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An Overview of the Porosity Classification in Carbonate Reservoirs and Their Challenges: An Example of Macro-Microporosity Classification from Offshore Miocene Carbonate in Central Luconia, Malaysia

Hammad T. Janjuhah, Josep Sanjuan, Mohamed K. Salah

Abstract**—**Biological and chemical activities in carbonates are responsible for the complexity of the pore system. Primary porosity is generally of natural origin while secondary porosity is subject to chemical reactivity through diagenetic processes. To understand the integrated part of hydrocarbon exploration, it is necessary to understand the carbonate pore system. However, the current porosity classification scheme is limited to adequately predict the petrophysical properties of different reservoirs having various origins and depositional environments. Rock classification provides a descriptive method for explaining the lithofacies but makes no significant contribution to the application of porosity and permeability (poro-perm) correlation. The Central Luconia carbonate system (Malaysia) represents a good example of pore complexity (in terms of nature and origin) mainly related to diagenetic processes which have altered the original reservoir. For quantitative analysis, 32 high-resolution images of each thin section were taken using transmitted light microscopy. The quantification of grains, matrix, cement, and macroporosity (pore types) was achieved using a petrographic analysis of thin sections and FESEM images. The point counting technique was used to estimate the amount of macroporosity from thin section, which was then subtracted from the total porosity to derive the microporosity. The quantitative observation of thin sections revealed that the mouldic porosity (macroporosity) is the dominant porosity type present, whereas the microporosity seems to correspond to a sum of 40 to 50% of the total porosity. It has been proven that these Miocene carbonates contain a significant amount of microporosity, which significantly complicates the estimation and production of hydrocarbons. Neglecting its impact can increase uncertainty about estimating hydrocarbon reserves. Due to the diversity of geological parameters, the application of existing porosity classifications does not allow a better understanding of the poro-perm relationship. However, the classification can be improved by including the pore types and pore structures where they can be divided into macro- and microporosity. Such studies of microporosity identification/classification represent now a major concern in limestone reservoirs around the world.

Keywords**—**Carbonate reservoirs, microporosity, overview of porosity classification, reservoir characterization.

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I. Introduction

Characterization of carbonate reservoirs requires the integration of quantitative physical parameters such as porosity and permeability. The heterogeneity of the carbonate rocks is the main reason for their indecorous characterization, and this has become all the more obvious as one attempts to characterize the petrophysical properties at different scales [1]. The great uncertainties about the petrophysical properties of carbonates are due to large variations in pore type, pore shape, and interconnectivity [2], [3]. Poor correlation between porosity and other physical properties, such as permeability and sonic velocity, is often encountered when using carbonate reservoirs [3], [4].

The province of Luconia in offshore Sarawak is a key geological unit for understanding the distribution of hydrocarbon resources as it is an important hydrocarbon province in Malaysia. More than 200 accumulations of carbonate reefs were seismically mapped in Central Luconia, of which about 65 have been tested by drilling. To date, it has been proven that 56 carbonate accumulations contain commercial quantities of unassociated gas [5], [6]. According to Janjuhah et al. [7] and Janjuhah et al. [8], these reservoirs are usually associated with grain-rich facies types

The purpose of this study is to provide a general review of classification schemes of porosity in carbonates with some emphasis on the microporosity. The article will demonstrate the limits of the application of the existing porosity classification in carbonate rocks and provide an example from Miocene carbonate rocks of Central Luconia considering total porosity as macro and microporosity.

II. Porosity Classification, Pore Types, And Their Limitations

Carbonate rocks have a wide range of pore sizes and often a complex interconnection network. Concerning permeability and velocity, porosity and other physical properties often exhibit poor correlations. For carbonate reservoir assessment, it is essential to understand the diagenetic processes that modify porosity [9]-[12]. Pore structures are the main control of permeability and elastic properties. Different rocks of the same depth with the same porosity may exhibit different permeability and acoustic velocities [13]. Many researchers have demonstrated the influence of pore structure on the petrophysical properties of carbonate rocks [14]-[21]. Due to the dispute between geologists and petrophysicists, most researchers have suggested considering a double porosity model for the classification of pore types [13], [22]-[26].

