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Depositional controls on petrophysical properties and reservoir characteristics of Middle Miocene Miri Formation sandstones, Sarawak

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Abstract: Rock exposures around the town of Miri, Sarawak, belonging to the Miri Formation (Middle Miocene strata), represent the uplifted part of the subsurface sedimentary strata of the Miri oilfield. Data derived from outcrop studies concerning facies and sand body characteristics, and petrophysical properties are crucial for subsurface reservoir characterization and modeling of hydrocarbon reservoirs deposited in similar settings. The aim of this paper is to integrate lithofacies and petrophysical properties of Miri sandstones, in order to characterize and quantify the Miri reservoirs.

The Miri Formation consists of a wide range of siliciclastic, tide-generated and storm-and wave- generated facies. Twelve lithofacies have been identified and grouped into two major facies associations: (i) the estuarine, tide-dominated, and (ii) the shoreface-offshore transition, storm-and wave-dominated facies associations. The estuarine lithofacies are characterized by distinct and diagnostic tidal signatures; tidal dune cross-bedding with mud draped cosets and foresets including mud couplets, bidirectional (herringbone) cross-bedding, rhythmic stratifications, flaser bedding, wave bedding and lenticular bedding. Shoreface-offshore transition, storm-and-wave facies association is represented by sandstone bodies with evidences of storm and wave generated sedimentary structures; swaley cross-stratified sandstones, amalgamated hummocky cross-stratified sandstones, bioturbated sandstones and mudstone inter-bedding with parallel stratified to hummocky cross-stratified sandstone.

Petrophysical properties were determined for six sandstone lithofacies: (i) Lithofacies A (multiple stacked trough cross-bedded sandstone, tidal channels and bars, estuary mouth), (ii) Lithofacies B (parallel-bedded sandstone of estuary upper flow sand flat), (iii) Lithofacies F (homogeneous coarse sandstone, outer estuarine tempestites), (iv) Lithofacies G (swaley cross-stratified, upper-to-middle shoreface sandstone), (v) Lithofacies I (fine-grained bioturbated sandstone of the lower shoreface) and (vi) Lithofacies L (fine-grained, hummocky cross stratified sandstone, offshore transition).

These lithofacies are characterized by a wide range of permeability values, which vary by several orders of magnitude (0.35 to 287 md), while porosity vary by only a few percent. Lithofacies A and F recorded the best reservoir properties; porosities are 23.3-29.7% and permeabilities are 9.64-287 md. Lithofacies G shows a wide range of porosity and permeability values that range from high to low reservoir properties; porosities are 23.5-27.5% and permeabilities are 3.4-45 md. Lower shoreface and offshore transition (lithofacies I and L respectively) display the lowest reservoir properties; porosities are 13.5-24.5 % and permeabilities are 0.35-3.4 md. In general, high reservoir quality of Miri sandstones is associated with coarser grain size, low clay contain and better sorted grains. Extensive clay drapes, bioturbation, and increasing proportion of very fine grains content result in significant decrease in permeability in both tide-generated and wave-generated lithofacies.

1. Introduction

The Middle Miocene sandstones of the Miri Formation are important reservoir targets for petroleum explorations in northeastern Sarawak, east Malaysia (figure 1). The Miri field was first discovered in 1910 and had produced about 80 million barrels of oil before its abandonment in 1972 (Tan *et al.*, 1999). Miri Formation outcrops are regarded as useful analogue to the hydrocarbon-bearing reservoirs of Miri subsurface, and possibly also for the offshore fields (Abdul Hadi, 1995; Mazlan, 1999; Tan *et al.*, 1999). However, to date, no systematic study has been conducted to integrate petrophysical properties and different reservoir lithofacies of shallow marine reservoir rocks of the Miri Formation. With a renewed interest and the possibility of reopening the Miri field, there is a real need for more a quantitative work in characterizing and evaluating the reservoirs of the Miri formation.

2. Depositional lithofacies of Miri Formation

Twelve facies have been identified from the outcrops of the Miri formation based on lithology, sedimentary structures, fossil traces, bed geometry and thin section information. The sedimentary facies which are described below and summarized in table (1), can be grouped into two facies associations representing sedimentation in the major palaeoenvironments of the Middle Miocene Miri Formation. These facies associations are the estuarine, tide-dominated and the shoreface-offshore transition, storm-and wave-dominated facies associations.

2.1 Estuarine, tide-dominated facies associations

A group of facies with distinct and diagnostic tidal features is recognized within the Miri outcrops. The common tidal signatures observed within this facies group are tidal dune cross-bedding with mud draped cosets and forests including mud couplets, bidirectional (herringbone) cross-bedding, rhythmic

