Bulletin of Earth Sciences of Thailand

Facies analysis and reservoir characteristics of 2E unit in North Malay Basin, Gulf of Thailand

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Received: 23 Jun 2022
Revised: 20 Jul 2022
Accepted: 20 Jul 2022

Abstract

This study was conducted to better understand the stratigraphy and depositional environment of the 2E unit in Block A of the North Malay Basin. This research integrated core interpretations and well data to establish the depositional environments and reservoir characteristics of the 2E unit by utilizing four cored wells.

Depositional environments were determined using sedimentology to identify lithofacies associations. These core-based lithofacies are compatible with tide-dominated delta and estuary interpretations for the deposition of the 2E unit. The deposition was influenced by daily tidal cycles, delta lobe switching, and fluctuation of freshwater input that resulted in the alternation of fluvial and tidal processes.

These variations in deposition are preserved in the 2E depositional facies. Sandstone-dominated facies (Ss, Sx, Sr, Sm, Sc, and Sf) were commonly deposited within the mouth of the river, including fluvial channels, tidal-dominated channels, and tidal bars. In contrast, the mudstone-dominated facies (Ml and Mp) and bioturbated heterolithic facies (Sb) were deposited in lower energy conditions, such as tidal flats.

Based on porosity-permeability cross plots, three flow units were identified. These flow units, ranked in order of decreasing average porosities and permeabilities, are (1) stratified sandstone unit, (2) heterogeneous sandstone unit, and (3) muddy sandstone unit. Reservoir qualities are good to excellent in the stratified sandstone unit with the average porosity of 27% and the average permeability ranges from several hundreds of mD to a maximum of 3.8 D. On the other hand, lower quality reservoirs are observed in the heterogeneous sandstone and muddy sandstone units with significantly low permeability, generally less than 100 mD.

The reservoir properties of the 2E unit in the North Malay Basin are controlled by the depositional setting. In the more tidally influenced units, the common occurrence of brecciated mud layers, mud drapes, and high bioturbation has a significant impact on the reservoir permeability. Such common occurrence would influence both the production and injection rates, thus impacting the future development of 2E unit.

Keywords: North Malay Basin, Lithofacies, Reservoir Characteristics

1. Introduction

The North Malay Basin (Fig. 1) covers an area of approximately 18,000 square kilometers and is one of the most successful petroleum basins in the Gulf of Thailand. The reservoirs have been sub-divided into four formations: Formations 0, 1, 2, and 3 in ascending order.

One of the important units, the Formation 2, was divided into 2A, 2B, 2C, 2D, and 2E sub-units. Sub-units 2A to 2D are well-documented and understood due to numerous studies and prolific historical production data from the hundreds of development wells that have been drilled since the 1990s (Drunesne and Crumeyrolle, 1993; Crumeyrolle, 1995; Crumeyrolle, 1996; Crumeyrolle and Singhasenee, 1996; Caplan, 1998; PTTEP, 2001; PTTEP, 2018). Recently, the 2E unit has become a significant producer in the southern part of the North Malay Basin and the hydrocarbon production was started in 2005. Although hydrocarbons have been continuously produced for more than a decade, there are few detailed sedimentology and reservoir characteristic studies of this unit that should be done.

Therefore, a study area covering about 900 square kilometers was evaluated in the southern part of the Block A, where the 2E reservoir is mainly produced. The main objective of this study is to better understand the stratigraphy and depositional environment of the 2E unit and to characterize the sedimentary facies and the reservoir properties by integrating cores and well data.

2. Geological Setting

The North Malay Basin is a Tertiary rift basin, oriented northwest-southeast and is controlled by the NW-SE fault series (Morley et al., 2011). The rift basin is bordered to the northwest by the Narathiwat Ridge and is bounded to the northeast by the Khorat Swell (Fig. 1B). The North Malay Basin was formed by the extension during Late Cretaceous to early Miocene and was subsequently filled by a very thick Oligocene-Miocene siliciclastic succession (Morley and Racey, 2011). The sedimentary succession is subdivided into four main units: Formations 0, 1, 2, and 3 (PTTEP, 2001), as shown in Figure 2.

Formation 0 consists of non-marine and fluvio-lacustrine deposits that represent the early basin-fill (Shoup, 2008) and this basin's lowermost package. This formation is predominantly composed of lacustrine black shale interbedded with thin-bedded sand bars and channels. Coarser sands and conglomerates were deposited along an active fault margin. The upper part of this formation is characterized by a thick shale, which was deposited in an extensive lacustrine environment. The base of Formation 1 occurs at an abrupt change into fluvial deposits (Crumeyrolle, 1995).

Formation 1 was deposited in the early post-rift phase when the basin was initially experiencing significant subsidence, resulting in more than 500 m thick sequences of fluvial red beds sediments. This formation consists of fluvial deposits with thick coarse-grained channels interbedded with red oxidized, clay-rich overbank deposits (Drunesne and Crumeyrolle, 1993).

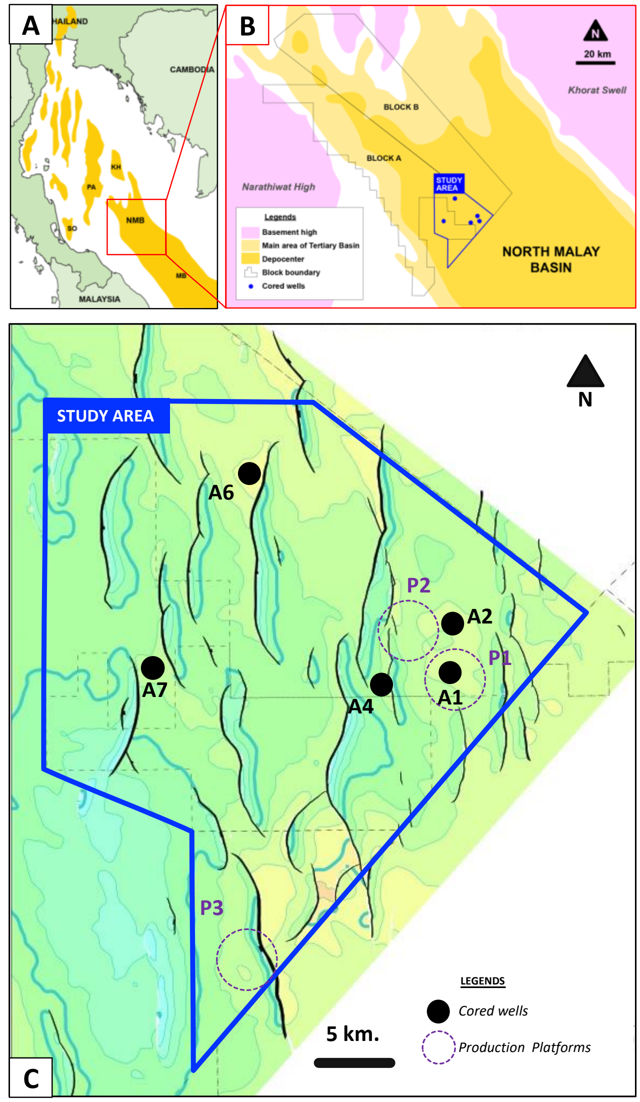

Figure 1. General location maps: A) Major Tertiary basins in Gulf of Thailand, showing the location of the North Malay Basin (modified after Morley et al., 2011). B) Location of petroleum concession Block A and B in North Malay Basin (modified after Shoup, 2008), and C) The insert depth-structural maps showing the study area with location of cored wells used for this research.