Archie [27] first focused on the relationship between rock structure and petrophysical properties to emphasize the importance of pore structure in the classification of pore types. Archie [27] classification is based on the matrix texture (Fig. 1) and pore type visibility (Fig. 2).

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 = 0.1mm, Medium = 0.2mm, Coarse = 0.4mm.	Crystals interlocking at different angles, generally allowing space for considerable porosity between crystals. Oolitic and other textures fall in this class

Fig. 1 Micrite texture classification of carbonate rocks by Archie [27]

Class	Description
Class A	No visible porosity under about 10x resolution microscope or where pore size is less than about 0.01 mm in diameter.
Class B	Visible porosity, greater than 0.01 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.

Fig. 2 Visible pore size classification of carbonate rocks by Archie [27]

Choquette and Pray [10] provided a particular descriptive scheme incorporating all essential types of carbonate pores which was widely accepted and used in the industrial and academic sectors (Fig. 3). The system is divided into two main genetic classifications: primary and secondary pore systems. Primary porosity occurs in the form of intergranular pores, which is also common in the terrigenous sand (clastic deposits) [10], [28]. This is the only similarity that the carbonate pore system shares with the terrigenous sand (clastic deposits), due to the great variety and nature of the carbonate grains and the texture of the sediments, as well as the high diagenetic potential. The preservation of primary pore systems during the conversion of sediments to limestone depends on the prevailing conditions [10]. However, the majority of pores in carbonate rocks are secondary in nature [10], [29], [30].

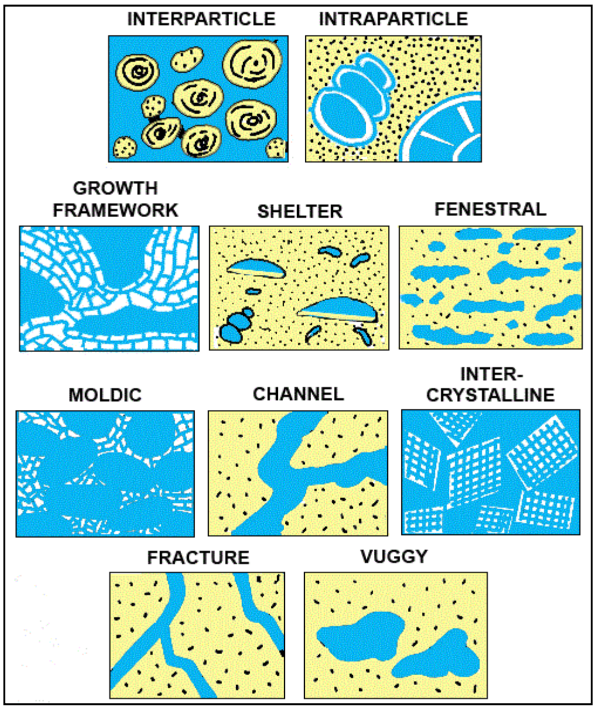

Fig. 3 Classification of limestone porosity, after Choquette and Pray [10]

Lucia [20], Lucia [31] used the Dunham [32] texture classification and the Choquette and Pray [10] classification to account for the important geological parameters that may reduce the uncertainty of predicting petrophysical parameters in carbonate geological models (Fig. 4). The classification of Lucia (1983) is based on two main classes, namely: interparticle and vuggy pores. Lucia [20] appreciated the work of Archie [27] and stated that the classification is still valid for the evaluation of the petrophysical properties in the case of a simple geological model, but is limited in providing comprehensive information on depositional and diagenetic processes. Lucia [20] also stated that both the Dunham [32] and the Choquette and Pray [10] classifications were widely used but neither provide a direct link to the quantitative characteristics of the reservoir that are representative of the borehole environment.

Lucia [20] attempted to bridge the gap by proposing an approach defining important mappable geological parameters for the petrophysical quantification of geological reservoir models. The basis of Lucia [20] classification is that the pore size distribution controls permeability and saturation and that the pore size distribution is related to the rocky tissue. The rock fabric includes texture (Dunham), grain size, pore types, and distribution. The texture is reduced to three components which are grain-dominated, muddy grain-dominated, and mud-dominated (Fig. 5). The classification of the pore system is simplified by establishing the following pore size classes: intraparticle, separate vugs, and vugs in contact [20].