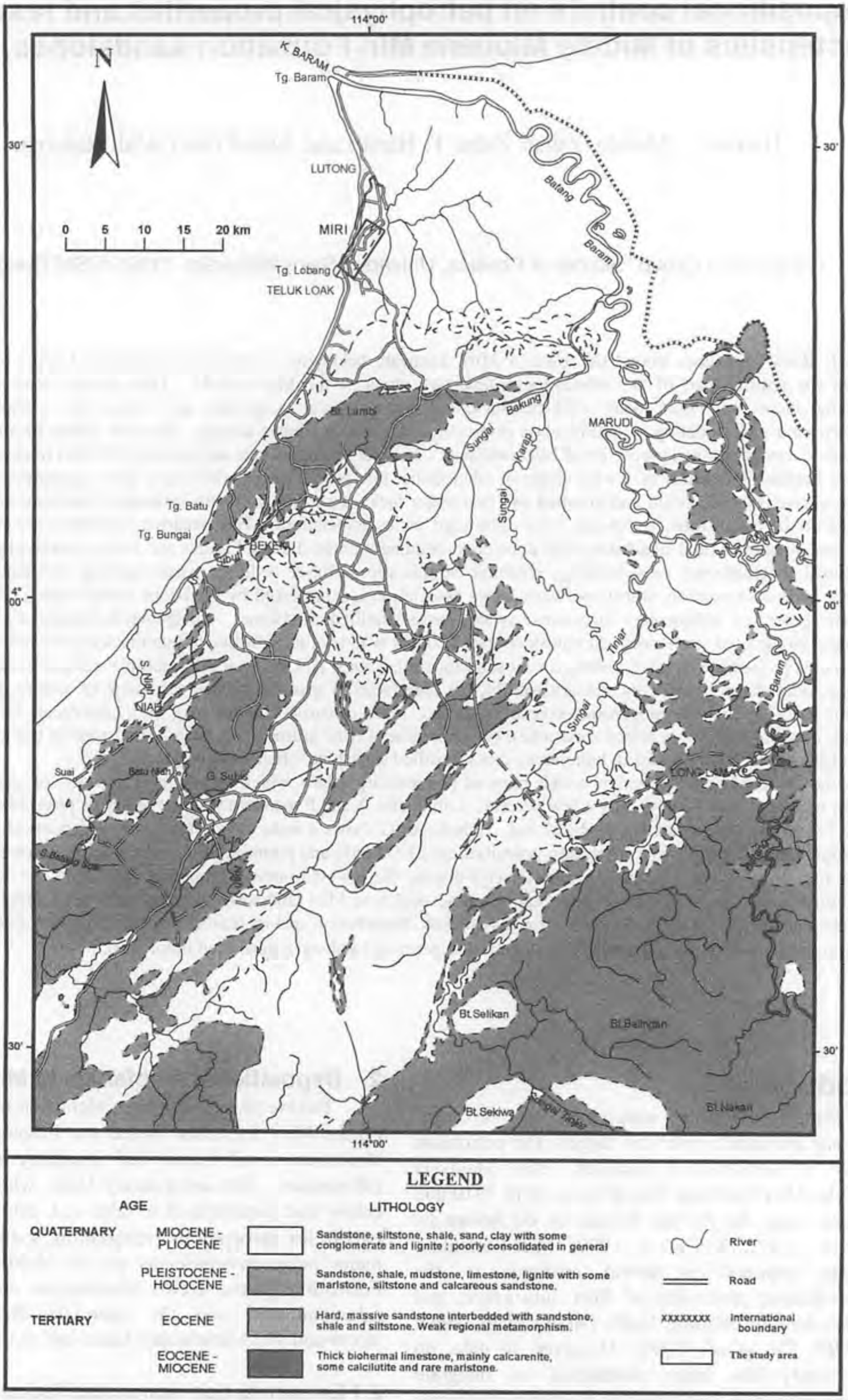


Figure 1.The location map of Miri area, showing the Middle Miocene Miri Formation and the study area

stratifications, flaser bedding, wave bedding and lenticular bedding. Generally, a tide-facies association thickness ranges from few tens of centimeters up to 3.5 m or more and displays fining upward, progradational, stacked tide-generated facies.

i. Facies A (trough cross-stratified sandstone with mud drapes)

This facies is composed of light reddish yellow, sublitharenite to quartzarenite, well to moderately well sorted, medium to fine grained sandstone. It is characterized by lenticular, tabular and wedge shaped sand bodies, dominated by trough cross-bedding. Sandstone bodies are separated by sub-horizontal to concave erosion and mud draped surfaces (table 1). Planar and herringbone cross-bedding is locally observed. Mud drapes, mud couplets, flaser mud bedding, mud clasts and horizontal mud laminas are common. Reactivation surfaces are locally present. Distribution of trace fossils is uneven throughout the sand; *Ophiomorpha* type is the most abundant type. Sand beds thicknesses range from 0.5 m up to 2.5 m, due to beds amalgamation, with a noticeable decrease in bed thicknesses upward. Bed thicknesses continue to exist consistently in lateral directions, up to tens of meters.

