

PETROPHYSICAL CHARACTERISATION OF PORE SYSTEM FOR A CARBONATE RESERVOIR IN THE HR STRUCTURE

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Summary

The purpose of reservoir characterisation is to figure out the spatial distribution of petrophysical properties such as porosity, permeability and water saturation that are key parameters for construction of the geological model. Characterisation of a carbonate reservoir is often difficult mainly due to the complexity of its pore system. This study presents an integrated approach to using well log and micro-geological data to characterise rock fabrics and their pore system for a carbonate reservoir in the HR structure. Based on well log data such as GR, PE, PHIN and RHOB, two major rock types of dolostone and limestone were identified. A further combination with thin section and SEM analysis results indicated four types of carbonate rock fabric, namely limestone with grain-dominated grainstone, limestone with grain-dominated packstone, dolostone with grain-dominated grainstone and dolostone with grain-dominated packstone. For each identified carbonate fabric, two types of pore were found, including interparticle and vuggy pores. The latter can be further subdivided into separate-vug pores and touching-vug pores. For the HR structure, the touching vug porosity and the interparticle porosity were estimated to be in the range of 1 - 3% and 1 - 8%, respectively. The inter-crystalline porosity, which might be considered as a subset of the interparticle porosity and could be estimated by SEM analysis, was found in the range from 1.5% to 3%. It is expected that the integrated analysis approach using well log and micro-geological data employed in this study can be applied to evaluate the characteristics of carbonate reservoirs at other well sites in Song Hong basin.

Key words: Petrophysics, pore system, carbonate reservoir, Ham Rong structure, Song Hong basin.

1. Introduction

Carbonate reservoir has been studied over many years. Characterisation of a carbonate reservoir is often difficult mainly due to the complexity of its pore system [2, 3, 4]. Carbonate pore types are considered the key factor affecting permeability and water saturation. This study presents an integrated approach to using well log and micro-geological data to characterise rock fabrics and their pore system for a carbonate reservoir in the HR structure and develop the appropriate workflows that can be probably used in log analyses and petrophysical interpretation.

Well log and samples were collected from well 106-HR-A belonging to the HR structure in Song Hong basin, offshore Vietnam, about 75km SE of Hai Phong city (Figure 1). In the late 1990s Nielsen et al. [5] conducted a comprehensive study on hydrocarbon generation for this area and suggested that the huge and still underexplored Song Hong basin provides attractive areas for further exploration. Al-Atroschi et al. [6] reported that a Pre-Tertiary carbonate reservoir was proven with the discovery of HR-1X ST4 and HR-2X in this structure.

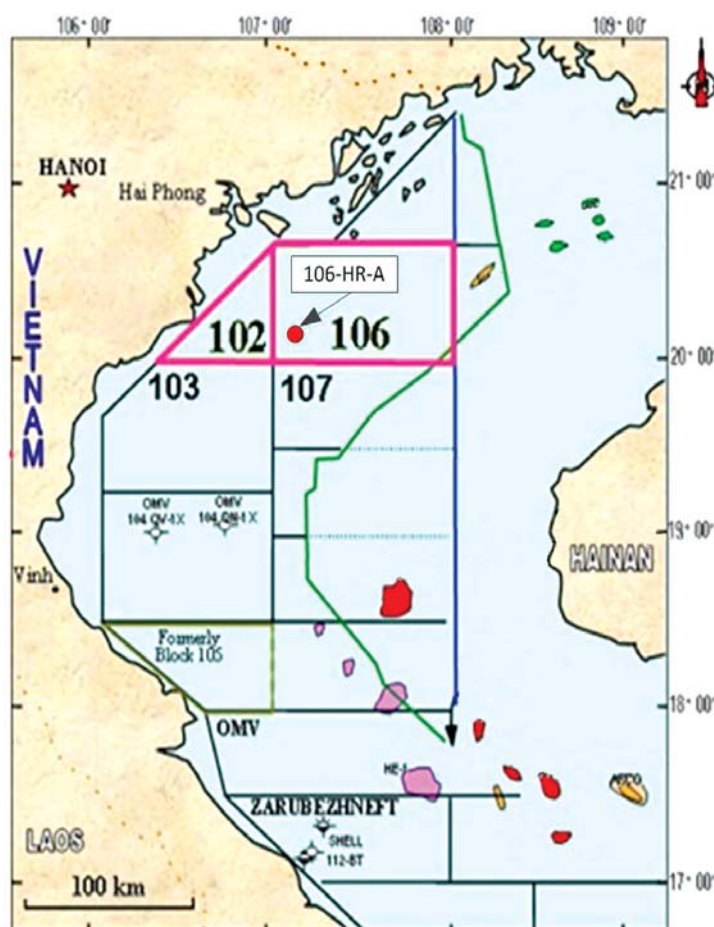


Figure 1. Location of study area [1]

