REVIEW ARTICLE

IMPLICATION OF RESERVOIR CHARACTERISTICS BASED ON OVERVIEW OF STRUCTURE AND SEDIMENTOLOGY OF OUTCROPS ALONG BINTULU-NIAH-MIRI AREAS

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ARTICLE DETAILS

ABSTRACT

Article History:

Received 04 January 2019
 Accepted 07 February 2019
 Available Online 4 March 2019

Six-day fieldwork was conducted in the north-west coast of Sarawak to examine the outcrops along Bintulu- Niah- Miri areas which cover southern part of Balingian Province and Baram Delta Province. The aim of this fieldwork is to synthesize the observations of structure and sedimentology of outcrops along Bintulu-Niah-Miri areas and discuss the implication of reservoir characteristics based on observation. The study was conducted by sketching the main structural elements of outcrops followed by detailed sedimentological analysis which include observation and facies description were conducted on different outcrops along Bintulu-Niah- Miri areas using sedimentary logs. The findings show that Bintulu- Niah- Miri areas outcrops consists of mixed-environment deposited succession with tidal and wave characteristic. This resulted in reservoir architect will be different and result in different in reservoir properties included horizontal and vertical permeability of fluids. Niah Cave is a good place to study the distribution of the types of breccia due to collapsed paleokarst at reservoir scale and also good analog for Central Luconia Platform where large resources of hydrocarbon have been discovered due to the its environment setting or forming process is same as Central Luconia Platform. In addition, Miri Airport Outcrop succession consist of Type 4- Fracture Create Flow Barriers which could lead to potential production problems.

KEYWORDS

Reservoir characteristics, sedimentology, depositional environment.

1. INTRODUCTION

Six-day fieldwork was conducted in the north-west coast of Sarawak to examine the outcrops along Bintulu- Niah- Miri areas from 15th to 20th February 2016 guided by Prof. Madya Ng Tham Fatt, Dr. Meor Hakif bin Amir Hassan and Dr. Ralph L. Kugler. This fieldwork will cover southern part of Balingian Province and Baram Delta Province. The objective of this fieldwork is to discuss the implication of reservoir characteristics based on synthesize the observations of structure and sedimentology of outcrops along Bintulu-Niah-Miri areas. The importance of this fieldwork is the surface outcrops in studied area can be used as analogue for subsurface reservoir studies of offshore hydrocarbon field especially in Balingian Province and Baram Delta Province. An understanding of the sedimentological characteristics and facies architecture of outcrops may allow us to understand production behavior of hydrocarbon and sweep efficiency in waterfloods to encounter the problems related to compartmentalization of reservoirs and other issues in field development planning.

2. REGIONAL BACKGROUND

This fieldwork will cover the southern part of Balingian Province and Baram Delta Province (Figure 1). The Balingian Province is part of peripheral foreland basin fill of Sarawak Basin which formed due to the closure of the Rajang Sea and the Sarawak Orogeny during the Late Eocene (Figure 2) [1]. The Nyalau Formation dominates the onshore geology of the southern part of the Balingian Province [1,2]. Some researchers identified common structural features in deforming foreland basins which indicate penecotemporaneous deformation in Nyalau Formation [3].

Figure 1: Geological Province map of Sarawak showing the study area within the southern part of Balingian Province and Baram Delta Province [4].

Figure 2: Illustration depicting the formation of Sarawak Basin by the subduction of Rajang Sea beneath Borneo [4].

The Balingian Province is a Tertiary basin that developed in Late Eocene times after orogenic uplift and folding of Cretaceous to Eocene sediment [1]. The Balingian Province consists of Tertiary succession of age ranging from Oligocene to Late Miocene (Figure 3). The Tertiary succession included the Tatau Formation, Buan Formation, Nyalau Formation, Setap Shale Formation and Liang Formation. The Nyalau Formation conformably overlies Oligocene Buan Formation Oligocene and Eocene Tatau Formation (Figure 3). However, the Nyalau Formation is unconformably overlain by Pleistocene-Holocene coastal deposits and alluvium in most of the area around Bintulu [5].

Figure 3: Stratigraphic framework for the onshore northwest coast of Sarawak represent the cycle and age of Nyalau Formation [5].

Nyalau Formation is characterized by alternating heterolithic beds, cross-bedded sandstones and coal-bearing mudstones [6]. Based on foraminifera, Nyalau Formation gives age from Early Oligocene (Rupelian) to the Early Miocene (Burdigalian) [6]. Detailed sedimentological study of upper Nyalau Formation aged Early Miocene indicates Nyalau Formation consists wave-, tide- and fluvial-influenced coastal deposits [5]. Nyalau Formation contains effective source rock whereby shales from Nyalau Formation was interpreted as gas-prone while the coal and carbargilite sediment from Nyalau Formation have the potential to generate oil [7].

The Baram Delta Province is a Tertiary basin that developed in Late Eocene times after orogenic uplift and folding of Cretaceous to Eocene sediment [1]. The Baram Delta Province consists of Tertiary succession of age range from Oligocene to Late Miocene (Figure 4). The Tertiary succession included the Setap shale, Lambir Formation, Miri Formation, Tukau Formation, Seria Formation and Liang Formation. The Miri Formation is interfingering with the Lambir Formation and Tukau Formation [1].

Figure 4: Stratigraphic framework for the onshore northwest Sarawak represents the units of Miri Formation [8].

