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Lateral Facies and Permeability Changes in Upper Shoreface Sandstones, Berakas Syncline, Brunei Darussalam

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Abstract - Several outcrops were studied to identify sedimentary facies and to analyze permeability distribution, through which an outcrop analogue for upper shoreface reservoirs can be established. Four facies were identified: upper shoreface, lower shoreface, offshore transition, and tidal ones. Stratigraphic correlation of eleven outcrops indicates that the upper shoreface sandstone is generally clean, well sorted, parallel, and planar cross laminated. The sand becomes thinner and pinches out to the northwest where the mud proportion increases within the sand. Muddier sand was deposited in a relatively low energy upper shoreface setting. The thickness of the upper shoreface reservoir sand generally is 5 m. It decreases to zero over approximately 1.3 km as the sand pinches out to the northwest. To the northeast, the thickness also decreases to 4 m over approximately 4 km. Permeability values are more variable laterally than vertically. The permeability distribution has an obvious relationship to the sedimentary facies and is mainly controlled by the proportion of mud and bioturbation. As the sand pinches out in the northwest, permeability decreases from 590 md to 97 md over 1 km. To the northeast, permeability also decreases to 152 md over approximately 4 km where the sand becomes highly bioturbated. These values indicate that the sands are of good to very good reservoir quality. It appears that there are no major barriers to the lateral flow of fluid within the upper shoreface sandstone.

Keywords: outcrops, facies, upper shoreface, permeability

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INTRODUCTION

Shoreface sandstone is one of the main hydrocarbon reservoir rocks in Brunei Darussalam. Shoreface sand can be clean and well sorted with a good lateral continuity. However, as the sand pinches out, there is a need to understand how the thickness of sand and proportion of mud change. Without a good understanding, it is difficult to determine spatial distributions of rock properties at the interwell scale in the subsurface while the rock properties are crucial factors for petroleum production and oil recovery enhancing (Liu *et al*., 1996). The study of facies changes and rock properties of shoreface sand laterally is becoming increasingly important in Brunei since there is no prior analog for such shoreface reservoirs.

The shoreface outcrops that form a prominent ridge in the Berakas Syncline provide an opportunity to study sand body geometry and facies architecture as well as reservoir properties (Figure 1). These outcrops are well exposed and have a

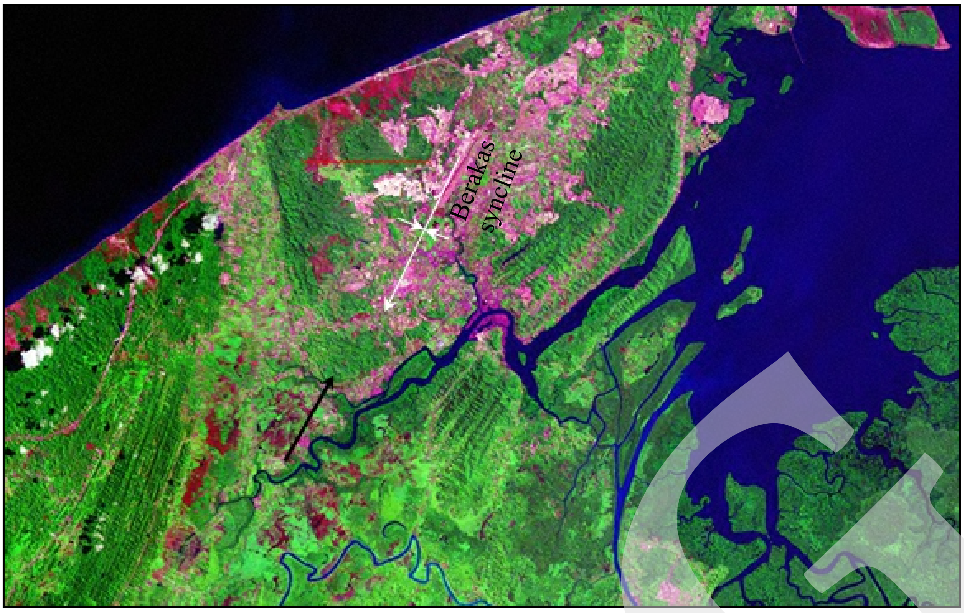

Figure 1. Landsat TM imagery of Brunei Darussalam and its vicinity. The ridge of Berakas Syncline is pointed by black arrow.

good lateral continuity. The shoreface outcrops represent the oldest sediments of the onshore Berakas Syncline (Sandal, 1996).

This research has two objectives: (1) to describe facies changes along the ridge in the Berakas Syncline (2) to identify relationships between facies and permeability distribution.