Lønøy [24] proposed a new pore space classification using the descriptive terminology of Lucia [20] and Choquette and

Pray [10]. Lønøy [24] introduced a class of 20 pore types (Fig. 6). Lønøy [24] classification provides proper access to sedimentological and diagenetic aspects. Lønøy [24] pointed out that his classification is based on the pore size instead of grain size, as Lucia [20]. The classification is useful for understanding the pore types of a small data set, but is too detailed and not worth using for large data sets.

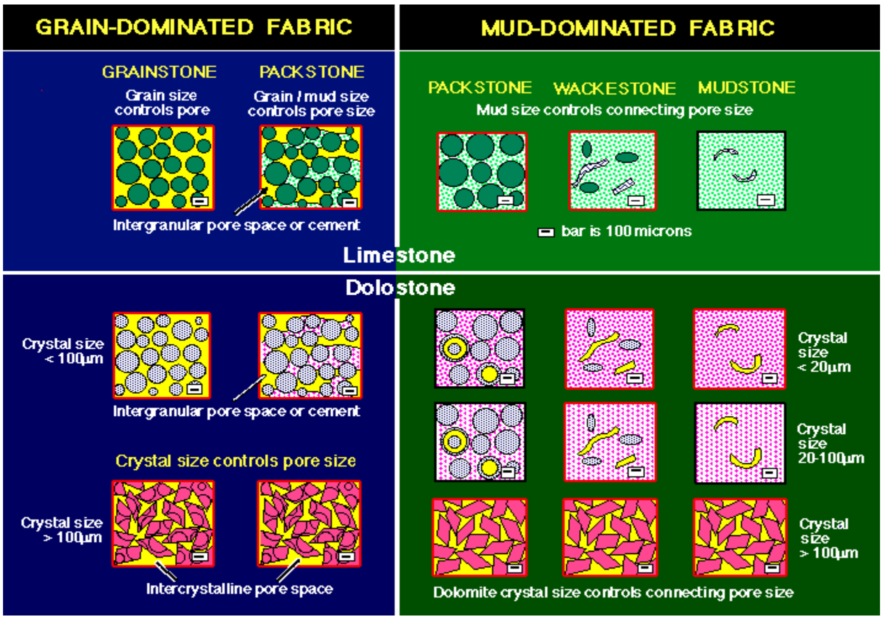

Fig. 4 Classification of interparticle carbonate pore spaces based on grain size and sorting of grains and crystals, after Lucia [20]

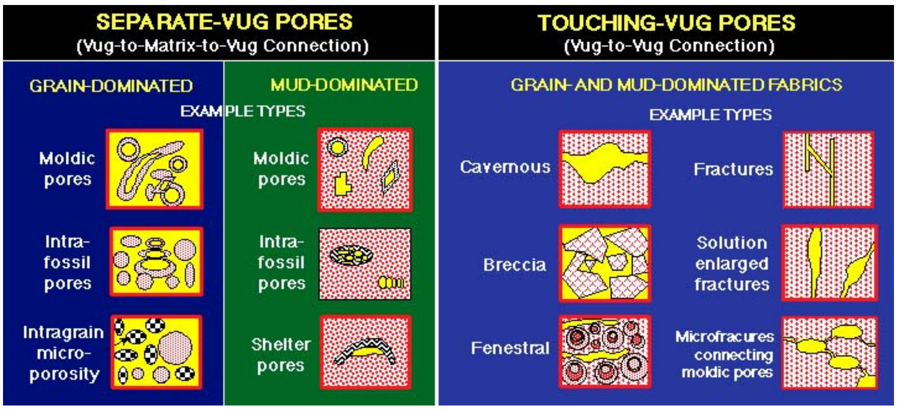

Fig. 5 Geological and petrophysical classification of vuggy pore spaces based on vugs interconnection, after Lucia [20].

