SEQUENCE STATIGRAPHY AND RESERVOIR HETEROGENEITY OF THE SERANG FIELD, KUTEI BASIN, INDONESIA

By

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ABSTRACT

The late Late Miocene sandstone reservoirs of the Serang Field, offshore Mahakam Delta, Indonesia, are interpreted within a sequence stratigraphic framework to explain relationships of facies associations, reservoir heterogeneity within the field, and related sandstone distribution outside the field.

Well logs were correlated and interpretated, and compared with cores to get a reliable interpretation of probable depositional environments, and to obtain log analogs to facilitate interpretation of non-cored intervals. The Serang Field core studies recognized ten facies associations that represent fluvial-deltaic environments: (1) prodelta, (2) transgressive coastal plain to lagoon (calcareous mudstone), (3) lower delta front, (4) delta front bar, (5) tidal flat, (6) interdistributay bay, (7) distributary channel, (8) delta plain marsh and swamp, (9) fluvial/distributary channel, and (10) crevasse channel and crevasse splay.

The sequence stratigraphic analysis of the Serang Field sediments resulted in recognition of three intermediate-term cycles (IC's): IC 1, IC 2, and IC 3, which were further divided into short-term cycles. Overall, these cycles are landward-stepping, and represent a long-term base-level rise.

Reinterpretation of the stratigraphy of the Serang Field demonstrates that the main reservoirs of the Serang Field (the transgressive phase of IC 1 and IC 2) are incised valley fills (IVF's). The IVF's of IC 1 form a sheet sandstone geometry. The IVF's of IC 2 consist of three short-term cycles that may represent short-term incised valley fills (IVF's). The source of sediment was from the paleo-Mahakam Delta, southwest of the study area. Prospective sandstones that are time-equivalent of unconformities at the base of IVF's are expected basinward of the Serang Field.

As a result of landward stepping, younger stratigraphic cycles have greater reservoir heterogeneity. Reservoir rocks and permeability barriers in the Serang Field are best understood within a sequence stratigraphic framework. Because of increasing mud content and bioturbation seaward, the rank of sediment bodies that act as reservoir in decreasing order is: (1) fluvial/distributary channels, (2) distributary channels, and (3) delta front bars. The rank of permeability barrier in decreasing order is: (1) marine mudstones, (2) floodplain mudstones, (3) valley walls, and (4) mudstone intraclast conglomerates and drapes.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The research presented here is designed to determine the origin of the reservoirs of the Serang Field, Kutei Basin, Indonesia (Figure 1.1). The main thrust of this research is to place the late Late Miocene producing reservoirs of the field into a sequence stratigraphic framework. I have investigated whether the reservoirs are part of a highstand delta or part of a lowstand delta that filled one or more incised valleys, or a combination of both. The reservoirs consist of anomalously thick fluvial-deltaic sandstone bodies (up to 100 ft). Discontinuous mudstones separating amalgamated sandstones may act as vertical and lateral permeability baffles. Overlying channel incision controls the preservation of mudstones within the main reservoirs. These facts indicate that the main reservoirs of the Serang Field were deposited under low accommodation-to-sediment supply ratios.

The Serang Field is one of the producing oil fields that is operated by Unocal Indonesia. The main reservoirs in the field have been interpreted as (a) stacked, fluvial-deltaic channel sands (Clark et al., 1994), and (b) lowstand valley fill (Vo et al., 2000). The field is located in an elongate three-way closure that is bounded on the east by the giant Serang-Santan growth fault. The fault is 20 km long and has a throw of over 6500 ft down to the east towards the Makassar Strait. Based on nannofossil data, the deposition of Serang Field reservoirs was during the late Late Miocene (Van de Weerd and Armin, 1992). At that time, a lobe of the Mahakam Delta shifted to the Serang Field area (Van de Weerd and Armin, 1992; Snedden et al., 1996). Thick carbonates (in a general range of 50-70 ft) were deposited above the producing intervals. The presence of carbonates result in a carbonate pull-up effect on seismic reflections. The interpretation of seismic data is also complicated by a fault shadow effect, because the location of the main reservoirs is below the growth fault (Clark et al., 1994). Hence, seismic data does not help much for a detailed stratigraphic study of the Serang Field.

The Serang Field was first drilled in 1973, and it was thought to be non-commercial at that time (Clark et al., 1994). Reinterpretation of 2D seismic and acquisition of 3D seismic changed the status of the field from non-commercial discovery into a field with proven original oil-in-place (OOIP) of 55 MMBO and initial gas-in-place (IGIP) 225 BCF. Understanding of the seismic fault shadow and carbonate buildup problems from the reinterpretation of seismic data combined with additional drilled wells resulted in field extension to the north and south and gave rise to later reserve additions (Clark et al., 1999). The revised estimation of original oil-in-place (OOIP) is 89 MMBO, whereas the initial gas-in-place (IGIP) estimation is 142 BCF including a 61 BCF gas cap.

Production at the Serang Field started in 1993, and peaked by mid 1994. The reservoirs of this field have a large gas cap and strong aquifer support (Vo et al., 2000). As the field matured, the originally thick oil column became thinner and water production increased significantly. By early 1996, production started to decline as a result of strong water influx. Horizontal wells drilled in this field since 1996 maintain the field production and optimize development from a thin oil column under the large gas cap and mitigate the strong water drive (Vo et al., 2000). This technique can provide a larger drainage area and reducing gas and water coning that in turn can improve the recovery.

Production and pressure data cannot be used to resolve the compartmentalization in the Serang Field because the field has a common fluid contact and pressure (Jim Stites, 2002, personal communication). The pressure measurement is consistent for the same interval in every well, indicating that the measured pressure is the pressure of the water influx. The reservoir is thought to be laterally and vertically in communication for reservoir modeling (Vo et al., 1999).

Althought the role of mudstone breaks as barriers that compartmentalize the reservoir in the Serang Field is suppressed by the strong water influx, they may act as baffles in future stages of development. A detailed stratigraphic analysis might help in better understanding the Serang Field and other similar fields; by recognizing baffles, the horizontal wells can be placed more precisely and the reservoirs can be drained more efficiently.

1.2 Research objectives

The objectives of the study are:

1. To put the Serang Field into a sequence stratigraphic framework.
2. To analyze the sandstones for heterogeneity and reservoir compartmentalization.
3. To predict sandstone distribution within and outside the field.

1.3 Arrangement of the report and products

This report consists of seven chapters:

1. Introduction. The purpose of this chapter is to give an introduction for the Serang Field location, the objectives of the study, hypotheses proposed, available data, and previous studies that have been done by other authors.
2. Methods of investigation. The purpose of this chapter is to describe the methods that were used in this study.
3. Regional geology. The purpose of this chapter is to put the study area in perspective with its regional setting.
4. Core studies: description and interpretation. The purpose of this chapter is to document the cores in text and graphically and propose interpretations of the depositional environments. The log responses of the corresponding cored interval were used as analogs to interpret the depositional environments of non-cored intervals.

5. Sequence stratigraphy in the Serang Field. The purpose of this chapter is to give an overview regarding the sequence stratigraphic analysis used in this study, the stratigraphic hierarchy, comparison between the incised valley fill versus freely migrating river systems, description and interpretation of sequences, and the proposed depositional model.
6. Sequence stratigraphy applied to reservoir heterogeneity and sandstone distribution in the Serang Field. The purpose of this chapter is to provide an explanation for the reservoir heterogeneity expected and discuss the expectation of sandstone distribution.
7. Summary and conclusions. This chapter contains the summary and conclusions of the research.

Besides the written report, the products of this study include:

1. Core descriptions and interpretations for each cored interval (in Plates 1a-1f). Core photos are included on CD.
2. Seven cross sections, three approximately strike oriented and four approximately dip oriented, in Plates 2-3. There are two cross section scenarios: (1) IVF's, and (2) freely migrating channel systems. The cross sections presented in Plates 2-3 are part of IVF's scenario, whereas the freely migrating channel systems scenario is included on CD.
3. Net sand and paleogeographic maps for each sequence that are included in the text.

1.4 Research hypotheses

Some alternate hypotheses tested in this research are:

1. The sandstone reservoirs of Serang Field were deposited as:
    a. Freely migrating channel deposits
    b. Incised valley fills
    c. Some combination of both

2. The sediment source of the Serang field was from:
    a. Southwest of the field (paleo-Mahakam delta)
    b. Northwest of the field (paleo-Sangatta delta)
    c. Both directions
3. The reservoirs of the Serang Field are deposited as:
    a. Seaward-stepping cycles
    b. Landward-stepping cycles
    c. Vertically stacked cycles
    d. Combinations of some or all of a to c
4. The reservoir bodies that produce the most heterogeneity and compartmentalization are:
    a. Fluvial/distributary channels
    b. Distributary channels
    c. Delta front bars
5. During the deposition of the Serang Field reservoirs, the additional sandstone volumes were distributed more:
    a. Landward of the Serang Field
    b. Basinward of the Serang Field

1.5 Research Contributions

The main contribution of this research is to give a better understanding of the genesis of the reservoirs of the Serang Field and their expected lithologic heterogeneity. This information can be applied to the future development of the Field and similar fields in the Kutei Basin and elsewhere. Mudstones may act as fluid-flow baffles. Because strong water influx is observed, baffles are considered as not effective in the Serang Field; however, they may compartmentalize reservoirs in other similar fields.

The other contribution of this research is to predict sandstone distribution outside the field, especially toward deep-water basinward of the study area. The transgressive phase of the intermediate-term cycle 1 in the study interval, which consists of thick and obvious amalgamated sandstone bodies, is considered to be connected with the reservoirs in some deep-water fields that are located basinward of the Serang Field (Art Saller, 2002, personal communication).

In this study several cycles are interpreted as descrete sequences; hence they are genetically not related to underlying and overlying cycles. By understanding the genesis of the cycles and their stacking pattern, the distribution of the sandstone outside the field and the reservoir heterogeneity within the field can be expected.

1.6 Data

The data set available for this study includes: (1) six cored intervals from three wells, and (2) log data, which includes digital well logs from 76 wells and mud log data from 30 wells. Seismic data were not used because carbonate pull-up and fault shadow effects complicate seismic interpretation. Production and pressure data were not used because the strong water drive results in consistent production trends and pressure measurement in the Serang Field.