The researched area is in the southern part of Brunei Muara District, Brunei Darussalam (Figure 2). This study focused on twenty outcrops which are located on Jalan Tutong, Jalan Telanai, and Jalan Dadap. The outcrops occupy the contour uphill. Most of the outcrops are weathered and friable. The upper parts of several outcrops could not be observed because they are very high and covered by vegetation. The outcrops comprise interbedded sandstones and shales with a measured total thickness of 101 m from the successions of eight lithologic sections. They have NW - SE and SW - NE structural strikes and dips 10° - 34°.

GEOLOGICAL SETTING

Structural Setting

The Berakas Syncline is bounded by the north-south Jerudong Anticline to the west, the northeast - southwest Muara Fault Zone to the northeast and the Bandar Seri Begawan (BSB) Fault to the south (Morley *et al*., 2003). The oldest unit occurs in the southern part, Lumapas area (middle Miocene) occupied by the Belait

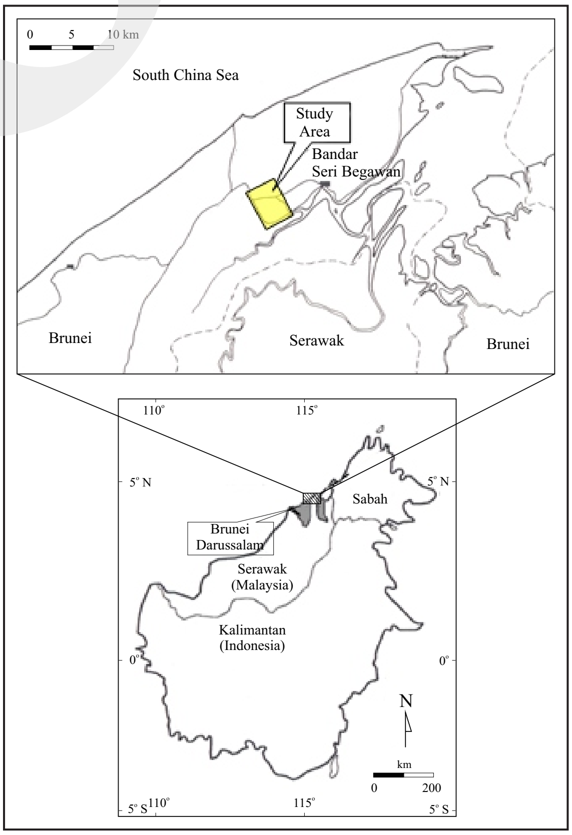

Figure 2. Locality map of the research area.

Formation and the youngest unit is present in the northern part, near the coastline (Late Miocene-Pliocene) occupied by the Liang Formation. Between Lumapas and the coastline, the prominent ridge is formed by the Belait Formation (Figure 3). The Belait Formation interfingers with the Setap Formation in the western and southern parts of the Belait Syncline.

Stratigraphic Setting

The studied area is projected to be part of the middle Miocene Belait Formation which is time equivalent to the Miri Formation and Setap Formation (Figure 4). The middle Miocene Belait Formation is composed mainly of interlayered thick-bedded sandstones and clays. The sandstones were deposited in shallow marine environments (Sandal, 1996). An uplift after Early Miocene caused erosion and resulted in a thick progradational sequence of Neogene clastic sediments. This formation can reach more than 6 km of the total thickness.

The reservoir sandstones of the Belait Formation were deposited in two depositional settings, tide-dominant and wave-dominant (Lambiase *et al.*, 2001). Tide-dominated sandstones include tidal channel, bar, and tidal flat sands and are associated with brackish water mudstones, tidal flat mudstones, and mangrove coals and coaly shales. The tidal channel and bar sands generally contain clean and fine to medium-grained size sand that commonly have trough cross-beds, lateral accretion surfaces, reactivation surfaces, and mud rip-up clasts. Mud drapes and lamination are also present locally. Individual channel and bar sands are 1 - 1.5 m thick and pinch laterally out. Tidal flat sands are thin bedded (0.01 - 0.1 m), fine to medium-grained sand with common mud drapes and lamination, lenticular and flaser bedding, current ripple lamination and minor wave ripple lamination. Tidal channel and bar sands contain only a few vertical trace fossils. The upper surfaces of the sandstones show abundant, large horizontal trace fossils when the tidal