***Interpretation*:** Facies A records deposition under tidal influence as expressed by cross-stratification with mud drape, reactivation surfaces and flaser mud bedding. Trough cross-bedding are formed by large compound dunes, sand waves, migrating during high energy tidal current, with periods of slack water marked by mud drapes (Dalrymple, 1992). The presence of reactivation surfaces and herringbone cross-bedding suggests significant subordinate tidal current (Dalrymple, 1992; Reading & Collinson, 1996). The lenticular geometry and erosive bases with thinning upward trends indicate deposition within channels (Buatois & Mángano, 2003). Facies A is interpreted to be a complex of multiple stacked tidal channels and bars deposits that developed in the outer zone of a tide-dominated estuary (Dalrymple, 1992; Wonham & Elliott, 1996; Yoshida *et al.*, 2004).

ii. Facies B (Parallel stratified sandstone with mud drapes)

Facies B is composed of light to yellowish gray, fine to very fine grained, moderately well sorted sandstone. The sandstones generally show parallel stratification, and locally display low angle cross-stratification (table 1). Cross-lamination dipping in opposite direction is also observed. Mud drapes ($\leq$ 1 cm) and horizontal and contorted mud laminas ($\leq$ 3 cm) are intensively strewn throughout this facies, giving the facies a wispy appearance in some intervals. Carbonaceous materials, whether preserved as thin drapes or flaser, are common. Trace fossils are uneven and sparse; *Ophiomorpha* types are the most common. Facies B displays fining-upward trend, where it grades upward into very fine grained sandstone with flaser bedding. Its thickness ranges from few tens of centimeters to about 2 m and is laterally extensive.

Interpretation: Tidal currents are considered as the depositional mechanism of this facies. The occurrence of mud drapes and mud flaser bedding indicates sediment deposits during slack water periods and suggest tidal influences. In addition, tidal action is indicated by the sporadic occurrence of cross-lamination dipping in opposite directions. This facies is interpreted as upper flow regime sand flat that occupies the head portion of an estuarine channel (Dalrymple *et al.*, 1990).

iii. Facies C (Wavy-bedded sandstone)

Facies C is composed of fine to medium grained medium sandstone beds, with asymmetrical to nearly symmetrical ripples at top draped by, 0.5-2 cm thick, continuous clay layers. The upper and the lower boundaries between ripple-bedded sandstone and clay are sharp. Sand of facies C comprises more than 70 %. Ripples heights are 2-5 cm with wavelength of 6-15 cm (table 1). Lenticular bedding, with isolated sand lenses and thin connected sand lenses, is rarely preserved between mud layers. Wavy sandstone bedforms are continuous up to a few meters along the outcrop. Trace fossil within facies C are absent.

Interpretation: Facies C is thought to represent the deposits of current ripples. Reineck & singh (1980) stated that the formation of wavy-bedding requires conditions where the deposition and preservation of both sand and mud are possible. Dalrymple (1992) indicated that the deposits wave bedding could be formed in mixed-tidal flat.

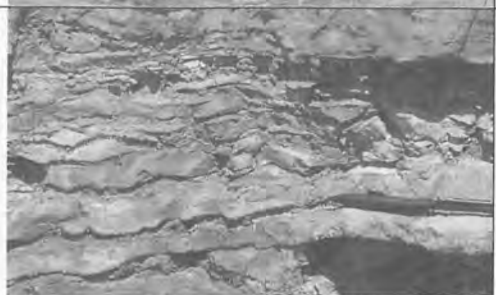
iv. Facies D (rhythmic stratified sandstone and mudstone)

Facies D is characterized by regular alternation of very fine to fine grained, parallel and undulating, thin sandstone layers interbedding with mud layers (table 1). Ripple cross-laminations, flaser and wavy-bedding are common within this facies. Sandstone thicknesses vary from less than 1 cm to 8 cm and generally exhibit sharp boundaries with mud intercalations. Loading structures of sandstone into underlying mud layers, forming flame structure, is very common. Facies D thickness varies from a few centimeters up to 150 cm and laterally extents up to several meters.

Interpretation: Facies D records alternation of bedload transport during current flow and suspension settlement during slack water periods. Reineck & singh (1980) defined this facies as inclined-heterolithic stratification, which are made up of various types of tidal bedding; thinly interlaminated sand/mud bedding, lenticular bedding or small ripple bedding. they also stated that this type of bedforms are very common in inter-tidal flat environments, where the lateral shifting of small tidal gullies on the inter-tidal flats, particularly in muddy and mixed parts, may produce this type of deposits.

v. Facies E (lenticular bedding)

This facies is characterized by black mud background with isolated, floating sand lenses, which form lenticular bedding. The sand lenses are very fine grained and show sharp contact with the background mud. Connected thick and flat sand lenses are common. Facies E thickness ranges from few centimeters up to 150 cm

Facies		Lithology and grain size trend	Thickness and sand body geometry	Depositional process	Facies association	Depositional environment
A: Trough cross-stratified sandstone with mud drapes. (Poro-perm range) 23.29 Φ(%) 29.42 5.25 k(md) 287		Well to moderately well sorted, fine to medium grained sandstone. Fining upward	lenticular, tabular and wedge shaped sand bodies, dominated by trough cross-bedding . Maximum thickness ~ 2.5 m, due to beds amalgamation. Bed thicknesses continue to exist consistently in lateral directions, up to tens of meters.	Deposition was under tidal influence as expressed by cross-stratification with mud drape, herringbone cross-bedding reactivation surfaces and flaser mud bedding	Estuarine, tide-dominated facies association	A complex of multiple stacked tidal channels and bars deposits that developed in the outer zone of estuary mouth.
B: Parallel stratified sandstone with mud drapes. (Poro-perm range) 19.34 Φ(%) 28.34 3.44 k(md) 12.6		Moderately well sorted and fine to very fine grained sandstone. Fining upward	Thickness ranges from few tens of centimeters to about 2 m and is laterally extensive, up to tens of meters.	Tidal currents are considered as the depositional mechanism, as indicated by the sporadic occurrence of cross-lamination dipping in opposite directions and mud drapes & flaser bedding		Upper flow sand flat, occupies the head portion of an estuarine channel
C: Wavy-bedded sandstone		Fine to medium grained. Fining upward	Ripples heights are 2-5 cm with wavelength of 6-15 cm. Thickness is ~ 10s cm and laterally continuous up to few meters along the outcrop	Tidal currents		Mixed tidal flat, fringing the estuary margins