1.6.1 Core data

Cores are available from three wells: SA-2RD, SA-5 and SA-3 RD2. The total thickness of core studied is about 392 ft. The SA-5 well has a total of 144 ft, the SA-2RD has a total of 145.6 ft, and the part of SA-3 RD2 core that is described is 102.5 ft thick. Not all available cores in the SA-3RD2 were studied because some were from below the studied interval; however, the interval 7601-7662 ft of SA3RD2 cores that are located below the studied interval were also studied and used as comparatives with studied intervals because they contain log responses that are similar to those that exist in the studied interval. Table 1.1 shows cores available for this study.

1.6.2 Log data

Of the 76 well logs available for this study, only 50 were used because some of the logs penetrate the hanging wall part of the field, some only penetrate shallower zones, and others present unsolved problems in calculations of their coordinates and depth.

The logs available for this study are gamma ray, resistivity, sonic, neutron, density, and caliper. All available logs were used in correlation. In some wells mud logs are also available. Mud logs provide information about rock types; however, information about bed thickness is very approximate and the details of sedimentary structures cannot be seen. Mud logs can be used as ground truth for lithologic interpretations derived from well logs.

1.7 Location

The study area, the Serang Field, resides within the Unocal Indonesia concession area in East Kalimantan, Indonesia. It is located in the Makassar Strait, northeast of the modern Mahakam delta, about 25 kilometers from the shoreline, and 12 kilometers north of the Attaka Field, one of the largest oil field in Indonesia (Figure 1.1). The Serang Field is located at 325 meters water depth.

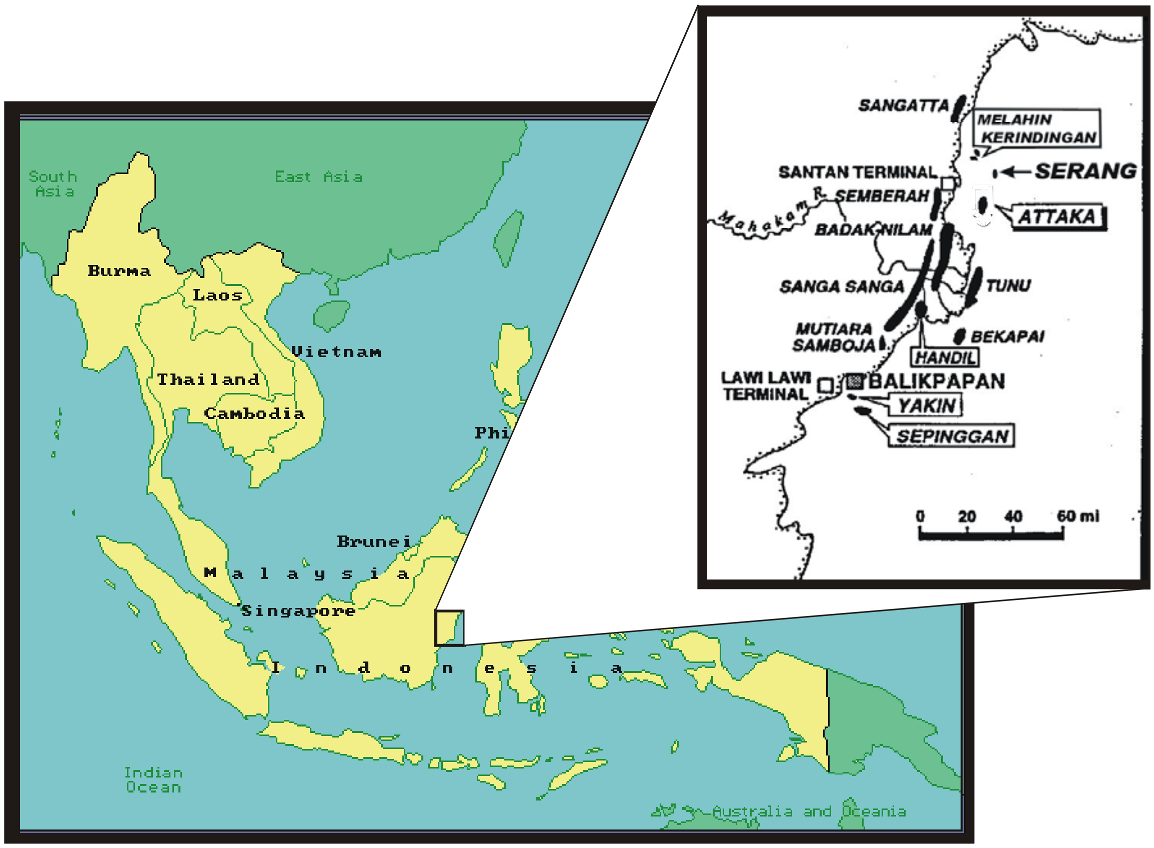


Figure 1.1: Location map of the Serang Field. Black spots indicate locations of oil fields.

Table 1.1:List of cores that were studied with the approximate length and approximate log depth

Interval	Approximate thickness	Approximate log depth	Depth correction
SA-2RD			
8196.4-8251.0	54.6	8197.4-8252.0	+1
8651.0-8742.0	91	8652.1-8674.3	+1
SA-5			
6553.0-6615.0	62	6554.0-6616.0	+1
6950.0-7032.0	82	6953.0-7035.0	+3
SA-3RD2			
7601.0-7662.0	61	7626.1-7682.0	+24
6587.0-66628.5	41.5	6607.0-6648.5	+4

1.8 Previous studies

The stratigraphy of Kutei Basin has been studied by several authors (e.g., Marks, 1982; Nuay, 1988; Wain and Berod, 1989; Van de Weerd and Armin, 1992). In their studies, they used different names for the formations that results in confusing lithostratigraphic nomenclature (Figure 1.2). The confusing lithofacies terminology used, especially for the Neogene stratigraphy, resulted from misunderstanding of the nature of cyclic deltaic stratigraphy and the nature and timing of tectonic inversion events (Allen and Chambers, 1998).

Armin et al. (1994) did a regional study of the stratigraphy of Unocal Indonesia's Northern Offshore Block and Attaka Unit. Their study is a Unocal internal report and was not published. The goals of their study were to build a regional stratigraphic framework, mapping the sandstone reservoir distribution, and understanding the structural evolution of the region. They found fifteen regional stratigraphic boundaries in their study area. These are both regionally correlatable sequence boundaries and transgressive surfaces. They used unconformities as sequence boundaries, and considered a surface that marks a landward shift depositional environment as a trangressive surface. Estimations of the ages of the strata were derived from nannofossil data.

Serang Field is a part of the Armin et al. (1994) study area. They identified one regional sequence boundary and one regional transgressive surface in my study interval in the Serang Field. Their sequence boundary matches with lowstand surface of erosion 1 (LSE-1) of this study interval, whereas their transgressive surface is located about 3 ft above the maximum flooding surface 2E (MFS-2E) in this study. Their transgressive surface was picked at a log marker, known as the RT marker or beta marker, characterized by a kick in low resistivity representing high smectite content (Armin et al. 1994). Sandstones above and below the marker have different mineralogy. The sandstones above the RT marker are volcanoclastic rich, whereas the sandstones below the RT marker are more quartzose. The difference of rock properties above and below the RT marker results in difference of amplitude in seismic data that can be traced regionally.

Several field-scale studies in the Mahakam Delta area have been published, such as Attaka Field (Schwartz et al., 1973; Trevena et al. 1993), Bekapai Field (De Matharel et al., 1976, 1980), Handil Field (Verdier et al., 1980), Badak Field (Huffington and Helmig, 1980, 1990), Sanga Sanga Field (Ferguson and McClay, 1997; McClay et al. 2000), Nilam Field (Butterworth et al., 2001), and also Serang Field (Clark et al., 1994, 1999; Vo et al., 1999, 2000). Location of the oil fields is on Figure 1.1. Mainly the focus of those studies is on the structural style of the region, sandstone distribution pattern, and petroleum system.

Recent studies recognized incised valley fills in the Nilam Field (Butterworth et al., 2001) and in the Miocene outcrop in the Perjuangan Quarry (Hook et al., 2001). Butterworth et al. (2001) did a study of reservoir architecture of the Nilam Field, onshore Kalimantan by using a sequence stratigraphic approach to explain the occurrence and character of the producing interval, called the G053B sand. They described the G series stratigraphic interval in the Nilam field as a 45 m multistory distributary channel sandstone reservoir deposited in lower and upper delta plain environments at the base of