2. Methodology of study

Characterisation of pore system was done over a carbonate reservoir interval of several hundred metres thick. The methodology is explained by the flow chart shown in Figure 2 with the main steps being explained in the following:

2.1. Lithological identification using well log data

The first step is lithological identification, in which one tried to separate major types of rocks, i.e. limestone and dolostone. This could be done using well log data such as density (RHOB), neutron (PHIN), Gamma ray (GR) and photoelectric number (PE). The zoning criteria proposed by Crain [7], as shown in Table 1, were applied in this study. The cross-plot value between neutron and density porosity (N-D) as well as the photoelectric

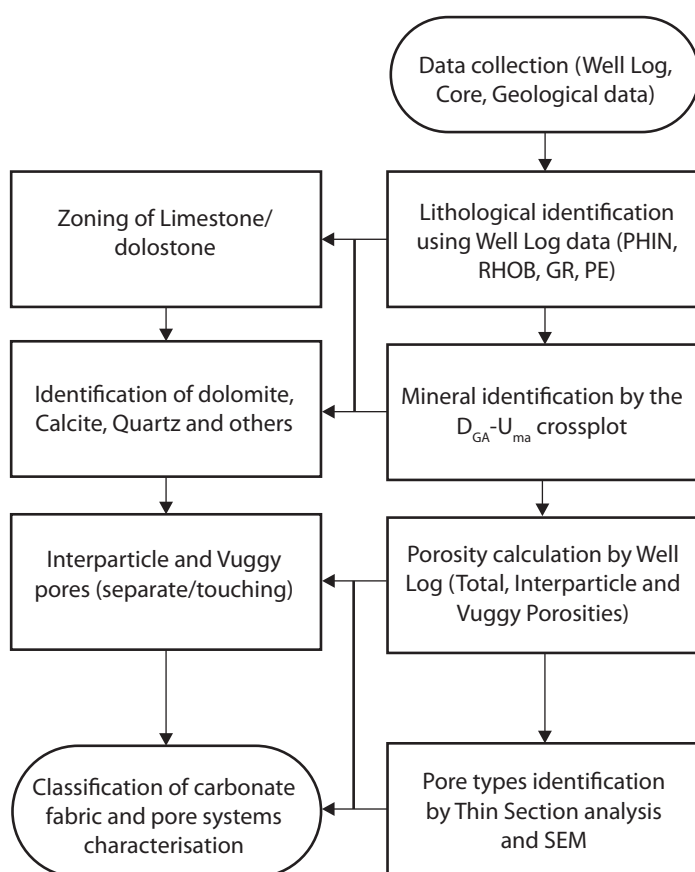


Figure 2. The flowchart of petrophysical characterisation of carbonate pore system used in this study

Table 1. Lithological zoning criteria by well log data [7]

Rock	N-D (LS scale)	PE		GR
		Crain (2014)	Lucia (2007)	
Sandstone	-7	2	1.81	Low
Limestone	0	5	5.08	Low
Dolostone	8+	3	3.14	Low
Anhydrite	15+	5	5.05	Low
Salt	-45	4.5	3.99	Low
Shale	13+	3.5		High

number are quite stable parameters to help the zonation. Some minor adjustments in PE values proposed by Lucia [3] are also mentioned in Table 1.

2.2. Mineral indication by the D_{GA} - U_{ma} cross-plots

After zonation, the next step is mineral identification using the D_{GA} - U_{ma} lithology cross plots as suggested by Burke et al. [8], where D_{GA} and U_{ma} stand for apparent dry density and apparent volumetric factor, respectively as explained below:

$$U = \frac{PEF \times (RHOB + 0.1883)}{1.07} \quad (1a)$$

$$D_{GA} = \frac{RHOB - RHOB_f \times \phi_t}{1 - \phi_t} \quad (1b)$$

$$U_{ma} = \frac{U - U_f \times \phi_t}{1 - \phi_t} \quad (1c)$$

Where:

U : Volumetric cross section (barns/cm³);

U_f : Pore fluid volumetric factor = 0.398barns/cc (assumed water in the pores);

$RHOB_f$: Pore fluid density, equal to 1.0g/cc (assuming water in the pores);

ϕ_t : Total porosity;

U_{ma} : The apparent volumetric factor (barns/cm³);

D_{GA} : The apparent dry grain density (g/cc).