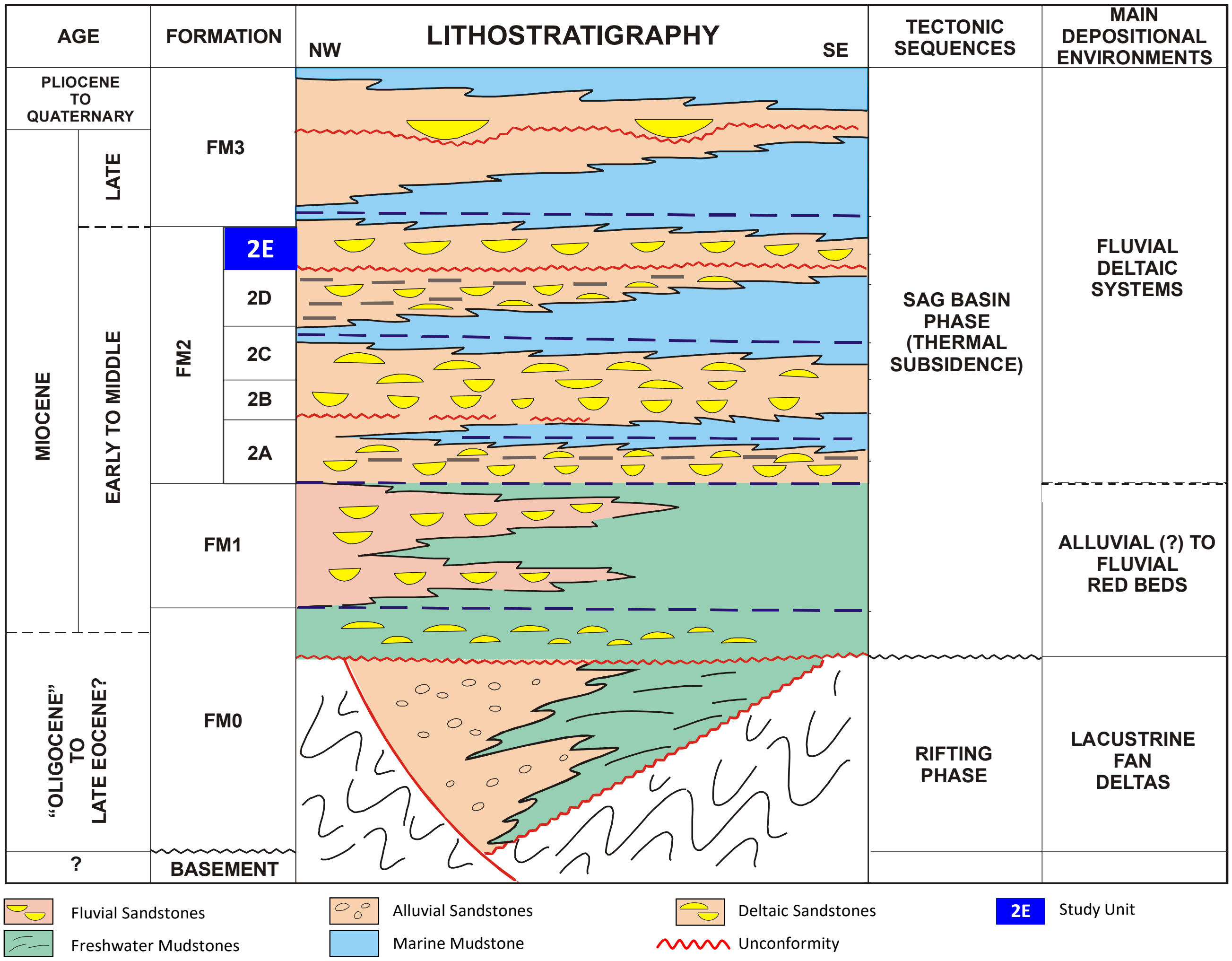

Figure 2. Regional stratigraphic framework of the North Malay Basin, showing the position of the study unit in blue (PTTEP, 2001)

The younger Formation 2 was deposited during continued thermal sagging in the Middle to Late Miocene. Due to continued subsidence, the basin started to be influenced by the marine incursions (Morley and Racey, 2011). The sediments of this formation were deposited in the fluvio-deltaic, coastal plain, and marginal marine environments. This formation has been subdivided, from the oldest to youngest, into five subunits: 2A, 2B, 2C, 2D, and 2E.

The latest formation, the Formation 3, was deposited in the Late Miocene to Pliocene. This formation was deposited in the shallow marine and shelf depositional settings.

The 2E unit is the youngest member of the Formation 2, which was deposited during a gradual marine incursion in the Middle to Late Miocene. Hydrocarbon production from this unit was started in 2005 by the completion of numerous development wells. Since then, this unit has become a significant producer, especially in the southern part of the Block A.

3. Methodology

This study focused on using conventional cores to establish the sedimentology and facies of the 2E unit, utilizing four cored wells in the Block A of the North Malay Basin. The conventional cores from the 2E unit comprise a total of 204 m of cored interval from wells A1, A2, A4, and A7 (Fig. 3). Stratigraphic depth of the cored intervals ranges from 1,200-1,500 m TVDSS.

The selected wells with cored interval were used for the well-to-well correlation across the study area. The lithostratigraphic correlation method has been applied to define the 2E unit boundaries and to subdivide them into individual sub-intervals. The correlation panel of the cored wells are illustrated in Figure 3.

The sedimentary facies were classified by integrating sedimentary textures, sedimentary structures, mineral compositions, and reservoir

Table 1. *Bioturbation Index (BI), Taylor and Goldring (1993)*

Grade	%Bioturbation	Classification
0	0	No bioturbatiom
1	1-5	Sparse bioturbation: few discrete traces and/or escape structures
2	6-30	Low bioturbation: bedding distinct, low trace density, escape structures often common
3	31-60	Moderate bioturbation: bedding boundaries sharp, traces discrete
4	61-90	High bioturbation: bedding boundaries indistinct, high trace density with overlap common
5	91-99	Intense bioturbation: bedding completely disturbed, limited reworking due to repeated overprinting
6	100	Complete bioturbation: sediment reworking due to repeated overprinting

