Porosity and Permeability Development of the Deep-Water Late-Oligocene Carbonate Debris Reservoir in the Surroundings of the Paternoster Platform, South Makassar Basin, Indonesia

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Abstract. The discovery of gas within the carbonate debris reservoir of the late Oligocene Berai formation near the Paternoster Platform, South Makassar Basin, is a new exploration play in Indonesia. The carbonate was deposited in a deep-water environment and is a good example of a less well known carbonate play type. The carbonate debris reservoir in this area consists of re-deposited carbonate, originally located on a large carbonate platform that has been eroded, abraded and transported to the deep-water sub-basin. The limestone clasts range from pebble-size to boulders within a matrix of micrite and fine abraded bioclasts. This carbonate debris can be divided into clast-supported facies and matrix-supported facies. The matrix-supported facies have much better porosity and permeability than the clast-supported facies. Porosity in both the transported clasts and the matrix is generally mouldic and vuggy, resulting mostly from dissolution of foraminifera and other bioclastics after transportation. In the matrix intercrystal porosity has developed. The porosity and permeability development of this deep-water carbonate debris was controlled by a deep-burial diagenetic process contributed by the bathyal shales de-watering from the Lower Berai shales beneath the carbonate reservoir and the Lower Warukin shales above the carbonate reservoir during the burial process.

Keywords: *carbonate debris; de-watering; deep burial; new play; paternoster platform.*

1 Introduction

Most of the productive carbonate reservoirs in Indonesia are shallow-water, high-energy carbonate banks and reefal build-ups. The main porosity development in these reservoirs was developed by sea-level fluctuations that generated secondary porosity. However, the reservoir in the Pangkat sub-basin,

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Paternoster Platform, South Makassar Basin (Figure 1), was deposited under very different conditions. The reservoir's carbonate debris or carbonate breccia consists of fragments and matrix that have been deposited in a deep-water environment during the late Oligocene [1].

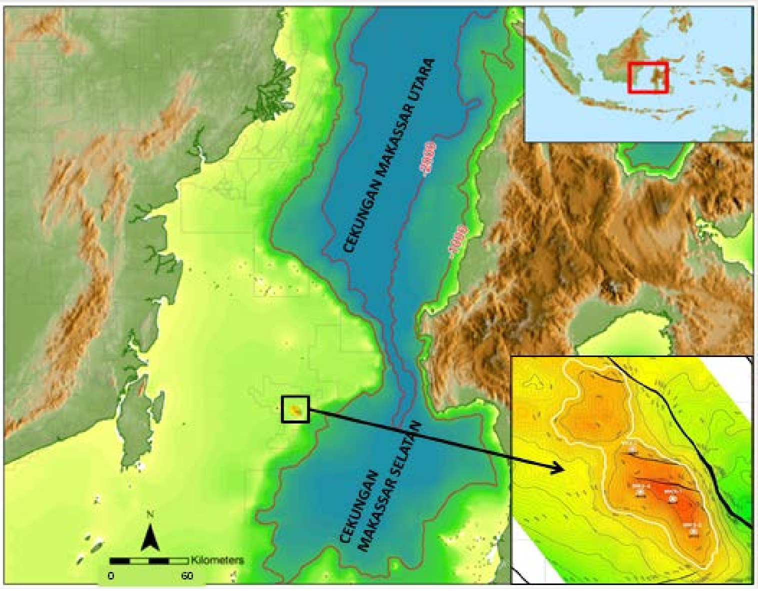

Figure 1 Research area location map (drawn by author).

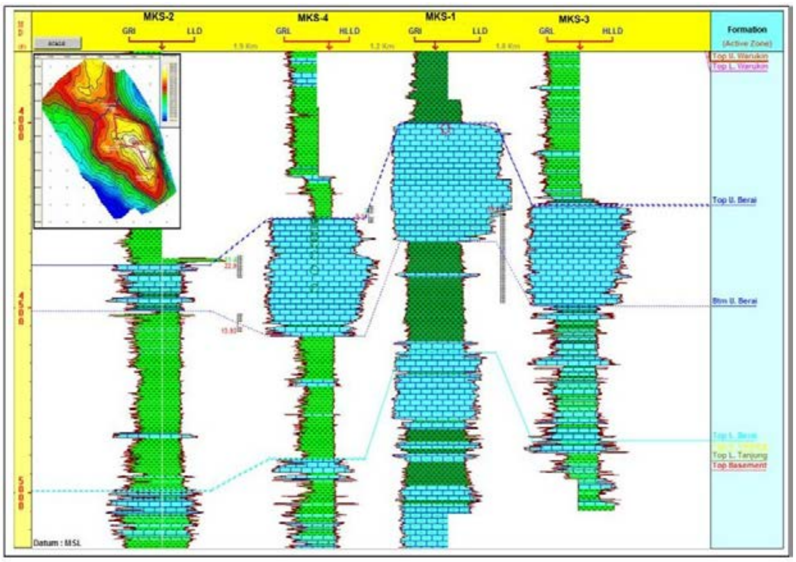

Figure 2 Gas discovery well correlation [2].

Pireno, *et al.* [2] and Tanos [3] identified the occurrence of this carbonate breccia reservoir in the Ruby Field through gas discovery at MKS-1 (tested 9.1 MMCFPD) [4], MKS-2 (dry hole) [5], MKS-3 (tested 39 MMCFPD) [6] and MKS-4 (tested 39 MMCFPD) [7] (Figure 2). This shows that the carbonate breccia in the Ruby Field can be categorized as world class reservoir quality, even though the reservoir was deposited in the deep-water environment with no influence from sea-level fluctuations.

Based on 3D seismic interpretation, the carbonate breccia reservoir has been deposited as a submarine fan in a bathyal environment with a sub-marine channel inlet that developed in the platform area, with a slope of around 10-20°. This research was aimed at understanding the porosity and permeability development of the deep-water carbonate breccia.