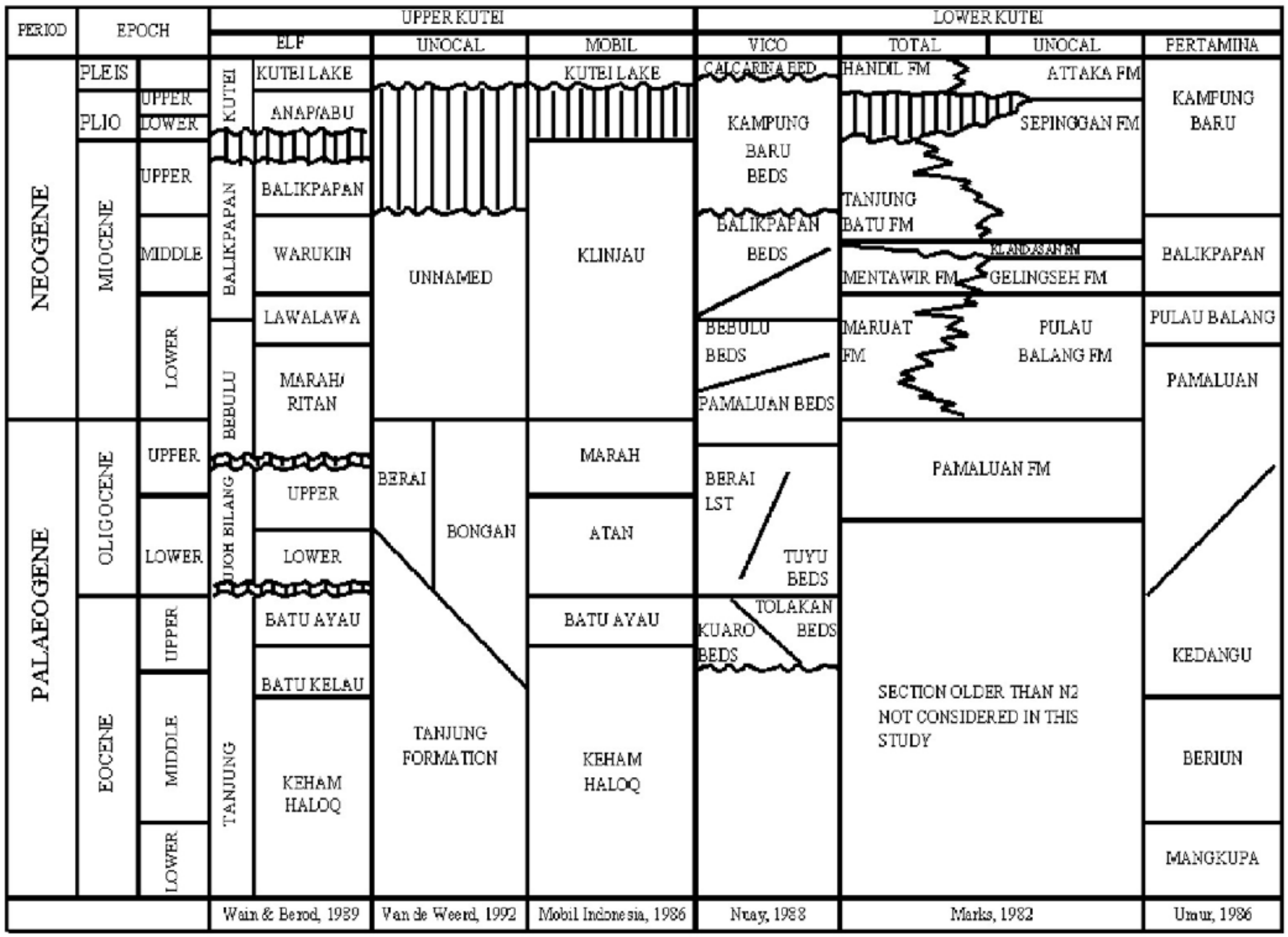


Figure 1.2: Summary of stratigraphic nomenclature of the Kutei Basin (modified from Allen and Chambers, 1998). The studied interval is upper Upper Miocene in age and is a part of Kampung Baru Formation.

the overall regressive Middle Miocene sequence. They interpreted the G053B sand as a back-filled incised valley. The interpretation of incised valley fill is based on these criteria: (1) gross morphology of the valley (3 km wide and 45 m deep), (2) evidence of incision and erosion of older stratigraphy, (3) significant basinward shift of facies associations, (4) development of interfluves, and (5) coeval fluvial to fluvial-tidal backfilling of the valley system.

Hook et al. (2001) did an outcrop study in the Perjuangan Quarry, near Samarinda, East Kalimantan, and reinterpreted the Lower-Middle Miocene succession that was previously considered as a single progradational cycle (Mora et al., 2000 in Hook et al., 2001). Hook et al. (2001) interpreted the outcrop as a mouth bar-channel couplet that was incised by a proximal channel Unit. They used the occurrence of a non-marine deposit above a marine deposit as criterion for an unconformity. Because the unconformity creates high relief, they interpreted it as incised valley. They also interpreted the outcrop as a fluvial-dominated deltaic succession instead of mixed fluvial-tidal deltaic deposits that are characteristic of the modern Mahakam Delta. They interpreted levee, crevasse splay, and interdistributary bay deposits. Because of the tidal influence, the modern Mahakam delta lacks those deposits (Allen and Chambers, 1998).

Study of reservoir characterization based on analyses of cores, logs, and subsurface maps in the Attaka Field was done by Trevena et al. (1993). They interpreted the reservoirs in the Attaka Field as Upper Miocene fluvial channel, distributary channel, and delta front bar deposits. The fluvial and distributary channel deposits are coarse- to fine-grained, cross-bedded, and have sharp erosional bases. Distributary channel sandstones can be distinguished from fluvial channel sandstones based on the burrows and mud drapes contents. The delta-front bar deposit is characterized by finer grain and more abundant bioturbation. The primary controls on porosity and permeability in the Attaka reservoir are depositional. The rank of porosity and permeability values in decreasing order is fluvial channel, distributary channel, and delta-front bar. Sand provenance and diagenesis also influence reservoir quality and performance. The shallower reservoirs (i.e., reservoirs above the RT marker) contain abundant volcanic rock fragments, feldspar grains, and smectite pore-lining cement that tend to decrease the porosity and permeability values.

Core study in the Serang Field was done by Siemers (1992) and Trevena (1996). Siemers did the core study in the SA-3RD2 and the SA-5 wells, while Trevena studied the SA-2RD well. The core studies were made for internal reports only and not published. According to Siemers' (1992) interpretation, the general depositional setting of the reservoirs of the Serang Field is in delta-like lobes of fluvial-dominated sediments that periodically prograded seaward across shallow-marine shelf deposits within a tectonically subsiding basin. This depositional style resulted in interstratified and interfingered vertical and lateral sequences of fluvial-deltaic and shallow-marine deposits.

Trevena (1996) did a core study in the SA-2RD well that consists of two cored intervals: 8196.4-8251.0 ft and 8651.0-8742.0 ft. He interpreted the upper interval as a succession of distributary channels and delta front bars with bay deposits capping the interval. The lower interval was interpreted as a succession of prodelta and low-energy delta front deposits that are truncated and overlain by tidally influenced channels followed by interdistributary bay and splay deposits that is truncated by fluvial or distributary channel deposits. In his report he also mentioned that Emiliano Mutti, a famous sedimentologist from Italy, interpreted the depositional environment for the lower interval as a delta shelfal lobe.

Table 1.2 shows the comparison of interpretations of major depositional environments of each cored interval by previous studies, and the interpretation in this report. There is an obvious difference in interpreting the upper interval of the the SA-2RD core. Trevena (1996) interpreted distributary mouth bar deposits above fluvial channel, whereas this study presents an interpretation of stacked fluvial/distributary channels with marine influence at the upper sand.

Table 1.2: Comparison of interpreted major depositional environments in the Serang Field by previous studies and this research

Interval	Interpretation of major depositional environment		
	Siemers (1993)	Trevena (1996)	This study
SA-2RD 8196.4-8251.0	-	Fluvial channel, distributary mouth bar, interdistributary bay	Fluvial/distributary channel, marine-influenced fluvial/distributary channel or estuarine channel, interdistributary bay
SA-2RD 8651.0-8742.0	-	Prodelta, low-energy delta front, distributary channel, interdistributary bay, crevasse splay, fluvial channel	Prodelta, lower delta front, fluvial/distributary channel, crevasse channel, crevasse splay
SA-5 6553.0-6615.0	Fluvial channel	-	Fluvial/distributary channel
SA-5 well 6950.0-7032.0	Fluvial channel, shallow-marine	-	Fluvial/distributary channel, interdistributary bay, transgressive coastal plain to lagoon, lower delta front, delta front bar
SA-3RD2 6587.0-6628.5	Fluvial channel	-	Fluvial/distributary channel
SA-3RD2 7601.0-7662.0	Delta front bar, shallow-marine	-	Delta front bar or distributary channel, lower delta front

CHAPTER 2

METHODS OF INVESTIGATION

2.1 Introduction

This study relies on well logs for correlations and interpretations of the Serang reservoirs. Only six cored intervals, from three wells that incompletely penetrate the studied interval, were available for this study. Fifty well logs were correlated and interpreted. Most of the well logs include gamma ray, resistivity, neutron, and density readings. Sonic and caliper logs were also available in some wells. In addition to electric logs, mud logs from some wells were also available. Mud logs were used as ground truth for lithologic interpretations derived from well logs.

In this Chapter, the methods of investigation that were used in this study are described. The methods include core descriptions, well log correlations, depositional environment interpretations, stratigraphic hierarchy recognition, net sand and paleogeographic maps, and reservoir heterogeneity and sandstone distribution analysis.

2.2 Core descriptions

Cores from SA-3RD2, SA-5 and SA-2RD were described in detail in order to get a reliable interpretation of sedimentological aspects and probable depositional environments. The sedimentological records found in cores and the interpreted depositional environments were tied to the log responses. The core-calibrated logs were used as analogs to interpret logs from non-cored intervals.

The cores were sketched by using a scale of 1 inch = 5 ft. In order to understand the history of deposition better, the cores were described stratigraphically from bottom to top, hence the naming of lithologic Units was done from the bottom (e.g., Unit 1 is the lowermost part of the cored interval). Most Units are separated by scour surfaces. Each

Unit indicates a depositional event and classified into facies. Facies were characterized based on textural properties of rock (i.e., grain size, sorting), colors, and physical and biogenic sedimentary structures.

Because the cores are located at the Unocal office at Balikpapan, Kalimantan, Indonesia, the first attempt in describing the cores was by core color photos, and comparing them with the previous core descriptions by Siemers (1992) and Trevena (1996).

In August 2002 a trip to Balikpapan allowed detailed study of the cores in person, and provided the opportunity to discuss them with Unocal sedimentologists, Art Saller and Art Trevena. There are some differences in descriptions and interpretations, especially for the SA-2RD core, and these will be explained later in the core descriptions chapter.

2.3 Well log correlation

All available wells were correlated in order to understand the depositional pattern in the Serang Field. For valleys, streams, or deltas, depositional dip direction can be estimated from the continuity of sandstone bodies, as they tend to be more continuous along depositional dip. For delta front sandstones, the sandstones are more continuous parallel to depositional strike.

Based on core study the amalgamated sandstones that built up the main reservoir of the Serang Field are interpreted as fluvial/distributary channels. Log correlation indicates that they are more continuous in southwest-northeast direction. It is assumed that the depositional dip is southwest - northeast and the depositional strike is northwest – southeast. In this study, seven stratigraphic cross sections, three with northwest – southeast orientation (Cross-sections A, B, C) and four with southwest – northeast orientation (Cross-sections 1, 2, 3, 4), were chosen (Figure 2.1). The cross sections are on Plates 2-3.

The first attempt in doing log correlation is defining and correlating the strongest events, such as regional transgressions. The next step is doing correlation of less continuous events, such as local transgressions. Correlation of the less continuous events must not cross the more continuous event. The discontinuity of an event may indicate erosion or regional unconformity.