The sedimentary rocks of the Miri Formation belong to the age range in between Middle Miocene and Late Miocene (13-9 Ma) [9]. Miri Formation was divided into Lower Unit and Upper Unit based on lithology and benthonic foraminifera assemblage [6,10]. Lower Miri Formation unit consists of interbedded shale and sandstone overlying the Setap Shale Formation while Upper Miri Formation which is characterised by irregular sandstone-shale alternations, and more arenaceous laterally [6]. The deposition environment of Miri Formation was interpreted as in a littoral to inner neritic shallow marine environment [6].

The age of Lambir Formation ranges from the late Middle to Late Miocene (14-10 Ma) [9]. The Lambir Formation is characterized by alternating sandstone and shale with some limestone and marl in certain location [6].

3. METHODOLOGY

The main structural elements of outcrops are sketched followed by detailed sedimentological analysis which include observation and facies description were conducted on different outcrops along Bintulu-Niah-Miri areas using sedimentary logs. Based on lithology, textures, sedimentary structures, geometry, bioturbation and trace fossil content, the formations are divided into different types of facies followed by facies association before depositional environment was deduced. Lastly, the implication of reservoir characteristics will be discussed based on overview of structure and sedimentology of outcrops along Bintulu-Niah-Miri areas.

4. BINTULU (LIANG FORMATION & NYALAU FORMATION)

Generally, the succession of Airport Road Stop (1) Outcrops (Figure 5) contains high net-to-gross or sand rich. The succession is fining-upward in grain size, from very fine to medium-grained accompanied by decreasing in the size of the preserved bedding. Strike of bedding is ranging from 10°-21° and dip reading 10°-15° toward South-East. The facies can be observed from the outcrop below unconformity included Facies NF2: Low angle cross-stratified sandstone; Facies NF3: Lenticular bedded heterolithic sandstone; Facies NF8: Wavy and flaser stratified heterolithic sandstone and Facies NF5: Trough cross stratified sandstone with channel-like geometry. The top section is characterized by dark grey, structureless mudstone facies and a coal layer on top.

Figure 5: View of Airport Road Stop (1) Outcrops.

Generally, the succession of Rangsi Hill Outcrops (Figure 6) consists of thick sandstone with poorly sorted mixture of sand, mud and rock fragments or conglomerates inclusion range from different size (cm - dm) (alluvial deposit) overlie on tilted thinly interbedded (4 cm-11 cm) sandstone and shale succession which separated by an angular unconformity. The angular unconformity could be due to Sarawak Orogeny which related to the closure of the Rajang Sea during the Late Eocene [2,6]. Strike of bedding below the angular unconformity is ranging from 120°-170° and dip reading 60°-79° toward South - West. The underlain tilted interbedded sandstone and shale succession could have formed due to tectonic event (Sarawak Orogeny) followed by erosion and deposition of thick sandstone with poorly sorted conglomerate inclusion. The underlain sandstone bed consists of fine grained sandstone with sand content of 60%. The younging direction is toward North West based on evidence of flute clast below the sandstone beds. The facies can be examined from the lower section of outcrop included fine-grained boudinaged sandstone facies and structureless mudstone facies. However, the sedimentary structure of the thin sandstone bed could not be determined due to high degree of weathering.

Figure 6: View of Rangai Hill.

Strike of beddings at Sungai Mas Camp Outcrop (Figure 7) are ranging from 295° - 327° and dip reading 24° - 32° toward North-East. The facies can be observed from the outcrop included Facies NF1: Hummocky cross-stratified sandstone; Facies NF2: Low angle cross-stratified sandstone; Facies NF3: Lenticular bedded heterolithic sandstone; Facies NF4: Coal bed; Facies NF5: Structureless mudstone; Facies NF6: Trough cross-bedded sandstone showing bundling; Facies NF7: Herringbone cross stratification sandstone; Facies NF8: Wavy and flaser stratified heterolithic sandstone; Facies NF9: Trough cross stratified sandstone; Facies NF10: Sigmoidal cross stratification sandstone and Facies NF11: Bioturbated mudstone. (*Detail Facies and Facies Association of Sungai Mas Camp Outcrop will be discussed in section 5.0.)

Figure 7: View of Sungai Mas Camp Outcrop.

Strike of beddings at Meteorology Department Outcrop (Figure 8) are ranging from 270° - 278° and dip reading 20° - 28° toward North. The facies can be observed from the outcrop included Facies NF1: Hummocky cross-stratified sandstone; Facies NF2: Low angle cross-stratified sandstone; Facies NF3: Lenticular bedded heterolithic sandstone; Facies NF4: Coal

bed; Facies NF5: Structureless mudstone; Facies NF8: Wavy and flaser stratified heterolithic sandstone and Facies NF9: Trough cross stratified sandstone. (*Detail Facies and Facies Association of Meteorology Outcrop will be discussed in section 5.0.)

Figure 8: View of Meteorology Department Outcrop.

Strike of beddings at Simlanjau Outcrop (Figure 9) are ranging from 70° - 73° and dip reading 8° - 9° toward South-East. According to Dr Meor, the top of succession of this outcrop is Pleistocene-Holocene (20, 000 year old) deposits followed by Liang Formation (about 1 million year old) and Nyalau Formation (20 million year old). Pleistocene-Holocene deposit is characterized by white colour, fine-grained, bioturbated sandstone with rootlets facies and medium-grained, bioturbated sandstone with herringbone facies and medium-grained sandstone with trough cross bedding facies. Liang Formation is characterized by dark grey, structureless mudstone facies and a coal layer on top. The facies of Nyalau Formation can be observed from the outcrop included Facies NF2: Low angle cross-stratified sandstone and Facies NF9: Trough cross stratified sandstone. This succession can be correlate with succession of Airport Road Stop (1) Outcrops.

