# THE IMPROVEMENT OF MODELLING IN CARBONATE RESERVOIR BY DUAL POROSITY VIA GEOLOGICAL AND ENGINEERING APPROACH


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# ABSTRACT

Carbonate heterogeneity has complex post-depositional diagenesis, superimposed on the original microstructures inherited from the initial deposition environment during sedimentation. This causes massive complexity in pore shape, pore size, pore connectivity, and distribution of pores in carbonate, which leads to the complexity in carbonate reservoir modelling domestically. The porosities of carbonate rocks can be separated into three types: macro-porosity (connected porosity), mesoporosity (unconnected vugs and pores result from diagenesis dissolution) and micro-porosity (isolated porosity). This thesis focuses to propose an improved dual porosity carbonate modelling approach. The main contribution of this work is to determine the method to recognize and quantify dual porosity in carbonate through six (6) information that can be obtained from a reservoir, namely geological core description and photomicrographs, RCA and SCAL analysis, nuclear magnetic resonance NMR, mercury-injection capillary pressure MICP, pressure transient analysis and a bonus for brownfield, production pressure profile. To test the effectiveness to quantify dual porosity, Field B in Central Luconia, Sarawak is selected as a study candidate. Data from conventional core provide direct observation of the rock pore geometry via photomicrograph, a diagenetic process which leads to segregation of macro and micro-porosity. Other petrophysical properties obtained via routine core analysis (RCA) and special core analysis (SCAL) provide the reservoir poro-perm condition. The mercury injection capillary pressure (MICP) curves translate the reservoir pore throat efficiency into macro and micro-porosity. Nuclear magnetic resonance (NMR) T2 relaxation distribution yields a bimodal trend for the dual-porosity reservoir. The pressure derivative transient analysis graph exhibits a V-shape yielding a dual-porosity reservoir. The pressure surveillance plot in the brownfield shows a flattening pressure depletion trend indicating microporosity charging to the production. These results are incorporated into a multiscale model and the simulation matches the reservoir's historical data and the type of dual porosity is identified as a matrix (connected) – matrix (isolated) type. Identifying the dual porosity in the carbonate reservoir enables the management to understand the reservoir hydrocarbon production and subsequently, lay out a proper reservoir management plan.

# ABSTRAK

Heterogeniti batu karbonat telah melalui diagenesis pemendapan yang kompleks. Ia berlaku ke atas struktur-mikro asal daripada persekitaran pemendapan awal. Ini menyebabkan kerumitan dalam bentuk dan saiz liang, ketersambungan liang, dan pengagihan liang dalam batu karbonat. Ini menyebabkan kesukaran dalam pembinaan model 3D untuk batu karbonat tempatan. Porositi batu karbonat boleh dikategorikan kepada tiga jenis, iaitu makro porositi (porositi bersambung), mesoporositi (liang tidak bersambung) dan mikro-porositi (porositi tidak bersambung). Objektif tesis ini adalah untuk bertambah-baik pembinaan model 3D untuk batu karbonat dengan menggunakan cara memodel dwi-porositi. Sumbangan utama tesis ini adalah untuk menentukan kaedah untuk mengenali dan kuantifikasi dwi-porositi dalam batu karbonat melalui enam (6) maklumat yang boleh diperolehi daripada takungan iaitu melalui tafsiran batu nipis geologi dan fotomikrograf, analisis analisis batuan rutin RCA dan analisis khas batuan SCAL, magnetic resonans nuclear NMR, tekanan kapilari suntikan merkuri MICP, analisis tekanan telaga minyak dan profil tekanan produksi minyak untuk ladang minyak. Medan B di Central Luconia, Sarawak telah dipilih sebagai calon kajian untuk menguji keberkesanan mengukur dwi-porosit. Hirisan batu nipis memberikan pemerhatian secara langsung tentang geometri liang batu melalui fotomikrograf, dan jugak pengasingan antara liang makro dan mikro. Keadaan poro-perm dalam batu karbonat boleh didapati melalui cara analisis petrofizik, iaitu RCA dan SCAL. MICP berjaya menterjemahkan kecekapan pengaliran liang makro dan mikro. Dwi-porosity juga boleh ditentukan daripada bentuk graf NMR yang memberi trend bimodal, dan bentuk V yang dipamerkan dalam graf analisis tekanan transien. Plot bacaan tekanan yang menjadi rata setelah pengeluaran minyak adalah suatu indikasi menunjukkan pengecasan mikro-porosity. Dengan mengabungkan analisis 6 kaedah ini, boleh mengesahkan bahawa batu karbonat di Medan B mempunyai dwi-porositi dan jenis dwi-porositi ini adalah matriks (bersambung) – matriks (tidak bersambung). Akhirnya, keputusan ini dimasukkan ke dalam model 3D dan simulasi sepadan dengan data sejarah, Mengenal pasti liang dwi-porosity dan kesannya membolehkan pihak pengurusan memahami pengeluaran minyak dan mengaturkan pelan pengurusan takungan yang betul.