1barn = 10⁻²⁸m² (barn is a unit of area which is used to describe the physical properties of nuclear, expressing the cross sectional area of nuclear reactions).

Eq. (1a) shows a conversion of photoelectric absorption factor (PE) and density (RHOB) to U , a parameter called volumetric cross section [9, 10]. The proximity of the data to the mineral endpoints of the triangle will help indicate the mineral composition.

2.3. Porosity calculation using well log data

Lucia [4] proposed the interparticle porosity be calculated based on the travelling time of acoustic log. Hence, vuggy porosity can be calculated by subtracting interparticle porosity from total porosity as follows:

$$\phi_t = \frac{\phi_D + \phi_N}{2} \quad (2a)$$

$$\phi_{intp} = \frac{DT - DT_{ma}}{DT_f - DT_{ma}} \quad (2b)$$

$$\phi_{vug} = \phi_t - \phi_{intp} \quad (2c)$$

Where:

ϕ_{intp} : Interparticle porosity;

ϕ_{vug} : Vuggy porosity;

ϕ_t : Total porosity based on ϕ_D and ϕ_N ;

DT_{ma} : Slowness of formation rocks (dolostone, limestone) $\mu\text{s}/\text{ft}$;

DT_f : Slowness of fluid $\mu\text{s}/\text{ft}$.

2.4. Pore type identification by thin section and SEM analyses

2.4.1. Thin section analysis by modal counting method

The thin section preparation involved vacuum impregnation with blue resin in order to distinguish and count visible porosity of the rocks. All thin sections have been described in terms of mineral composition, texture, and rock classification. Mineral composition and visible porosity have been performed by modal analysis which was applied for quantitative mineral volume on thin section since 1956 [11]. The percentage of mineral species can be calculated as follows:

$$\% \text{ mineral} = \frac{\sum \text{counting points}}{\text{total number of counts}} \times 100\% \quad (3)$$

The modal analysis was done by counting 300 points at 20X magnifications in each thin section as shown in Figure 3. The basic data records for modal analysis include mineral species, grain size, fracturing and pore observations, based on which the percentage of porosity per total number of points can be calculated.

2.4.2. SEM analysis

Pore system can be assessed from SEM images by using ImageJ (IJ 1.48v), which was developed by Wayne Rasband (1997) at the United States National Institute of Health [12]. Creating a histogram for each image and establishing a threshold in the histogram, SEM images are first converted into binary images to be analysed by ImageJ software. The procedure is shown in Figure 4. The SEM analysis results included a summary table containing total number of pores, percentage of pores, pore size, and the area of the binary image of each individual pore.

2.5. Carbonate fabric classification and pore type characterisation

There are many classification systems proposed for carbonate rocks, but in this study the classification proposed by Lucia [3, 13] was selected due to its advantage in allowing the linkage between carbonate pore-size distribution and pore type. Choquette and Pray [14] had earlier indicated that pore-size distribution is controlled by pore type. Lucia [3, 13] pointed out further that the different types of pore have effects on petrophysical properties. In Lucia's classification [3] two main types of porosity are interparticle porosity and vuggy porosity. Interparticle porosity is defined as the pore space located between grains, allochems and crystals, while vuggy porosity is defined as the pore space within grains/crystals, fossil chambers, fractures and large irregular cavities. Furthermore, vuggy pore space can be subdivided into separate-vug pores which are interconnected only through interparticle pore network, i.e. leached grains

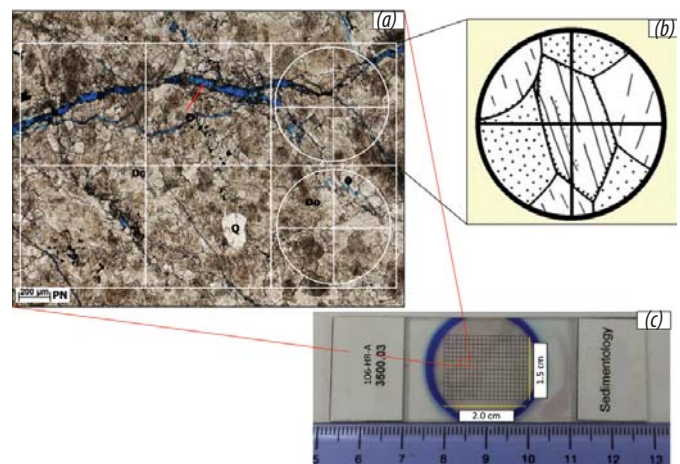


Figure 3. Counting point framework: Field numbers (a); Field of view (b); Grid system (c)