2 Geologic Setting

The Paternoster Platform is located at the southeastern edge of the Sunda Shield and is part of the micro-continent that has docked to the Sunda Shield to the west [8]. The Paternoster Platform is a northeast-southwest trending paleo-basement high structure located offshore in Southeast Kalimantan and is bounded by the Adang Fault to the north, the Meratus Ridge to the west and the South Makassar Basin to the east. It covers an area of about 20,000 km^2. The Paternoster Platform is divided into 2 (two) parts by the development of the NW-SE oriented Pangkat half-graben from the early Tertiary. The southern platform looks more stable than the northern platform due to the higher tectonic activity in the northern platform. This can be identified by looking at seismic data of the Berai carbonate deposition system, which show that the Berai carbonate consists of a flat carbonate platform over the southern platform and the existence of a large amount of pinnacle reef growth over the carbonate platform at the northern platform (Figure 3). This can be explained by the fact that the northern platform is located between the Pangkat sub-basin and the Adang Fault to the north, the latter of which was active moving upward until the Early Miocene.

There is also the occurrence of NW-SE trending, early Tertiary half-grabens on the Paternoster Platform, which are identified in the Barito Basin as well [2, 9] (Figure 4). The development of these NW-SE trending half-grabens in the Barito Basin and the Paternoster Platform is like a secondary effect of small-scale tensional structures, subsequent to the large-scale development of the NW-SE Central Kalimantan structural low related to the Adang Fault movement [9,10] (Figure 5).

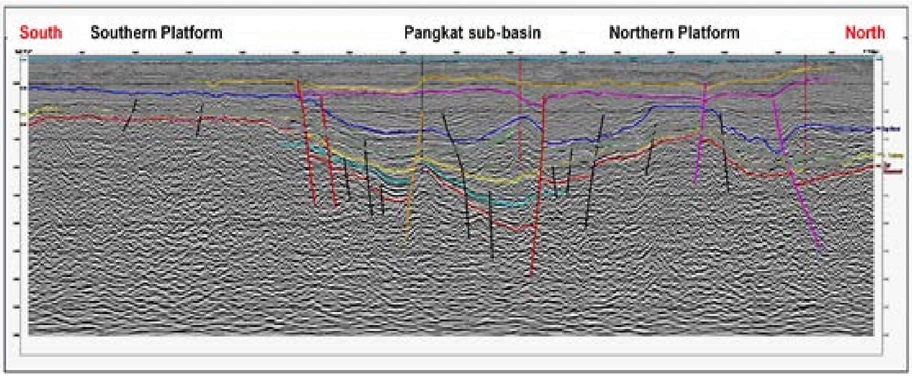

Figure 3 Seismic line across Paternoster Platform.

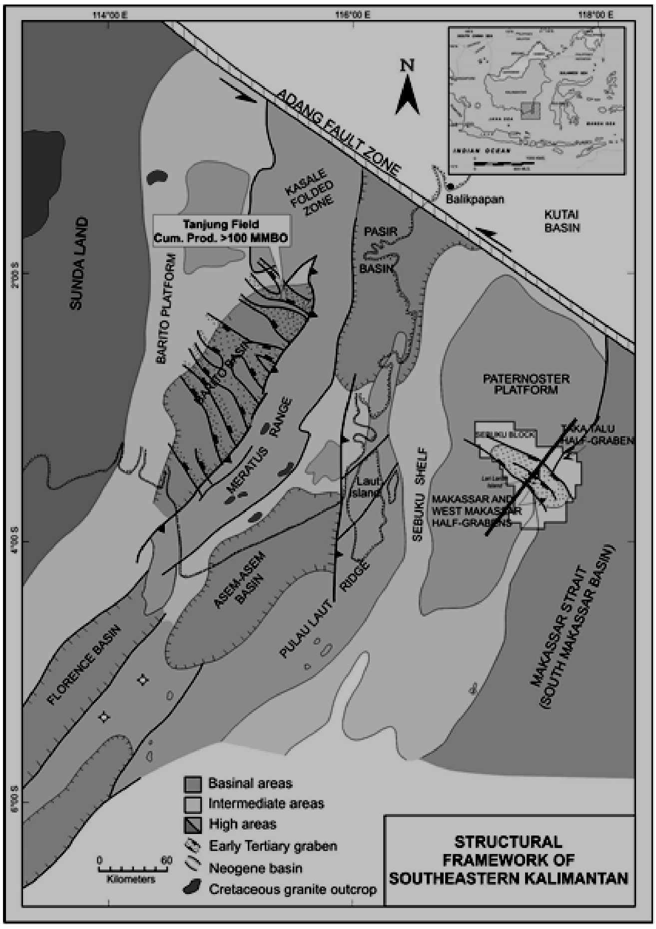

Figure 4 Structural Framework of Southeastern Kalimantan [2].

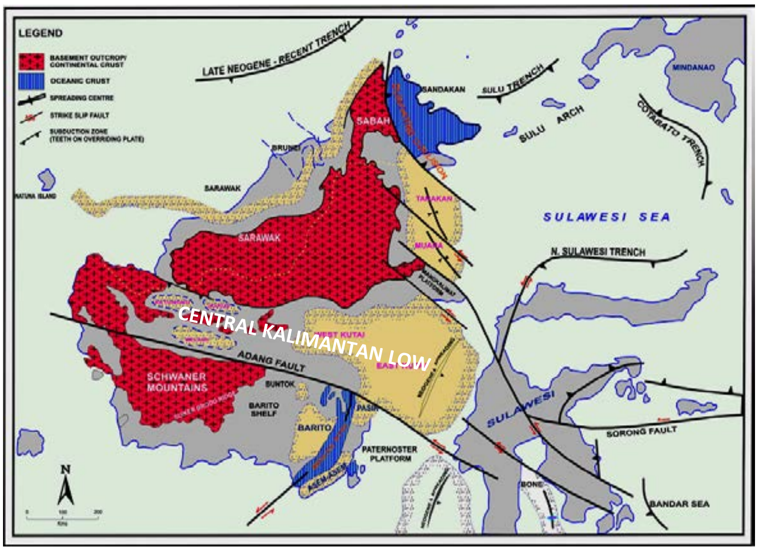

Figure 5 Tectonic Map Kalimantan-Sulawesi [9].