After correlation is done, the next step is analyzing the organization of stratigraphic cycles by identifying significant surfaces for sequence stratigraphic analysis: lowstand surfaces of erosion (LSE's), transgressive surfaces of erosion (TSE's), and maximum flooding surfaces (MFS's). In this research, the naming of those three significant surfaces was given according to their sequence. For example, the LSE, TSE, and MFS for stratigraphic cycle 1 are called LSE-1, TSE-1, and MFS-1 respectively.

LSE's are caused by a lowering of base level, subaerial exposure, and incision of drainages into older deposits (Weimer, 1992). In this study, the LSE's are chosen as the sequence boundary. TSE's are caused by marine wave erosion that resulted from a rise in relative sea-level and water deepening (Weimer, 1992). MFS's are flooding surfaces that represent the maximum landward extent of marine deposits and are located at the center of condensed sections (Posamentier, 1998). MFS's were created when the basin was starved of terrigeneous material (Van Wagoner et al., 1990), usually during high sea-level.

Because a subsurface correlation is subjective (i.e., logs can be correlated in different ways), some criteria were needed as a guideline for correlation. A correlation style can differ for different area, depending upon the location of the studied area on the depositional dip profile (i.e., in coastal plain, shallow-marine, or offshore marine). Below is a summary of criteria used in this study in recognizing LSE's, TSE's and MFS's.

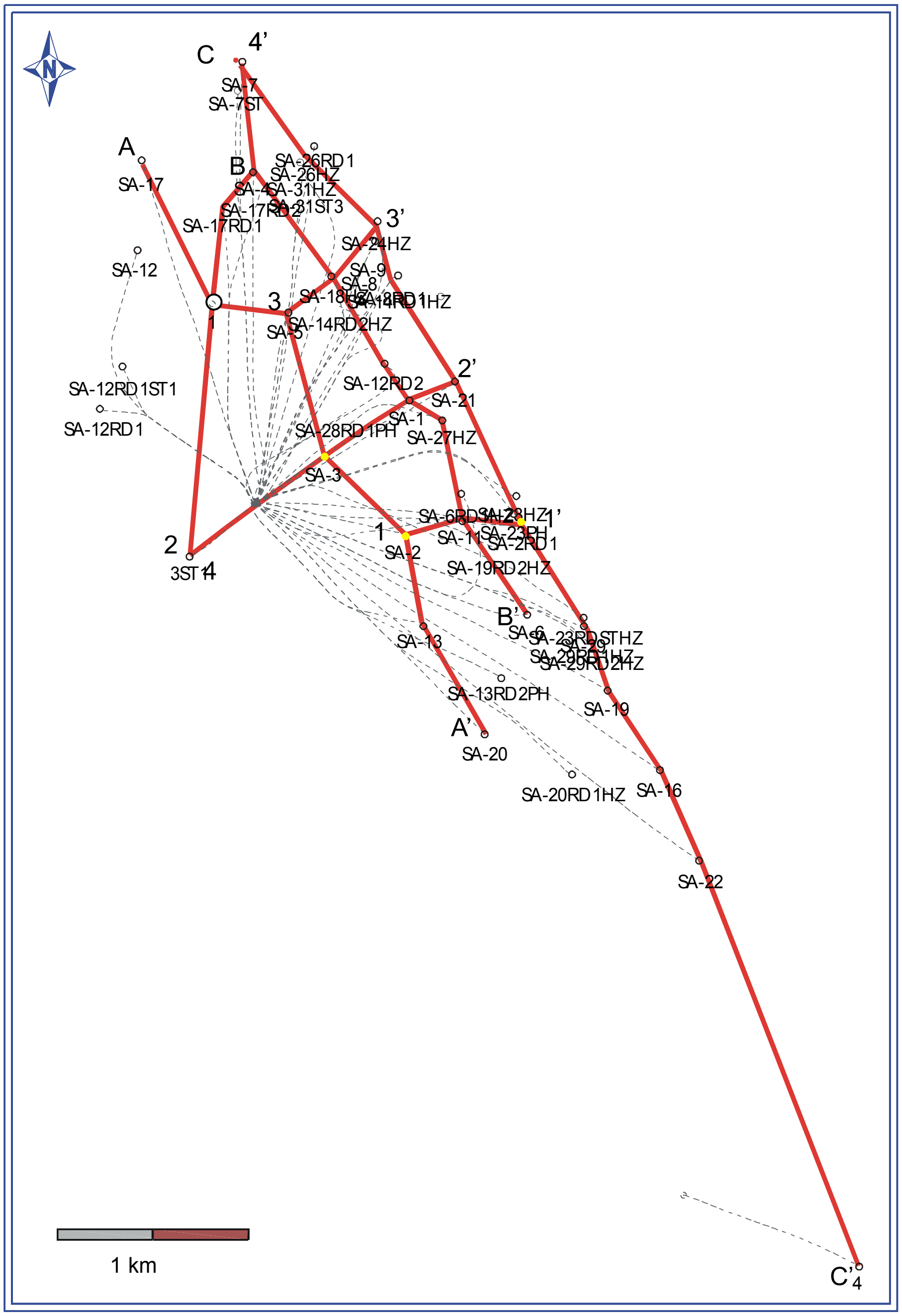


Figure 2.1: Base map of the study area with seven cross sections as displayed in Plates 2-3. Cross-sections A, B, and C are approximately strike-oriented, whereas cross sections 1, 2, 3, and 4 are approximately dip-oriented. Big circle indicates location of the SERANG-1 well that is used as the reference well in this study. Gray spots indicate location of cored wells.

2.3.1 Criteria for recognizing lowstand surfaces of erosion (LSE's)

According to Van Wagoner et al. (1990) the recognition of LSE's candidates is based on these criteria:

1. Abrupt basinward shift of facies associations. This criterion is indicated by a missing facies association that does not follow Walther's Law of Succession.
2. Marked contrast in grain size. A sharp contact on electric log between blocky fluvial sandstone and serrated sandy mudstone of delta front can be considered as a sequence boundary candidate.
3. Regional mappable extent of the surface. The wide lateral extension indicates that the incision was related to a significant fall in base level rather than simple channel switching or other normal progradational phenomena
4. Onlapping of younger strata onto the unconformity surface (e.g., onlapping of incised valley fills onto valley wall).

Besides those four criteria, increased channel clustering can be used as a criterion for recognizing LSE's in a non-marine setting (Shanley and McCabe, 1994). This interpretation requires two assumptions: (1) the low rate of accommodation results in a distinctive channel-stacking pattern, and (2) the sediment influx was constant and the increase of channel clustering is not related to an increase of sediment influx (Posamentier, 1998).

LSE's may merge with TSE's in the interfluves between incised valleys. Unconformities across the interfluves can be recognized by identifying base-level fall-to-rise turnaround at the contact between transgressive deposits above and regressive deposits below (e.g., floodplain deposits above and lower delta front deposits below).

Because fluvial channel sandstones laterally change facies association into overbank deposits, a non-marine succession does not always start with fluvial sandstone. Therefore, the base of a non-marine succession may be reflected by high gamma ray that indicates floodplain deposits or an upward-decreasing gamma ray log pattern that indicates crevasse splay deposits.

LSE's of short-term cycles reflect unconformities on a smaller scale. For example, channel belt incision can be considered as a lowstand surface of erosion for short-term cycles.

2.3.2 Criteria for recognizing transgressive surfaces of erosion (TSE's)

TSE's are surfaces that mark the first significant transgression. At that time channels are flooded and fluvial sedimentation ceases. TSE's are picked at the contact where there is evidence of greater marine influence over estuarine or non-marine strata. In subsurface data, TSE's are picked at the contact between low gamma ray with blocky log pattern below that represents channel sandstones, and increasing gamma ray above that represents transgressive coastal deposits.

Figure 4.7 shows an example of the identification of TSE using core and logs. Based on core study, the kick in low gamma ray, low neutron and low density (refer to Figure 4.7) represents carbonaceous mudstone that is interpreted as a transgressive coastal plain to lagoonal deposit. The carbonaceous mudstone indicates the presence of marine influence after the deposition of channel sandstones below. In this case the TSE is picked at the contact between the upward-increasing gamma ray log pattern that represents the waning of fluvial channel energy and the low gamma ray, low neutron and low density of transgressive coastal plain to lagoon deposits.

2.3.3 Criteria for recognizing maximum flooding surfaces (MFS's)

MFS's represent surfaces that exist at the time of maximum transgression of the shelf or maximum landward position of the coastline (Posamentier, 1998). During the time of maximum transgression relatively slow pelagic and hemipelagic sediments are deposited on the middle to outer shelf and beyond that results in deposition of a condensed section. MFS's are characterized by pronounced fine-grained marine mudstone within an overall muddy succession. MFS's are located at the center of condensed sections; they are picked at the contact between an upward-fining and upward thinning transgressive succession below and upward-coarsening and upward thickening regressive succession above (Posamentier, 1998). Condensed sections are thin deposits that result from relatively slow pelagic and hemipelagic sedimentation and represent relatively long periods of geologic time (Loutit et al., 1988).

In non-marine settings the criteria for MFS's are related to channel-stacking patterns and the channel-to-floodplain ratios (Posamentier, 1998). As a consequence of the increase of accommodation rate during the formation of MFS's, the alluvial plain is aggraded. The aggradation of alluvial plain is characterized with an upward decrease in channel-to-floodplain ratio. In coastal and shelf environments MFS's can be expressed as a tongue of brackish or coastal plain deposits that are interbedded with fluvial sediments. Coal, organic-rich mudstones, and thin carbonates are assumed to mark significant flooding events that represent the time of maximum transgression in these environments (Miall, 1996).

2.4 Interpretation of depositional environments from subsurface data

In this study, interpretation of depositional environments from subsurface data was done by using acceptable log interpretation methods and analogs to calibrate the log response of non-cored wells. Some log patterns, such as funnel, cylinder, bell, and serrated, are often discussed in the literature. Many researchers have related these log patterns to sandstone depositional environments (e.g., Coleman and Prior, 1982; Galloway and Hobday, 1983; Cant, 1992). Because any log pattern is not created by one specific interpretated depositional environment, the stratigraphic position of a log pattern relative to other log patterns is also considered in the interpretation of depositional environment using subsurface data.