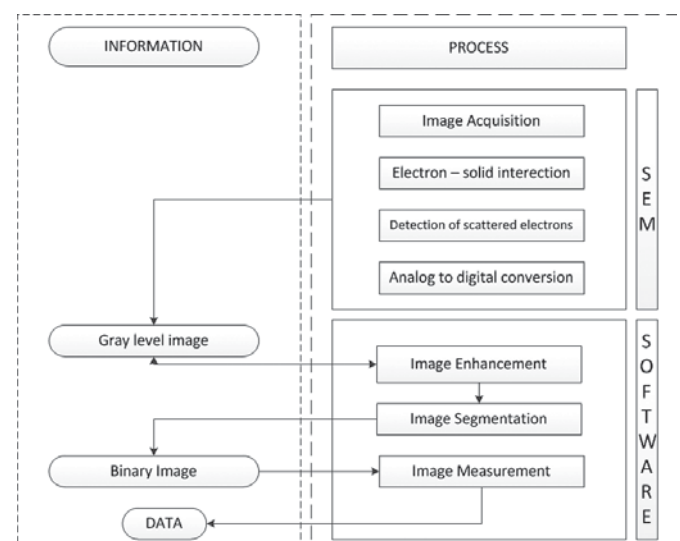


Figure 4. The flowchart of the acquisition and processing of SEM image [15]

Table 2. Lucia's carbonate classification [3, 13]

Petrophysical class occupied with the range of crystal size	Dolostone	Limestone
Class 3: < 20µm	Fine crystalline mud-dominated dolostones	Mud-dominated (e.g. packstone, wackestone and mudstone)
Class 2: 20 - 100µm	- Grain-dominated packstones - Medium crystalline mud-dominated dolostones	Grain-dominated packstone
Class 1: 100 - 500µm	- Grainstone - Large crystalline grain-dominated dolopackstones - Mud-supported dolostone	Grainstone

Table 3. Classification of carbonate rock fabrics by thin section analysis

Zone	Lithology	Contained mud	Rock fabric classification (Lucia's classification, 1995)			
			Type of fabric	Petrophysical class	Range of grain size (µm)	Fracture
1	Dolostone (Grainstone)		Grain-dominated	Class 1	100 - 200	✓
2	Limestone (Grainstone)		Grain-dominated	Class 1	20 - 100	✓
3	Dolostone (Grainstone)		Grain-dominated	Class 1	100 - 150	✓
4	Dolostone (Packstone)	✓	Grain-dominated	Class 2	20 - 100	✓
5	Limestone (Grainstone/Packstone)	✓	Grain-dominated	Class 1/Class 2	20 - 100	✓
6	Dolostone (Grainstone)		Grain-dominated	Class 1	200 - 350	✓

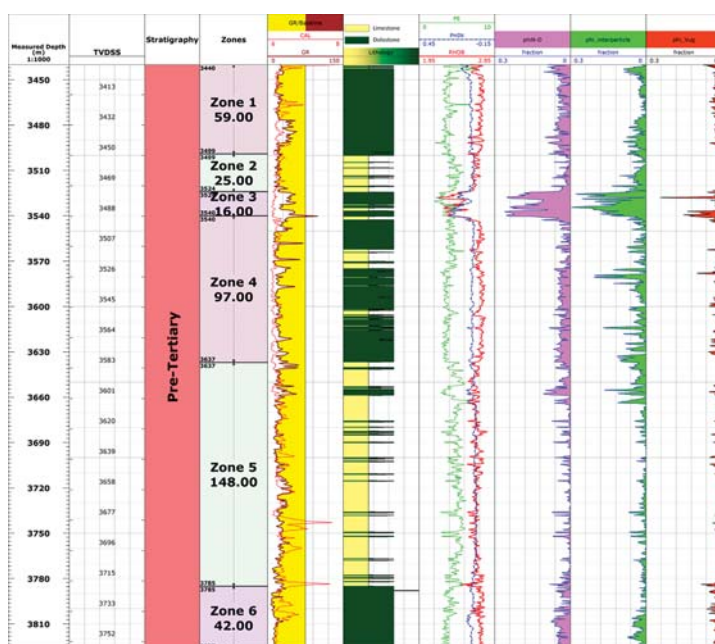


Figure 5. Porosity and type of rock distribution at well 106-HR-A

and fossil chambers and touching-vug pores that form an interconnected pore system of significant extent, i.e. solution-enlarged fractures, and irregular cavities. Lucia's classification [3, 13] divides carbonate rocks into three classes based on crystal size and groundmass components as shown in Table 2.