Figure 9: View of Simlanjau Outcrop.

4.1 Niah Cave (Subis Limestone)

Based on the geometry and exposed inclined bedding layer at left side of the Niah Mountain due to cementation at an early stage of marine burial diagenesis (Figure 10), Niah Mountain could have made up of limestone as an isolated carbonate platform which known as the Subis Limestone. The Subis Limestone carbonate platform is built up from antecedent surface (seabed), as corals and other framework-building organisms were growing upward, keeping up with rising sea level from transgressive tract until highstand system tract. The current Niah Mountain (Subis Limestone) is subaerial exposed and in lowstand systems tract (Figure 11) and resulted in formation of karst feature by weathering processes.

Figure 10: View of isolated carbonate platform which known as the Subis Limestone. Niah Cave is part of Subis Limestone

Figure 11: Model for an Isolated Carbonate

In addition, Subis Limestone could have undergone terrestrial processes including erosion and fluvial deposition. The evidence for fluvial processes included transported breccia and sediment due to paleoriver as well as eroded feature can be seen in Niah Cave (Figure 13) supported by flowing river across limestone can be seen along the way toward Niah Cave (Figure 14).

Niah Cave is part of Subis Limestone with geometry of laterally extensive (Figure 10) but vertically restricted. The cave systems are separated by unaltered thick host limestones. The laterally extensive nature of the paleo-caves is characteristic of phreatic environments [11]. Based on Caribbean Karst Model, Niah Cave could be Phreatic Caves formed at ancient water table or in between vadose and phreatic which is right above of ancient old meteoric lens (Figure 12) and now in Vadose Zone. This idea is supported by presence of chaotic breakdown breccia on the floor of cave (Figure 13); ceiling crackle breccia on roof resulted in breakout dome; presence of stalactite feature which formed due to precipitation of dissolute calcium carbonate via the fracture (proven by water dropping from top of cave).

Figure 12: Caribbean Karst Model [11].

Figure 13: Niah Cave presence of chaotic breakdown breccia on the floor of cave; ceiling crackle breccia on roof resulted in breakout dome (Top photo) and presence of stalactite feature which formed due to precipitation of dissolute calcium carbonate via the fracture (down photo).

Figure 14: Flowing river across limestone

4.2 Miri (Lambir Formation & Miri Formation)

Generally, the succession of Bukit Song Outcrops contains high net-to-gross or sand rich. The succession consists of mainly thin bedded sandstone with thickening-upward in the size of the preserved bedding. Strike of bedding is ranging from 75°-80° and dip reading 15° -20° toward South-East.

Five lithofacies have been determined from the Bukit Song Outcrop based on lithology, sedimentary structures, bioturbation, fossil traces content and bed geometry. These five major lithofacies included: Facies LF1: Heterolithic sandstone; Facies LF2: Low angle cross-stratified sandstone; Facies LF3: Trough cross-bedded sandstone; Facies LF4: Structureless sandstone with coal clast shell fragments and Facies LF5: Bioturbated mudstone.

4.2.1 Facies LF1: Heterolithic sandstone

Facies LF1 is characterized by yellowish to light grey, moderately sorted, very fine grained with heterolithic sandstones. Wavy and flaser stratification can be observed in this facies. Soft sediment deformation can be observed in heterolithic sandstone. The sandstone is sparsely bioturbated. The thickness of sandstone bed range from 3 cm to 9 cm.

4.2.2 Facies LF2: Low angle cross-stratified sandstone

Facies LF2 is characterized by light yellow, well-moderate sorted, very fine to fine grained with low angle cross-stratified sandstones. Parallel carbonaceous lamination can be observed in this facies. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha) can be observed throughout the facies. The thickness of sandstone bed range from 0.10 m to 0.70 m.

4.2.3 Facies LF3: Trough cross-bedded sandstone

Facies LF3 is characterized by light yellow, moderate sorted, fine grained

with trough cross-bedded sandstones. Mud drape can be observed in this facies. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha) can be observed throughout the facies. The thickness of sandstone bed range from 0.10 m to 0.30 m with channel-like geometry.

4.2.4 Facies LF4: Structureless sandstone with coal clast shell fragments

Facies LF4 is characterized by light grey, well to moderate sorted, medium grained sandstones with coal clast and shell fragments. The size of coal clasts range from 0.2cm to 6.0 cm while the white colour shell fragments is about 1mm. The sandstone is absent to sparsely bioturbated. The thickness of sandstone bed is about 0.3 m.

4.2.5 Facies LF5: Bioturbated mudstone

Facies LF5 is characterized by dark grey bioturbated mudstone. The mudstone is moderate to commonly bioturbated. The trace fossil can be observed throughout the facies. The thickness of mudstone bed range from 0.10 m to 0.70 m.