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## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| UTM | - | Universiti Teknology Malaysia |
| PETRONAS | - | Petroleum Nasional Berhad |
| SW | - | Water saturation |
| NMR | - | Nuclear Magnetic Resonance |
| MICP | - | Mercury Injection Capillary Pressure |
| C | - | conductivity |
| HMC | - | High magnesium calcite |
| LMC | - | Low magnesium calcite |
| DPDK | - | Dual porosity dual permeability |

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $\phi$ | - | Porosity |
| D | - | Darcy |
| mD | - | miliDarcy |
| K | - | Permeability |
| $p$ | - | Pressure |
| A | - | Area |
| l | - | Length |
| $\mu$ | - | viscosity |
| Ko | - | Oil permeability |
| Kw | - | Water permeability |
| Kg | - | Gas permeability |
| Q | - | Flow rate |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Research Background

Carbonate reservoirs hold a large proportion of the world's oil and gas reserves. Some notable large reserves are located in the Middle East, Libya, Russia, Kazakhstan and North America. The hydrocarbon reserves in the carbonate reservoir account for almost 60% of the world's oil reserves and 40% of the world's gas reserves based on Schlumberger Market Analysis in 2007 (Kargarpour, 2020). The Middle East, famous for its rich oil and gas reserves, has 60% of the world's proven oil reserves, where almost 70% comes from carbonate reservoirs. The region also has 41.3% of the world's proven gas reserves, and 90% of these reserves are in carbonate reservoirs. The world has an estimated 3000 billion barrels of remaining oil and 3000 trillion SCF gas in place stored in carbonate reservoirs. However, the complexity of carbonate reservoirs has put a halt to many recoveries throughout the centuries of oil and gas exploration. In recent years, carbonate reservoirs have regained interest in improving recoveries, considering the challenges of decreasing reserves from conventional clastic reservoirs. (Christian, 2016)

Malaysia's Exploration and Production business started with the formation of Malaysia's national oil company, Petroliam National Berhad (PETRONAS) and has been managing petroleum resources and petroleum-related national policies to ensure that Malaysians enjoy the benefits obtained from their indigenous petroleum wealth.

Malaysia has a total of 332,300 kilometres of offshore area which includes part of the Straits of Melaka, South China Sea, Sulu Sea and Celebes (Sulawesi Sea) and 60% of these offshore waters are less than 200 metres in water depth. The shallow waters give rise to great petroleum exploration opportunities for Malaysia's petroleum business in a relatively mild environment. Offshore Terengganu, Sarawak and north-western Sabah are the few active petroleum provinces in Malaysia's waters. Among these regions, Central Luconia province was recognised through a series of marine seismic surveys in 1965 and 1966, to be dominated by carbonates build-ups. (The Petroleum Geology and Resources of Malaysia, 1999). Central Luconia Province is located in the offshore Sarawak, bounded to the east and west by the Baram delta and West Luconia delta, and bounded by Balingian Province in the south. The gas development in Central Luconia offshore Sarawak started as early as 1982 by (Wee & Liew, 1988). The geological detail of Central Luconia shall be discussed in Chapter 2.

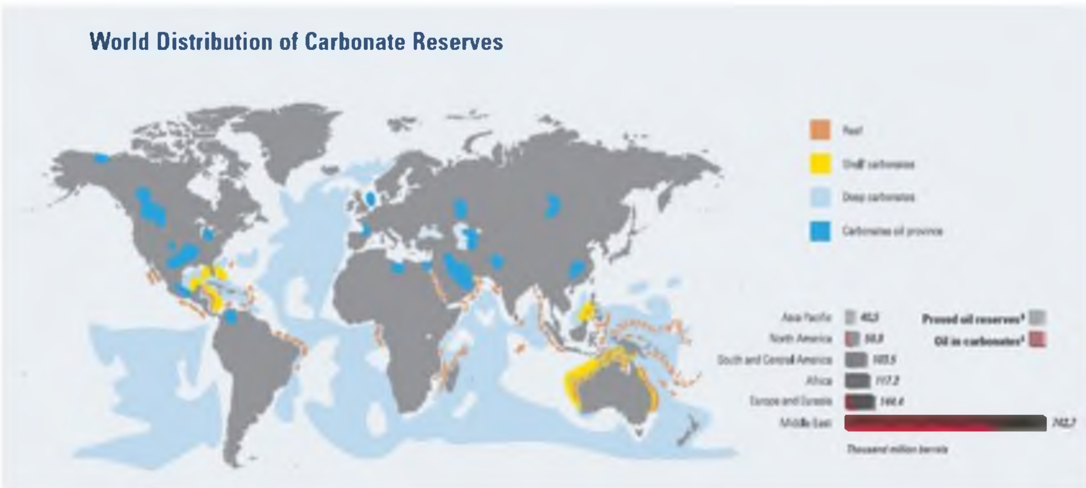


Figure 1.1 World distribution of Carbonate Reserves (Christian, 2016)