In summary, Archie [27] has demonstrated that to understand the pore types one had to consider the texture of the carbonate rock. To explain the origin and development of porosity Choquette and Pray [10] have developed a classification of effective porosity. To fill up the gap between the relationships of different pore types to petrophysical properties of rock (e.g., permeability) Lucia [33] proposed a new classification scheme. However, Lucia [33] neglected the importance of microporosity in his classification, while microporosity can contribute positively to improve the poro-perm correlation [34]. Lønøy [24] took the initiative by introducing the pore size in his classification to improve the relationship between porosity and permeability. However, Lønøy [24] generalized the concept of microporosity and presented it in the same manner as the macroporosity classification is presented. The microporosity classification should cover the aspect of the morphology of micrite particles, crystallometry, and the size of micropores.

III. Application of Macro and Microporosity Classification from Central Luconia Carbonate Reservoir

The studied cores represent the carbonate rocks from cycles IV and V of Central Luconia, Offshore Sarawak, Malaysia. A total of 192 well A plugs were collected from the core to measure porosity, permeability and grain density. From these central plugs, 80 thin-sections were prepared and studied under transmitted light, both qualitatively and quantitatively. For a quantitative analysis of thin-sections into grains, matrix, cement, and visible porosity, a point counting software (J. Microvision) was used by 700 shots per blade. Weger et al. [17] introduced the Digital Image Analysis (DIA) method using four images as a representative of the entire thin-section to quantify the amount of microporosity. However, due to the limited resolution of the images, the uncertainty remains high. Contrary to what was mentioned in the current study, the entire thin layer is covered with 32 high-resolution petrographic images for each thin section; they are connected as a photo panel to quantify the amount of macroporosity to reduce the uncertainty associated with the variation of the pore geometries. Macroporosity includes all different types of pores (e.g., greater than 10 µm). Total porosity is calculated by injecting helium under a pressure of 1800 to 2000 psi, using a poro-perm instrument developed by Vinci Technologies. The microporosity was obtained by subtracting the macroporosity acquired using thin-sections from the total porosity calculated from the measurements of the central plug.

Pore Type	Pore Size	Pore Distribution	Pore Fabric	R^2
Interparticle	Micropores (10−50 µm)	Uniform	Interparticle, uniform micropores	0.88
		Patchy	Interparticle, patchy micropores	0.79
	Mesopores (50−100 µm)	Uniform	Interparticle, uniform mesopores	0.86
		Patchy	Interparticle, patchy mesopores	0.85
	Macropores (>100 µm)	Uniform	Interparticle, uniform macropores	0.88
		Patchy	Interparticle, patchy macropores	0.87
Intercrystalline	Micropores (10−20 µm)	Uniform	Intercrystalline, uniform micropores	0.92
		Patchy	Intercrystalline, patchy micropores	0.79
	Mesopores (20−60 µm)	Uniform	Intercrystalline, uniform mesopores	0.94
		Patchy	Intercrystalline, patchy mesopores	0.92
	Macropores (>60 µm)	Uniform	Intercrystalline, uniform macropores	0.80
		Patchy	Intercrystalline, patchy macropores	
Intraparticle			Intraparticle	0.86
Moldic	Micropores (<10−20 µm)		Moldic micropores	0.86
	Macropores (>20−30 µm)		Moldic macropores	0.90
Vuggy			Vuggy	0.50
Mudstone microporosity	Micropores (<10 µm)		Tertiary chalk	0.80
			Cretaceous chalk	0.81
		Uniform	Chalky micropores, uniform	0.96
		Patchy	Chalky micropores, patchy	

Fig. 6 New porosity classification of carbonate rocks proposed by Lønøy [24]

$$\text{Microporosity} = \text{Total porosity (central plug)} - \text{Macroporosity (thin section)}$$

They also pointed out that the well-observed pores types are isolated in nature. Central Luconia carbonates were heavily leached, resulting in the partial or complete destruction of the primary rock framework, forming an enlarged isolated molded porosity.