Log analogs were tied to cores; therefore they were assumed to reflect the depositional environments as interpreted from the cores. The log analogs were gained from my core studies in the Serang Field and previous core studies in the Attaka Field

(Trevena et al., 1993). The Attaka Field is located about 12 km south of the Serang Field. Cores from the Attaka Field are in the same formation as those from the Serang Field.

2.4.1 Logs used for interpretation of depositional environment

The main log used for interpretation of depositional environment using subsurface data is the gamma ray logs; however, other logs are also useful in lithologic determination because not all physical properties of rock are recorded by gamma-ray logs. The gamma ray log measures natural radioactivity in rocks (Doveton, 1994). Mudstone has a high natural radioactivity, whereas sandstone and limestone normally have a lower natural radioactivity. Gamma ray can also be used in detecting organic-rich materials, as uranium is often naturally associated with organic materials.

Resistivity logs measure the electrical conductivity of the rock that is controlled by its fluid and mineral content (Doveton, 1994). This tool mainly provides information about the composition of pore fluids; however, resistivity logs can also be used to assist lithologic determination, as some minerals give distinctive patterns in resistivity logs (e.g., high resistive ash content may show a low resistivity kick, low resistive coal may show a high resistivity peak).

Sonic logs measure the velocity of sound waves in the formation (Doveton, 1994). Sonic velocity is dependent on the lithology and the porosity. More compact materials such as impermeable carbonate tend to have higher sonic velocity, whereas less compact ones such as coal tends to have low sonic velocity.

Neutron and density logs are very useful for porosity measurement (Doveton, 1994); however, they can also be used to assist lithologic interpretation. Neutron logs emit neutrons and measure the energy of returning neutrons that provides a measure of the porosity of the formation. Density logs work by emitting gamma radiation and detecting the proportion of the radiation that returns to the detectors on the tool. The amount of radiation returned is proportional to the overall density of the formation. The overlay of neutron and density logs can be used to aid lithologic interpretation. For example, carbonate tends to have low neutron and high density readings whereas coal tends to have high neutron and low density readings. On gamma ray logs both are characterized by low gamma ray readings.

2.4.2 Log analogs

The Serang Field core studies resulted in recognition of several depositional environments that suggest fluvial-deltaic environments. The log responses of cored intervals were used as analogs for the interpreted depositional environment. Core studies and analogs are discussed in Chapter 4. Figures 2.2 and 2.3 show log analogs from the Attaka Field. Below are relationship between log analogs and their interpreted depositional environments.

Prodelta to lower delta front tend to have serrated log pattern, as in Serang SA-2RD cores, SA-5 cores, and SA-3 RD2 cores (refer to Figure 4.3, 4.9, 4.11). Transgressive coastal plain to lagoon (calcareous mudstone) is characterized by a kick in low gamma ray, low sonic, high density and low neutron readings (refer to Figure 4.3). Delta front bars tend to have an upward-decreasing gamma ray pattern, as in Attaka D-11 cores and Attaka I-5 cores (refer to Figures 2.2 and 2.3). They may also have a thin, blocky log pattern, as in Serang SA-3RD2 cores (refer to Figure 4.12). Tidal flat deposits have a moderate gamma ray pattern, indicating the mud-prone nature of tidal flat deposits, as in Serang SA-3 RD2 core (refer to Figure 4.11). Interdistributary bay / embayment has an overall high gamma ray readings. Because bays consist of heterolithic facies, they may form upward-decreasing or upward-increasing gamma ray log pattern, as in Serang SA-2RD core (refer to Figure 4.3). At Attaka D 11 core, interdistributary bay is characterized by high gamma ray readings with upward-decreasing pattern (Figure 2.2).

Where fluvial and distributary channels are undifferentiated, I classified them as fluvial/distributary channels. Fluvial/distributary channels and distributary channels are characterized by low gamma ray with sharp base and blocky or bell-shaped profile. A serrated gamma ray log signature that is caused by muddy tidal drapes, as in D-11 core of the Attaka Field (Figure 2.2) may indicate distributary channels (Trevena et al., 1993). Interbedded channel sandstones with well-preserved abandoned channel fills that are capped by coal, as in SA-5 core (Figure 4.11), may also indicate distributary channels because coals are well developed in rising water-table environments. However, the absence of coal does not straight forward point to a fluvial channel interpretation. Unfavorable conditions for coal development (e.g., high sediment supply) in delta plain environments can produce high-energy multistory distributary channels without interbedded coal.

Distributary channels can also be recognized based on their stratigraphic position. Channels that are located in regressive phase of an intermediate-term cycle are interpreted as distributary channels because they tend to be limited in lateral extent and encased in delta front to lower delta plain environments. On the other hand, the channel belts that are located in the transgressive phase of an intermediate-term cycle are undifferentiated. They could be both fluvial channel or distributary channels. For these reasons, these channel belts are classified as fluvial/distributary channels.

Delta plain marsh and swamp deposits (coal) have high gamma ray, low density, and high neutron readings as in the Attaka D-11 core (Figure 2.2) and the SA-3RD2 (refer to Figure 4.11). In the SA-5 core (refer to Figure 4.9) coal is too thin (0.5 ft) and not resolved by the gamma ray tool. The density and neutron readings of the coal in the SA-5 core are similar to those of the SA-3 RD2 and the Attaka D-11, suggesting that density and neutron logs are more sensitive to coal compared to gamma ray log.

In the SA-2RD well (refer to Figure 4.3), crevasse channel and crevasse splay have an upward-decreasing gamma ray pattern that suggests an increase of energy of transportation. Crevasse channel is differentiated from crevasse splay based on its lower gamma ray readings and its thicker upward-decreasing gamma ray pattern. Lower delta plain/tidal delta plain is characterized by serrated, high gamma ray readings as in the Attaka D-11 and the Attaka 1-5 cores (Figure 2.3 and Figure 2.4). A kick of low density and high neutron in the lower delta plain indicates carbonaceous material content.

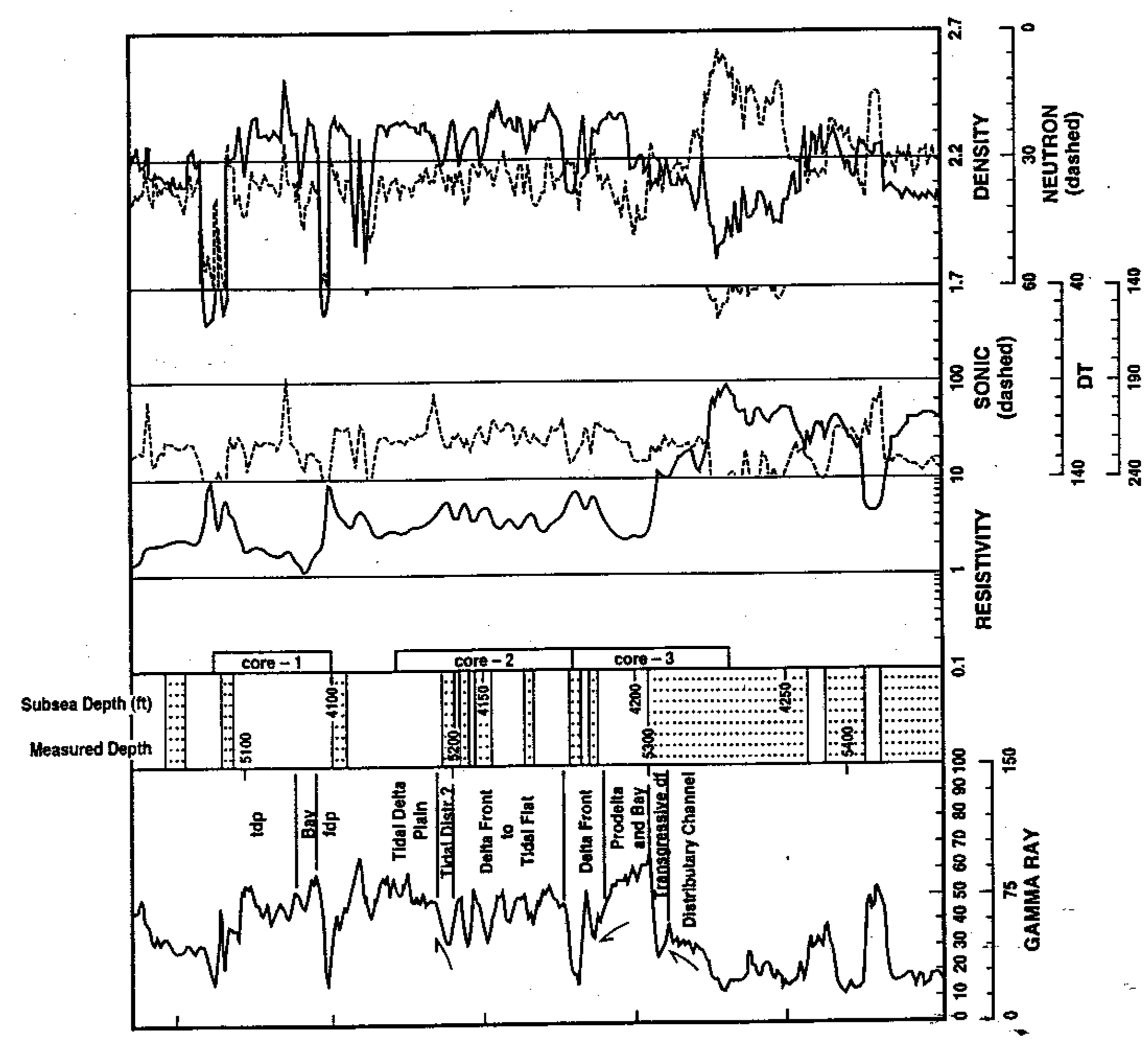


Figure 2.2: Log response from the Attaka D-11 well and the interpretation of depositional environments (from Trevena et al., 1993).