Generally, Miri Formation (Figure 15) has very high net to gross. Five lithofacies have been determined from the outcrops of Miri Formation based on lithology, sedimentary structures, bioturbation, fossil traces content and bed geometry. These five major lithofacies included: Facies MFA: Herringbone cross stratification sandstone; Facies MFB: Hummocky-cross stratification sandstone; Facies MFC: Laminated sandstone; Facies MFD: Heterolithic sandstone and Facies MFE: Low angle cross-stratified sandstone. However, it can be noted that generally the lower part of Miri Airport Outcrop is characterised by sand body with tidal signal included Facies MFA: Herringbone cross stratification sandstone; Facies MFC: Laminated sandstone and Facies MFD: Heterolithic sandstone followed by upper part of Miri Airport Outcrop is characterized by sand body with wave signal included Facies MFB: Hummocky-cross stratification sandstone and Facies MFE: Low angle cross-stratified sandstone.

Figure 15: Overview of Miri Airport Road outcrop.

4.2.6 Facies MFA: Herringbone cross stratification sandstone

Facies MFA is characterized by light yellow to light grey, well sorted, very fine to fine grained with herringbone cross-stratified/ bipolar cross-stratified sandstones. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha) can be observed throughout the facies. The thickness of sandstone bed range from 0.3m to 1.8m.

4.2.7 Facies MFB: Hummocky-cross stratification sandstone

Facies MFB is characterized by light grey, well sorted, very fine to fine grained with hummocky cross-stratified sandstones. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha) can be observed throughout the facies. The thickness of sandstone bed range from 0.1m to 1.1m.

4.2.8 Facies MFC: Laminated sandstone

Facies MFC is characterized by yellowish to light grey, well sorted, very fine to fine grained with laminated sandstones. Parallel carbonaceous lamination can be observed in this facies. The sandstone is sparsely bioturbated. The thickness of sandstone bed range from 0.4m to 0.8m.

4.2.9 Facies MFD: Heterolithic sandstone

Facies MFD is characterized by yellowish to light grey, moderately sorted, very fine grained with heterolithic sandstones. Wavy stratification can be observed in this facies. The sandstone is sparsely bioturbated. The thickness of sandstone bed range from 4 cm to 8 cm.

4.2.10 Facies MFE: Low angle cross-stratified sandstone

Facies MFA is characterized by light yellow, well sorted, very fine to fine grained with low angle cross-stratified sandstones. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha) can be observed throughout the facies. The thickness of sandstone bed range from 0.3 m to 1.2 m.

Numerous normal faults can be observed at Airport Road Anticline outcrop. The density of fault more concentrated at the crest of the anticline structure. Listric normal fault F1 with strike of 225° and dip of 56° towards North-West with fault throw of 0.55 m. Normal fault F2 with strike of 46° and dip of 61° towards South-East with fault throw of 0.31 m. Normal fault F3 with strike of 48° and dip of 66° towards South-East with fault throw of 0.35 m. Normal fault F4 with strike of 228° and dip of 70° towards North-West with fault throw of 0.33 m. The normal fault zone is characterized by a few structural features included drag feature; fault-bounded lens shaped structure; telescoping on parallel strands; deformation band and fault gouge. In addition, juxtaposition associated with the normal fault can be observed in this outcrop.

Fault- bounded lens shaped structure can be observed at the outcrop, the size of lens can range from meter to centimeter. There is an increase in dip of lamination inside lens compared to dip of lamination outside the lens. However, the dip of lamination at the lens tip is significantly higher than dip of lamination at the center of lens. The deformation band density inside the lens is higher compare to outside.

Furthermore, there is an increase in number of deformation bands towards the fault plane. The spacing of deformation bands is narrow (mm) as getting near the fault plane while spacing of deformation bands is wider as away from fault plane (cm). Deformation band in fault zone could reduce the permeability of sandstone [9].

Telescoping along parallel strands were common at the normal fault zone in Airport Road Anticline outcrop. Telescoping along parallel strands were contribute to formation of thick clay between sand beds and not as thick clay gouge.

Systematic joint perpendicular to sandstone bedding can be observed at Miri Airport Road outcrop. The length of joint is around 0.5m with spacing ranging from 3cm to 25cm. Strike is ranging from 248°-251° and dipping toward North-West.

5. SEDIMENTOLOGY AND IMPLICATION FOR RESERVOIR CHARACTERISTIC

5.1 Sedimentary facies characteristics of Bintulu Outcrops (Nyalau Formation)

11 lithofacies have been determined from the Bintulu Outcrops (Nyalau Formation) based on lithology, sedimentary structures, bioturbation, fossil traces content and bed geometry. These 11 major lithofacies included: Facies NF1: Hummocky cross-stratified sandstone; Facies NF2: Low angle cross-stratified sandstone; Facies NF3: Lenticular bedded heterolithic sandstone; Facies NF4: Coal bed; Facies NF5: Structureless mudstone; Facies NF6: Trough cross-bedded sandstone showing bundling; Facies NF7: Herringbone cross stratification sandstone; Facies NF8: Wavy and flaser stratified heterolithic sandstone; Facies NF9: Trough cross stratified sandstone; Facies NF10: Sigmoidal cross stratification sandstone and Facies NF11: Bioturbated mudstone.

5.1.1 Facies NF1: Hummocky cross-stratified sandstone

Facies NF1 is characterized by light yellow, well - sorted, very fine to fine grained with hummocky cross stratified sandstones. Parallel carbonaceous lamination and mud clast can be observed in this facies. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha, Skolithos) can be observed throughout the facies. The thickness of sandstone bed range from 0.20 m to 0.70 m.