The facies scheme developed by Janjuhah et al. [35], Janjuhah, et al. [36], which is based on eight cores covering roughly 70% of the Central Luconia region, is adopted for this study. The facies scheme was established based on its depositional texture and the wireline log response (Fig. 7). According to facies scheme of Janjuhah et al. [35], the Well A core is covered with 15% Facies 1 (coated grain packstone) followed by 40% Facies 2 (Coral (m) lime grainstone) and 45% Facies 4 (skeletal lime packstone) (Fig. 7). The Central Luconia core is dominated by mouldic porosity followed by intraparticle, interparticle, vuggy, and fracture porosity [37] (Fig. 7). They also highlighted that the Well A observed pore types are isolated in nature. Central Luconia carbonates were heavily leached, resulting in the partial or complete destruction of the primary rock, forming an enlarged isolated molded porosity.

Quantification of the microporosity indicates that the Miocene carbonates contain an appropriate amount of microporosity, which can be the sum of 40–50% of the total porosity (Fig. 8). The presence of this microporosity is directly related to deposition and diagenesis. The higher the amount of microporosity, the more the area is micritized and cemented. On the other hand, the amount of microporosity decreases with more dissolution. Due to the limited resolution of transmitted light microscopy, this phenomenon was also validated using FESEM (Field Emission Scanning Electron Microscopy) images where the micropores were visible (Fig. 9). The porosity and permeability that control the performance and qualities of the reservoir are studied by considering the impact of the microporosity and deducing it from the total porosity revealed by the fact that the microporosity has a significant impact on the Miocene Luconian carbonates (Fig. 10). The relationship between macroporosity and permeability represents a good fit with an increase of R^2 (coefficient of correlation) values compared to cross-plot of total porosity verse permeability. The R^2 increased from 0. 45 (total porosity vs. permeability) to 0.68.

It is also reported that the Miocene carbonates have experienced a long period of diagenetic modifications [38]. This long diagenetic history could lead to frequent facies changes in the reservoir, as shown in Fig. 10. Taking into account the pore types controlled by diagenesis can improve the framework of porosity classification. The texture and lithotype of the rock can reveal the development history of reservoir porosity.