A simplified stratigraphy of the Paternoster area has been built based on offshore well data, geological data of the onshore area and seismic data [11,12] (Figure 6). Sedimentation commenced in the early-middle Eocene (Lower Tanjung Formation) within the grabens as non-marine sediment, estuarine/ shallow lacustrine. This sediment section is proved as source rock and contains sand reservoirs (Tanjung oil field). During the late Eocene the first marine incursion came from the south and covered the East Java Basin and the Makassar Straits area with marine shales from the Upper Tanjung Formation as cap rock for the Lower Tanjung sands reservoir. Deposition of marine shales within the grabens continued up to the early Oligocene as deep marine shales. Up to the early Oligocene, the Paternoster Platform was still a land area/no deposition.

During the late Oligocene, for the first time the Paternoster Platform area was covered by marine materials. A carbonate platform deposited over it with a carbonate shale going out to the basinal area. At the margin of the northern platform, the Berai carbonate breccia was deposited as a submarine fan through a submarine channel across the bounding fault and down to the basin. In the early Miocene, over the northern platform big pinnacle reefs were deposited, subsequent to the basement subsidence that was controlled by the sinking of the South Makassar Basin in the east. During the early Miocene, the pro-delta shales of the Lower Warukin Formation were deposited in the graben area. Due to continuing subsidence in the South Makassar Basin during the early-middle

Miocene, the Lower Warukin Formation was deposited as prograding delta sequences in the Pangkat half-graben.

In the mid-middle Miocene, a regional unconformity was defined at the base of the Upper Warukin Formation, which in some areas initiated a second phase of reefal carbonate deposition. Subsidence in the South Makassar Basin was discontinued at the end of the middle Miocene. Marine transgression occurred in the late Miocene and then the carbonate platform and reefal facies of the Upper Warukin Formation over the whole Paternoster Platform were deposited in both basinal and platform areas. The marine transgression continued faster and then deposited the claystones, sandstones and carbonates of the Dahor Formation.

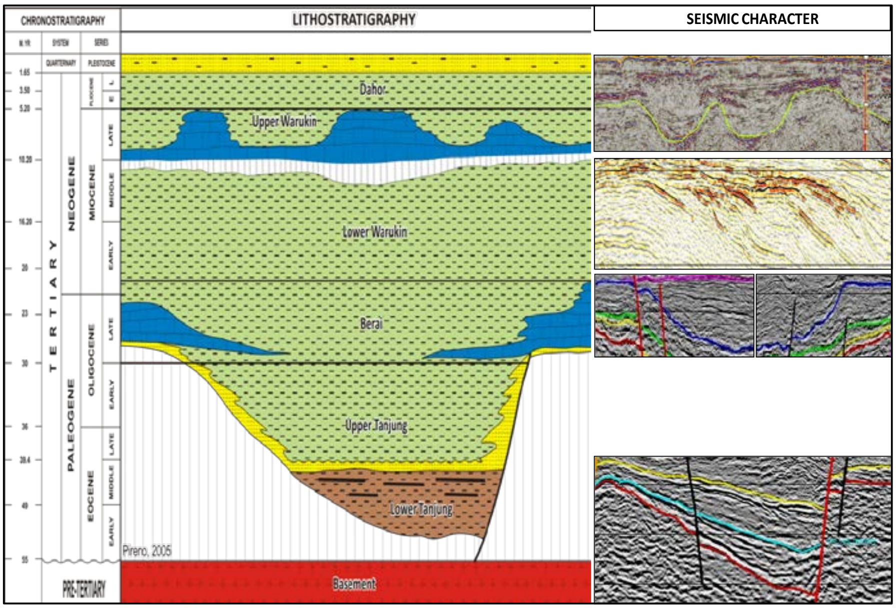

Figure 6 Chronostratigraphy of Paternoster area [11].

3 Methodologies

The data that have been used for this research are 2D/3D seismic data, cores from MKS-3 and MKS-4 wells, cutting data, thin-section analysis, SEM photo micrography, well information data, and geological final well reports (12 exploration wells) [3-8, 13-15]. The work flow can be seen in Figure 7.

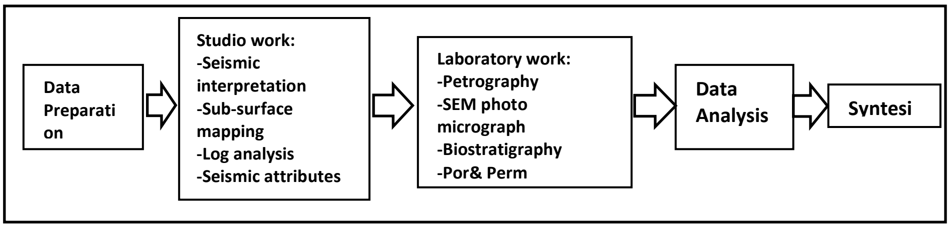

Figure 7 Work Flow Diagram.