3. Results and discussion

3.1. Zonation

Neutron (PHIN), density (RHOB), Gamma ray (GR) and photoelectric factor (PE) were successfully used in lithological identification. As seen in Figure 5 and Table 3, a total of 6

carbonate reservoir zones with two main facies were identified, i.e. limestone facies with PE of about 5.08 and dolostone facies with PE of about 3.14.

3.2. Mineral identification using the $D_{GA}-U_{ma}$ cross-plot

The $D_{GA}-U_{ma}$ cross-plots were plotted for 6 reservoir zones as shown in Figure 6. The main clusters are grouped either at the calcite or dolomite vertex. There is a good agreement between the $D_{GA}-U_{ma}$ cross-plot and thin section analysis results in mineral identification.

3.3. Results of carbonate fabrics characterisation using thin section and SEM analyses

Four types of carbonate rock fabric were found as shown in Table 3, i.e. i) limestone as grain-dominated grainstone; ii) limestone as grain-dominated packstone; iii) dolostone as grain-dominated grainstone; and iv) dolostone as grain-dominated packstone.

Based on Lucia's [3] classification two petrophysical classes were identified, i.e. 1) Class 1: for limestone or dolostone as grain-dominated grainstone, which has inter-crystalline pores space; and 2) Class 2: for limestone or dolostone as grain-dominated packstone, which has some interparticle pores (including the pores between allochems and clastic grains) filled with mud. These