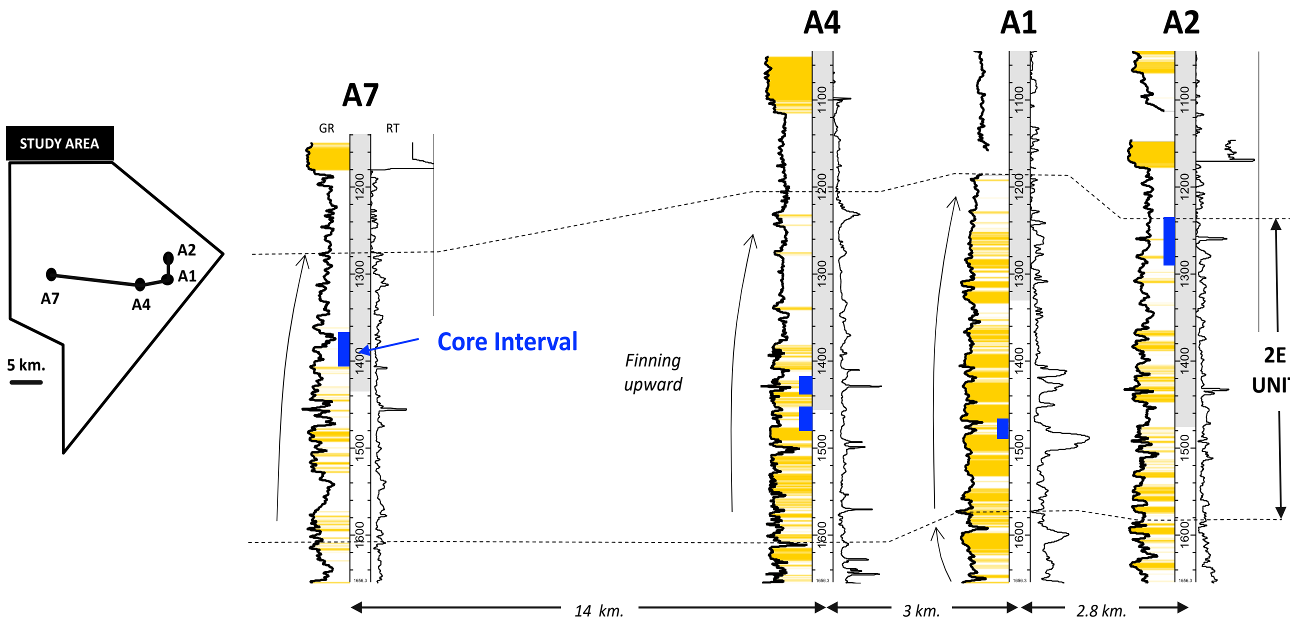

Figure 3. Stratigraphic well correlation of 4 cored wells in the study area, showing the core intervals in blue.

properties, which were gathered from existing internal reports.

Detailed core descriptions were completed to define reservoir facies and to understand the depositional setting. Core descriptions included sedimentological characteristics, such as (1) composition, (organic content, mineralogy, grain size, roundness, and sorting), (2) bedding style (thickness, vertical trends, erosional surfaces, and lithology), (3) primary physical sedimentary structures, and (4) burrowing (intensity, diversity, and nature of burrowing) and other indicative features. Those characteristics were documented and analyzed.

The classification of bedding styles and the terminology of heterolithic bedding (flaser, wavy, lenticular) in this study follows Reineck and Wunderlich (1968), Nichols (1999), and Boggs (2013). Degree of bioturbation intensity ("BI") was based on Taylor and Goldring (1993), as shown in Table 1.

Based primarily on the core descriptions, the depositional facies (lithofacies) were defined with an emphasis on subdividing the facies into flow units.

Facies were named using a system of letter codes that indicate key characteristics. Each facies (lithofacies) is described with a compilation of letter codes. The first letter indicates grain size in capital letters: S – sand, M – mud; the second letter describes sedimentary structures and key diagnostic features in lower-case letters: s – structureless, x – cross-stratified, r – ripples, m – mud clasts, p – parallel lamination, f – flaser, w – wavy, l – lenticular, c – carbonaceous, and b – bioturbation. According to the codification presented here, the lithofacies code Sf, for example, means sandstone with flaser bedding.

Facies associations were defined by analyzing the vertical relationship between each lithofacies. Therefore, group of lithofacies were used for characterizing the facies associations.

Based on core data, wireline log correlations and vertical relationships of facies associations, the depositional environments were described.

Reservoir properties were gathered from existing routine core analysis results, completed for TOTAL Exploration & Production Thailand. The data includes permeability to air, helium injection porosity, and grain density determinations. Petrographic observations were also integrated, comprising the information on the rock composition by point counting, grain sizes, and evaluation of visible porosity. Moreover, constituents of sandstones were obtained from X-Ray diffraction analysis (XRD) at the same depths as selected plug samples.

This study used a cluster analysis technique to document the distribution of porosity and permeability in 2E reservoirs. In order to classify the reservoir into different flow units, core-derived porosity and permeability from 4 wells (A1, A2, A4, and A7) were used.

4. Results and interpretations

4.1 Sedimentary Facies

By integrating sedimentary textures, sedimentary structures, mineral compositions, and reservoir properties, eleven sedimentary facies were identified:

Facies Ss: Structureless medium-grained sandstone

This facies (Fig. 4A) consists of beds up to 4-6 m thick of medium- to fine-grained sandstones without any preserved primary sedimentary structures. Commonly, this facies contains scattered plant debris. Clay rip-up clasts are occasionally found, corresponding to erosive and amalgamated bases. The presence of structureless sandstones in this facies is probably related to high-energy depositional setting where there was rapid deposition. This facies is most likely a fluvial channel deposit.

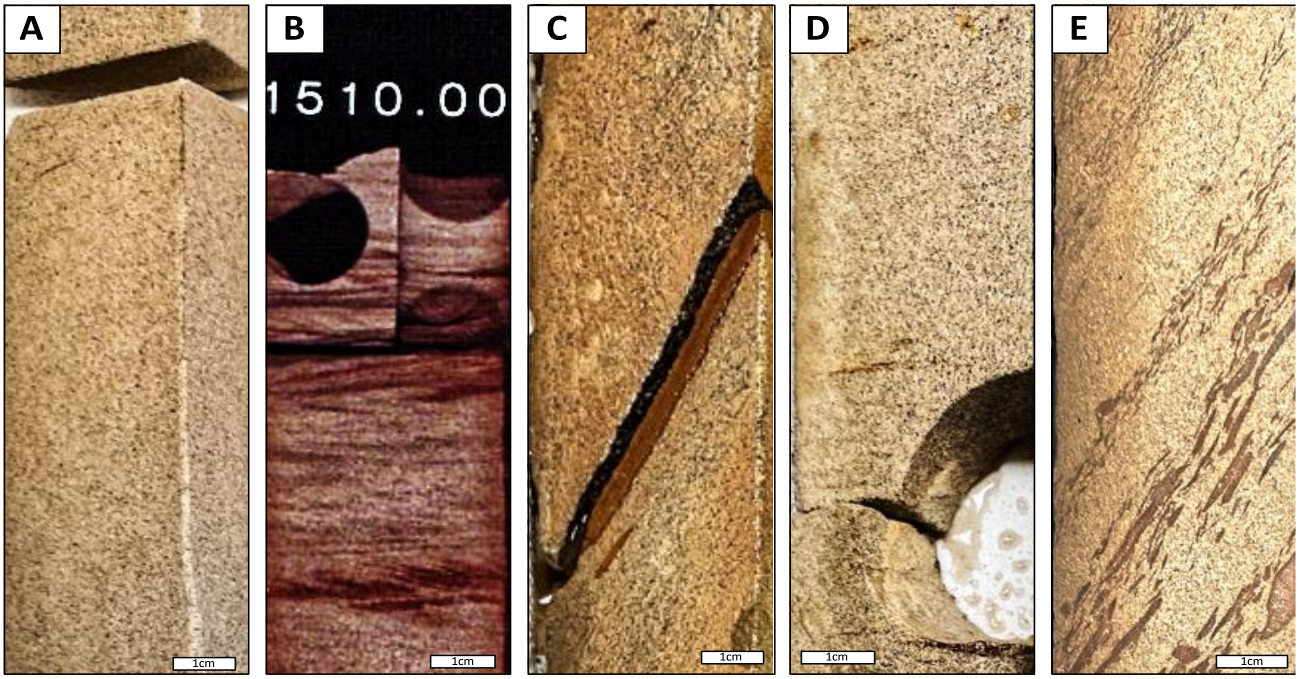

Figure 4. Selected core photographs from the study area, depths correspond to the top of each sample. A) Facies Ss – Structureless coarse- to medium-grained sandstone (well A1, 1491.10m). B) Facies Sx – Trough to planar cross-bedded, medium- to fine-grained sandstone (well A1, 1510.50m). C) Facies Sx – Trough to planar cross-bedded with clay rip-up clasts, coarse- to medium- grained sandstone (well A4, 1889.45m). D) Facies Sr - Current ripple-laminated sandstone with abundant plant debris (well A1, 1509.80m). E) Facies Sm - Mud-clast brecciated sandstone, showing intense accumulation of clay rip-up clasts during major flood event (well A4, 1863.80 m).