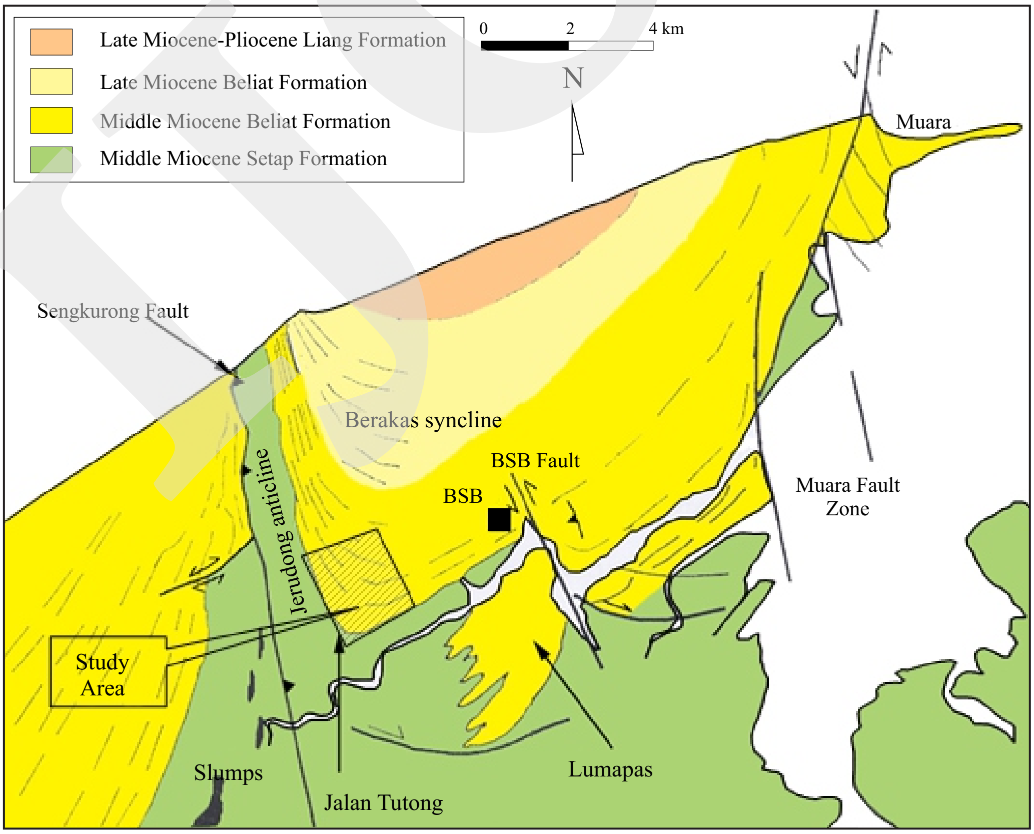

Figure 3. Structural trends of Brunei Darussalam (redrawn from Morley *et al.*, 2003).