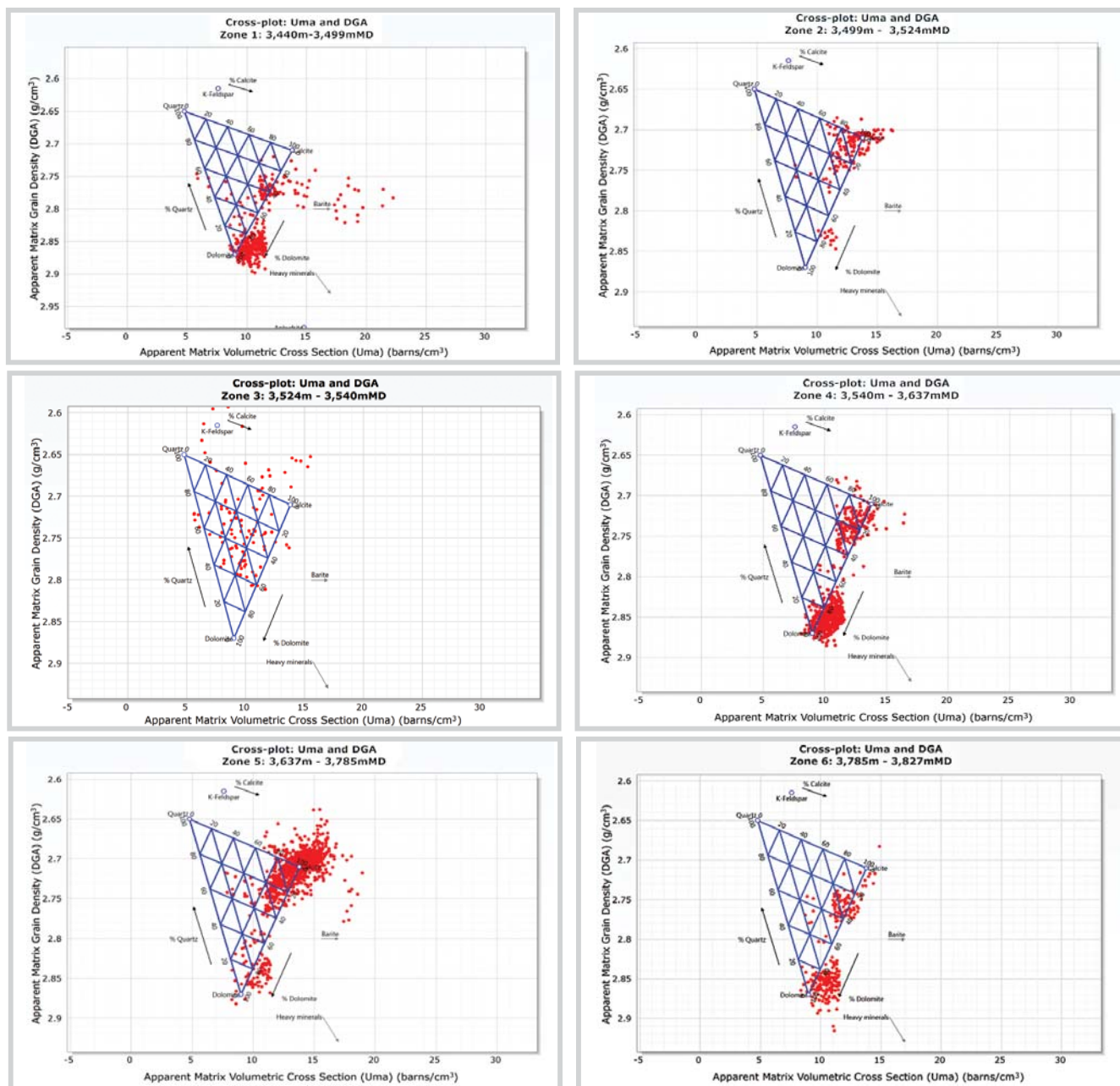


Figure 6. Mineral identified based on $U_{ma}-D_{GA}$ cross-plot at different zones

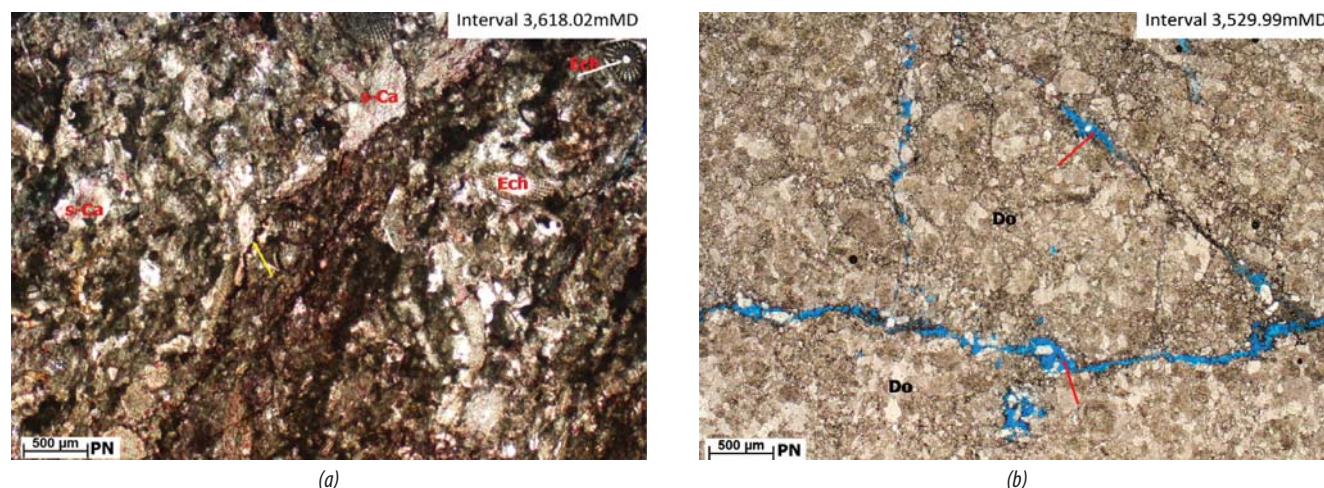


Figure 7. The photomicrograph of the dolostone fabrics: Grain-dominated packstone with sparry calcite filled up fractures in zone 4 (a); Grain-dominated grainstone in zone 3 (b)