Facies Sx: Planar to trough cross-stratified sandstone

Facies Sx is characterized by planar to trough cross-stratified (Fig. 4B), medium- to fine-grained sandstones. This facies is rarely interbedded with parallel-laminations, ripple-laminations, and mud-drapes. Occasionally, this facies is intercalated with mud layers ranging from a few millimeters to several centimeters thick. Rounded to sub-rounded elongated clay rip-up clasts are regularly observed in the basal part of the beds (Fig. 4C). Scattered plant debris are common throughout this facies and are more condensed in the cross-laminated foresets. The thickness of this facies ranges from 0.4 to 2.5 m, usually associated with Facies Ss and Sr. Biogenic structures are very rare (BI <1).

The presence of thick cross-bedded sand beds and the absence of any trace fossils suggest that the deposition occurred under relatively high energy conditions. Channel lag deposits are indicated by rounded and elongated mud rip-up clasts. According to these sedimentary features, this facies can be interpreted as channel-filled sediments.

Facies Sr: Ripple-laminated sandstone

This facies (Fig. 4D) mainly consists of fine-grained sandstones with current-ripple lamination and locally climbing ripples (frequently observed in well A1). Discontinuous mud drapes and plant debris are occasionally preserved. The lower contacts of this facies are gradual from the underlying Facies Ss and Sx. Meanwhile, the upper contacts are either abrupt to the overlying Facies Sx and Ss, or gradual to the Facies Sf. Climbing ripples, observed in well A1, overlies the trough cross- and parallel-laminated beds (Sx). Burrowing index is low (BI 0-2).

The occurrence of asymmetrical ripple laminations and, especially, climbing ripple laminations indicates rapid deposition by unidirectional currents with a high sedimentation rate. Since this facies commonly overlays cross-laminated sandstones, it was probably deposited in an upper point bar setting. This facies is also found in thinner beds that may have been deposited as crevasse splays or other floodplain deposits.

Facies Sm: Mud-clast brecciated sandstone

Brecciated mud clasts with a sandy matrix characterize this facies (Fig. 4E). Individual beds range from 0.2 to 1 m thick and stacked units can be up to 3-4 m thick. Mud clasts are typically in elongated shapes with long axes ranging between 2 to 66 mm. Internally, some clasts contain distinctive structures, such as laminations, while others are structureless (probably eroded fluid mud beds). Most of the facies can be described as matrix-supported, moderate to poorly sorted, with sub-rounded to sub-angular mud clasts. Cross-stratification is common throughout the unit where brecciated layers diminish.

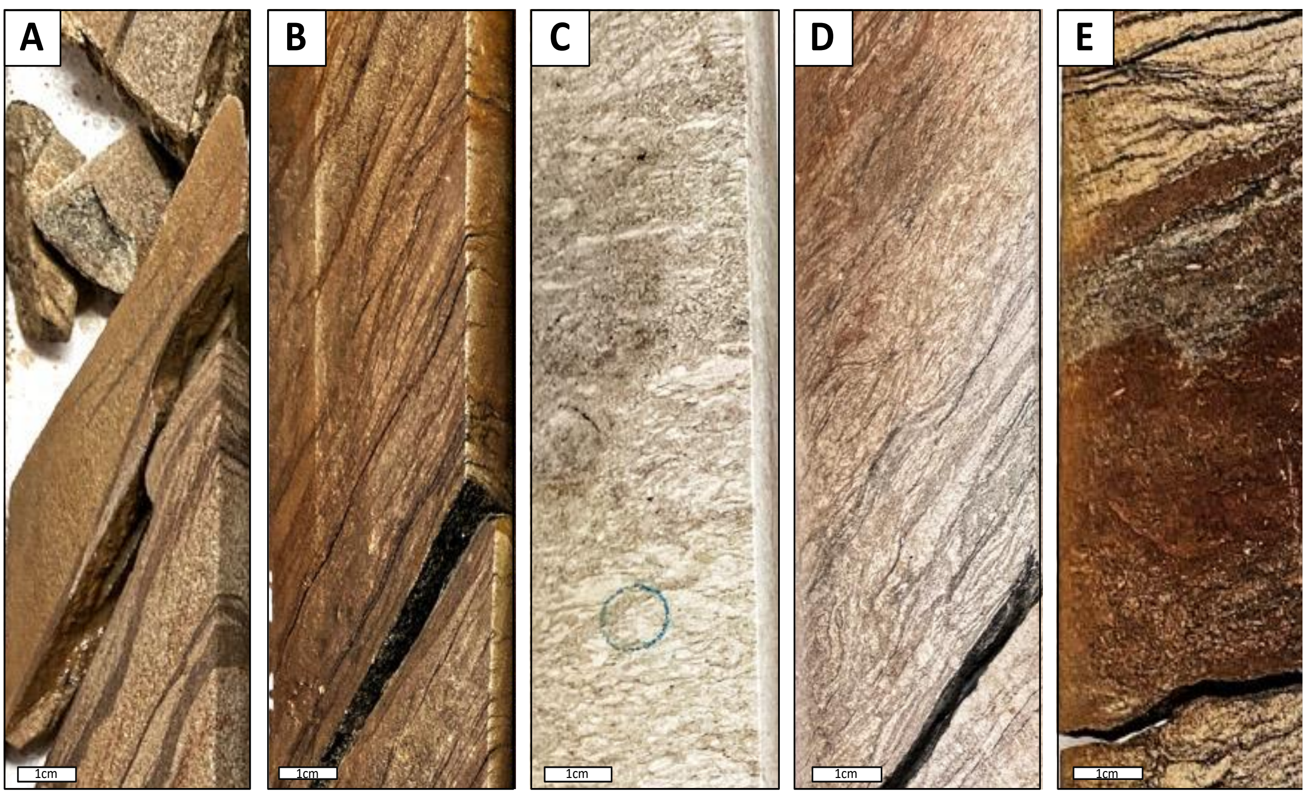

Figure 5. Selected core photographs from the study area, depths correspond to the top of each sample. A) Facies Sf – Muddy sandstone with flaser-bedding (well A4, 1851.55m). B) Facies Sf – Muddy sandstone with wavy-bedding (well A4, 1838.20). C) Facies Sb: Highly bioturbated sandstone (well A1, 1497.65m). D) Facies Sb: Highly bioturbated sandstone (well A4, 1840.15m). E) Facies Sc: Carbonaceous sandstone with very rich plant fragments (well A1, 1506.75m).

It commonly occurs with discontinuous carbonaceous drapes. This facies has only been observed in well A4 as stacked amalgamated beds with unclear contacts between each brecciated sand bed. The amalgamated brecciated sandstone overlies Facies Sx. Biogenic structures are absent.