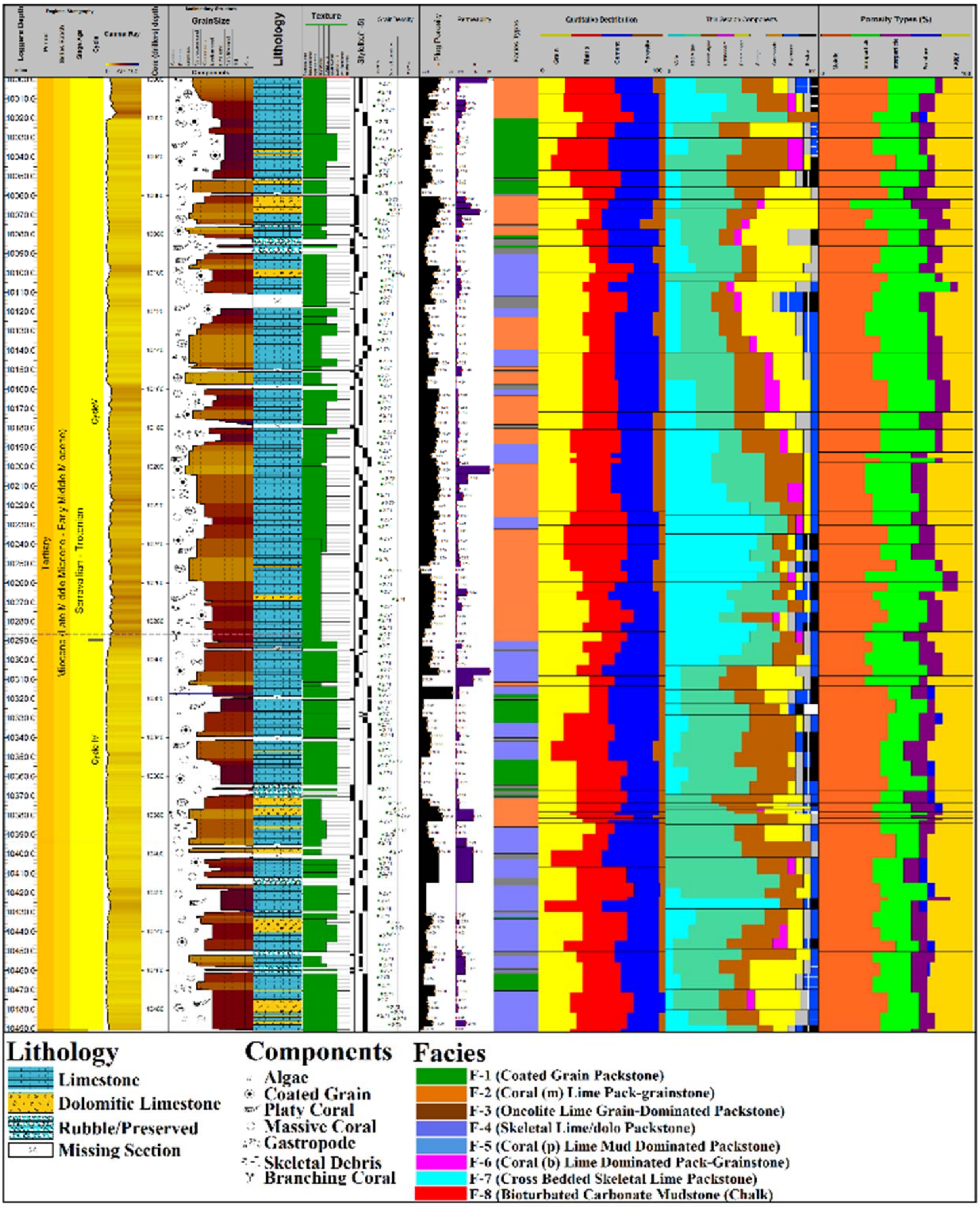

Fig. 7 Sedimentological log showing qualitative and quantitative description of Well A including poro-perm data and different pore types in offshore Sarawak, Central Luconia, Malaysia (after Janjuhah, et al. [35])