4 Berai Carbonate Debris Flow

4.1 Lithology

The MKS-3 and MKS-4 cores consist of re-deposited limestone that can best be described as carbonate breccia containing clasts and matrix [1,16]. The limestone clasts range from pebble-size to boulder-grade in a matrix of lime mud and abraded bioclasts with poor sorting. Planktonic foraminifera are found in the matrix. The clasts of packstone-wackestone contain red algae, mollusk fragments, echinoderm plates, miliolid and both smaller and larger rotaliid foraminifera, as well as coral fragments. The degree of lithification of the clasts prior to transportation was variable, ranging from soft to highly indurated. The

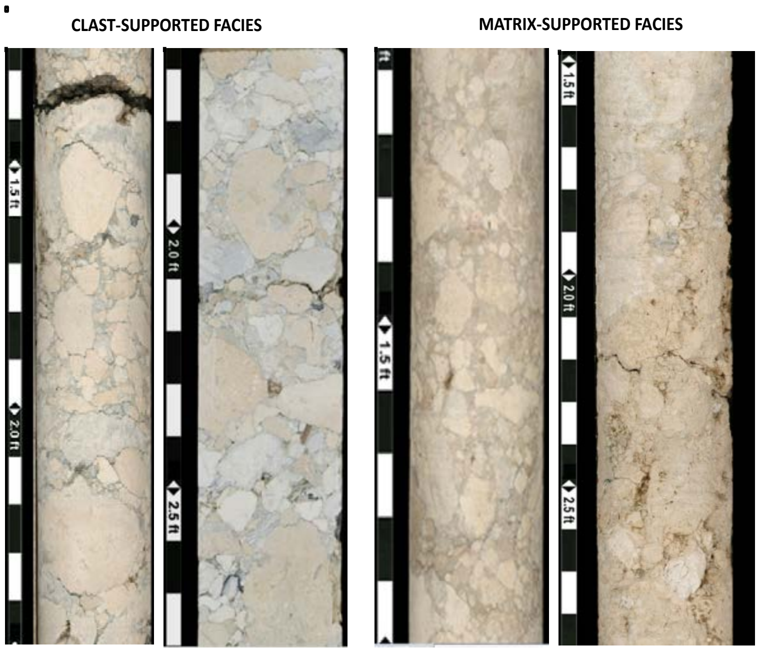

Figure 8 Chronostratigraphy of Paternoster area [11].

bioclasts in the matrix are comparable to those in the clasts and it is likely that the matrix is a product of disaggregation of poorly lithified clasts during transportation. Observation of the cores indicates that the carbonate breccia can be divided into clast-supported facies and matrix-supported facies (Figure 8).

4.2 Depositional Environment

3D seismic data from the area show the existence of NW-SE mound structures in the basinal area that are confirmed as positive lobe features (Figure 9). Based on the flattened 3D seismic data, it was observed that the Berai carbonate breccia has the geometry of a lobe deposited as a submarine fan in the deep-water environment (Figure 10). The shallow-water carbonate material was transported to the basin through a submarine channel inlet in the shallow water platform area as a result of small-scale half-graben development created as a tensional fault due to the subsidence of the South Makassar Basin in the late Oligocene (Figure 11) [17,18]. Because the Berai carbonate breccia has very rare planktonic foraminifera, the depositional environment just follows the depositional environment of the shales beneath the Berai carbonate breccia and the shales above the Beraicarbonate breccia. Both of the shales were deposited in the bathyal environment, so the depositional environment of the Berai carbonate breccia should be in the bathyal too. An isopach map of the Berai carbonate breccia shows a fan lobe (Figure 12) and seismic acoustic impedance data also show the porous zone as having the features of a fan lobe (Figure 13).

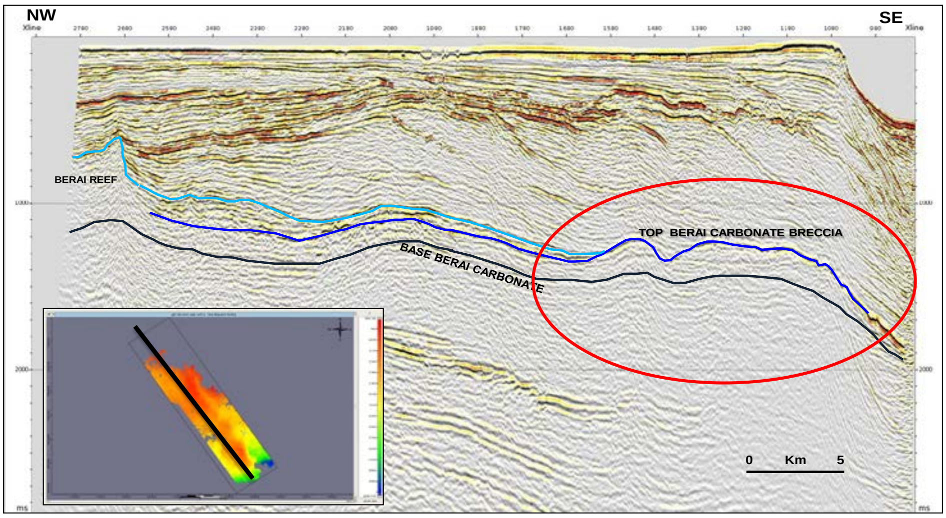

Figure 9 3D seismic line shows the mound structure at Ruby Field.

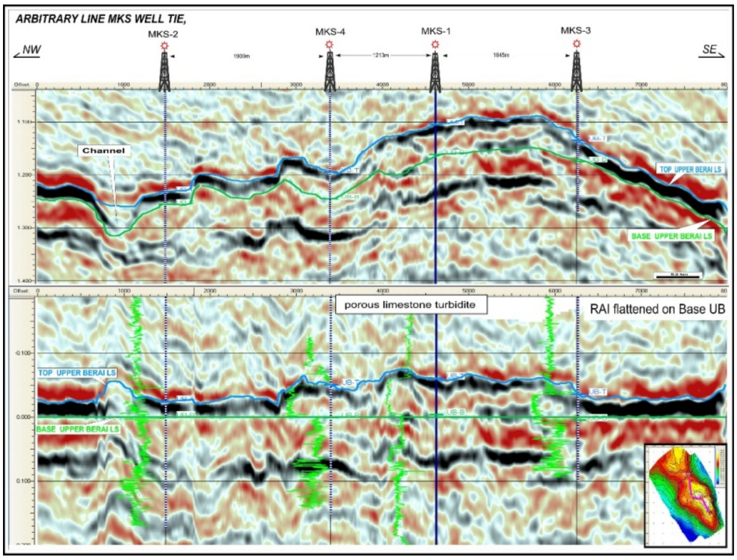

Figure 10 3D seismic line across well MKS-2, MKS-4, MKS-1 and MKS-3 and lower picture flattened at base Berai shows mound structure at Ruby Field.