The predominance of brecciated mud layers suggested a local source of numerous thin mud beds that were transported short distances and then rapidly deposited (Li et al., 2017). Two types of mud clasts, the floodplain-laminated muds and estuarine channel-fluid muds, are mixed and preserved as rip-up clasts. While the laminated muds were caused by cut bank collapse, fluid muds were carried by the tidal current from the mouth of the river and then deposited in the fluvial-estuary transition.

Facies Sf: Muddy sandstone with flaser- to wavy-bedding

These deposits are characterized by heterolithic beds of sandstone/mudstone facies, including flaser- and wavy-bedding (Fig. 5A, Fig. 5B). Current ripples and combined-flow ripples are common in the sand beds. Sandstones are medium- to fine-grained. In muddier intervals, mud drapes are relatively continuous, while they are more discontinuous in sandier intervals. Burrowing intensities are relatively low compared to Facies Sb, generally lower than 30% (BI = 0-2).

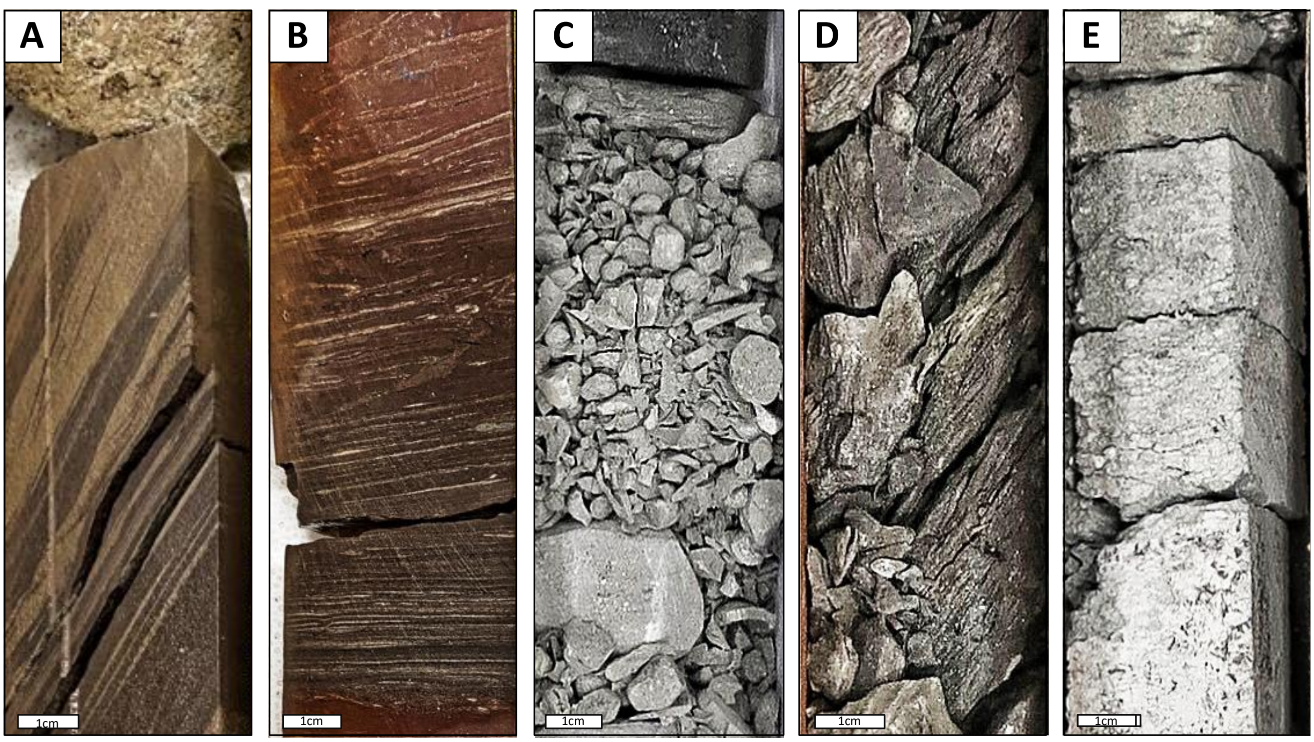

Figure 6. Selected core photographs from the study area, depths correspond to the top of each sample. A) Facies Ml: Sandy mudstone with lenticular-bedding, dominated by dark grey mudstone interlayered with sandy lenses (well A1, 1846.45). B) Facies Mp: Parallel-laminated mudstone, predominantly dark grey mudstone with sideratic cementation and sporadic burrowing (well A1, 1503.75). C) Facies Co: Coal (well A1, 1505.20 m) D) Facies Co: Organic shale with abundant plant fragments (well A4, 1794.15 m). E) Facies Ps: Paleosoils (well A1, 1495.45 m).

The presence of tidal features, including double mud drapes, fluid mud layers, and flaser beds, indicates tidal conditions that have daily cyclic variations in tidal energy. A limited number of burrow types suggested a stressed environment. The “stress” may have been caused by fluctuations in energy conditions, deposition rate, and/or variable salinity in an estuarine setting.

Facies Sb: Bioturbated sandstone

This facies mainly consists of fine-grained sandstones interbedded with mudstones. Primary structures are assumingly similar to Facies Sf, but are rarely preserved due to strong disturbance by intensive burrowing (Fig. 5C, Fig. 5D). Moderate to high diversity and density of burrowing is observed with a BI between 3 to 5, comprising various sizes of both vertical, sub-vertical, and horizontal burrows, ranging in size from several millimeters to centimeters.

High burrowing index and diversity of burrows indicate moderate to low energy, oxygenated, and almost open marine conditions. This burrowed sandstone facies was probably deposited in a tidally reworked mixed flats to sandflats depositional environments.

Facies Sc: Carbonaceous sandstone

Facies Sc is defined by sandstones with a very high concentration of plant debris (Fig. 5E) and a lack of preserved primary sedimentary structures. Grain size ranges from fine- to medium-grained sands, moderate to poorly sorted, mixed with various sizes of wood fragments. These facies have only been observed in well A1, where they overlay ripple-laminated sandstone of Facies Sr and are overlain by paleosoils (Ps).

Abundant plant remains and carbonaceous detritus have somehow represented the deposition adjacent to the terrestrial environment, suggesting deposition in a coastal plain depositional environment.

Facies Ml: Sandy mudstone with lenticular-bedding

This facies is dominated by dark grey planar-parallel laminated mudstones with thin sandy and silty laminae (Fig. 6A), considered as lenticular bedding. Occasional current ripples, combined-flow ripples, and syneresis cracks can be observed. Absent to sparse burrowing, comprising millimeter-scaled horizontal burrows and millimeter- to centimeter-scaled vertical to sub-vertical burrows, is classified as escape burrows. Slightly low bioturbation index (BI = 0-2) and diversity within sandy mudstones may indicate restricted environments.

Varying bioturbation intensity and syneresis cracks correspond to water salinity, energy condition, and sedimentation rate fluctuations. Silty to sandy laminae represent periodic high-energy events where the sediments are derived from the fluvial influx. The sedimentary features that appear in this facies are possibly deposited under tidal flats depositional environments.

Facies Mp: Parallel-laminated mudstone

This facies are characterized by parallel-laminated to structureless, dark grey to reddish mudstones (Fig. 6B) with the thickness ranging from 0.2-8 m and the average is 3 m. The basal and upper contacts are either sharp or gradational: normally interbedding with Facies Ml or abruptly overlain by Sb, Co, and Ps. Siderite nodules and sideratic cementations are regionally present. Biogenic structures are very rare to uncommon (BI<1).