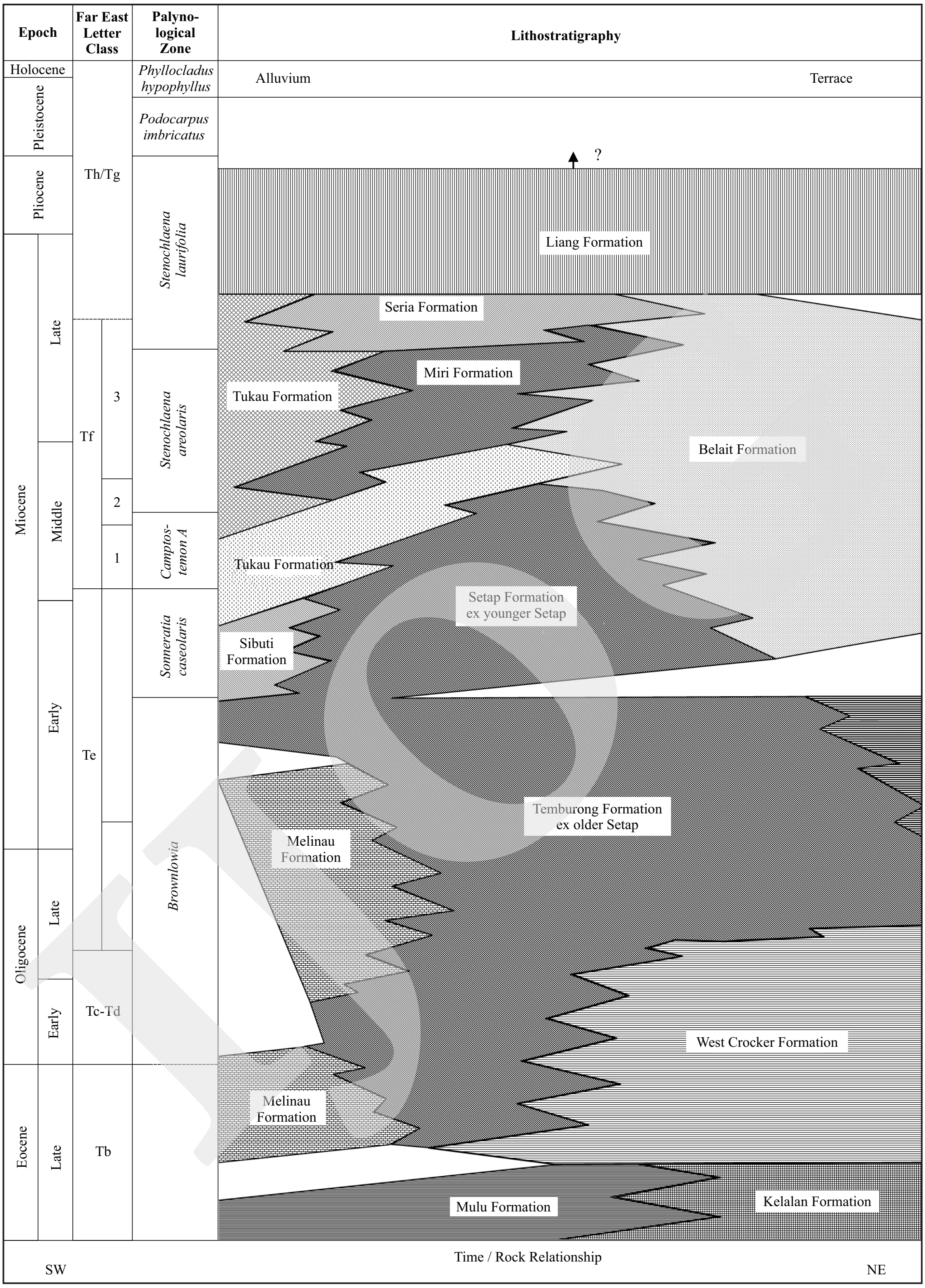

Figure 4. Neogene/Paleogene stratigraphy in the Central Brunei Area (redrawn from Sandal, 1996). The patterns do not represent anything.

channel and bar sands pass upward abruptly into embayment mudstones. Tidal flats contain the most abundant trace fossils.

Wave-dominated sandstones were interpreted as shoreface sands associated with beach, offshore transition, and shelf deposits. They accumulated on marine coastlines quite far from any delta or river mouth. The sands are much cleaner than sands which occur close to a fluvial system where supplied mud is high. The sand is well sorted and fine to medium-grained. It has common wave ripples, wavy bedding, trough cross-bedding, parallel lamination and low angle cross-bedding as well as swaly cross stratification. Shoreface deposits are extensively bioturbated.

METHODS

This study was conducted through two stages; firstly field observation, and second permeability measurement. Field observations were done for twenty outcrops included sedimentary structures, grain size, sorting, degree of bioturbation (Table 1) and true thickness measurement in order to define the facies. Afterwards, the upper shoreface sands were correlated by projecting beds along strike.

Table 1. Degree of Bioturbation

Degree	Estimation of bioturbation percentage
Low	1% - 25%
Moderate	26% - 50%
High	51% - 75%
Very high	76% - 100%

Permeability was measured within the upper shoreface sandstones from five outcrops. They were measured in 1 m vertical intervals using a portable air permeameter Tiny Perm II.

RESULT AND ANALYSIS

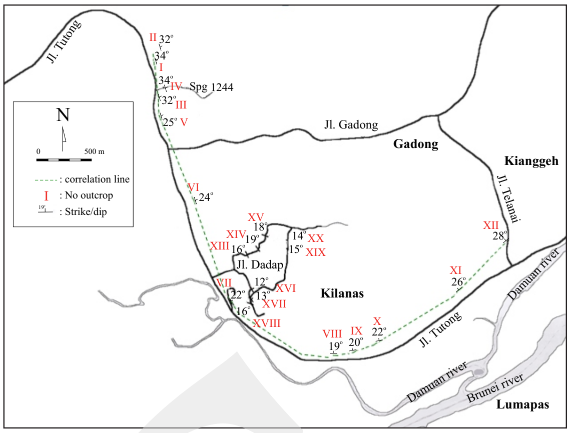

Figure 5. The location of Outcrops I - XII on Jalan Tutong, Jalan Telanai, and Jalan Dadap.

Sedimentary Facies

Four sedimentary facies were interpreted from twenty outcrops that occupy the ridge in the southern Berakas Syncline. Eleven outcrops occur along Jalan Tutong, one occurs on Jalan Telanai, and eight occur along Jalan Dadap (Figure 5). Facies identification primarily was based on lithology, sedimentary structure, sorting, bioturbation intensity, and thickness. In addition, strike and dip were also measured to construct the correlation. The four facies are offshore transition, lower shoreface, upper shoreface, and tidal (Figure 6 and 7). Variations of the thickness and sedimentary structure can be seen in Figure 8.