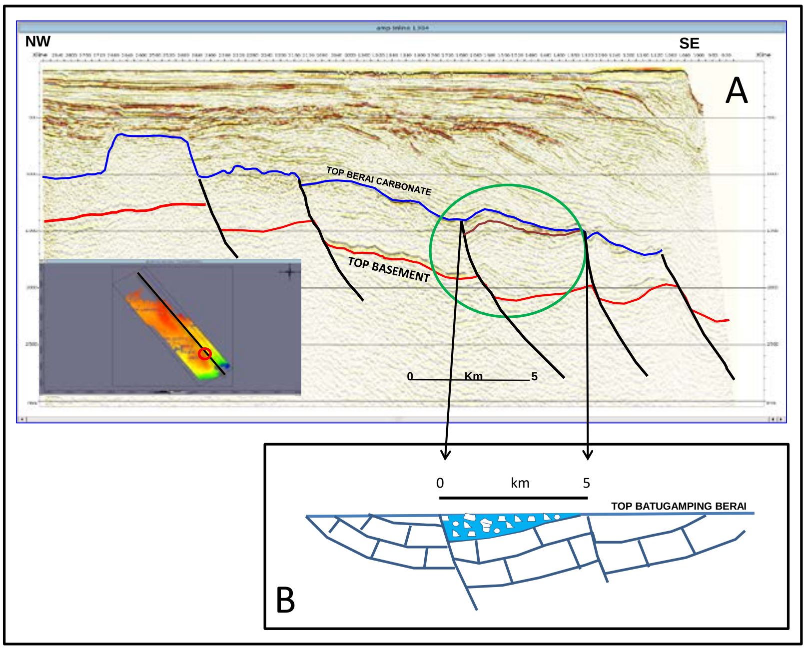

Figure 11 3D seismic line located on the north platform shows series of tensional faults that one of them (circle) is developed as sub-marine channel as the media transportation carbonate material rolling down to the Pangkat basin. The inset shows a sketch of the channel inlet in the Berai carbonate breccia.

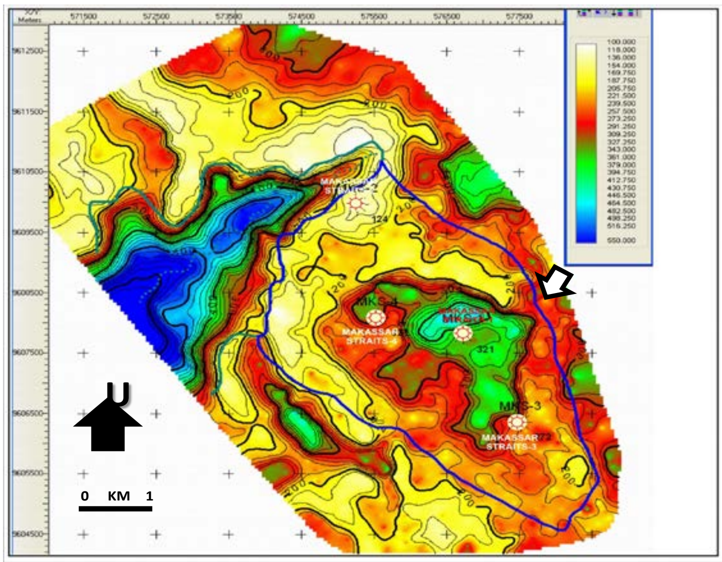

Figure 12 Isopach map of the Berai carbonate breccia in the basinal area.

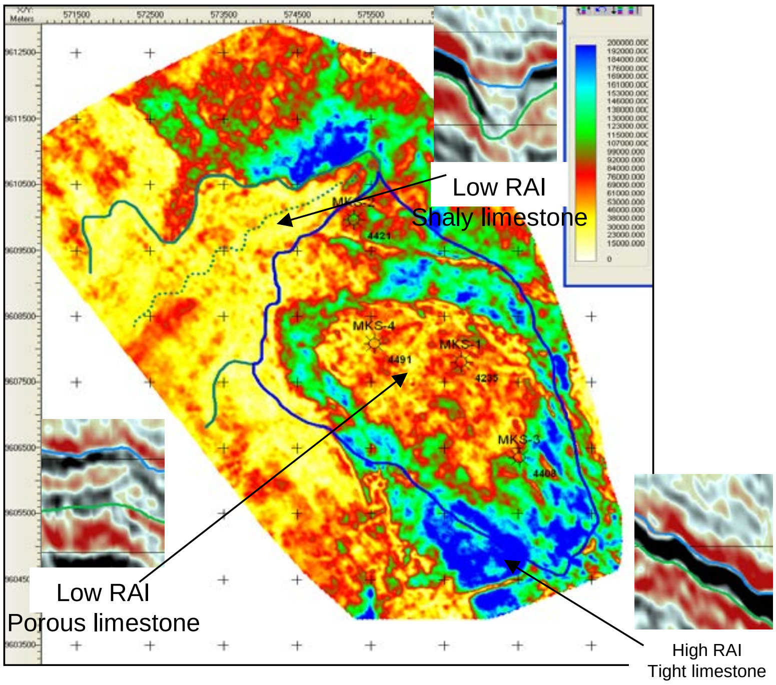

Figure 13 Acoustic Impedance map of Berai carbonate breccia.

4.3 Diagenesis

Based on the core analysis, the diagenetic evolution of the Berai carbonate breccia can be subdivided into processes that occurred before and after transportation of the limestone clasts.