Some of the significant differences between the clastics reservoir and the carbonate reservoir are the origins of their grains. Clastics are sandstone deposition that is transported from one place to another and then deposited at the sedimentary basins, whereas carbonates are growth in-situ within the basin of deposition. The growth of carbonate is particularly dependent on the surrounding of the marine environment, for example, the chemical composition of seawater, the rate of rising and fall of sea level and other factors largely affecting the sediment texture of the carbonate reservoir. While clastics sedimentation also depends on sediment supply and accommodation space, the chemical composition of seawater and diagenesis alterations of sediment grain give a lesser impact on the clastics compaction process. In terms of reservoir properties, the porosity of a clastic reservoir is sensitive to burial depth compaction, while carbonate is able to preserve excellent properties to great burial depths – far off the burial trends from clastic compaction. Due to this reason, the hydrocarbon column heights within a better-preserved carbonate reservoir rock may extend far beyond apparent structure closure which the top and lateral seals are controlled by chemical compaction of flanking beds. (Wagner, n.d.)

Typical clastic reservoirs are commonly identified as a single-porosity system and are divided into four basic porosity types: intergranular, microporosity, dissolution, and fracture porosity (Pittman, 1979). Carbonate reservoirs are often characterized as a dual-porosity system, and the pore types in carbonate rocks are more varied due to carbonate as a plant skeletal organism and the post diagenetic sedimentation effect on carbonate which alter the porosity of a carbonate reservoir. Choquette and Pray recognize three basic groups of pore types, namely fabric selective, non-fabric selective and fabric selective or not. (Choquette & Pray, 1970). These pore types are further subdivided into interparticle, intraparticle, intercrystal, moldic, fenestral, fracture and vugs, and will be discussed in detail in Chapter 2.

In the context of a textbook, porosity is defined as the reservoir storage capacity, which is the ratio of void space (pore volume) to bulk volume in a rock. It is reported either by a fraction or by percentage. Dual porosity as the term describes has two porosity systems within the reservoir and is often described as being of primary or secondary origin. Primary porosity is the original porosity that existed at the time of deposition, while secondary porosity is defined as porosity created by the subsequent process of deposition, which was superimposed on the rock or sediment by the diagenetic process. (Zarrouk & McLean, 2019).

However, in reality, carbonate reservoirs that only contain primary porosity are very rare. Secondary porosity is more accurately described as a rearrangement or reconstruction of the original pore network, for example, the dolomitization of a porous lime mud reorganized and help preserves the porosity that was already present. The combination of multiple porosity results in carbonate exhibiting dual-porosity which will cause properties heterogeneity. (Mazzullo & Chilingarian, 1992). Others define a dual-porosity reservoir as a rock characterized by primary porosity from original deposition and secondary porosity from some other mechanism, and in which all flow to the well effectively occurs in one porosity system, and most of the fluid is stored in the other. Naturally fractured reservoirs and vugular carbonates are classified as dual-porosity reservoirs, as are layered reservoirs with extreme contrasts between high-permeability and low-permeability layers. (Schlumberger, n.d.)

Commonly used approaches in the clastic reservoir by using net-to-gross and porosity cut-offs often do not properly characterize the carbonate reservoir as the carbonate reservoir is acutely susceptible to macro-porosity and microporosity irregularity, for example, high-porosity carbonate interval may be non-pay reservoir due to dominance of microporosity which gives low hydrocarbon saturation and low porosity carbonate may give good hydrocarbon production results due to naturally occurred micro-fracturing or chemical dissolution between microporosity that forge a high-way for hydrocarbon flow.

This main discussion of this thesis is to showcase the methods for identifying dual-porosity and the way to implement the findings for model prediction. Among those methods, geological thin section and borehole images (BHI) are the direct specimens to qualitatively identify dual-porosity occurrence. Other methods include quantitatively acquiring engineering data from reservoirs such as reservoir pressure data from production profile, special core analysis SCAL, routine core analysis RCAL (porosity-permeability cross plot), mercury injection capillary pressure MICP and Nuclear magnetic resonance NMR. A domestic carbonate field from Central Luconia Province, offshore Sarawak will be selected as the case study to complement the discussion.