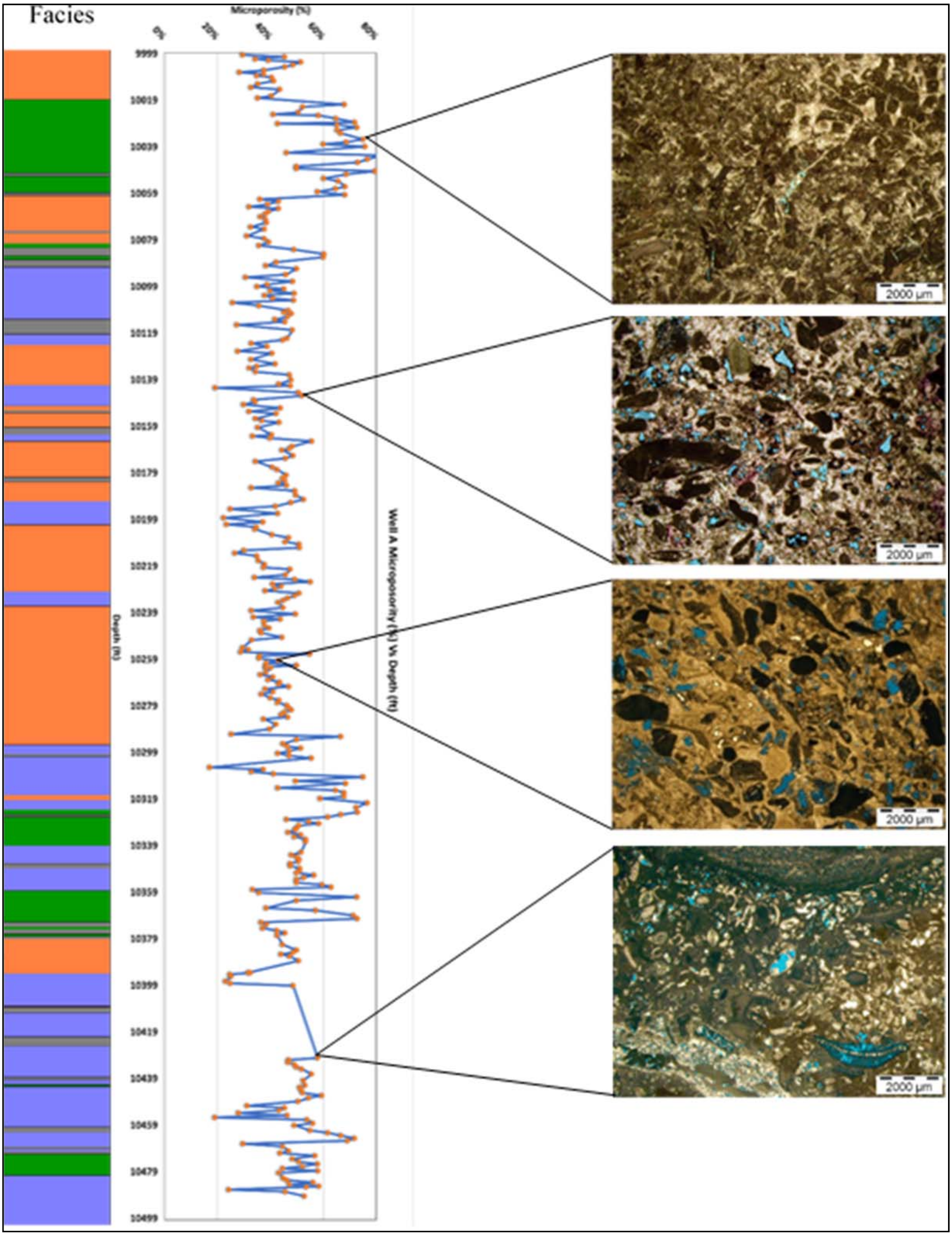

Fig. 8 Relationship between microporosity and different diagenetic events observed in Well A