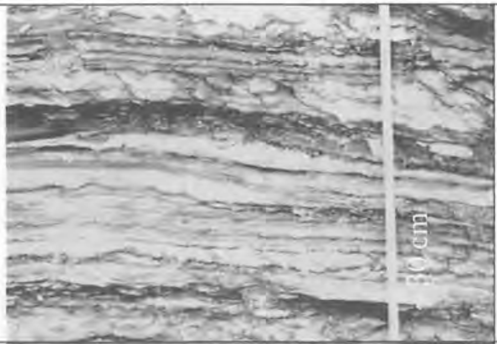
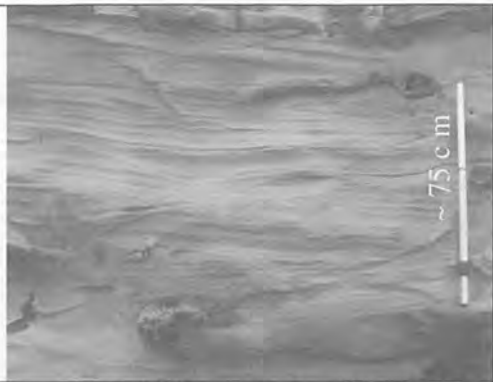
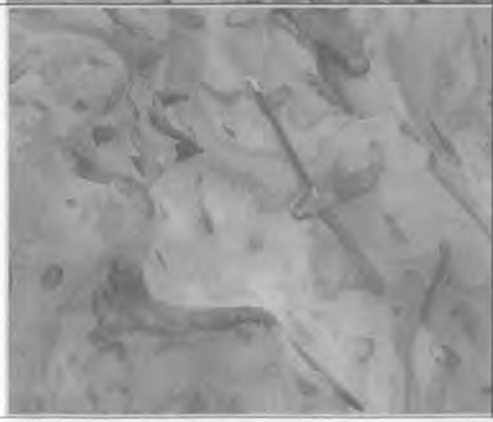
D: Rhythmic stratified sandstone and mudstone		Very fine grained sandstone + mudstone	Sandstone thicknesses vary from < 1 cm to 8 cm. Maximum thickness is ~150 cm	Tidal currents, indicated by alternative periods of bedload transport during current flow and suspension settlement during slack water	Estuarine, tide-dominated facies association	Meandering tidal gullies, mixed and mud flats.
E: Lenticular bedding		Very fine grained sandstone lenses.	Maximum 150 cm	Dominant periods of quiescence, where fine sediments settle down, with periodic current activities depositing sand		Mud tidal flat, fringing the estuary margins
F :Homogenous coarse grained sandstone (Poro-perm range) 25.73 Φ(%) 29.7 43.65 k(md) 59.34		Medium to coarse grained. No clear trend.	Bed thicknesses continue to exist consistently in lateral directions, up to few meters. Maximum thickness is ~30cm	Deposited by homogenous mass flow caused by storm action in tidally influenced environment.		Tempestites formed at the estuary mouth

Table (1): Lithofacies of Miri Formation and their sedimentological properties and environmental interpretation.

G: Swaley cross-stratified sandstone (Poro-perm range) 23.42 Φ(%) 27.33 3.42 k(md) 44.82		Moderately well sorted and very fine grained sandstone. Blocky to slight fining upward.	Sandstone bodies thicknesses vary from > 1 m up to 3 m and are laterally extensive up to tens of meters	High energy, episodic and repeated storm events.	Storm-and wave-dominated facies association	Middle to upper shoreface
H: Amalgamated hummocky cross-stratified sandstone		Moderately sorted, fine sand to coarse siltstone. Blocky to fining upward	Beds thicknesses are more or less constant and laterally extend up to 400 m, sheet like or tabular geometry	Intermediate energy, frequent episodic storm wave activities		Lower-middle shoreface
I: Fine grained bioturbated sandstone (Poro-perm range) 13.5 Φ(%) 23 0.35 k(md) 3.39		Moderately sorted and very fine to fine grained. Blocky to fining upward.	The thickness of this facies ranges from few tens centimeters to 4 m or more, due to amalgamation. Recognizing an individual depositional unit throughout the amalgamation is difficult, due to beds obliteration by bioturbation. Laterally extensive up to tens of meters	Low intensive and frequent storm action and high organisms activity		Lower shoreface