Facies Change Laterally Along Upper Shoreface Sandstone

By projecting the strike of beds, ten outcrops from Progradational Parasequence 1 were correlated in order to recognize facies change along the upper shoreface sandstone. The succession in each outcrop is marked by the presence of an offshore transition facies which is overlain by a

Figure 6. Tidal channel sandstone (A) with an erosional base (E) in outcrop I. It contact with a storm bed below (B). Laterak accretion planes occur throughout the tidal sand (C) (Stabilo pen circled as scale is 10,5 cm long).

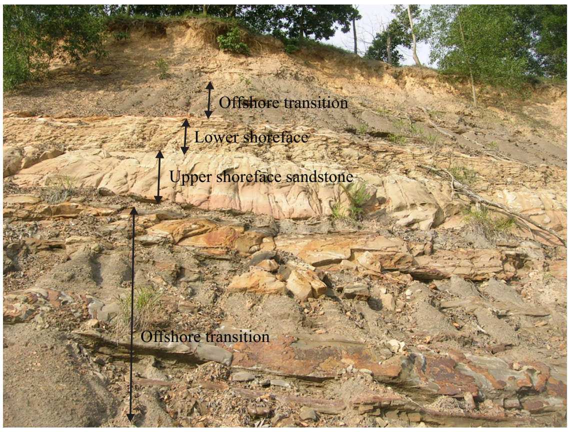

Figure 7. Stratigraphic successions of offshore transition facies, upper shoreface facies and lower shoreface facies at Outcrop V (This section is 10 m thick).

progressively shoreward facies. Interbedded mudstones and sandstones occuring at the base are followed by wavy bedded sandstones with mud laminations that are overlain by upper shoreface sandstones at the top. The distribution of sandstone varies in thickness, sorting, bioturbation, and mud proportion (Figure 9).

The thickest and cleanest sandstone was observed in the 5 m thick Sand A of Outcrop VI which is located in the northwestern part of the upper shoreface sandstone distribution. The clean sandstone appears to be continuous to Outcrop V, which is 833 m to the northwest. It becomes thinner (2.8 m thick) and pinches out towards Outcrop III, which is 180 m from Outcrop V. The upper shoreface sandstone discussed before disappears in Outcrop I where just tidal facies is present. This outcrop is 342 m from Outcrop III. However, before it disappears, the sandstone becomes poorly sorted and muddy in Outcrop III (Figure 9).