5.1.2 Facies NF2: Low angle cross-stratified sandstone

Facies NF2 is characterized by light yellow, well sorted, very fine to fine grained with low angle cross-stratified sandstones. Parallel lamination can be observed in this facies. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha) can be observed throughout the facies. The thickness of sandstone bed range from 0.20 m to 2.70 m.

5.1.3 Facies NF3: Lenticular bedded heterolithic sandstone

Facies NF3 is characterized by yellowish, moderately sorted, very fine grained with heterolithic sandstones. The sand content of this facies is about 20% - 30%. Lenticular bedding and rhythmic lamination can be observed in this facies. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha, Skolithos) can be observed throughout the facies. The thickness of sandstone bed range from 3 cm to 9 cm.

5.1.4 Facies NF4: Coal bed

Facies NF4 is characterized by black coal bed. The coal bed is non bioturbated. The thickness of coal bed is about 25cm.

5.1.5 Facies NF5: Structureless mudstone

Facies NF5 is characterized by dark grey structureless mudstone. The mudstone is sparsely bioturbated. Occasionally, rootlets and organic debris laminae can be observed throughout the facies. The thickness of mudstone bed range from 0.17 m to 2.1 m.

5.1.6 Facies NF6: Trough cross-bedded sandstone showing bundling

Facies NF6 is characterized by light yellow, well-moderate sorted, fine grained with trough cross-bedded sandstones showing bundling. Mud drape and tidal bundles can be observed in this facies. Alternating packages of thick bundles (Spring) and thin bundles (Neap) can be observed in this facies. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha) can be observed throughout the facies. The thickness of sandstone bed range from 0.10 m to 0.70 m.

5.1.7 Facies NF7: Herringbone cross stratification sandstone

Facies NF7 is characterized by light yellow to light grey, well sorted, fine grained with herringbone cross-stratified/ bipolar cross-stratified sandstones. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha) can be observed throughout the facies. The thickness of sandstone bed range from 0.20cm - 0.80 cm.

5.1.8 Facies NF8: Wavy and flaser stratified heterolithic sandstone

Facies NF8 is characterized by yellowish to light grey, moderately sorted, very fine grained with heterolithic sandstones. Wavy and flaser stratification can be observed in this facies. The sandstone is sparsely bioturbated. The thickness of sandstone bed range from 0.3 m to 1.4 m.

5.1.9 Facies NF9: Trough cross stratified sandstone

Facies NF9 is characterized by light yellow, well to moderate sorted, fine grained with trough cross stratified sandstones. The sand and mud content of this facies is about 90% and 10% respectively. Mud drape can be observed in this facies. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha) can be observed throughout the facies. The thickness of sandstone bed range from 0.10 m to 4.0 m with channel-like geometry.

5.1.10 Facies NF10: Sigmoidal cross stratification sandstone

Facies NF10 is characterized by light yellow to light grey, well sorted, fine grained with sigmoidal cross-stratified sandstones. Mud drape and tidal bundles can be observed in this facies. The sandstone is sparsely to moderately bioturbated. The trace fossil (Ophiomorpha) can be observed throughout the facies. The thickness of sandstone bed range from 0.20cm - 0.60 cm

5.1.11 Facies NF11: Bioturbated mudstone

Facies NF11 is characterized by grey structureless mudstone. The mudstone is moderate to commonly bioturbated. Trace fossil can be observed throughout the facies. The thickness of mudstone bed range from 0.20 m to 2.1 m.

5.2 Facies Association of Bintulu Outcrops (Nyalau Formation)

Six facies association have been determined from the Sungai Mas Camp outcrop. These six facies association included Facies Association NF1: Shoreface; Facies Association NF2: Muddy Tidal Flats; Facies Association; NF5: Offshore; Facies Association NF3: Tidal Channel Facies Association NF6: Point Bar and Facies Association NF4: Tidally Reworked Bars and Dunes (Figure 16). The succession is interpreted as shoreface and offshore succession overlain by tidal bar and tidal channel successions (Figure 16).

Figure 16: Sedimentary log showing facies and facies association of Sungai Mas Outcrop

Three facies association have been determined from the Meteorology Department outcrop. These three facies association included Facies Association NF1: Shoreface; Facies Association NF2: Muddy Tidal Flats and Facies Association NF3: Tidal Channel (Figure 17). The succession is interpreted as shoreface succession overlain by muddy tidal flat and tidal channel successions (Figure 17).

Figure 17: Sedimentary log showing facies and facies association of Meteorology Department Outcrop.

5.2.1 Facies Association NF1: Shoreface

Facies Association NF1 is characterized by very fine to fine-grained, well-sorted sandstones with low angle cross-stratification (Facies NF2) and hummocky cross-stratification (Facies NF1) which can be isolated or amalgamated. The sandstones are sharp-based with coarsening-upward packages. The sandstone is sparsely bioturbated. The trace fossil (Ophiomorpha, Skolithos) can be observed throughout the facies. Interpretation:

A researcher suggested that hummocky cross-stratification is commonly confined to shallow marine sedimentary rock formed by relatively large storm waves in the ocean [12]. Other researcher also stated hummocky cross-stratification and low angle cross-stratification are recognized as influence of waves [13]. Hence, Facies Association NF1 has been interpreted as wave-dominated shoreface deposits based on its stratigraphic position and relation with other facies associations.