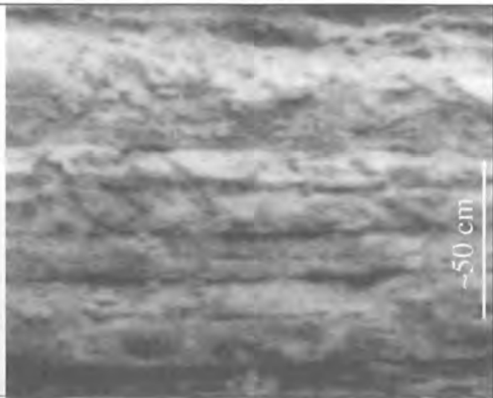
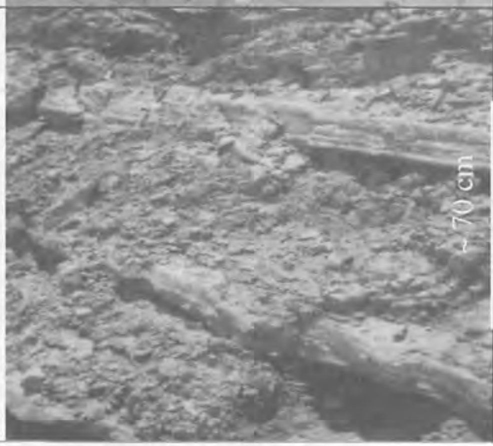
J: Interbedded to bioturbated siltstone and fine sandstone		Very coarse grained silty sand to very fine grained sandstone. Fining upward	Maximum ~ 0.5 m	Waning storm action and fair-weather condition.	Storm-and wave-dominated facies association	Distal lower shoreface
K: Bioturbated siltstone		Siltstone. Blocky to slight fining upward.	Maximum ~ 0.5 m	Low energy environment, deposition was controlled by silt particles fallout with intense animal activities.		Upper offshore transition
L: Fine grained parallel stratified and hummocky cross-stratified sandstone and mudstone inter-bedding (Poro-perm range) 19.91 Φ(%) 22.44 0.71 k(md) 1.20		Moderately sorted and very fine grained. Blocky to slight fining upward.	Maximum thickness is ~ 5m. Mud beds thicknesses range from 50 to 150 cm, while sand beds are 30 to 80 cm thick and continues to exist consistently in lateral directions, sheet like, up to tens of meters.	Alternative fair-weather conditions and combined or pure oscillatory flows		Offshore transition

Table 1 (continued)

Figure 2. Two large outcrops in the study area (Miri town, Sarawak). A- Show trough cross-bedding (channel and bar deposits) at the base of tide-dominate facies association (Airport road outcrop). B- A thick section of tide-dominated strata at the base and wave-dominated strata towards the top (Hospital road outcrop)

