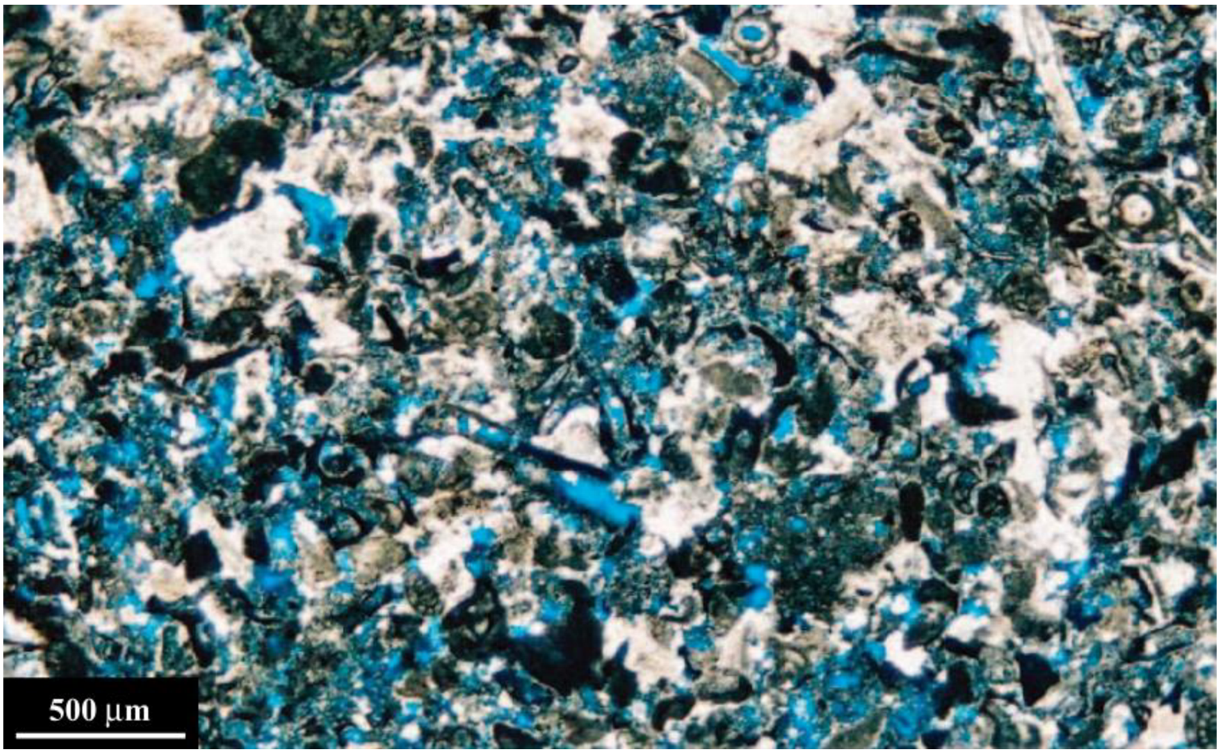


Figure 12 microporosity (10–50 µm pore diameter) with uniform porosity distribution, Φ= 17.6%, k = 0.84 md (Lønøy, 2006)