Prior to transportation, the limestone was subjected to processes that occur under marinephreatic and fresh-water phreatic conditions. The latter include the leaching and replacement of skeletal aragonite associated with corals and molluscs and of any early marinecements. This was accompanied, or shortly followed, by the precipitation of very fine blocky and equant calcite in the resultant secondary pore space and also the occurrence of bladed isopachous cement. However, it can be noted that some clasts do retain secondary mouldic and vuggy porosity resulting from this early dissolution episode. Figure 14 shows the shallow-water diagenesis process before transportation.

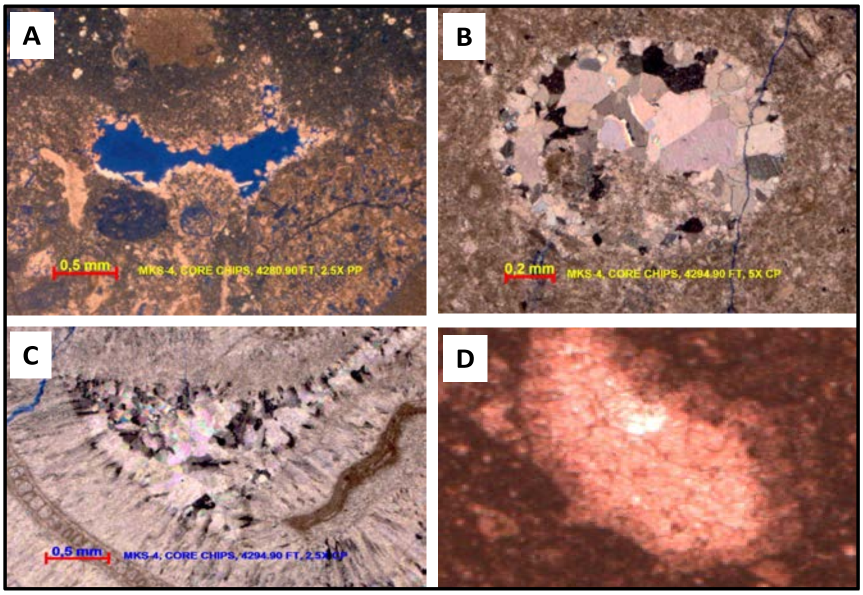

Figure 14 Diagenesis process developed in the shallow environment that identified in the limestone clast, featuring isolated vuggy porosity (A), minor equant calcite cement (B), fibrous calcite cement (C) and bladed isopachous (D)

Following transportation and redeposition, the limestone clasts were locally cemented by calcite. Subsequently, leaching occurred, which has largely affected foraminifera in both the clasts and matrix, resulting in secondary mouldic and vuggy porosity (Figure 15). The secondary porosity is often lined by very fine dolomite, which also occurs along fractures and microstylolites (Figure 16). Stylolites were also observed around the margins of the better lithified clasts as as a result of grain contacts and pressure solution associated with compaction.

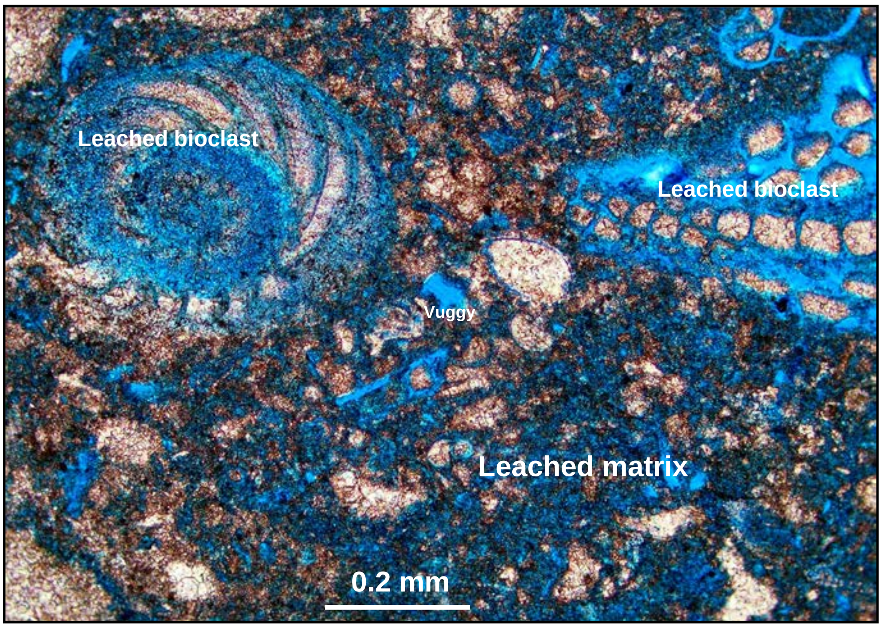

Figure 15 Petrographic thin section in matrix-supported facies shows leaching in bioclastic and sparite calcite formed vuggy porosity.

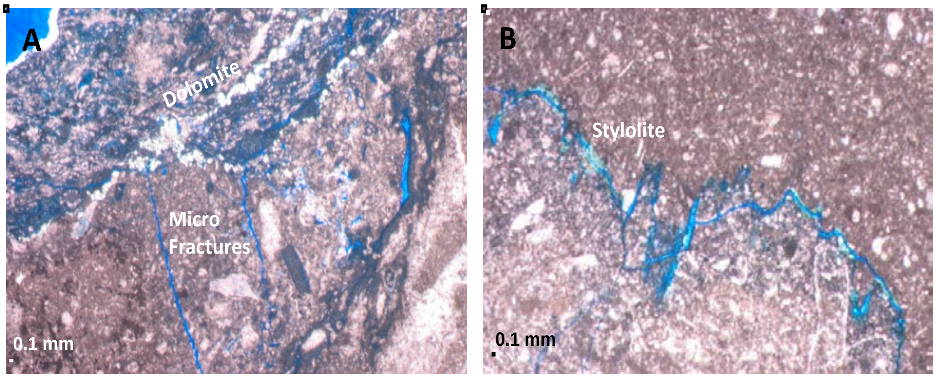

Figure 16 Petrographic thin section shows micro-fractures porosities cut at the edge of clast (A) and leaching in the micro-stylolite.