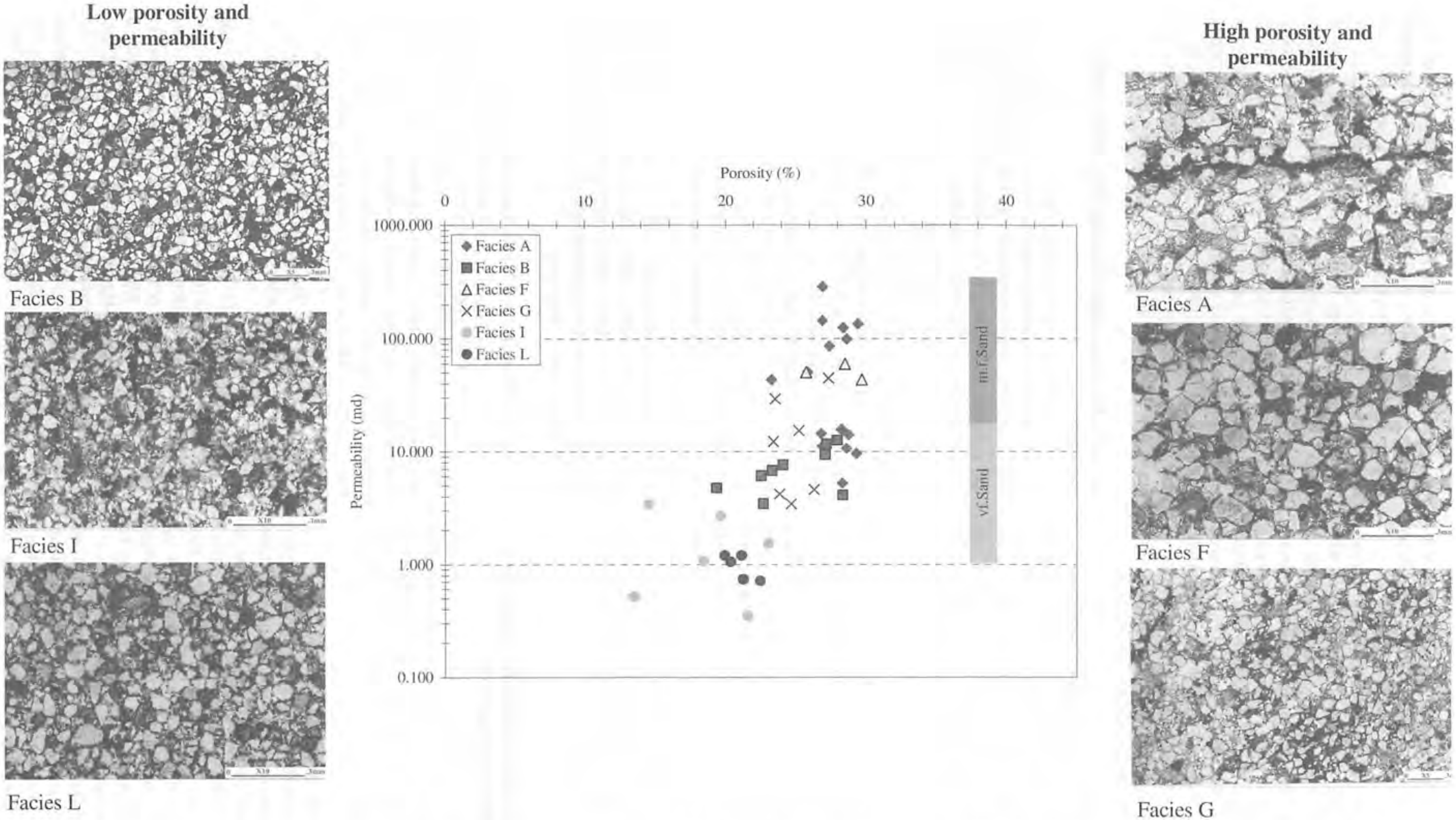


Figure 3. Porosity-permeability plot and thin sections of Miri sandstone lithofacies. High quality reservoir sandstones are shown on the right side of the chart, whereas low sand properties are on the left side of the chart. Grain size is indicated by dark and light grey; dark grey representing medium to fine sand and light gray is very fine sand.

(table 1). Horizontal to sub- horizontal *Ophiomorpha* with burrows varying in width up to 2 cm, and *Palaeophycus* occur locally.

Interpretation: This facies reflects dominant periods of quiescence, where fine sediments settle down, with periodic current activities depositing sand. Terwindt & Breusers (1972) stated that lenticular bedding indicate conditions of low current or wave action supplying meager amount of sand, with dominant slack water periods depositing mud. Reineck & singh (1980) showed that the tidal flats may contain lenticular bedding formed as a result of current changes. Facies E is interpreted as having been formed in low energy inter-tidal flat, particularly in mud flat, with fluctuating sand supplies.

vi. Facies F (Homogenous coarse grained sandstone)

This facies is characterized by light whitish-gray, medium to coarse grained, moderately well to poorly sorted, internally structureless sandstone beds. Its thickness varies from few centimeters to 30 cm. it occasionally occurs as single beds in between tide-generated facies. Trace fossils are absent. Bed thicknesses continue to exist consistently in lateral directions, up to few meters.

Interpretation: Reineck & singh (1980) used the term homogenous bedding or massive bedding in describing sediments with non-internal arrangement. These sediments could be formed by very rapid sedimentation and dumped as a homogenous mass (Reineck & singh, 1980). Facies F occurs as single bed within tide-generated succesion. Thompson (1968) and Larsonneur (1975) indicated that great wave action impacting onto tidal flats along exposed coasts is able to produce coarse grained sediments and wave generated structures. Facies F is interpreted as having been deposited by a homogenous mass flow caused by great storm action in tidally influenced environment.

2.2. Shoreface-to-offshore transition, storm-and wave-dominated facies associations

This facies association generally displays vertically stacked wave-and storm-generated facies, with maximum composite thickness of 12 m or more. A good example of this facies association is clearly preserved at Hospital Road outcrop (figure 2).

i. Facies G (Swaley cross-stratified sandstone)

Facies G is characterized by light gray swaley cross-stratified and flat laminated sandstone with no mudstone partings (table 1). Sandstones are sublitharenite, fine to very fine grained, and moderately well sorted. Rare mud clasts and mud drapes are locally strewn throughout this facies. Sandstone bodies thicknesses vary from > 1 m up to 3 m and are laterally extensive up to tens of meteres. Trace fossils are sparse, but occasionally become intensive at the base; mostly of *ophiomorpha* and *Skolithos* types.

Interpretation: Walker & plint (1992) described the swaley cross-stratification as sandstone body, thicker than 2 m, composed of amalgamated hummocky cross-stratification with no mudstone partings. According to Prave *et al.*, (1996), the deposition and preservation of fair weather mud-partings within amalgamated hummocky cross-stratification represents the palaeodepth of hydrodynamic energy conditions, either permitted or prevented mud partings formation. In contrast to facies H (thick amalgamated hummocky cross-stratified sandstone), facies G record deposition under somewhat higher energy conditions within the wave-dominated shoreface, where no fair-weather mud partings are present between the amalgamated hummocky beds due to storm overprinting. Walker & plint (1992) pointed that such these characteristics are typically attributed to the middle and upper shoreface, well above fair weather wave base.

ii. Facies H (amalgamated hummocky cross-stratified sandstone)

Facies H consists of light gray, thick hummocky cross-stratified to parallel stratified very fine to fine sand beds. Sand grains are moderately sorted. Mudstone layers and partings, between a few centimeters to 10 cm thick, separating the amalgamated hummocky cross-stratified units are very common (table 1). In contrast to facies L, the sandstone beds are thicker and dominant, 0.5 to 1.5 m thick. Sandstone beds thicknesses are more or less constant and laterally extend up to 400 m, with sharp lower and upper contacts. Traces fossils are very rare; *ophiomorpha* and *Skolithos linearis* occur locally.