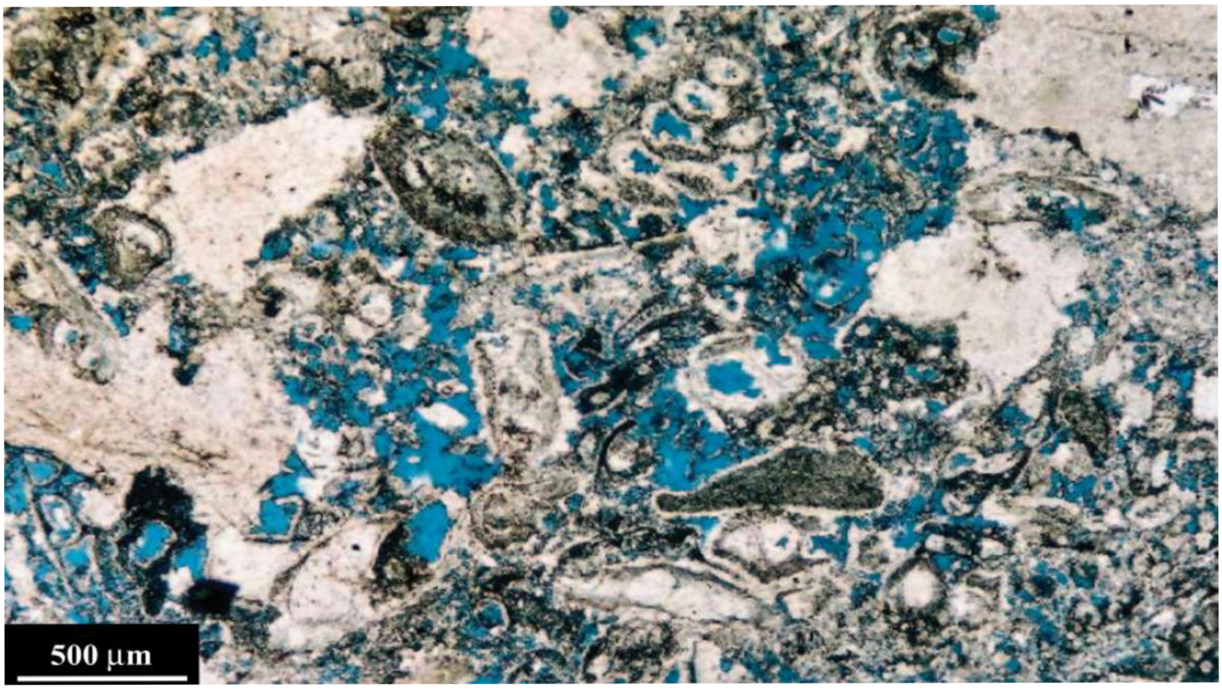


Figure 13 mesoporosity (50–100 µm pore diameter) with uniform porosity distribution, Φ = 19.3%, k = 9.47 md (Lønøy, 2006)

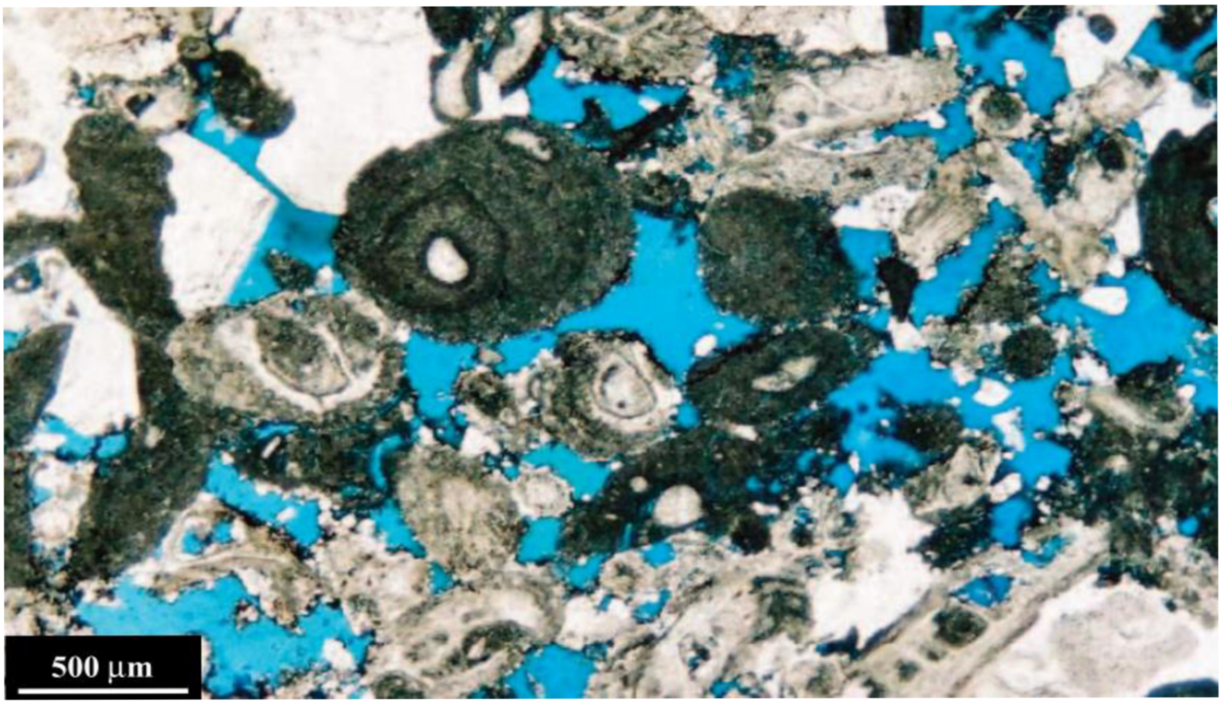


Figure 14 macroporosity (>100 µm pore diameter) with uniform porosity distribution, Φ = 15.3%, k = 132 md (Lønøy, 2006)