The sedimentary features of this facies indicate low energy depositional setting. Low diversity and intensity of trace fossils suggested that this facies was probably deposited in a coastal plain or prodelta setting.

Facies Co: Coal and organic shale

Facies Co consists of coal and organic shale (Fig. 6C, Fig. 6D). Thickness varies from 5 cm to 1.5 m. Upper contacts are generally sharp and can

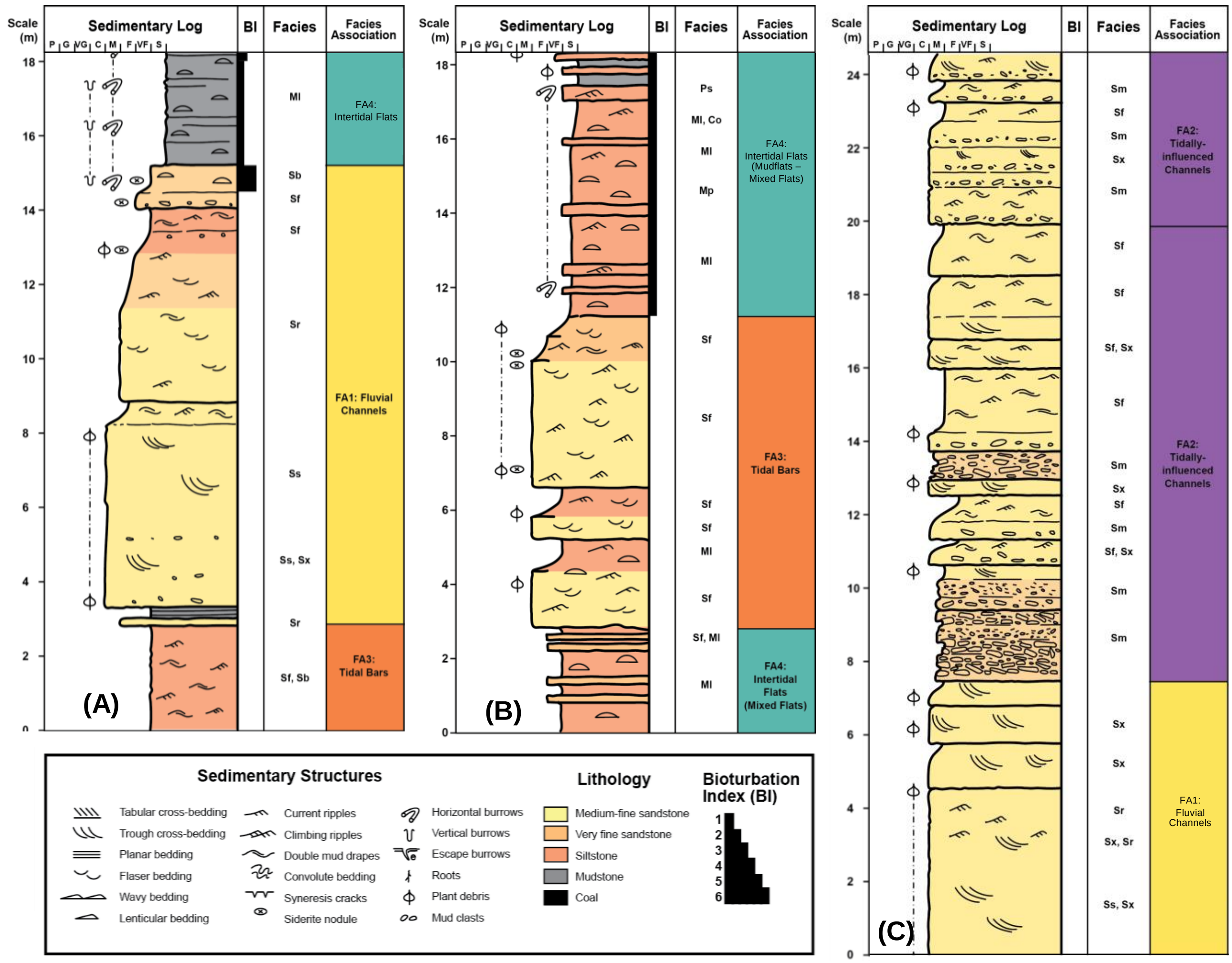

Figure 7. Representative core description logs showing: (A) vertical successions of fluvial channel passing gradually into intertidal flats (well A4), (B) FA3-tidal bars (well A7) passing gradually into intertidal flats, and (C) vertical successions of fluvial channels overlain by FA2- tidally influenced stacked channels (well A4).

be overlain by either Sb, Sf, or Ml, while the basal contacts are gradational and overly paleosol unit (Ps).

These coals or organic-rich shales were generally deposited in a poorly drained swamp or marsh in a coastal plain depositional setting. Additionally, this facies is also associated with channel-fill deposits in the upper part of abandonment channels

Facies Ps: Paleosoils

This facies is characterized by light grey mottled mudstones with abundant rootlets and plant fragments (Fig. 6E). This facies lacks preserved primary structures. However, rare slickensides can be seen in cores. The upper contacts were typically overlain by coal (Co), and some were cut by sharp contact and followed by coarser-grained deposits, as shown in well A1 (depth 1495.2 m).

In this facies, the presence of rooted mudstone is probably related to mud deposition during floods followed by the subaerial exposure period that punctuated the flood plain cycles.

4.2 Facies Associations

Facies association is organized by using several of the lithofacies as described above, which are directly related to depositional environments. Four main types of depositional environments can be distinguished:

FA1: Fluvial channels

These sand bodies consist of classic fining-upward sequences of fluvial deposit. The sequences have cross-laminated sandstones (Sx) in the lower part with abundant plant debris and locally clay chips and they are commonly interbedded with massive sandstones (Ss). These facies are frequently overlain by ripple-laminated sandstones (Sr) and are capped by carbonaceous sandstones (Sc). Occasionally, the top of the succession is paleosoils and coal.

Moreover, abundant plant fragments and sideratic cementation probably indicate deposition on a coastal plain.

The complete sequences of this facies association form fining-upward succession, commonly 5 to 12 m thick. The overall net to gross is approximately 60% sand and it can be as high as 100% sand. Representative lithostratigraphic profiles of this facies association are shown in Figures 7A.

FA2: Tidally influenced channels

This facies association is characterized by amalgamation of brecciated sandstone beds (Sm) that are typically interbedded with cross-laminated sandstones (Sx) and occasionally intercalated by discontinuous mud drapes sandstones (Sf). These packages are overlying stacked fluvial channel succession (FA1), with an overall thickness of 17 m (Fig. 7C).

Tidal currents are evidenced by flaser beds, double mud drapes within current rippled sandstones, and eroded fluid mud clasts within brecciated mud layers.

Fluid-mud layers can be recognized by structureless to faintly laminated nature and are commonly interbedded with coarser grains that form the specific alternated association of river-flood sands and tidal-dominated fluid muds. Fluid muds indicate high suspended sediment concentration freshwater flow mixed with brackish water. This feature is most likely to occur at the channel bottom, where a main distributary channel discharge is mixed with brackish water in an estuarine setting.

FA3: Tidal bars

These deposits are characterized by the interbedding of cross-beds and tidal bundles (Sx, Sr, and Sf), regularly observed in wells A4 and A7 (Fig. 7B). Current ripple-laminated beds typically developed at the topmost of this succession. During the flood portion of the tidal cycle, bed set thicknesses and grain sizes usually decrease upward. Biogenic structures tend to be limited due to the rapid deposition of bedforms. The thickness of individual bar units observed from cores ranges from 0.7 to 1.2 m, and stacked bar sand bodies can be as high as 7-8 m.