5.2.2 Facies Association NF2: Muddy Tidal Flats

Facies Association NF2 is characterized by coal bed (Facies NF4), structureless mudstone (Facies NF5) with rootlets and plant fragments, small-scale channelled unit of trough cross stratified sandstone (Facies NF9) and lenticular bedded heterolithic sandstone (Facies NF3). Interpretation:

Mudstone with plant fragments and roots in place which reworked by pedogenic processes are interpreted as the uppermost of tidal mud flats [14]. Lenticular bedding (Facies NF3) with marine trace fossils typically indicates deposition from reversing tidal current [15]. The small-scale channelled sandstone trough cross stratified sandstone (Facies NF9) indicate depositional in tidal gullies that crossed the tidal flats [16]. Hence, Facies Association NF2 has been interpreted as muddy tidal flats deposits based on its stratigraphic position and relation with other facies associations.

5.2.3 Facies Association NF3: Tidal Channel

Facies Association NF3 is characterized by wavy and flaser stratified heterolithic sandstone (Facies NF8), trough cross-bedded sandstone showing bundling (Facies NF6), herringbone cross-stratified/ bipolar cross-stratified sandstones (Facies NF7), lenticular bedded heterolithic sandstone (Facies NF3) with channel-like bed geometry and trough cross stratified sandstone (Facies NF9) which are amalgamated with channel-like bed geometry. The fining-upward packages association has basal erosion and mud drapes are ubiquitous through the Facies Association NF3.

Interpretation:

The channel-shape, ubiquitous mud drapes and marine/ brackish trace fossils suggest deposition in tidal channel [14]. Mud / organic debris drapes and herringbone cross-stratified/ bipolar cross-stratified sandstones indicate strong tidal influence. Hence, Facies Association NF2 has been interpreted as tidal channel deposits based on its stratigraphic position and relation with other facies associations.

5.2.4 Facies Association NF4: Tidally Reworked Bars and Dunes

Facies Association NF4 is characterized by wavy and flaser stratified heterolithic (Facies NF8); sigmoidal cross stratification sandstone (Facies NF10) and Trough cross stratified sandstone (Facies NF9). They are well to moderate sorted. The sandstone is sparsely to moderate bioturbated. The trace fossil (Ophiomorpha) can be observed throughout the facies. The succession is coarsening-upward in grain size from fine to medium-grained accompanied by an increase in the size of the preserved bedding. The lower part of sand body consists of heterolithic wavy laminae while the upper part of sand body consists of heterolithic flaser laminae followed by trough cross stratified sandstone (two-dimensional dune). The sand body are characterized by thick inclined heterolithic bed (~3m) which can be traced up to 60m.

Interpretation:

The facies association is interpreted as tidal reworking of sand bars. Larger dunes climbing over smaller dunes produced thickening and upward coarsening patterns during the reworking process. Features observed in sand bodies indicate tidal influence included sigmoidal cross-stratification and mud drapes and tidal bundles [14]. Moderate to well sorted, with sub-angular grains, sigmoidal cross-stratified, coarsening upwards sand with degree of bioturbation of moderate and dominated by Dactyloidites ottoii, although Ophiomorpha, Planolites are also present are

interpreted as tidally reworked bars and dunes [13]. Although a group researchers suggested upward-coarsening facies model for features in the Ager Basin (Eocene), northern Spain which interpreted to be a "tidal bar", others explained this feature should be caused by deposit of a compound dune [17,18]. Hence, based on its stratigraphic position and relation with other facies associations, Facies Association NF4 has been interpreted as tidally reworked bars and dunes.

5.2.5 Facies Association NF5: Offshore

Facies Association NF5 is characterized by bioturbated muddy deposits (Facies NF11), very fine to fine-grained, well-sorted sandstones with low angle cross-stratification (Facies NF2) and lenticular bedded heterolithic sandstone (Facies NF3). The degree of bioturbation is moderate to common. Facies Association NF5 gradually coarsening upwards as the mud content decrease and transition into Facies Association NF1 (shoreface) deposits.

Interpretation:

Rossi & Steel stated offshore or offshore transition is characterised by abundance of trace fossil, abundance of fine-grained, heterolithic deposits and marine mudstone [13]. Hence, Facies Association NF5 has been interpreted as offshore deposits based on its stratigraphic position and relation with other facies associations.

5.2.6 Facies Association NF6: Point Bar

Facies Association NF6 is characterized by concave upward channel profiles with lenticular bedded heterolithic sandstone (Facies NF3)

commonly forming inclined stratification (IHS) and coal bed (Facies NF4). Interpretation:

The inclined heterolithic strata are interpreted as lateral accretion deposits on tidal point bar surface and in high-sinuosity tidal channel [14]. Coal layer marks abandonment of channels [14].

6. IMPLICATION FOR RESERVOIR CHARACTERISTIC

6.1 Deposition Environment

Correct interpretation of depositional environment plays an important role in estimating the geometry of sand body as different sedimentological processes could have different impact on the reservoir architecture and affect the heterogeneity on fluid flow within the hydrocarbon reservoir. Recognition of the mixed-energy character of depositional system is crucial for reservoir characterization which would have impact on reservoir modelling and characterization [13].

In general, Bintulu areas outcrops consists of mixed-environment deposited succession with tidal and wave characteristic. Tide-influenced and wave-influenced deposits are better sorted than fluvial-dominated deposits [13]. Hence, this could indicate that the successions have good reservoir properties in general.