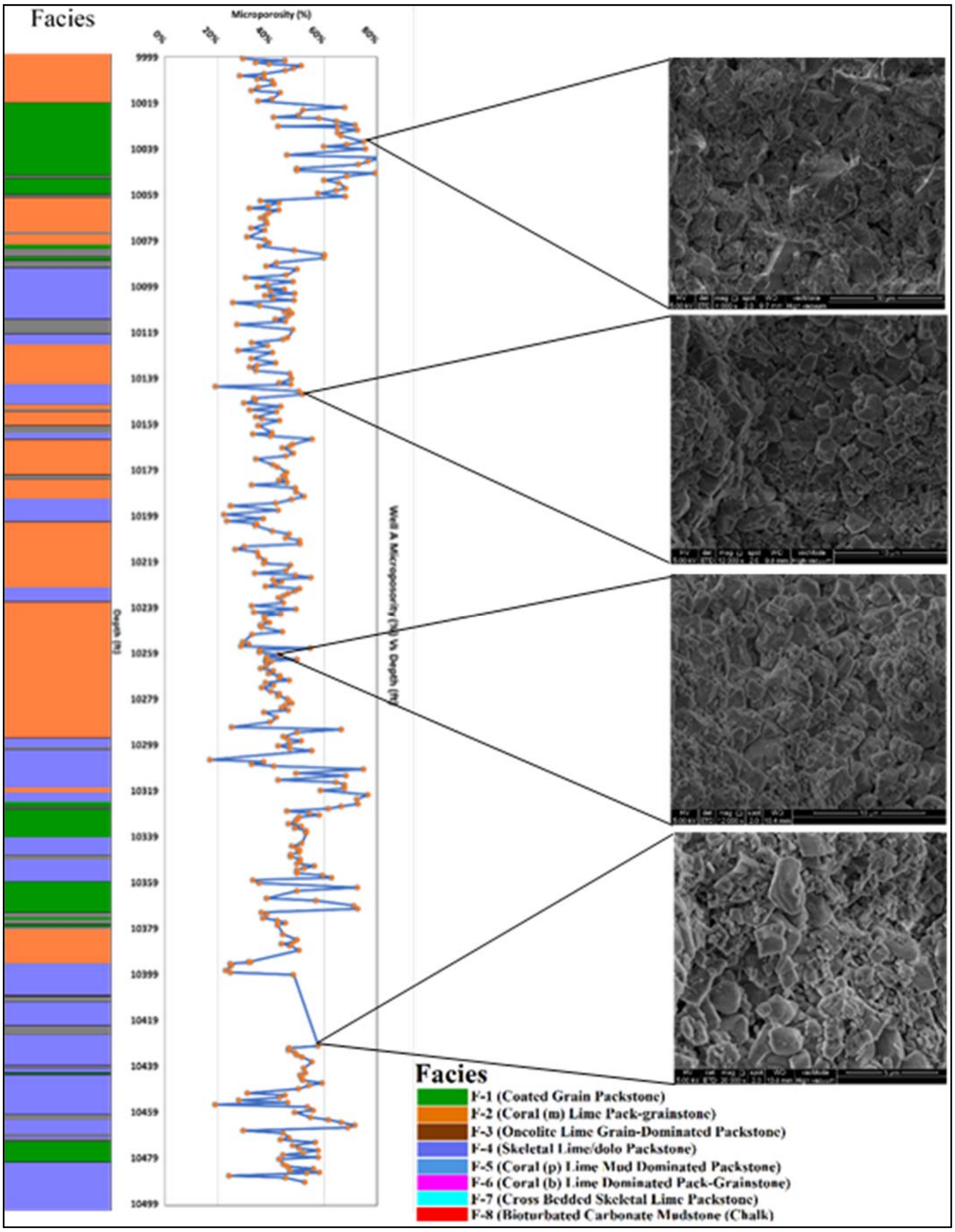

Fig. 9 The observation of the various microtextures with microporosity is evident using FESEM at different depths of the reservoir interval at Well A

IV. Need of New Classification Scheme

Some case studies on limestone microtextures have certainly been made – mainly Clerke, et al. [39], Moshier [40], Domingo, et al. [41], Lambert, et al. [42], de Periere, et al. [43] and Rahman, et al. [44] – but it is also true that study on the integration of microporosity of limestone and microtexture of micrite with their petrophysical properties are apparently absent. Linking particle analysis with the petrophysical characteristics of limestone seems to be essential for improving our current understanding of the carbonate pore system. A previous step is necessary (terminologies proposed by Choquette and Pray [10]), establishing a new classification scheme in which the parameters of the pore structure, as well as the microporosity, can be considered as an integral part of the classification of the porosity.

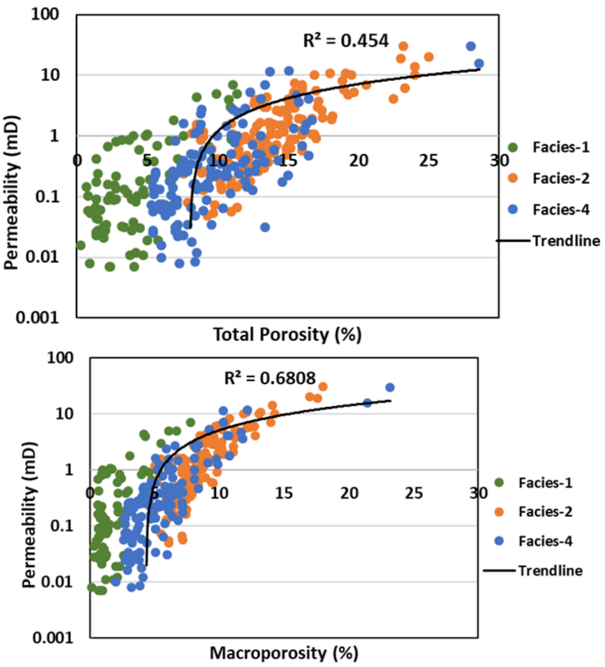

Fig. 10 Total porosity, macroporosity and permeability cross plots. (A) cross plot of total porosity versus permeability labelled with the different corresponding facies. (B) macroporosity versus permeability cross plot giving a better coefficient of correlation in Well A, Central Luconia

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