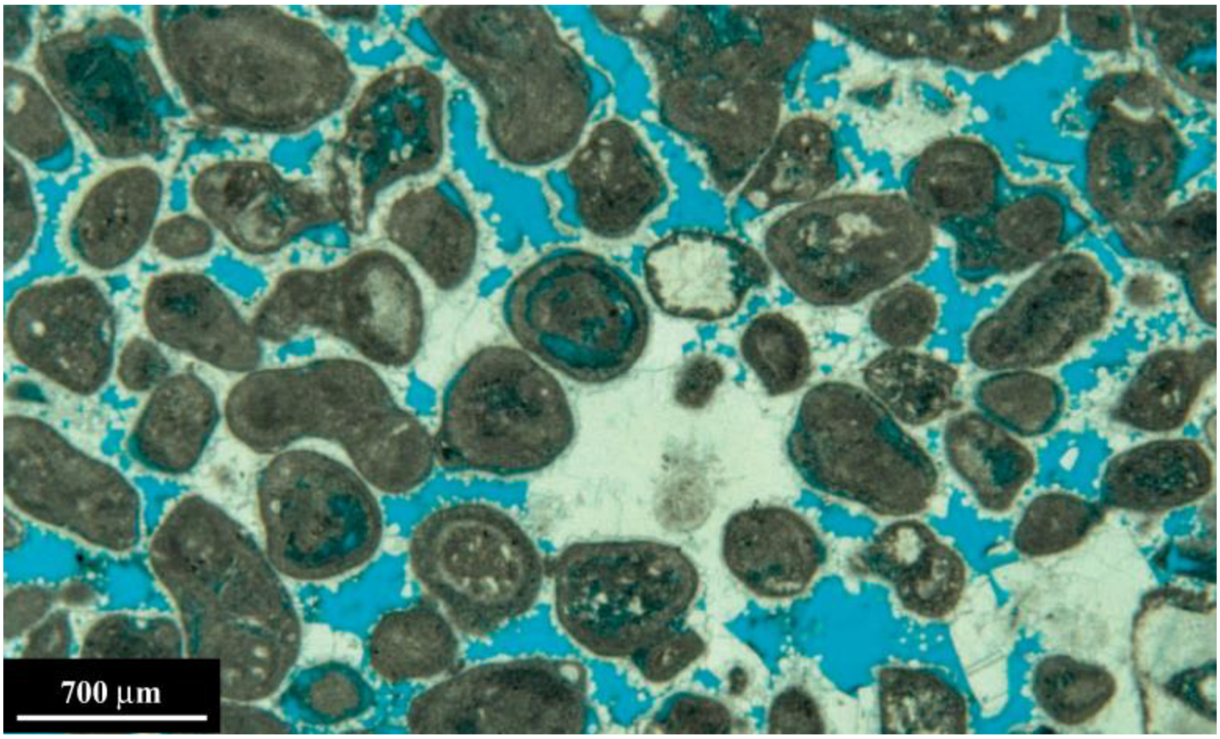


Figure 15 macroporosity (>100 μm pore diameter) with uniform porosity distribution and pore lining calcite cement, $\Phi = 9.7\%$, $k = 0.465$ md (Lønøy, 2006).

4.5 Pore distribution

Porosity distribution is an entirely new feature in pore-type categorization that has a considerable impact on porosity-permeability connections (as previously observed by Lucia et al., 2004a, b). Interparticle pores, intercrystalline pores, and mudstone micropores have been visually characterized as uniform or patchy. A patchy porosity distribution is shown to have considerably greater permeability compared with a uniform porosity distribution at similar porosities. Because the porosity focuses across a smaller region, the pore system is better linked than with an equivalent, uniformly dispersed pore volume. Furthermore, a patchy porosity pattern is frequently associated with subsequent dissolution with little corrosion of pore throats, and that procedure also favors connected pores. A porous, sucrosic dolomite with anhydrite nodules can be used to demonstrate the influence of patchy porosity on porosity-permeability relationships. With respect to where the plugs are located, core plugs from these dolomite may have uniform porosity distribution or various degrees of patchiness. Porosity is going to be higher in plugs with uniform porosity distribution (no anhydrite) compared to plugs with patchy porosity distribution (with anhydrite). However, the impact upon permeability is low since pore-throat widths are the same (regardless of anhydrite). The sole impact on permeability that could be seen is a slight rise in tortuosity. In both cases, the permeability is virtually consistent, however the porosity is lowered in the anhydritic sample. Naturally, different degrees of porosity patchiness exist, and possibly, there is a relationship between patchiness and porosity-permeability. Patchiness may most likely be determined using thin section in a particular manner. However, the patchiness of the plug, not the thin section, affects the porosity-permeability link. Grain density can possibly be employed as a metric of patchiness in plugs with just two mineral phases, where grains and patchily spread cement have considerably varying grain densities. In this study, an effort to utilize grain density as a unit of measurement for patchiness was a failure because only few specimens possessed the proper mineral combination.