FA4: Intertidal flats

This facies association is mainly composed of fine-grained deposits in paralic setting. Intertidal flats commonly contain interbedded flaser-, wavy-, and lenticular-bedding (Facies Sf-Ml) (Fig. 7B). These deposits can be subdivided into three main depositional areas: mudflats, mixed-flats, and sandflats.

Mudflats predominantly deposit dark grey silty to sandy mudstones, with parallel lamination and lenticular-bedding (Mp, Ml), interbedded with coal and saltmarsh paleosoils sediments. Bioturbation is usually moderate to high intensity, but tends to be low diversity due to a restricted environment. Discontinuous silty- to sandy lenses are very thin, mostly less than 1 cm thick.

Mixed flats and sandflats contain relatively coarser sediments than the mudflats and can be characterized by flaser- to wavy beds, ripple lamination, common bioturbation, and occasional combined-flow, which corresponds to Facies Sf and Sb. Tidal bundles are generally observed in these fringing facies, presented by abundant mud couplets and neap-spring tide cycles. Bioturbations are varied, ranging from uncommon to high intensities. Relatively high diversity is observed in Facies Sb with various sizes of burrows, including horizontal, vertical, and sub-vertical burrows. Some sub-vertical burrows can be defined as escape burrows with sizes 2 – 5 cm long.

4.3 Depositional environments

Depositional environment interpretation in this study is based on the presence of distinctive primary sedimentary and biogenic structures.

As a result, several indicative features have been observed from cores, and some of them allow us to recognize the tidal influence during deposition. These features include double mud drapes, heterolithic sediments, fluid mud layers, brecciated mud layers, and burrowing.

The spectrum of bedding between flaser, wavy, and lenticular bedding was interpreted to represent deposition by daily tidal variations and neap-spring tidal cycles. Accordingly, these

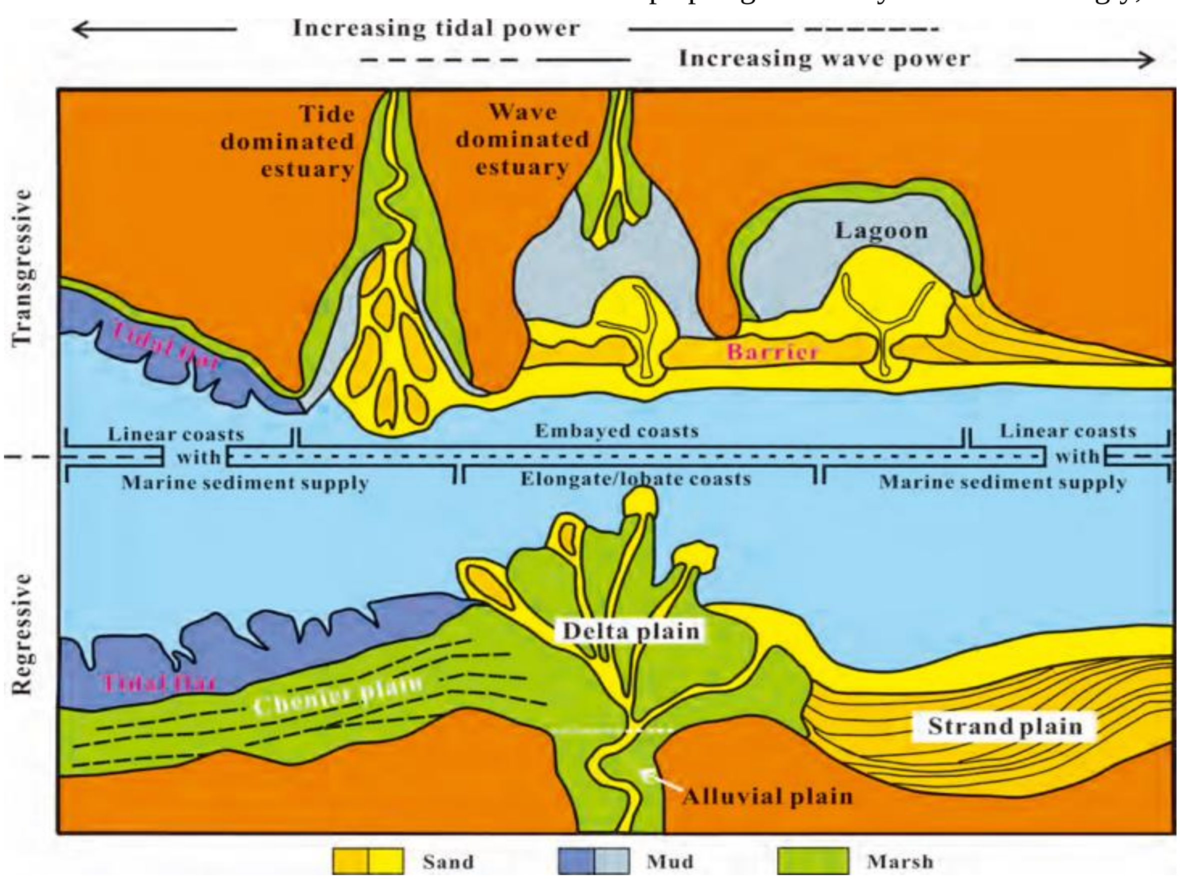

Figure 8 Distribution of major coastal depositional features during progradation (lower panel) transgression (upper panel), based on relative power of river, wave, and tide. The tidal power increasing to the left, (Boyd, Dalrymple, and Zaitlin, 1992).

cyclic bundles are strongly suggested as a tidal process.

Furthermore, the increase in tidal currents and energy evidenced by immature clay rip-up clasts within brecciated mud layers (as seen in FA2) indicated a limited transportation distance during a short period of each flood tide (Li et al., 2017).

Homogeneous or faintly laminated mud layers more than 1cm thick are typical of fluid mud deposits (Davis & Dalrymple 2012). These fluid muds suggest deposition of suspended load due to mixing of fresh water and salt water. The mixing caused a very rapid deposition of muds that created structureless mud beds and especially settled at the channel bottom. The presence of fluid muds suggests an influx of sediment laden freshwater into a tidally dominated estuary.

Additionally, freshwater fluvial channels are also presented and are commonly interbedded with tidal-influenced bundles. Freshwater fluvial channels can be identified by the presence of several key features, including sand bodies with erosional bases that contains interbeds of structureless bedding, trough-cross bedding, and planar-cross bedding. These amalgamated channel sand beds are recognized in FA1 and predominated in wells A1 and A4 with fining-upward or blocky vertical successions. The thickness of these amalgamated channel sand beds ranges from 5 to 12 m. Sand bodies typically contain scattered plant debris and mud rip-up clasts due to adjacent terrestrial environments.

A depositional diagram in Figure 8 is considered as a good model for the 2E unit. Regarding this diagram, the study area is believed to be located at the left end, where tidal energy increases significantly. As a result, the progradation of fluvial channels (FA1) was developed in a tide-dominated delta environment during regression (lower panel of the diagram in Fig. 8). It was replaced by tidally influenced channels (FA2) and tidal flats (FA4) in tide-dominated estuary environment during transgression (upper panel of the diagram in Fig.8). Sub-environment within tide-dominated estuary can be identified for each facies association. For example, tidally influenced channels (FA2) and tidal bars (FA3) are most likely to be deposited within the estuary funnel, where tidal energy dominates during tidal variations. In contrast, fluvial channels (FA1) are deposited in a more proximal area, possibly situated in the fluvial-tidal transition zone or upper estuary channels during river floods.