6.1.1 Case 1: Meteorology Department Outcrop

The Meteorology Department outcrop succession is interpreted as shoreface (FA: NF1) succession overlain by muddy tidal flat (FA: NF2) and tidal channel (FA: NF3) (Figure 18).

Figure 18: The Meteorology Department outcrop succession is interpreted as shoreface (FA: NF1) succession overlain by muddy tidal flat (FA: NF2) and tidal channel (FA: NF3)

From bottom, shoreface (FA: NF1) sand body could be a good reservoir which characterized by thick (>18m) and laterally extensive sheets. This reservoir is expected to have good horizontal flow properties and vertical flow between beds in this case. However, the Shoreface (FA: NF1) sand body is overlain or separated by mudstone horizon of muddy tidal flat deposit (FA: NF2) which is poor in both permeability and porosity. This characteristic of muddy tidal flat deposit (FA: NF2) mudstone horizon allows the shoreface (FA: NF1) sand body (which could be reservoir) be sealed to prevent migration of hydrocarbon.

Within the muddy tidal flat deposit (FA: NF2) mudstone horizon, there is an isolated channel-like sand body enclosed by mud and a coal layer bed, followed by depositions of tidal channel deposits (FA: NF3) in between muddy tidal flat deposit (FA: NF2) mudstone horizon. Coal bed could be important for seismic data as a key horizon marker for stratigraphic correlation. The isolated sand body and channel-like tidal channel deposits (FA: NF3) sand body enclosed within muddy tidal flat (NF2)

deposited mud horizon could lead to overpressure which may resulted in drilling problem such as blowouts. However, tidal channel deposits (FA: NF3) channel-like sand body is still could be good reservoir with geometry of sand body perpendicular to shoreline and laterally thinning away from channel axis. This reservoir is expected to have good horizontal flow properties but limited vertical flow between beds due to individual channel was separated by muddy tidal flat deposit (FA: NF2) mudstone horizon. In addition, wavy-bedded mudstone layer and mud-draped surfaces within tidal channel deposits (FA: NF3) channel-like sand body could be barriers baffles or barriers to fluid flow within the reservoir.

6.1.2 Case 2: Sungai Mas Camp Outcrop

The Sungai Mas Camp outcrop succession is interpreted as shoreface (FA: NF1) and offshore (FA: NF5) succession overlain by muddy tidal flat (FA: NF2), tidally reworked bars and dunes (NF4) and tidal channel (FA: NF3) (Figure 19,20).

Sungai Mas Camp Outcrop

Figure 19: The Sungai Mas Camp outcrop succession is interpreted as shoreface (FA: NF1) and offshore (FA: NF5) succession overlain by muddy tidal flat (FA: NF2), tidally reworked bars and dunes (NF4) and tidal channel (FA: NF3).

Sungai Mas Camp Outcrop

Figure 20: The Sungai Mas Camp outcrop succession is interpreted as shoreface (FA: NF1) and offshore (FA: NF5) succession overlain by muddy tidal flat (FA: NF2), tidally reworked bars and dunes (NF4) and tidal channel (FA: NF3).

From bottom, shoreface (FA: NF1) sand body could be a good reservoir which characterized by and laterally extensive sheets. This reservoir is expected to have good horizontal flow properties and vertical flow within shoreface (FA: NF1) sand body in this case. However, the shoreface (FA: NF1) sand body is overlain or separated by mudstone horizon of offshore (FA: NF5) deposited mudstone horizon which is poor in both permeability and porosity. This characteristic of offshore (FA: NF5) deposited mudstone horizon allows the shoreface (FA: NF1) sand body (which could be reservoir) be sealed to prevent migration of hydrocarbon.

At the depth of 20m of the logged outcrop, which is right above the offshore (FA: NF5) deposited mudstone horizon, shoreface (FA: NF1) sand

body is overlain by tidal channel (FA: NF3) deposited mud horizon. As mentioned above shoreface (FA: NF1) could be a good reservoir for hydrocarbon and sealed by mud horizon and coal within tidal channel (FA: NF3). Coal bed could be important for seismic data as a key horizon marker for stratigraphic correlation. In addition, it is noted that tidal channel (FA: NF3) in this outcrop section contain thin-bedded sandstone which could be the reservoir which always been overlook by geologist as they are below logs and seismic resolution.

At the depth of 36 m of the logged outcrop, tidally reworked bars and dunes (NF4) sand body is underlain by shoreface (FA: NF1) sand body followed by muddy tidal flat deposit (FA: NF2) mudstone horizon. Tidally reworked bars and dunes (NF4) sand body and shoreface (FA: NF1) sand body both could be a good reservoir. Tidally reworked bars and dunes (NF4) sand body are thin laterally away from channel axis and also thins away seaward. Numerous tidally reworked bars and dunes (NF4) sand body are coalesce to form broad parallel sand sheet in this outcrop. This reservoir is expected to have good horizontal flow properties and vertical flow within tidally reworked bars and dunes (NF4) sand body and also between tidally reworked bars and dunes (NF4) sand body and shoreface (FA: NF1) sand body. Muddy tidal flat deposit (FA: NF2) in this section could be seal of the below reservoir to prevent migration of hydrocarbon. However, the isolated sand body enclosed by muddy tidal flat (FA: NF2) deposited mud horizon could lead to overpressure which could cause drilling problem such as blowouts.