To determine what model has the most accurate prediction abilities for porosity and permeability, all of the specimens in the Lønøy. (2006), database were categorized using Choquette and Pray. (1970), Lucia. (1983, 1995, 1999), and new classification of Lønøy. (2006). as an indicator, the coefficient of determination (R2) was utilized, with a greater R2 suggesting a stronger relationship between porosity and permeability. Tables 3 and 4 show the findings. In porosity-permeability crossplots of Lønøy. (2006), interparticle pores, intercrystalline pores, and mudstone micropore systems present an average R2 between 0.79-0.96, compared to the R2 of Lucia. (1983, 1995, 1999), which is indicates lower values of 0.62–0.79. There are a number of reasons why Lønøy. (2006), method produces a considerably better connection between porosity and permeability, which are:

1. The influence of patchy porosity distribution on the porosity-permeability relationship
2. The distinction between interparticle and intercrystal porosity (as proposed by Choquette and Pray, 1970) and the addition of mudstone microporosity

3. The application of pore-size differentiation rather than particle size and sorting distinctions (samples through the research data set indicate broadly different pore sizes inside each of Lucia's, 1995, 1999, interparticle classes due to the variable extent of interparticle and intercrystalline cementation and allochem sorting).

To assess the impact of points 2 and 3 on the porosity-permeability connection, samples having a patchy porosity distribution were eliminated from the data set. This resulted in R2 = 0.77 for interparticle class 1, R2 = 0.74 for interparticle class 2, and R2 = 0.68 for interparticle class 3. This is a considerable improvement for class 2, but every class nevertheless possess significantly lower coefficients of determination than those in Lønøy. (2006), scheme. In the Lucia. (1983, 1995, 1999), classification scheme, intraparticle, moldic (both micro- and macromoldic), and some of the low-porosity vuggy pores of the new classification of Lønøy. (2006), are classed as separate-vug pores. The separate-vug pore structure has an R2 = 0.86, which is close to R2 values for intraparticle pores (R2 = 0.86), moldic micropores (R2 = 0.86), and moldic macropores (R2 = 0.90). Yet, for identical permeability, various pore types may have significant differences in porosity cutoffs. This adjustment in cutoff can have a significant impact on net/gross ratios in specific hydrocarbon sites. Except for some low-porosity specimens, vuggy pores in the new categorization system are categorized as touching-vug pores in the Lucia. (1983, 1995, 1999), classification system. The coefficients of determination of the categorization systems are equivalent (R2 = 0.50 in the new classification system; R2 = 0.45 in the Lucia classification system).

Chapter 5: Conclusion

In conclusion, Lønøy and Lucia carbonate pore system classifications highlights the importance of understanding the geological heterogeneity of reservoir rocks for effective hydrocarbon exploration and production. Carbonate rocks are one of the most challenging types of reservoir rocks to characterize due to their complex and diverse nature. Therefore, accurate rock typing and pore system characterization are essential for optimizing reservoir performance, reducing production costs, and maximizing hydrocarbon recovery.

Both classifications have been widely used in the petroleum industry for many years and have proven to be effective in identifying and characterizing different types of pore systems in carbonate reservoir rocks. Lucia method is often used to determine the matrix porosity of carbonate rocks. However, the Lucia method can also be used to estimate the total porosity, which includes both the matrix porosity and the pore space within the rock's fabric. The method can also be used to estimate the permeability of the rock. Nevertheless, the Lønøy method is specifically designed to characterize the different types of pore systems within the rock, including micropores, mesopores, and macropores. It provides information on the pore size distribution, the total pore volume, and the capillary pressure curves, which can be used to predict permeability.

So, to summarize, while the Lucia method is often used to determine the matrix porosity of carbonate rocks, it can also provide information on the total porosity and permeability of the rock. The Lønøy method, on the other hand, is designed to specifically characterize many more different types of pore systems within the carbonate rock.

In addition to the Lønøy and Lucia classifications, other schemes such as the Choquette and Pray classification, the Depositional Environment Classification, and the Sequence Stratigraphic Framework can also be used for rock typing and pore system characterization. By combining different approaches, it is possible to overcome the limitations of individual classifications and obtain a more accurate and reliable characterization of carbonate reservoir rocks. This can lead to more efficient and cost-effective oil and gas exploration and production, as well as reduced environmental impact.

Finally, the overview of both classifications provides valuable insights into the geological heterogeneity of carbonate reservoir rocks. While each approach has its strengths and limitations, a combination of multiple schemes and techniques can provide a more comprehensive understanding of reservoir characteristics. This can ultimately lead to more efficient and sustainable hydrocarbon exploration and production, benefiting both the petroleum industry and society as a whole.

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