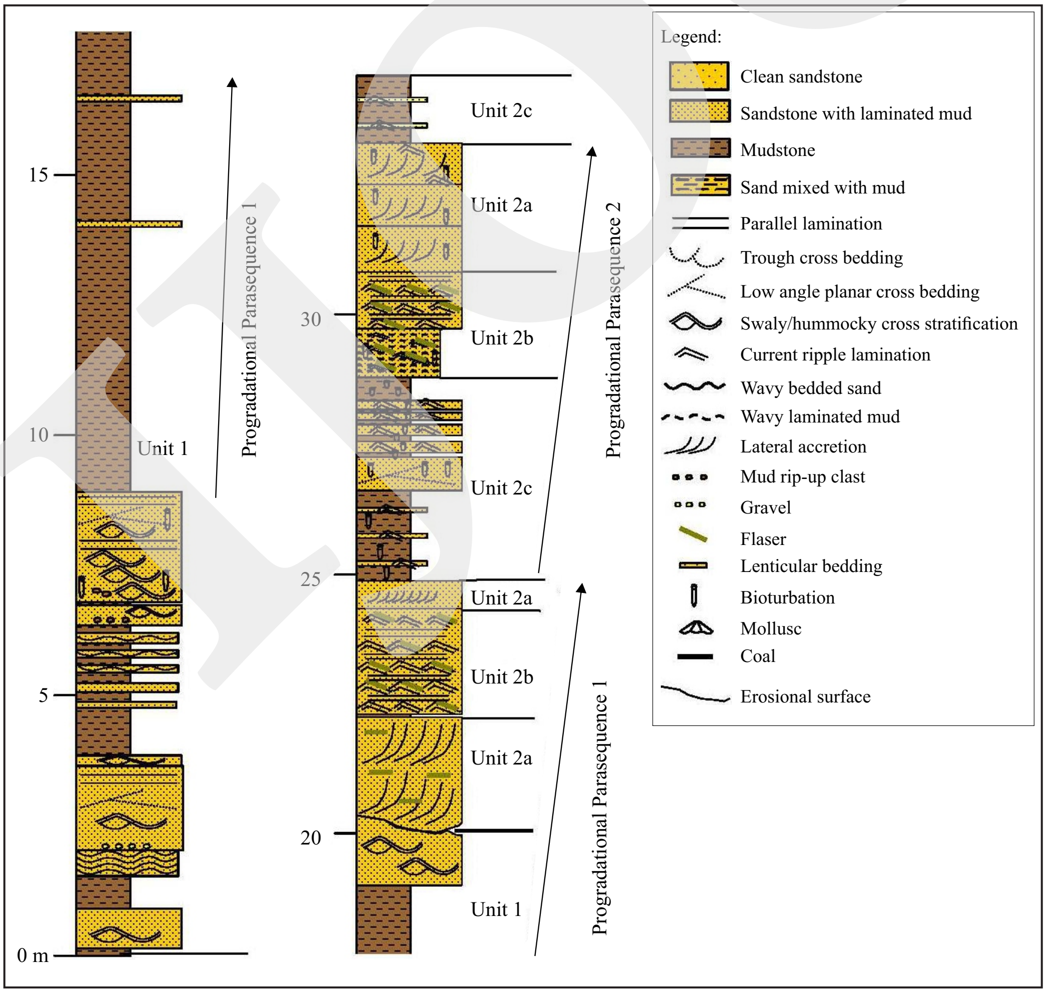

Figure 8. Schematic stratigratigraphic succession of Outcrop I, containing offshore transition facies in Unit 1 and tidal facies in Unit 2.

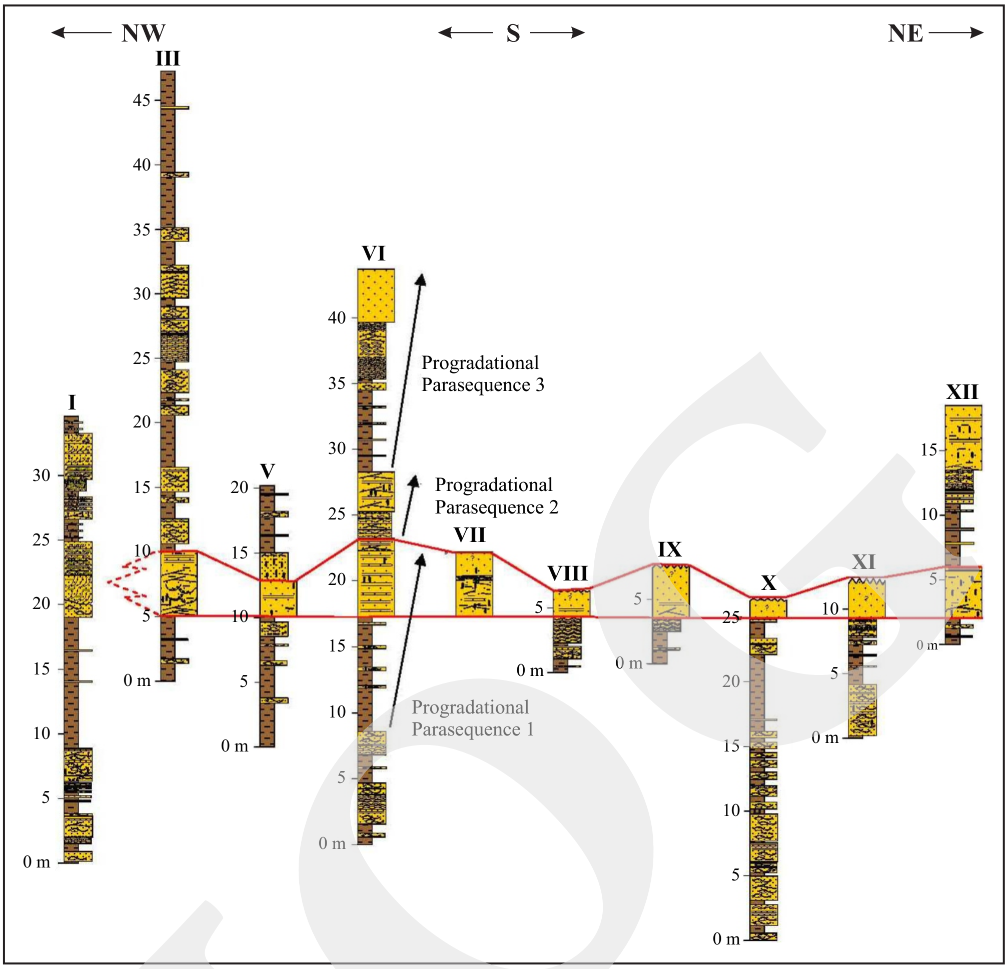

Figure 9. Correlation of upper shoreface sandstone from Progradational Parasequence1. The outcrops are not spaced proportionally to the distances between outcrops.

The sandstone that was observed in Outcrop VI is continuous 990 m to the southeast to Outcrop VII where it is 5 m thick. However, the sand becomes moderately sorted, moderately bioturbated, and mixed with mud locally.

The upper shoreface sandstone is also present in Outcrop VIII which is 1.11 km from Outcrop VII, as well as in Outcrop IX that is 180 m from the previous outcrop. The last two sandstones are well sorted with unknown thicknesses.