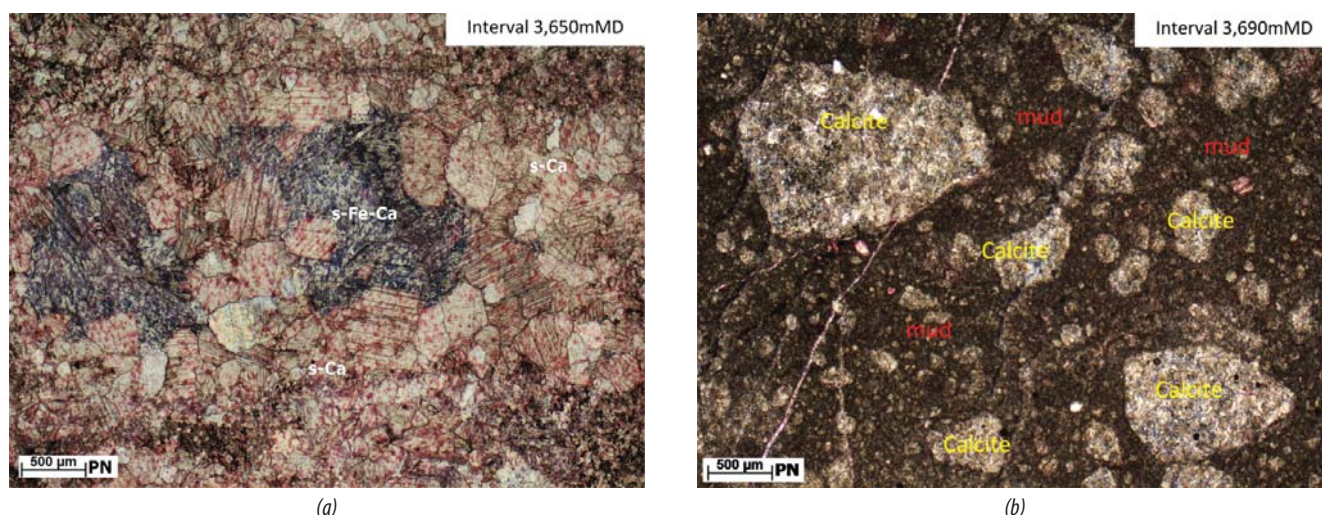


Figure 8. The photomicrograph of the limestone fabrics in zone 5: Grain-dominated grainstone (a); Grain-dominated packstone (b)