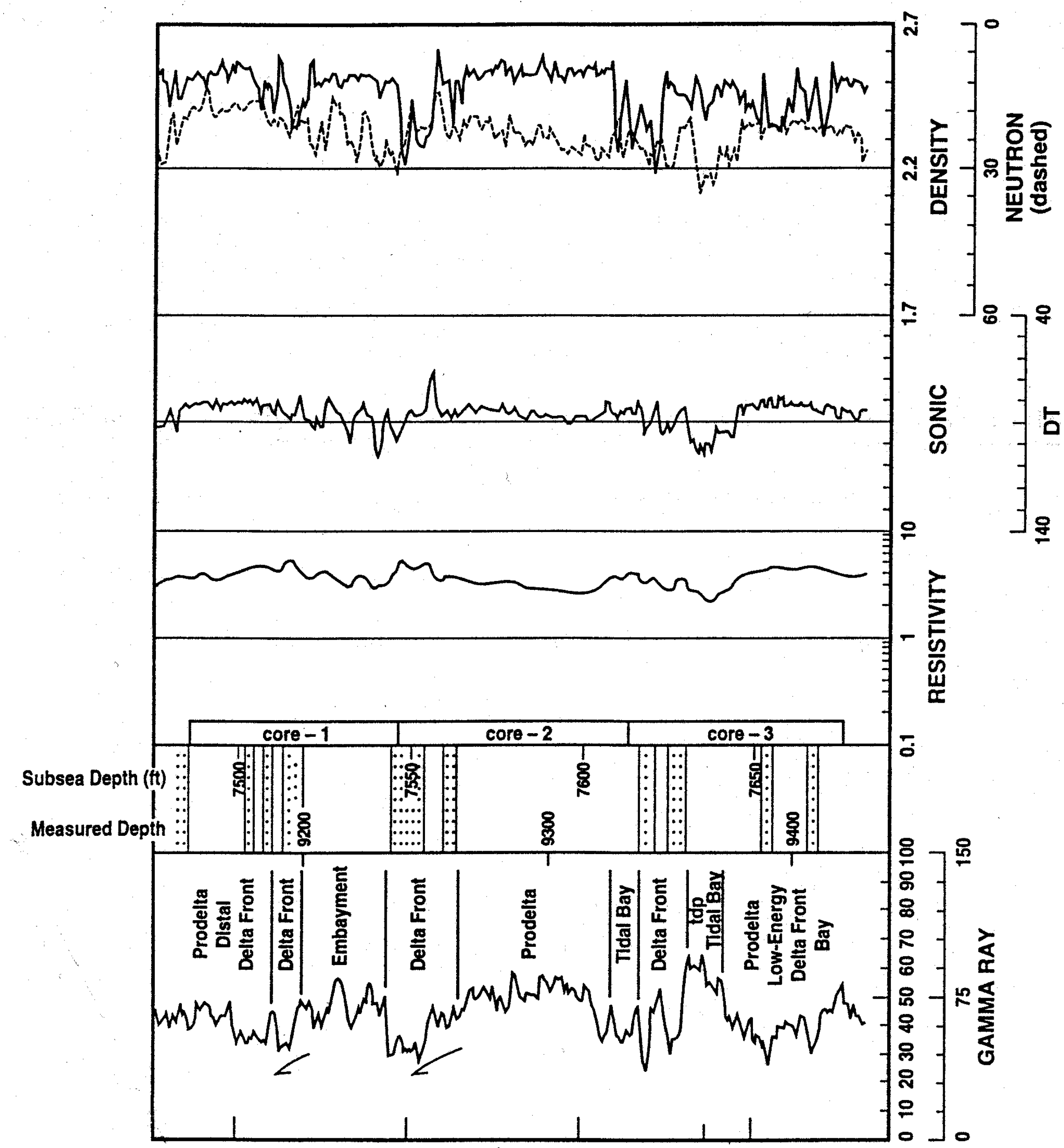


Figure 2.3: Log response from the Attaka I-5 well and the interpretation of depositional environments (from Trevena et al., 1993).

2.5 Recognition of stratigraphic hierarchy

The stratigraphic cyclicity can be recognized after stratigraphic correlation was done. Stratigraphic cycles can be scaled as long-term, intermediate-term, and short-term (refers to Figure 5.2) as discussed in Chapter 5. In this study, both maximum flooding surfaces and candidates for unconformity are identified and correlated. Because maximum flooding surfaces are easier to be recognized compared to unconformities, the first attempt in recognizing stratigraphic cycles is subdividing the study interval based on maximum flooding surfaces.

Long-term cycle reflects the trend made by stacking pattern of intermediate-term cycles. The stacking pattern can be identified from (1) changes in sandstone geometry and connectivity, and (2) changes in the degree of preservation of rock (Gardner, 2001a). In subsurface data the changes in degree of preservation of rock can be inferred from changes in log-pattern diversity. For example, blocky log pattern indicates low degree of preservation because the abandoned channel fills were not preserved. On the other hand, upward-increasing gamma ray log pattern indicates high degree of preservation.

A long-term base-level rise results from landward-stepping cycles, whereas a long-term base-level fall results from seaward-stepping cycles. In channel belts a trend of less interconnected, more laterally extensive sandstone geometry with higher log-pattern diversity to the younger stratigraphic cycle indicates a landward-stepping cycle. On the other hand, a trend of more interconnected, less laterally extensive sandstone geometry with lower log-pattern diversity to the younger stratigraphic cycle indicates a seaward-stepping cycle (Gardner, 2001b). Because the channel belts in the study area reflect a trend of less interconnected, more laterally extensive sandstone geometry with higher log-pattern diversity to the younger stratigraphic cycle, it is interpreted that the studied interval was deposited during a long-term base-level rise.

The long-term cycle was further subdivided into intermediate- and short-term cycles. Markers that are continuous on the field scale and represent major maximum flooding surfaces were assumed as regionally correlatable. Three mudstone markers, named MFS 1,MFS 2, and MFS 3, were used to subdivide the study interval into intermediate-term cycles. These markers have high gamma ray values and are interpreted to record episodes of maximum marine floodings. Less continuous flooding surfaces are assumed as maximum flooding surface for short-term cycles.

The candidates for unconformity (LSE's) were picked based on criteria as listed above. LSE's for intermediate-term cycles were picked at the base of amalgamated sandstones that are laterally extensive in a field scale and represent a changing of environment from marine to non-marine. Less continuous candidates for unconformity are considered as LSE's for short-term cycles.

2.6 Net sand and paleogeographic maps

Net sand and paleogeographic maps were done for each cycle. The objectives of net sands and paleogeographic mapping are: (1) to understand the lateral distribution of sandstone bodies and area of major sediment input in each cycle, and (2) to understand the evolution of the geographic condition in the study area.

Net sand maps were done by using gamma ray cut-off of 60 API. This value is thought to be a good representation for sand cut-off in the Serang Field. As seen in the SA-3 RD2 cored interval 6587-6628, this value represents medium- to fine-grained sandstone. This value is also a suggested cut-off for sand in the Mahakam Delta (Allen, 1985).

Paleogeographic reconstruction was accomplished by projecting depositional environment information from cross sections. The paleogeographic maps are in agreement with net sand maps. In interfluves the net sand is low, whereas in the channel or valley axes the net sand is high. Because of this relationship, the paleogeographic and net sand maps were combined. Paleogeographic information was superimposed on the net sand contour to explain the nature of sandstone thinning. In most cases, the thinning of sandstone corresponds to the thickening of mudstone that can act as a barrier to fluid flow.

2.7 Sequence stratigraphy applied to sandstone distribution and reservoir heterogeneity analysis

Sandstone distributions can be predicted by understanding the depositional setting and the position of sandstones within a stratigraphic cycle (Gardner, 2001a). In a seaward-stepping cycle, more sediment is eroded and transported to deeper water because the accommodation is placed basinward. In stratigraphically younger cycle, less accommodation is created and less heterogeneity is expected. On the other hand, in a landward-stepping cycle more sediment is stored in the coastal plain because the accommodation is placed landward. In stratigraphically younger cycle, more accommodation is created and more heterogeneity is expected.

In this study, reservoir heterogeneities were described qualitatively in terms of distribution of reservoir rocks (sandstones) and permeability barriers (mudstones). The occurrence of thick mudstones that may act as effective permeability barriers can be recognized from the thinning of sandstone in net sand maps.

Reservoir property analysis and the ranking of reservoir quality were done qualitatively based on core study. The ranking of lateral and vertical heterogeneity was done based on log-core calibrated correlation.

CHAPTER 3

REGIONAL GEOLOGY

3.1 Introduction

The purpose of this Chapter is to put the study area in perspective with its regional setting. The study area is located offshore of the Mahakam Delta (Figure 1.1). The Delta is sited at the eastern part of the Kutei Basin, East Kalimantan, Indonesia. The Kutei Basin is one of the most prolific hydrocarbon basins in Indonesia and has proven reserves between 11 and 16 billion bbl of oil equivalent (BBOE) (Peters et al., 2000).

In this Chapter, the discussion of regional geology of the study area is divided into four sections. The first section explains the tectonic setting of Kalimantan Island, the island where the onshore part of the Kutei Basin is located. This island is also known as Borneo. The second section presents the geologic setting of the Kutei Basin as a part of Kalimantan Island. The third section reviews the structural style of the Kutei Basin that controls the thick deposition in the Kutei Basin. Relation between tectonics and sedimentation in the Kutei Basin is discussed in the third section. The last section describes the petroleum system of the Kutei Basin that is controlled by the tectonics and sedimentation history of the Basin.

3.2 Tectonic setting of Kalimantan

Kalimantan is the second largest island of Indonesia, behind the Papua. The Indonesian archipelago is located at the boundaries of three major plates: West Pacific, Indo-Australian, and Eurasian plates (Figure 3.1). The interaction of those plates results in the complex mosaic of small oceanic basins, rifted continental fragments, subduction

Figure 3.1: Plate tectonic setting of the Southeast Asia region showing its Early Cretaceous continental cores (modified from Hall et al., 1995)

zones, island arcs, and collision zones that make up the archipelago (Van de Weerd and Armin, 1992; Hall, 1995; McClay et al., 2000).

In the Early Cretaceous, the southwestern part of Kalimantan was a part of a stable crust known as Sundaland (Van de Weerd and Armin, 1992; Hall, 1995; Moss, 1997). Sundaland includes southwestern Kalimantan, western Java Sea, Sumatra, and Peninsular Malaysia (Figure 3.1). Basins formation in Kalimantan was initiated by the rifting away of Kalimantan from Sulawesi (Hamilton, 1979; Moss et al., 1997).