SEM photomicrography also showed dissolution in the matrix and intercrystal porosity generated within the matrix (Figure 17).

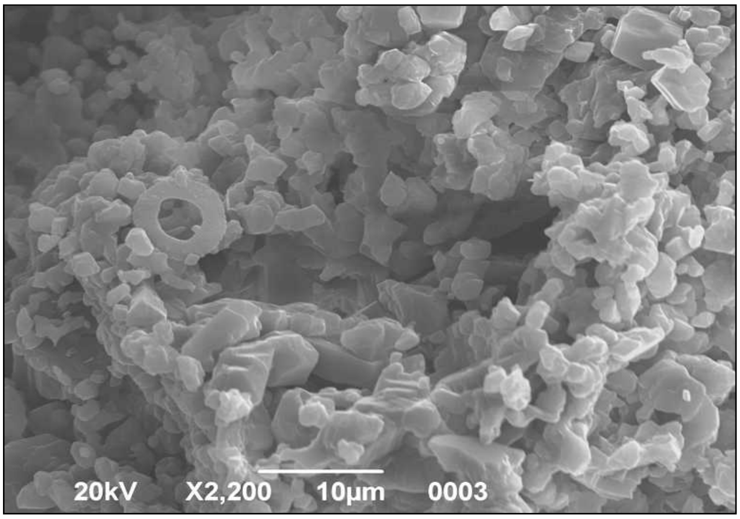

Figure 17 SEM photo micrograph shows inter-crystal micro-porosity in the matrix.

4.4 Pore System

The effective pore system found in the carbonate breccia is dominated by secondary mouldic and vuggy porosity as a result of bioclastic and micritic dissolution during deep-burial diagenesis. The occurrence of stylolite and micro/macro fractured porosities are responsible for maintaining the development of the pore system. Isolated primary porosity of intra-particles was found in the foraminifera and coral fragments in the clast-supported facies, while the secondary mouldic and vuggy porosity is more developed within the matrix-supported facies. The development of intra-matrix micro-porosity within the matrix maintains the good permeability of the Berai carbonate breccia.

Porosity and permeability measurements of the carbonate breccia in the laboratory were done by routine core analysis (core plug) and full-core diameter analysis (core) using samples taken from the MKS-4 cores. The results of the measurements by both routine core and full core analysis can be seen in Tables 1 and 2. The results of the porosity and permeability measurements from the laboratory do not seem to match the DST results, which flowed around 40 MMCFGPD with the permeability calculation ranging from 200 mD-600mD. It is assumed that the porosity and permeability measurements based on the cores are not representative for the whole reservoir tank. A combined plot of the porosity and permeability measurements from the routine core analysis, full-diameter core analysis and drill stem test data can be seen in Figure 18 [19].

Table 1 Porosity and Permeability Data from Routine Core Analysis of MKS-4 Samples.

Fades	Porosity (%)		Permeability (Ka mD)	
	Minimum	Maximum	Minimum	Maximum
Clast Supported	1.1	16.6	0	17.1
Matrix Supported	9.4	28	4.4	34.5

Table 2 Porosity and Permeability Data from Full-Diameter MKS-4 Samples.

Facies	Porosity (%)		Permeability (Ka mD)	
	Minimum	Maximum	Minimum	Maximum
Clast Supported	4	15	1.48	39.6
Matrix Supported	11.3	21.7	11.4	53.7

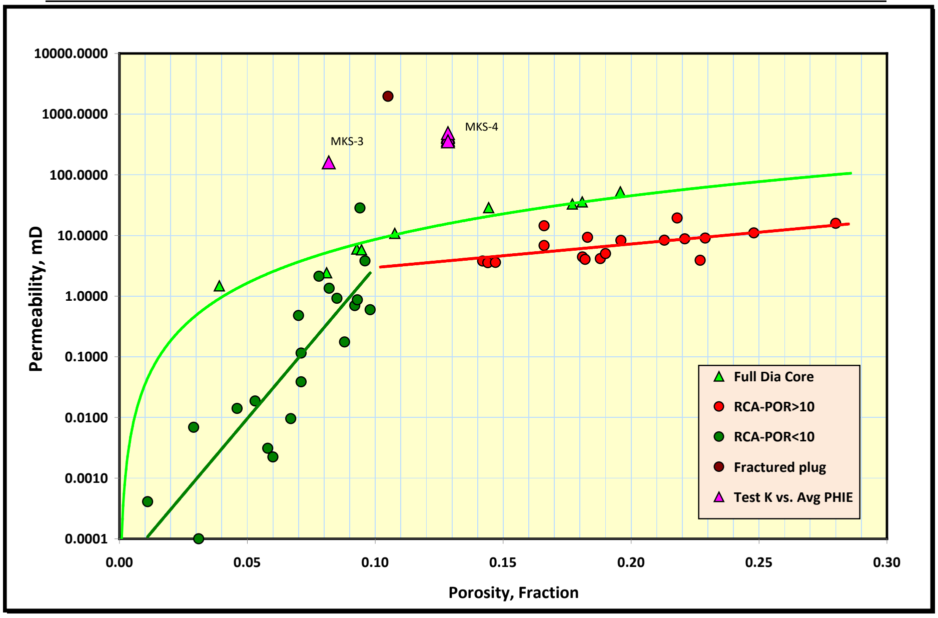

Figure 18 Combination cross-plot of porosity and permeability from routine core analysis, full diameter core analysis and DST data shows that the highest permeability is from DST.

5 Porosity and Permeability Development

By petrography, petrology and SEM photomicrography the existence of some types of porosities was identified, i.e.: mouldic, vuggy, intercrystal, matrix, intra-particle dissolution, inter-particle dissolution, macro/micro fractured and stylolite (Figure 19). Even though the Berai carbonate breccia, away from meteoric water influx, was never influenced by sea-level fluctuations, the porosities and permeability within this rock still look well developed. How come?