Interpretation: Dott & Bourgeois (1982) and Walker & plint (1992) reported that the hummocky cross-stratification is formed by frequent episodic storm wave activities. The amalgamated hummocky cross-stratified sandstone generally represent proximal high energy storm beds that are commonly produced by repeated storm events (Buatois & Mángano, 2003), while mud partings represents post-storm and fair-weather conditions. Brenchley *et al.*, (1993) and Krassay (1994) reported that amalgamated hummocky sandstones are distinctive feature of the lower-middle shoreface.

iii. Facies I (fine grained bioturbated sandstone)

This facies is generally characterized by light gray, very fine to fine grained, massive and ubiquitously bioturbated sandstone (table 1). Sedimentary structures observed within this facies include faint parallel stratification scattering rarely throughout the sand, and carbonaceous layers locally present in the upper part of this facies. Horizontal *Ophiomorpha* burrows with irregular margins of 1-3 cm width can be clearly recognized (Figure 2). The thickness of this facies ranges from few tens centimeters to 4 m or more, due to amalgamation.

Interpretation: In this facies, there is no clear evidence of tide or wave processes, possibly due to of reworking by bioturbation. The close association of this facies with the storm generated beds, of facies J and L, and the occurrence of *Ophiomorpha* burrows suggests a sandy sallow marine deposit. Elliott (1986) pointed that the magnitude of bioturbation and consequently the preservation of storm generated structures, in shallow marine setting, vary considerable in response to the magnitude and frequency of storm and sedimentation rate. Reinson (1984) pointed that the lower shoreface sedimentary structures mainly include planar laminated beds, which are often almost completely obliterated by bioturbation. The Environmental interpretation of this facies could be lower shoreface, above storm wave base.

iv. Facies J (interbedded to bioturbated siltstone and fine sandstone)

Facies J is characterized by irregular alternations of thick to medium siltstone and very fine grained sandstone beds with parallel laminated mudstone. Some sand beds are capped by poorly developed symmetrical ripples (table 1). The common sedimentary structures observed throughout these beds are faint parallel laminations. Sand beds are laterally continuous, up to ten meters, and their thicknesses range from 5-10 cm. beds boundaries are generally sharp and flat, but some have ill-defined and bioturbated boundaries. Vertical to sub-vertical *Ophiomorpha* borrows are fairly scattered throughout this facies. The composite beds of facies J range from ten centimeters to few meters thick. Facies J grades upward into bioturbated siltstone facies.

Interpretation: Sedimentological analysis of facies J suggests the interplay of storm deposits and fair-weather sedimentation. Facies J commonly overlays the storm generated facies, of facies L, and most probably reflects waning storm deposition, where faint parallel lamination and low preservation of remnants symmetrical ripples at bed tops suggest sporadic distal storm events. This facies assemblage is interpreted to have been deposited in distal lower shoreface, due to the last phase of waning in storm depositional events.

v. Facies K (bioturbated siltstone)

Facies K is composed of dark gray, massive, and intensely to fairly bioturbated siltstone (table 1). Faint irregular parallel lamination is the only physical sedimentary structure observed locally throughout this facies. Commonly noted trace fossils include *Chondrites*. Facies thickness varies from few centimeters to 50 cm. facies K has a low degree of preservation in Miri outcrops and commonly overlies facies J.

Interpretation: This facies reflects low energy environment, deposition was controlled by silt particles fallout with intense animal activities. Obliteration of sedimentary structures in this facies resulted form reworking of primary fabric by bioturbation. In contrast with facies J, this facies reflects quieter and deeper depositional setting, probably just below or near fair-weather wave base.

vi. Facies L (mudstone inter-bedding with parallel stratified to hummocky cross- stratified sandstone)

Facies L is composed of parallel laminated mudstone inter-bedding with light gray medium to thick sandstone beds (table 1). Mud beds thicknesses range from 50 to 150 cm, while sand beds are 30 to 80 cm thick. The thinner sandstone beds (≤ 50 cm) generally exhibit flat to low angle (<10°) parallel stratification and few are structureless. Hummocky to low angle cross-stratifications tend to be accumulated in thickest sandstone beds. Mud clasts are rarely strewn at the base of sandstone beds. Trace fossil is rarely preserved at the base of sandstone beds; *Ophiomorpha* and *Skolothos*, which indicate shallow marine setting, are the most common. Facies L thickness ranges from 1 m up to 5 m and continues to exist consistently in lateral directions, with sheet like sandstone bodies up to tens of meters.

Interpretation: Facies L reflects alternative fair-weather conditions, sediments fall-out, and combined, unidirectional and oscillatory, or pure oscillatory flows. The occurrence of hummocky bedforms clearly indicates a storm origin for the sandstone beds (Buatois & Mángano, 2003). Leckie (1988) stated that the occurrence of low angle and hummocky cross-stratification in sandstones can be produced by storm wave, which were deposited rapidly, probably below fair weather wave base. Facies L is interpreted as having been deposited in offshore transitional setting, which is commonly characterized by a regular alternation of sandstone and mudstone (Pemberton *et al.*, 2001).

2. Petrophysical properties of Miri sandstone

Fifty sandstone samples were collected from several outcrops of Miri Formation for various petrophysical analysis and measurements. These samples were chosen based on lithofacies; most of the samples were sandstones that represent Miri Formation reservoir rocks. Porosity and permeability were determined for six sandstone lithofacies: (i) Lithofacies A, (ii) Lithofacies B, (iii) Lithofacies F,(iv) Lithofacies G, (v) Lithofacies i and (vi) Lithofacies l. Porosity was determined using a water immersion under vacuum technique and permeability was determined by a gas permeability technique (Monicard, 1980). This study was supported by twelve standard thin sections representing the six sandstone lithofacies.