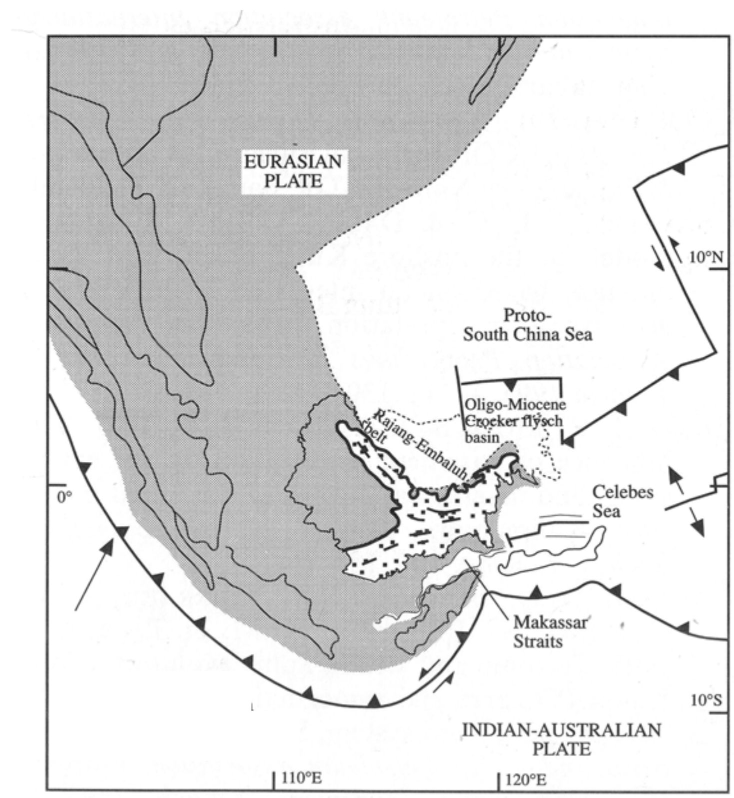


Figure 3.2: Reconstruction of the Kalimantan region at 40 Ma, showing the opening and extension within the Kutei Basin (from Moss et al., 1997, with tectonic setting adapted from Hall et al., 1995)

Kalimantan has been regarded as a stable craton during the Middle-Late Cenozoic (Hamilton, 1979). According to paleomagnetic data, in Early Miocene-Middle Miocene (20-10 Ma) Kalimantan experienced its counter clockwise rotation as a response to the clockwise rotation of the Philippine Sea Plate (Hall, 1995). Figure 3.2 shows the position of Kalimantan at 40 Ma before it rotated. The counter clockwise rotation caused the north Kalimantan margin uplifted and produced deep regional unconformity in the north Kalimantan margin (Tan and Lamy, 1990 in Hall, 1995). West Sulawesi and most of the adjacent Sundaland blocks were also rotated counter clockwise with a smaller degree. The rotation of Kalimantan was accommodated on the south side of the proto-South China Sea by southward subduction linked to the strike-slip boundary in west Kalimantan (Hall, 1995).

3.3 Geologic setting of the Kutei Basin

In the regional tectonic setting, the Kutei Basin is located in the eastern part of Sundaland (Figure 3.1). The basin covers an area of approximately 60,000 km^2 with up to 14 km thick of Tertiary sediment (Allen and Chambers, 1998). The Kutei Basin is separated to the north from the Tarakan Basin by the Mangkalihat Spur. To the south it is separated from the Barito Basin by an extension of the Meratus Mountain. In the Early Tertiary, Tarakan, Kutei, and Barito Basins were parts of a large and interconnected area of subsidence and sedimentation. Miocene uplift segmented the area into separate basins (Van de Weerd and Armin, 1992). To the west, the basin is bounded by the Central Kalimantan Mountains, and to the east it is opened to the Makassar Strait (Figure 3.3).

The northern and southern margins of the Kutei Basin are marked by a thinning of sediment. The Sangkulirang fault zone forms the northern margin of the basin to the north Makassar Basin. The Bengalon river fault is located south of the Sangkulirang Fault. Both Sangkulirang and Bengalon River Faults are oriented northwest - southeast. The southern margin of the basin is delineated by the onshore continuation of the Adang

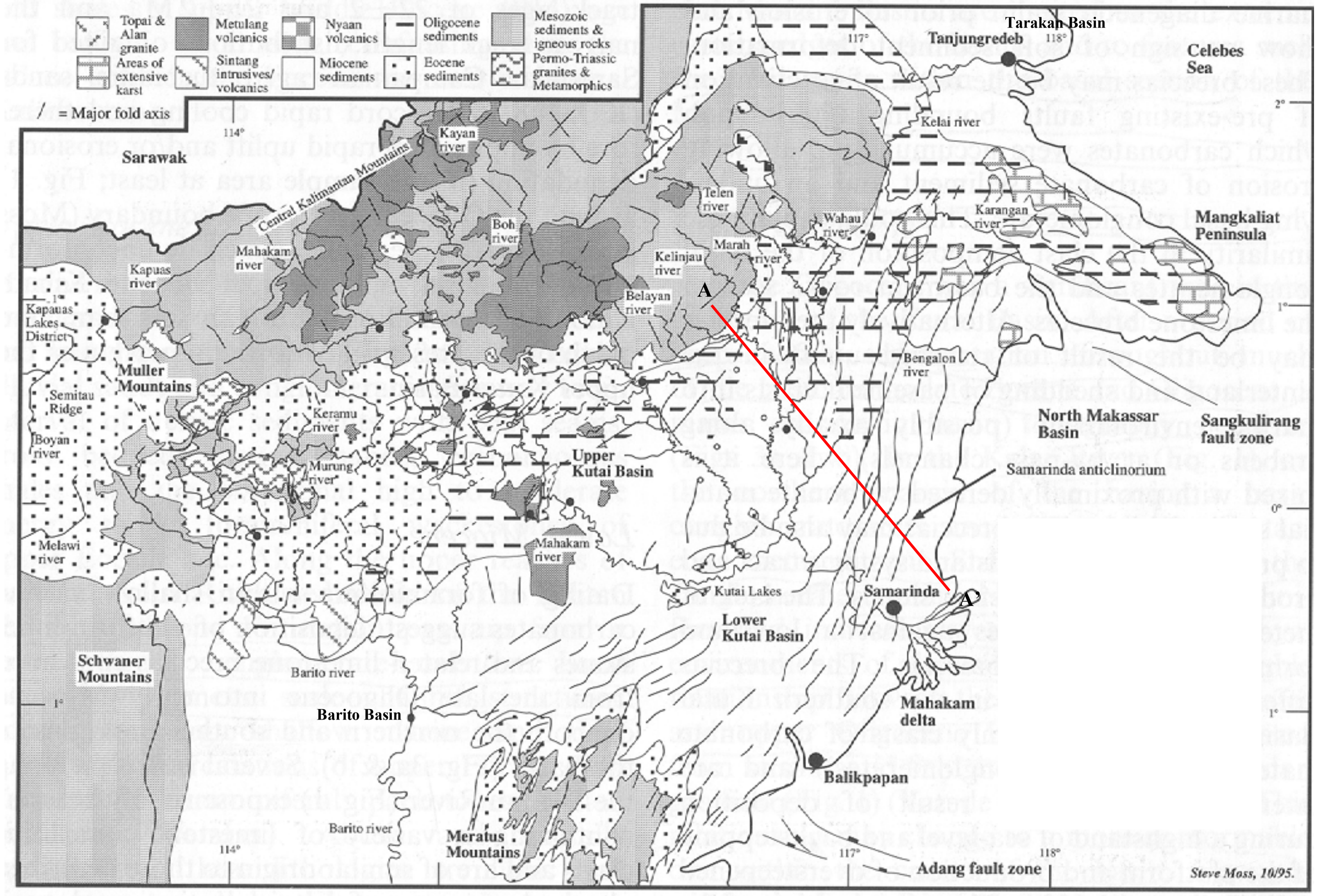


Figure 3.3: Geological map of the Kutei Basin and East Kalimantan (modified from Moss et al., 1997). Line A-A' is the line of the cross section in Figure 3.5.

Fault that has a northwest - southeast orientation. According to seismic data, the fault zone splays into a synthetic transfer zone in offshore Kalimantan (Moss et al., 1997).

Informally, the Kutei Basin is subdivided into the Upper Kutei Basin and the Lower Kutei Basin. The Upper Kutei Basin is located at the western part of the basin. The eastern part of the basin is called as the Lower Kutei Basin. Mahakam Delta is a part of the Lower Kutei Basin. The Serang Field is located at the offshore part of the Lower Kutei Basin. The Upper Kutei Basin, together with Central Kalimantan Mountains, has been uplifted during Miocene tectonic inversion and become a major provenance for the deltaic sediments deposited in the Lower Kutei Basin (Ott, 1987, Van de Weerd et al., 1992, Chambers and Daley, 1995). Over 8 km of sediments have accumulated in the Kutei Basin since the Miocene (Hamilton, 1979) (Figure 3.4).

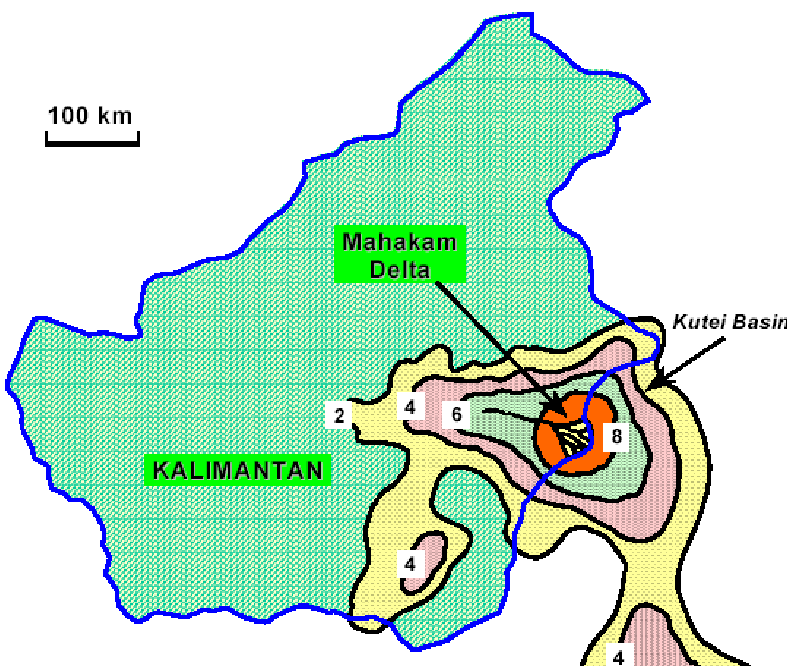


Figure 3.4: Isopach map showing the amount of sediment accumulated in the Kutei Basin since Miocene. Thickness is in km (from Allen and Chambers, 1998 modified from Hamilton, 1979).