At the top section of outcrop is characterized by tidal channel deposits (FA: NF3) channel-like sand body which could be good reservoir with geometry of sand body perpendicular to shoreline and laterally thinning away from channel axis. This reservoir is expected to have good horizontal flow properties but limited vertical flow between beds as the individual channel could be separated by muddy tidal flat deposit (FA: NF2) mudstone horizon. In addition, mud-draped surfaces within tidal channel deposits (FA: NF3) channel-like sand body could be barriers baffles or barriers to fluid flow within the reservoir.

6.2 Karst Reservoirs

Loucks have described the how carbonate paleo-cave could become reservoir started from near-surface process (formation of phreatic cave; brecciation; localized fracturing; chemical precipitation; collapse of cave walls and ceiling) until it being buried into subsurface where breccia clasts are rebrecciated (Figure 21) [19]. Hence, Subis Limestone which is product of near-surface karst processes could be good carbonate reservoir even after buried at the subsurface of offshore.

Carbonate reservoir are known to be challenging due to their complex pore system make then difficult to characterize and develop efficiently. However, by understanding the forming process of the limestone unit could help in roughly predict the geometry of the pore system. Niah Cave provide the opportunity for us to observe the distribution of the types of breccia due to collapsed paleokarst at reservoir scale.

Figure 21: Diagram depicting the collapse of a cave during the passage from the phreatic zone to the vadose zone and further brecciation in the deep subsurface [19].

Furthermore, due to its environment setting or forming process is same as Central Luconia Platform, Niah Cave can be good analog for Central Luconia Platform where large resources of hydrocarbon have been discovered. Central Luconia is a gas-producing carbonate province offshore Sarawak formed by carbonate build-ups and influenced by terrestrial processes including erosion and fluvial deposition at exposed shelf during lowstands [20]. Terrestrial processes could lead to deposition of siliciclastic deposits which may act as thief bed migrating hydrocarbons away from carbonate reservoir [21].

6.3 Anticline structure, Faults, Joints and Beddings

Anticline structure could be good structural trap for hydrocarbon. However, it can be observed that the crest of Miri Airport Outcrop anticline structure consists of numerous of fold-related faults related strain which could lead to leakage (tertiary migration) of hydrocarbon or compartmentalization due to fault juxtapositions. Characteristics of fault play an important role in hydrocarbon basin analysis and design of field-scale development reservoirs as fault can be barrier and conduit for fluid flow. Deformation band in fault zone could reduce the permeability of sandstone [9].

Several flow paths of fluid can be expected at fault zone:

a) Fluid flow across fault

Cross-fault leakage connectivity allows fluid flow across fault and resulted in inter-reservoir fluid communication. However, juxtaposition fault may increase or decrease cross fault leakage connectivity [22]. Hence, juxtaposition fault could lead to reservoir compartmentalization [23].

b) Fluid flow along fault

Fault could act as a conduit which induces fluid flow or migration of hydrocarbon.

c) Leakage over spill point (Juxtaposition spill point/ gouge failure spill point/ filled to seal capacity)

At faulted trap, fluid might spill at spill point under several conditions as introduced' included juxtaposition spill point, gouge failure spill point or filled to seal capacity and lead to leakage or tertiary migration [24]. These spill points are known as "Cryptic" spill points which cannot be seen on seismic or reconstructed from the structural/stratigraphic framework of the trap.

In addition, beddings and joints within bedding across the sandstone bed is also important parameter for reservoir characterization or modelling. Thin beds (Bukit Song Outcrop) and joints (Miri Outcrops) could be overlook in seismic section due to resolution. High net-to-gross (Bukit Song Outcrop) thin-bedded succession could be good reservoir which always overlook from logs and seismic. In addition, joints can act as conduit which enhance the hydrocarbon or fluid flow from reservoir. Furthermore, joints patterns and orientation measured from the outcrop could be crucial information in design of well direction. The reservoir should be drilled perpendicular to the joint to get the maximum hydrocarbon from the reservoir bed (sandstone). It is a good idea to plan a borehole trajectory with bedding orientation in mind, because, even in complex structures, fractures tend to be perpendicular to bedding [25].

Generally, Miri Airport Outcrop succession consist of Type 4 Fractured Reservoir Type - Fracture Create Flow Barriers. Type 4 Fractured Reservoir Type could lead to potential production problems included reservoir commonly highly compartmentalized; wells underperform compared to matrix capabilities; recovery factor highly variable across field and permeability anisotropy opposite to other adjacent fractured reservoirs of other fracture types [26].

7. CONCLUSIONS

Bintulu- Niah- Miri areas outcrops consists of mixed-environment deposited succession with tidal and wave characteristic. This resulted in reservoir architect will be different and result in different in reservoir properties included horizontal and vertical permeability of fluids. Niah Cave is a good place to study the distribution of the types of breccia due to collapsed paleokarst at reservoir scale and also good analog for Central Luconia Platform where large resources of hydrocarbon have been discovered due to its environment setting or forming process is same as Central Luconia Platform. Miri Airport Outcrop succession consist of Type 4- Fracture Create Flow Barriers which could lead to potential production problems included reservoir commonly highly

compartmentalized; wells underperform compared to matrix capabilities; recovery factor highly variable across field and permeability anisotropy opposite to other adjacent fractured reservoirs of other fracture types.

ACKNOWLEDGEMENT

I would like to thank Prof. Madya Ng Tham Fatt, Dr. Meor Hakif bin Amir Hassan and Dr. Ralph L. Kugler. for their guidance during the fieldtrip.

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