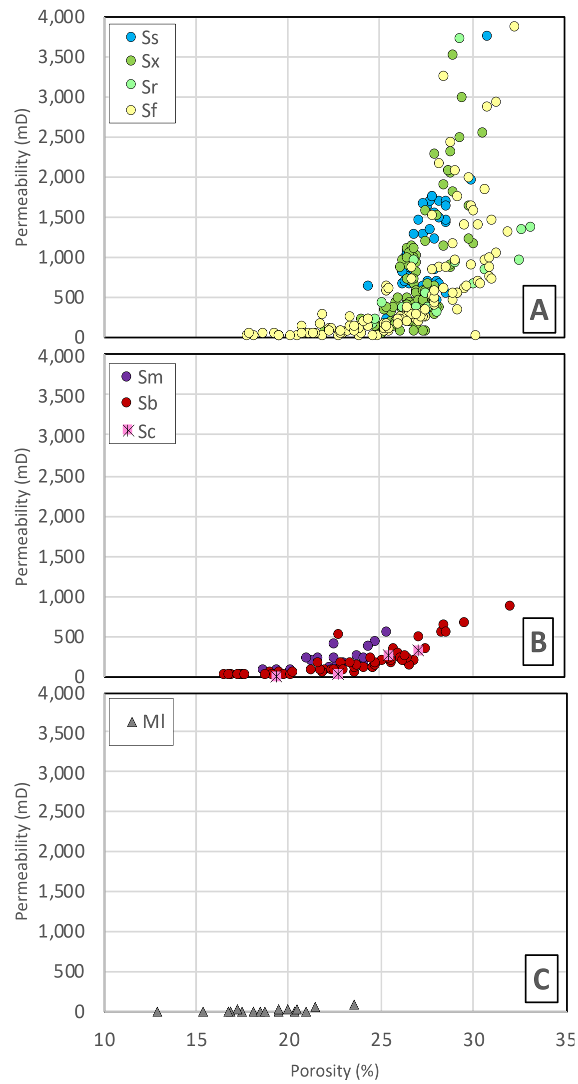

Figure 9. Porosity-permeability cross-plots for three main flow units, colored by lithofacies. 1) FU1: stratified sandstone, 2) FU2: heterogeneous sandstone, and 3) FU3: muddy sandstone

4.4 Reservoir Characteristics

By integrating the results from sedimentary facies and the porosity-permeability relationship, three major flow units can be categorized:

FU1: Stratified sandstone

This flow unit comprises facies Ss, Sx, Sr, and Sf, dominated by coarse- to fine-grained sandstones with various types of bedforms, such as cross-beddings, ripple-laminations, flaser- to wavy-bedding, and structureless features.

Core porosities and permeabilities were measured on 298 core plugs. Porosity ranges from 17 to 33% and has an average of 27%. Permeability ranged from 2.8 to 3848 mD with an average of 701 mD (Fig. 9A). Although the sedimentary structures of all these facies are different, they still exhibited high values of porosity and permeability compared to the other reservoir units. Within this unit, the different facies have important variations in reservoir properties

FU2: Heterogeneous sandstone

This unit mainly contains medium- to fine-grained sandstones with significant features that impact reservoir quality, such as carbonaceous. material, bioturbation, or brecciated mud layers (facies Sc, Sb, and Sm).

Core plug porosity from this group ranges from 16 to 32% and an average of 22%. Permeability ranges from 0.26 to 838 mD with an average of 162 mD (Fig. 9B). Compared to the stratified sandstone unit, the chaotic and heterogenetic textures presented within this reservoir type probably exhibit decreasing porosity- permeability trends. Additionally, the amount of burrowing is considered one of the critical factors that control the range of porosity and permeability.

FU3: Muddy sandstone

Facies Ml has low core porosities and permeabilities, as shown in Figure 9C, due to the predominant mud lamination and high intensity of bioturbations. Porosity ranges from 13 to 23% (averaging 18%), and permeability ranges from 0.07 to 70 mD (averaging 13 mD).

As seen in the studied cores, the 2E reservoirs consist mostly of channel and bar sands. Reservoir quality for this unit is relatively good to excellent, with an average of 25% porosity and several hundreds mD of permeability.

Thick vertically-stacked channel bodies are frequently observed, consisting of fluvial and tidally influenced channels, generally 5-12 m thick. Channel thicknesses from the core investigation are comparatively aligned with the channel thickness trend from the entire study area, which ranges from 0.5 to 50 m. Regarding thick sand bodies, these reservoirs are expected to be traced easily on any amplitude maps. Hence, a detailed analysis of seismic anomaly is strongly recommended to reduce the exploration risk.

Although sand bars do not predominate the studied core interval, they are often presented in well data. The thickness of the individual bar units observed from cores ranges from 0.7 to 1.2 m and stacked sand bodies can be up to 7-8 m.

5. Conclusions

Unit 2E of Block A in the North Malay Basin was deposited in a paralic setting during Middle to Late Miocene. Overall, the depositional setting can be characterized as tide-dominated delta and estuary, where fluvial channels deliver sediment to a basin with significant tidal energy.

Fluvial/deltaic processes and tidal processes were active at the mouth of the river. Away from river input, sediment was reworked dominantly by tidal currents.

Eleven lithofacies have been recognized in cores based on facies analysis. Sandstone-dominated facies (Ss, Sx, Sr, Sm, Sc, and Sf) were commonly deposited near the mouth of the river, including fluvial channels, tidally dominated channels, and tidal bars. Sediments were initially deposited as fluvial channels in the areas near sediment influx into the basin and were reworked by tidal currents to be deposited on tidal bars in the distal areas, away from river input. In contrast, the mudstone-dominated facies (Ml and Mp) and bioturbated heterolithic facies (Sb) indicated lower energy conditions, such as tidal flats deposits. Sometimes the mud-dominated facies could be away for large distances from the active channel.

Based on porosity-permeability cross plots, three flow units were identified. These flow units, ranked in order of decreasing average porosities and permeabilities, are (1) FU1: stratified sandstone (Ss, Sx, Sr, and Sf), (2) FU2: heterogeneous sandstone (Sc, Sb, and Sm), and (3) FU3: muddy sandstone (Ml).

The cluster plot shows an excellent relationship and provides a new insight between the porosity and permeability of each facies. The reservoir heterogeneity seems to be associated with lithofacies, sand body types, and depositional settings. Reservoir qualities are good to excellent in the stratified sandstone unit, with average porosity of 27% and several hundreds of mD to 3.8 D of permeability. In contrast, lower quality reservoirs are observed in the other two units: heterogeneous sandstone and muddy sandstone units; permeability is significantly low, generally less than 100 mD.

The reservoir properties of the 2E unit in the North Malay Basin are controlled by the depositional setting. In the more tidally influenced units, the common occurrence of brecciated mud layers, mud drapes, and highly bioturbation has a significant impact on reservoir permeability that would affect both production and injection rates, thus influencing the future development of 2E unit.

6. Acknowledgements

I would like to express my sincere thanks to my thesis supervisors, Professor Joseph Michael Boyles and Professor Thasinee Charoentitirat for technical guidance, constant encouragement and constructive suggestions throughout this research. I would like to thank PTT Exploration and Production Company Limited for the financial support for database contribute to this research. Appreciation is given to PCRC staffs for supporting and providing core data.

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