The sandstone becomes poorly sorted with unknown thickness in Outcrop X that is 270 m from Outcrop IX. In Outcrop XI, the sand is present with unknown quality and thickness. To the northeast, the sand is poorly sorted and highly bioturbated in Outcrop XII and slightly thinner at 4 m thick. Outcrop XII is approximately 1.485 km from Outcrop X.

Permeability Distribution

Vertical Permeability

The main focus of the permeability analysis is the upper shoreface sandstones of Progradational Parasequence I. A total of 20 permeability measurements were made in sandstones from Outcrops III, V, VI, VII and XII (Figure 8). The sandstones from other outcrops, *i. e.* VIII, IX, X, and XI could not be measured because they are inaccessible.

Lateral Permeability Distribution

The highest permeability (average 590 md) was observed in the 5 m thick, clean, and well sorted Sand A of Outcrop VI. Permeability decreases slightly to the northwest (Outcrop V) and southeast (Outcrop VII). In Outcrop V, the average permeability is 353 md where the clean and well sorted sand becomes thinner. In Outcrop VII, the average permeability decreases to 233 md where the sand is moderately sorted and moderately bioturbated.

Permeability is greatly reduced in Outcrop III and Outcrop XII, with the average permeabilities of 97 md and 152 md respectively. Typical sands in these two outcrops are poorly sorted, muddy, and highly bioturbated.

Controls on Permeability

The permeability variation in the upper shoreface sandstone is closely related to sedimentary facies. The pattern primarily reflects the energy regime of the depositional processes affecting sedimentation. The high permeability zones correspond to a high energy regime as suggested by clean, well sorted, massive, or parallel laminated sandstone. In contrast, relatively low permeability zones were formed by a relatively low energy regime that is characterized by a high proportion of mud and a high degree of bioturbation in parallel and low angle planar cross laminated sandstone. Increased bioturbation intensity tends to decrease permeability because sorting becomes much poorer.

Permeabilities may be more variable than what was measured. Vegetated areas between outcrops may indicate zones with more mud that have permeabilities lower than 97 md. In addition, the sandstone heaving ridge that extends well beyond the studied area to the northeast.

DISCUSSION

Implications for Reservoir Prediction in the Subsurface

Accurate estimation of recoverable reserves is important because it is the basis for economic decisions. One has to consider the variations in thickness and permeability to avoid overestimation of recoverable reserves in an upper shoreface reservoir. Such variations will influence the calculation of volumetric reservoir and estimation of fluid communication.

Thickness and Lateral Communication of Reservoir

In the studied area, upper shoreface reservoir sand generally is 5 m thick. However, as the sand pinches out to the northwest, the thickness decreases to zero (100 %) over approximately 1.3 km (from Outcrop VI to Outcrop I). To the northeast, the thickness decreases to 4 m (20 %) over approximately 4 km (from Outcrop VI to Outcrop XII).

The lateral permeability distribution is more variable than in the vertical direction. As suggested by the average permeability of 97 md to 590 md, the upper shoreface sand generally has good lateral communication. By general convention, this range of permeability can be classified as good to very good quality (Figure 10 and Table 2). A very good permeability (590 md) is present in Outcrop VI. It decreases slightly to be a good permeability which can be observed in Outcrop V (353 md) and Outcrop VII (233 md).

Permeability decreases greatly to 97 md in Outcrop III where the sand pinches out to the northwest. To the northeast, permeability also decreases to 152 md in Outcrop XII. The last two values are still good for reservoir quality. It indicates that there are no major barriers to the lateral flow of fluid. Relatively low permeability caused by muddier sand and moderately-highly bioturbated sand, does not significantly influence fluid communication within the sand. However, it is clear that permeabilities are not homogeneous in one sand body.

Reservoir Modelling in the Subsurface

Stochastic Inversion

A 5 m thick sand bed cannot be detected using deterministic seismic inversion (normal seismic). The thin sand bed possibly can be imaged using stochastic inversion, provided that the sand thickness is higher than the sampling rate of the seismic data (Allo, 2005, Pers. Comm.).

Wireline Signatures

Based on the lateral outcrop dimension in order of 4 - 6 km, the gamma signatures will

Table 2. Qualitative Description of Permeability Values (after North, 1985)

Qualitative description	k-value (md)
poor to fair	< 1.0 - 15
moderate	15 - 50
good	50 - 250
very good	250 - 1000
excellent	> 1000

be lower (< API) in clean, well sorted, and higher permeability sands (the averages of 353 md to 590 md) as seen in Outcrops V and VI. In poorly sorted, highly bioturbated, and lower permeability sands (the averages of 97 md - 233 md), the gamma signatures will be higher (> API), as seen in Outcrops III, VII, XII (Figure 11).