## 1.2 Problem Statement

With the increasing demand for secondary and tertiary oil and gas recovery from explored and produced fields, the subsurface ability to locate the remaining oil has become indispensable alongside the business effort to look back at the remaining potential in existing assets. Though many modellers have done a considerable amount of studies on the 3D geological modelling of fracture porosity for dual-porosity reservoirs, many domestic studies only focus on the single porosity equivalent reservoir modelling. The absence of courage to incorporate the dual porosity concept within the subsurface reservoir models are mainly due to an insufficiency of knowledge to implement dual-porosity engineering data into reservoir modelling and a shortfall of field data to support the theory of dual-porosity modelling. Nevertheless, these drawback has caused inaccuracy in modelling results, which may possibly lead to unsuccessful history matching and even underestimating or overestimating the hydrocarbon in-place of a carbonate reservoir (Chen, Cai, Fan, Li, & Ni, 2008).

The fundamental factor that controls the carbonate heterogeneity is nonetheless the complex post-depositional diagenesis, which is superimposed on the original microstructures inherited from the initial depositional environment during sedimentation. This creates a massive complexity in pore shape, pore size, pore connectivity and distribution of pores. The knowledge of porosity values alone is insufficient to describe the trends in the dual porosity-dual permeability relationship in carbonate rock. (El Husseiny & Vanorio, 2016)

Classifying porosity data qualitatively based on a geological concept which aims to evaluate the depositional environment is insufficient to identify dual-porosity existence in carbonate rocks. This further suggests the need for quantifiable engineering parameters that can describe the rock characteristics and can be used as an input for subsurface reservoir modelling. The remaining question will be on how to identify these parameters and how to properly utilize them in the subsurface reservoir models.

The discussion will include the porosity evolution of carbonate rocks, and the qualitative and quantitative methods to identify dual-porosity in carbonate. Finally, the integration between geological data and engineering data for dual-porosity modelling in the carbonate field.

The hypothesis of this study is predicted as below:

i. Carbonate reservoirs have dual porosity. The type of dual porosity is a matrix (connected) – matrix (isolated) type.

ii. Dual porosity can be identified qualitatively and quantitatively via geological data and engineering parameters. Carbonate rock textures can identify the relationship between micropore and macropore under microscope SEM. Macropore will mainly contribute to primary porosity while diagenesis micropore contributes to secondary porosity, resulting in a dual-porosity effect on engineering parameters including routine core analysis RCA, mercury injection capillary pressure MICP, nuclear magnetic resonance NMR, pressure transient analysis and pressure production trend.

iii. The dual porosity concept can be incorporated into reservoir modelling with quantifiable engineering parameters.

## 1.3 Objective

The main objective of this study is:

(a) To identify the presence and the type of dual porosity in the carbonate reservoirs in Field B (a carbonate gas field in Central Luconia).

(b) To qualitatively and quantitatively characterize the carbonate rock porosity that is impacting the petrophysical properties (porosity, permeability, capillary pressure, water saturation and relative permeability) based on a combination approach for a better estimate (Mbal matches with historical data) in the hydrocarbon in-place volume and flow behaviour.

## 1.4 Research Scope

The scope of this study includes:

(a) Identifying detailed geological aspects of Carbonate reservoirs in Field B, including identification, description, and characterization of hydrocarbon reservoir in Carbonate rocks, stratigraphic principal, depositions, and diagenetic of Carbonate reservoirs

(b) Identify and validate Field B dual-porosity geology and engineering parameters acquisition methodology and available data, via 6 methodologies: geological photomicrograph analysis, routine core analysis RCA, mercury injection capillary pressure MICP, nuclear magnetic resonant NMR, pressure transient analysis and production pressure trend.

(c) Integrating the dual-porosity in reservoir modelling for Field B dual-porosity modelling

## 1.5 Significant of research

Application of dual-porosity modelling concept in carbonate reservoir model can accurately predict the reservoir performance by providing a much more accurate resource prediction in the reservoir. The underestimated single porosity modelling, if switched to dual porosity modelling, can contribute up to 30% additional resource on top of single porosity gas initial in-place GIIP and vice versa, an overestimated single porosity modelling may reduce in-place volume by up to 30% from the single porosity prediction model. By understanding the possibility of dual porosity existence in the reservoir, engineers are encouraged to deduce a better observation and calculation on field data instead of neutralising the obtained data as outliers.

In addition, managements are able to lay out a proper reservoir management plan that allows the micropore to charge into the wellbore within a sufficient amount of time, gas initially in-place contribution could possibly increase after the transition charge period and thus generating additional recoverable potential to the field.

Lastly, the depleted carbonate reservoir field can very likely be a good candidate for the geo-environmental future which is the carbon capture and storage known as CCS (CO2 sequestration). This aligns with the effort to reduce carbon dioxide in the atmosphere, in conjunction with the country's and world's aim to mitigate climate change. Therefore, identifying dual-porosity in the carbonate reservoir is crucial not only for the short-term benefit of the operating company for oil and gas production but also serves in a long run for the reservoir management plan.

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