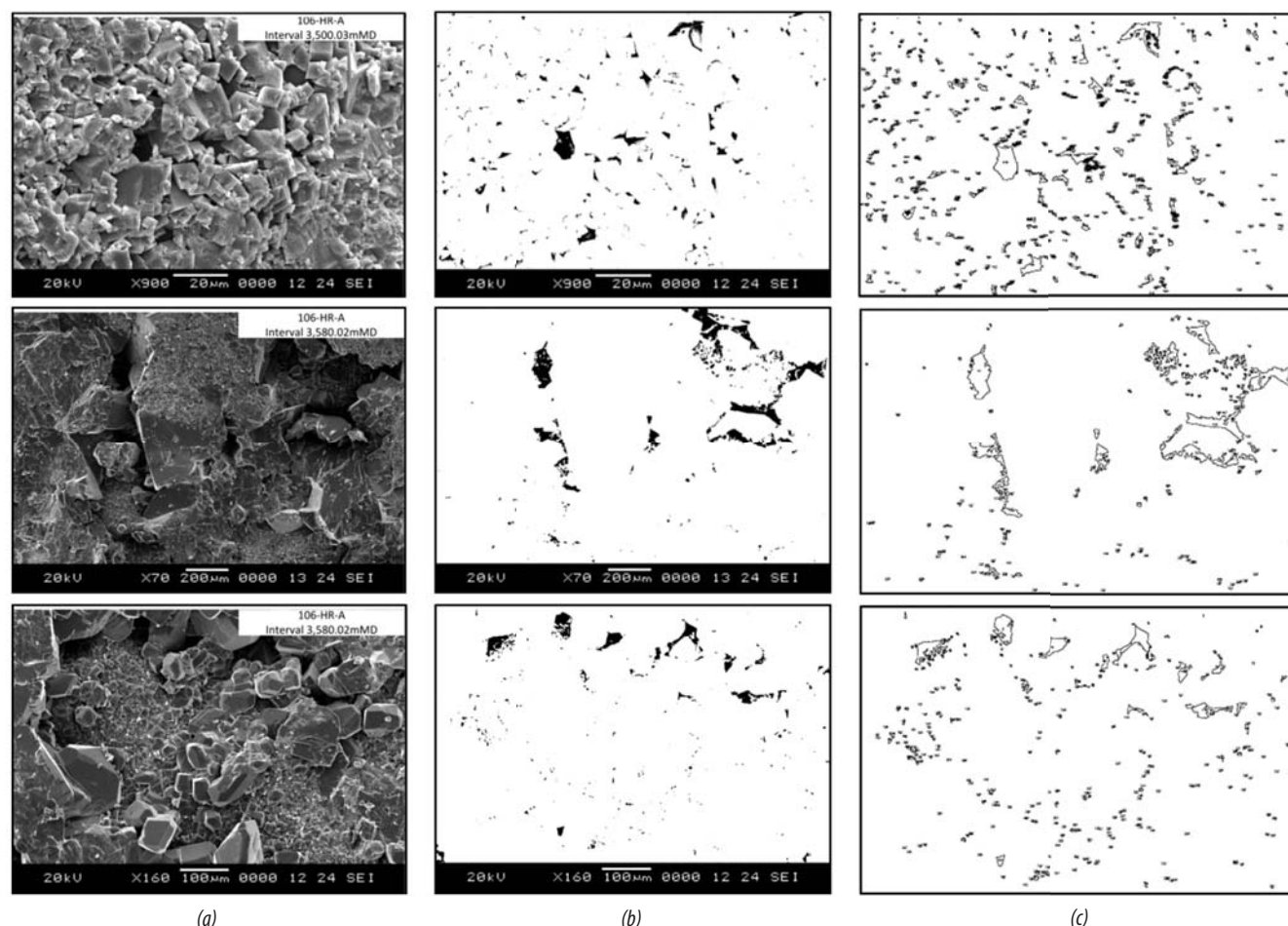


Figure 9. Segmentation of microspore: Original SEM image (a); Binary image, on which the micro-pore network can be identified by the darkest spots (b); Pore geometry (c)

rocks are strongly fractured and filled up with sparry calcite and silicic mineral.

The thin section photomicrographs as illustrations for dolostone and limestone fabrics for zone 3, 4 and 5 are shown in Figures 7 and 8, indicating two main types of grain-dominated grainstone and grain-dominated packstone.

The original SEM images (Figure 9a) were first converted into binary images (Figure 9b) that will be analysed by the ImageJ software, i.e. the pores could be identified as the darkest spots. As a result, one could obtain the percentage of different pore types, and the inter-crystalline porosity of grain-dominated grainstone was found to be in the range from 1% to 3% of the whole

Table 4. Carbonate rock fabrics and pore system characterisation

Zone	Lithology	Type of fabric	Calculated Porosity (%)						
			By thin sections			By SEM	By well log data		
			Total	Inter-particle	Touching vug	Inter-crystalline	Total	Inter-particle	Vug
1	Dolostone	Grainstone	4		4	1.73	5.04	3.47	1.79
2	Limestone	Grainstone	4	2.3	1.7	3.02	3.47	2.01	0.20
3	Dolostone	Grainstone	9.6	2.3	7.3		17.99	14.45	4.21
4	Dolostone	Packstone	0			2.92	4.23	4.21	0.06
5	Limestone	Grainstone/ Packstone	3	1.25	1.75	1.5	0.95	0.55	0.41
6	Dolostone	Grainstone	0				4.52	2.93	1.59

image. The range of inter-crystalline porosity is quite similar to that of interparticle porosity estimated by thin section analysis, which indicated that the pores between the carbonate mineral crystals play a main role in the interparticle porosity. In addition, the pore geometry could be visualised as seen in Figure 9c and the pore sizes were found in the range from 0.1µm to 30.8µm in diameter.

The final results of an integrated petrophysical analysis using both well log and micro-geological data of thin section and SEM analyses in this study are summarised in Table 4.

4. Conclusions and recommendations

More than 400m thick carbonate rock interval was analysed at the study well site in the HR structure. Six lithological zones were identified as limestone and dolostone having main fabrics as grainstone with grain-dominated fabric and packstone with grain-dominated fabric. Different pore types were identified such as interparticle, vuggy and inter-crystalline. It is worth noting that the $D_{GA}-U_{ma}$ cross-plots proved to be useful for identification of predominant minerals. It could be plotted for each zone identified and could help to indicate the predominant mineral.

As a result, the analysis interval at the study well was divided into six zones. Zones 1, 3 and 6 were classified as dolostone of grain-dominated grainstone with total porosity of about 2 - 17% in which interparticle porosity varies from 2% to 14% and touching vug from 1% to 4%. Zones 2 and 5 were classified as limestone of grain-dominated grainstone and packstone with total porosity from 1 to 4% in which interparticle porosity varies from 0.5% to 2% and touching vug from 0.2% to 0.4%. Zone 4 is dolostone which was classified as grain-dominated packstone with total porosity from

2% to 4% in which interparticle porosity varies from 2% to 4%.

It is noted that zone 3 of grain-dominated grainstone dolostone (Tables 3 and 4) is somewhat special comparing with the other zones as all of the porosity components are significantly higher. It is suspected that the solution-enhanced pores might be the reason for the high porosity in this zone. Further detailed analysis is recommended for pore characterisation of this dolostone zone.

The use of Lucia's [3, 13] classification in carbonate fabric characterisation and linkage with the pore system is very helpful. The integrated analysis proposed and applied in this study for petrophysical characterisation of carbonate rock pore system can be applied for other well sites in the HR structure in the Song Hong basin.

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