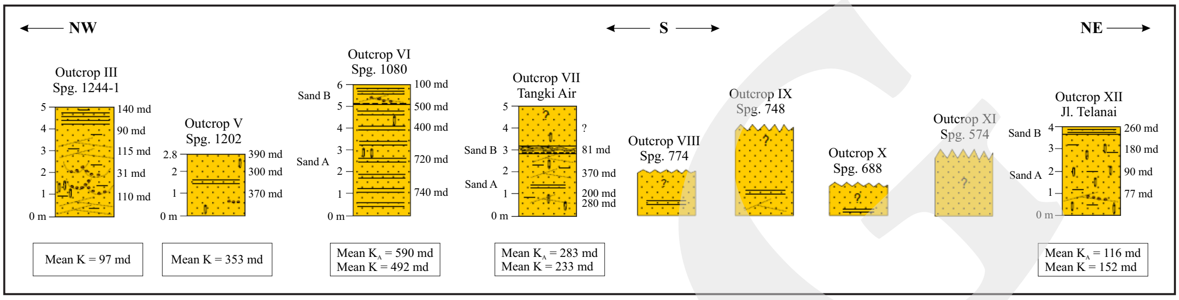

Figure 10. Permeability measurements within the upper shoreface sandstone from Progradational Parasequence1 of Outcrops III, V, VI, VII, and XII. These sandstone are not spaced proportionally to the distances between outcrops.

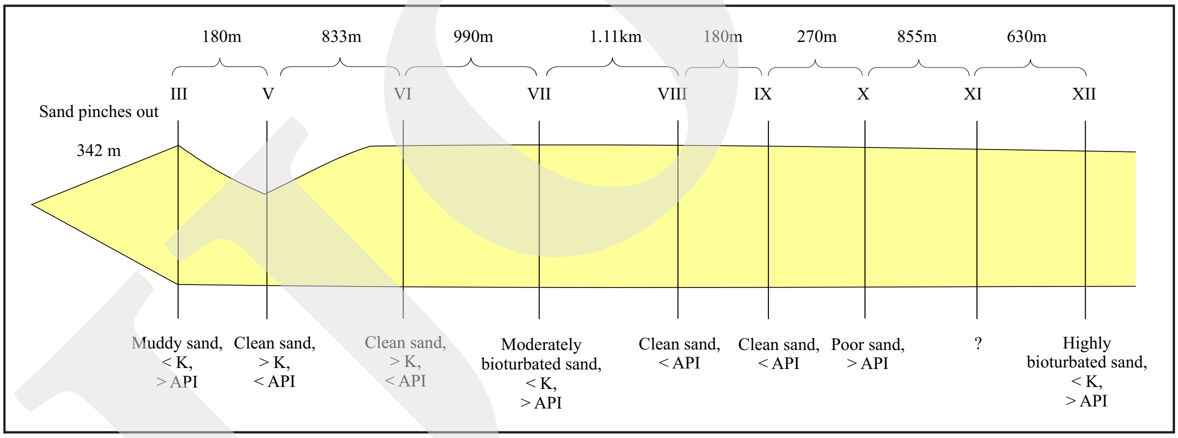

Figure 11. Schematic section of reservoir quality.

CONCLUSION AND SUGGESTION

Several conclusions can be drawn from the research of facies and permeability distributions.

The sediments were deposited within upper shoreface, lower shoreface, offshore transition, and tidal environments. The correlation of upper shoreface sandstones from Progradational Parasequence 1 in ten outcrops indicates that the clean upper shoreface sandstone becomes thinner and is replaced to the northwest by tidal facies. Before it disappears, the sand becomes muddy.

The energy that formed the sandstones in the upper shoreface varied, from high to relatively low. Variation of energy affected the character of sediments. High energy deposited clean, massive or parallel laminated, and weakly bioturbated sandstone. Lower energies are associated with muddier sand and more bioturbation.

The upper shoreface reservoir sand generally is 5 m thick. As the sand pinches out, the thickness decreases to zero over approximately 1.3 km. To the northeast, the thickness decreases to 4 m over approximately 4 km.

The lateral permeability is more variable than the vertical permeability. Permeability exhibits a lateral distribution pattern that reflects sedimentary facies. High permeability zones correspond to high energy upper shoreface environments. Lower permeability zones are associated with relatively low energy upper shoreface environments.

The upper shoreface sandstones which are well to poorly sorted and very fine – fine grained do not have homogenous permeabilities in one sand body. As the sand pinches out to the northwest, the permeability decreases from 590 md to 97 md over 1 km. To the northeast, the permeability also decreases to 152 md over approximately 4 km.

The permeability values are classified as good to very good qualities and indicate there are no major barriers to the lateral flow of fluid.

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