Interparticle porosity is the most dominant porosity type in all the sandstone lithofacies, although minor amount of intraparticle porosity is also present. Porosities generally range from 13.5 to 29.7 %. Porosity is considered as a useful predictor in evaluating the reservoir quality of Miri sandstones; high reservoir properties commonly possess porosity greater than 23%. Lithofacies A, F and G are dominated by porosity values greater than 23% (ranging 23-29.7%), whereas lithofacies i and l are characterized by the lowest porosities (≤ 23 %) (figure 3).

Channel and bar sandstone lithofacies and upper shoreface lithofacies can be divided into two petrophysical groups that show unique porosity and permeability trends, reflecting different grain sizes (figure 3). At the same porosity value, medium to fine grained sandstones of lithofacies A exhibit permeabilities 15-25 times greater than the very fine grained sandstones of lithofacies A. Upper shoreface lithofacies displays a wide permeability range, from 44.82 to 3.42 md, reflecting a decrease in grain size from medium and fine sand to very fine sand. Lithofacies F has good petrophysical properties, but it is less permeable than lithofacies A. its average porosity and permeability values are 27.79 % and 51 md, respectively. lithofacies B exhibits porosities ranging from 19.34 to 27.19 % and permeabilities ranging from 3.43 to 11.68 md. The lowest porosity and permeability values are correlated with lithofacies i and l (average 18 % and 1.5 md); these are very fine grained and bioturbated sandstone lithofacies (figure 3).

3. Depositional controls on petrophysical properties and reservoir characteristics

The most important control on porosities and permeabilities of Miri sandstones are grain size and sorting. The best reservoir properties are generally correlated with lithofacies that were deposited in higher energy depositional environments; lithofacies A and F and G. thin section examination of lithofacies A and F and G show that the pores of these sandstones are large and better connected. In lithofacies A and G, the sandstones are medium to very fine grained, well to moderately well sorted, sub-rounded to sub-angular. lithofacies F is generally medium grained, moderately well sorted and sub-angular to angular. Peterson and Clarke (1991) observed that the best reservoir quality are the sandstones formed in high depositional energy, due to good sorting and low proportion of detrital clay. In lithofacies B, finer grained sediments, high proportion of detrital sediments, and clay interclastic and layers resulted in moderate to low reservoir properties. The present of extensive mud drapes in this lithofacies may also create permeability barriers at facies scale (Buatois *et al.*, 2003). The poor reservoir properties in lithofacies I and l are generally caused by finer grained detrital quartz and high degree of bioturbation. Buatois *et al.*, (2003) stated that bioturbation may reduce porosity and permeability by damaging pore connectivity and causing clay dispersion throughout the matrix. In general, extensive clay drapes, bioturbation, and increasing proportion of very fine grains content result in a significant decrease in permeability in both tide-generated and wave-generated lithofacies.

CONCLUSION

Twelve lithofacies have been identified from the outcrops of Miri formation based on lithology, sedimentary structures, fossil traces, bed geometry and thin section information. These are grouped into two major facies associations: (i) the estuarine, tide-dominated, and (ii) the shoreface-offshore transition, storm-and wave-dominated facies associations.

The estuarine, tide-dominated facies association is characterized by a variety of depositional settings that represents a tide-dominated estuary, (i) tidal channels and sand bars of estuary mouth (lithofacies A), (ii) upper flow regime sand flat of sub-tidal to inter-tidal upper estuary channel (lithofacies B), (iii) mixed tidal flat deposits (lithofacies C and D), (iv) mud tidal flat deposits (lithofacies E)and (v) tempestites deposits formed at the estuary mouth (lithofacies F). the best reservoir properties, in tide-generated facies, are shown by lithofacies A and F; porosities range from 23.3 to 29.7% and permeabilities range from 9.64 to 286.8 md. Whereas, Lithofacies B generally possess a moderate to low reservoir quality, due to high proportion of detrital clay; porosities are 19.34-27.19 % and permeabilities are 3.43-11.68.

Shoreface-to-offshore transition, storm-and-wave facies association is represented by: (i) Lithofacies G (upper to middle shoreface), (ii) Lithofacies H (middle shoreface), (iii) Lithofacies I (lower shoreface), (iv) lithofacies J (distal lower shoreface), (v) lithofacies K (upper offshore transition) and (vi) lithofacies L (offshore transition). upper to middle shoreface lithofacies has good reservoir properties, but exhibits a wide range of porosity and permeability values, due to variations in its grain size, porosities are 23.5-27.5% and permeabilities are 3.4-45 md. Lithofacies I and K are low quality reservoirs, due to high proportion of fine grained detrital sediments and high degree of bioturbation; porosities are 13.49-23 % and permeabilities are 3.39-0.35 md.

.The variations in reservoir properties of Miri sandstones are attributed to their lithofacies and textural parameters. The most porous and permeable lithofacies were deposited in the higher-energy depositional environments with good sorting and low clay content.

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