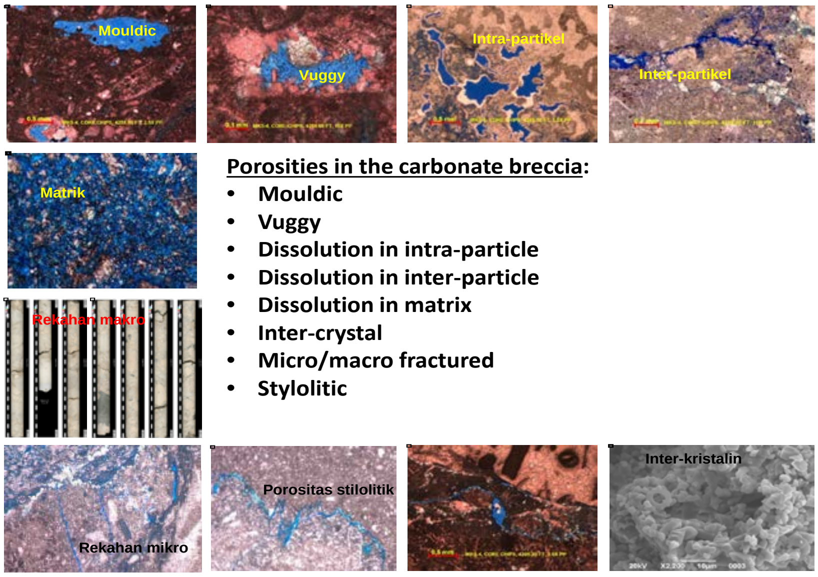

Figure 19 Porosities that have been developed within Berai carbonate breccia.

In the petrographic and SEM photomicrograph analysis, the existence of micro rhombic dolomite was identified, filled within inter-clast pore, stylolite, micro-fractures occurring partly within the matrix, which indicates the infiltration of unsaturated fluids containing magnesium elements. As described above, the fact that the Berai carbonate breccia was deposited in a deep-water environment means that there was no influence from meteoric water [20]. The Berai carbonate breccia deposits sit on the early-Oligocene bathyal shales and are covered by early Miocene deep-water shales that reach fluids with Mg elements coming from clay minerals. Due to the compaction process during burial, fluid content within both shales are compressed out as dewatering fluids, which are moved and intrude into the porous carbonate rock, enhancing porosity development by dissolution. The magnesium contents in the fluid will react with calcium elements in the carbonate rock that is diluted within the fluid, and will create rhombic dolomite precipitation in the micro fractures, stylolite, vuggy and mouldic porosities within the matrix.

6 Hydrocarbon Maturation Model

The Lower Tanjung source rock interval is stratigraphically located beneath the Berai Formation. A maturation model conducted on the deepest part of the

Pangkat half-graben indicates that hydrocarbon cracking commenced in the early Miocene, or around 2-3 million years after the deposition of the Berai carbonate breccia, and cooking continued during the deposition of the Lower Warukin Formation. During the middle-late Miocene there was a cooling down due to the folding structure and subsidence continued from the late Miocene up to the present day. The source rock has entered into the gas window from the middle Pliocene until the present day. It was proved that the Ruby Field located above the hydrocarbon kitchen produces gas and minor condensate (Figure 20) [21-23].

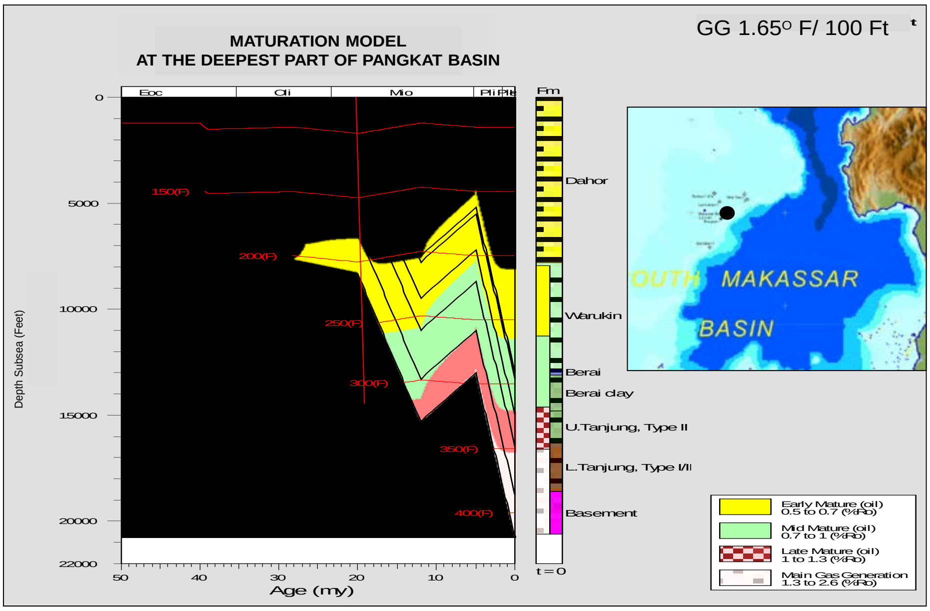

Figure 20 Maturation model in pseudo-well at the deepest part of Pangkat half-graben.

7 Conclusions

Porosity and permeability development within the deep-water Berai carbonate breccia was created by fluid intrusion due to shale dewatering as a burial effect during the sedimentation process. The fluids that came out from the shales during compaction reached magnesium content from clay minerals. The aragonitic-bioclastics that originated from the poor lithified carbonate platform, would be affected by these fluids, creating porosity and enhancing the reservoir quality. Evidence of the dissolution of bioclastics and sparite in the carbonate breccia by dewatering fluids is the occurrence of micro-dolomites in the micro-fractured, stylolite, matrix, vuggy and mouldic porosities. The dissolution porosities mentioned above have been preserved by hydrocarbon that migrated to this reservoir rock before the porosities were damaged due to further cementation.

Acknowledgements

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