3.4 Structural Style of the Kutei Basin

The structural style of the Kutei Basin is dominated by a series of north northeast – south southwest trending folds and secondary faults. The structures were formed during Tertiary deformation. The style is quite different in the north and south margin of the basin. In the north margin, the structures are oriented northwest - southeast. In the south margin of the basin, the structures are oriented northeast - southwest. The structural style in the south margin of the basin is an inherited basement fabric instead of the result of Tertiary deformation (Cloke et al., 1999).

The structure of the Kutei Basin is known as the Samarinda Anticlinorium or the Mahakam Foldbelts (Figure 3.5). The folds consist of asymmetric anticlines that are separated by broad synclines. The anticlinal ridges are tight and characterized by abrupt changes in axial dip from steep east to steep west. They are laterally continuous for more than 100 Km. The cores of the anticlines are dominated by shelf to bathyal mudstones. The synclines have sand-prone deltaic sediments exposed at the surface (Chambers and Daley, 1995). The structure changes gradationally from east to west. In the east, the structure is characterized by simple anticlines and synclines with little or no uplift. In the west it is typified by a complex fold/thrust belt with uplift and erosion of up to 1.4 km sediments (Ferguson and McClay, 1997). The Serang Field, which is located in the eastern part, has a simple three-way closure against a major growth fault trapping mechanism.

There are several explanations for the origin of the Samarinda Anticlinorium / Mahakam Foldbelts. The explanations include: (1) diapirism of thick prodelta fine-grained sediments (Ott, 1987), (2) regional gravity gliding of material with uplift of the Central Kalimantan Mountainss to the west (Ott, 1987), (3) growth faulting and inversion through strike-slip movement along Adang and Sangkulirang faults (Biantoro et al., 1993), (4) punctuated inversion through a series of detachment folds and breakthrough faults above a variably uplifted regional overpressured mudstones (Chambers and Daley, 1995), and (5) inverted delta growth faults (Ferguson and

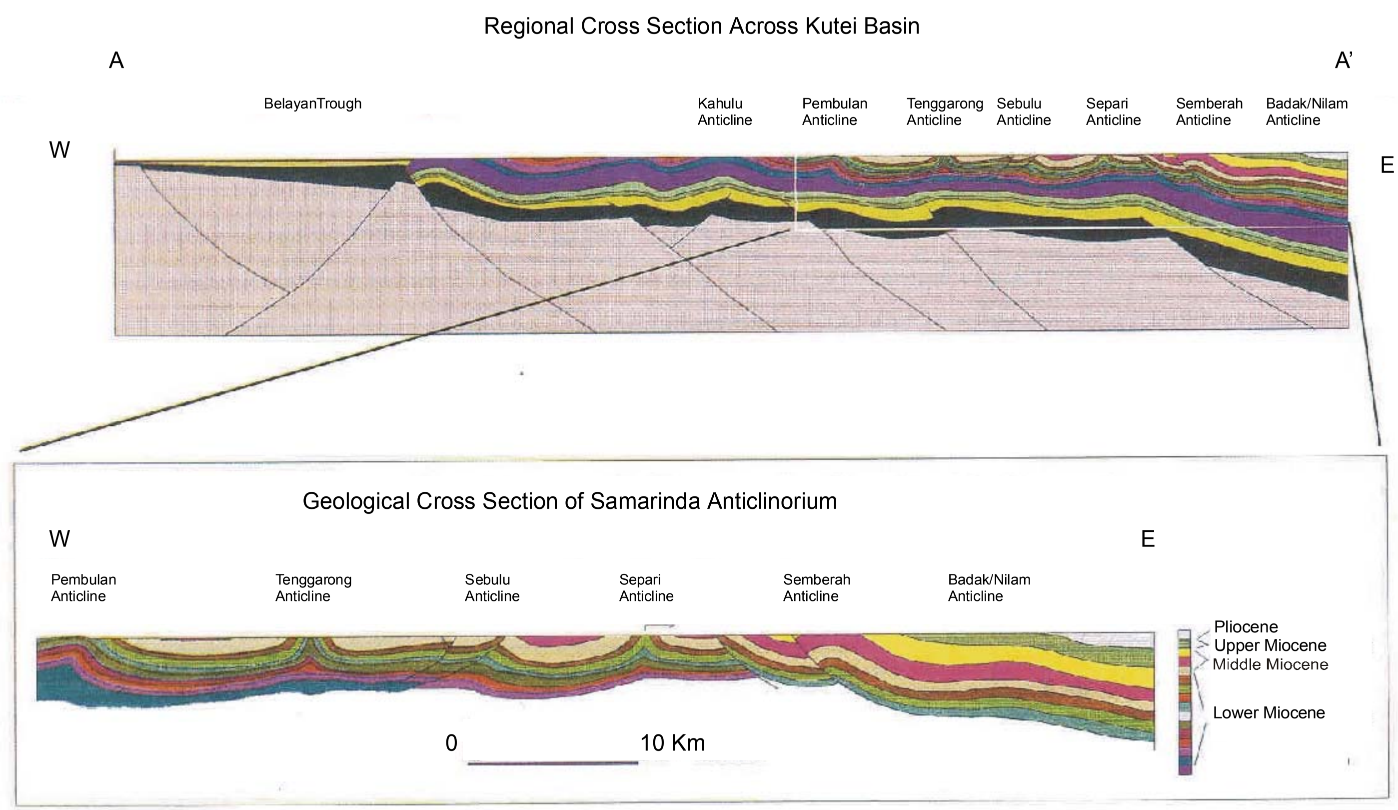


Figure 3.5: A cross section along the northwest margin of the Kutei Basin to the Mahakam Delta, showing the structural style of the Kutei Basin. Note that to the east the sediments are thicker. The younger sediments in the east are resulted from reworking of the older sediments in the west. The Serang Field is not located within the cross section (from Allen and Chambers, 1998).

McClay, 1997). Further explanation about the origin of the folds is beyond the discussion of this chapter.

The offshore Kutei Basin structural style is characterized by detached deformation. In the Mahakam depocenter a series of large, low relief detached folds developed above the shelf break. Linked growth fault and toe thrusts were developed north and south of the depocenter. Deltaic loading is thought to be the main driving force of this deformation (Hickman et al., 2000). In the offshore area, growth faults are abundant and only a few thrust faults are recognized (Armin et al., 1994). The linked growth faults were dying out towards the central foldbelt.

3.5 Tectonics and sedimentation of the Kutei Basin

During the development of the Kutei Basin, tectonic and sedimentation were related. The Tertiary rocks of the Kutei Basin were deposited with angular unconformity contact above the Mesozoic and older strata. The Mesozoic and older deposits, known as Rajang / Embaluh Groups, were metamorphosed and folded during pre-Tertiary orogenies and preserved in cratonic areas (Hamillton, 1979; Moss et al., 1997).

Rift basins, one of them is the Kutei Basin, were developed during the Eocene and Oligocene above a Cretaceous accretionary prism in east Kalimantan to south Sulawesi regions (Hamilton, 1979; Moss et al., 1997). Figure 3.6 shows major tectonic and evolution of facies association (called "facies" in the diagram) of the Kutei Basin. The basin was formed in Middle to Late Eocene. The Middle Eocene strata represent a syn-rift section that is remarkably similar throughout Kalimantan and characterized by the presence of basal conglomerate (Moss et al., 1997). The alluvial Eocene strata of the Kilham Haloq Formation were deposited in the inner basin (Van de Weerd and Armin, 1992; Moss et al., 1997). This formation is also variably known as Tanjung Formation and Kuaro Formation (Figure 1.3).

During Late Eocene to Oligocene the basement was rifted. The rifting caused the basin to subside (Hamilton, 1979; Van de Weerd and Armin, 1992; Moss et al., 1997).

The subsidence led to the formation of carbonate banks and reefs flanking mud-prone basins. During that time, mudstone was deposited in marginal to open marine environments. Interruption of basin subsidence by uplift was indicated by the deposition of some coarser silisiclastics that are locally associated with the mudstone sequence (Satyana, 1999).

From Late Oligocene to Early Miocene, shallow-marine carbonates were deposited on the northern and southern margins of the basin. Collision of micro-plates with east Sulawesi and subduction beneath north Borneo that is related to the counter clockwise rotation of Borneo took place in the late Early Miocene (Hall, 1995, Moss et al., 1997). This event produced regional compression and formation of opposing thrust belts in Borneo and Sulawesi that in turn resulted in the uplifting/inversion of the Paleogene rifts in Kalimantan (Van de Weerd and Armin, 1992, Hall, 1995, Moss et al., 1997). The inversion was responsible for the reworking of earlier sediments and continuing deposition of syn-inversion deltaic packages.

Deposition of deltaic sediments continued in Middle and Late Miocene and Pliocene. Several mega sequences with shallowing upward trend from bathyal mudstones to delta plain/fluvial channel sandstones were deposited along with the eastward progradation of the deltaic system. Based on seismic profiles, Van de Weerd and Armin (1992) recognized several Middle and Upper Miocene deltaic lobes (Figure 3.7). They subdivided the Lower Kutei Basin into southern, central, and northern areas. According to them, based on nannofossil data, deposition of the Serang lobe took place in late Late Miocene (N 17).

According to Snedden et al. (1996) the Upper Miocene deltaic sediments can be subdivided into four depositional sequences, each bounded by unconformities. Two lobes existed in the ancient Mahakam Delta: southern and northern. The northern lobe of the fourth sequence correlates to the Serang Field reservoirs. There are four sediment sources interpreted: the South Mahakam Delta, the North Mahakam Delta (Attaka), the Sangatta Delta, and the Sepinggan Delta. The Sangatta Delta is located north of the

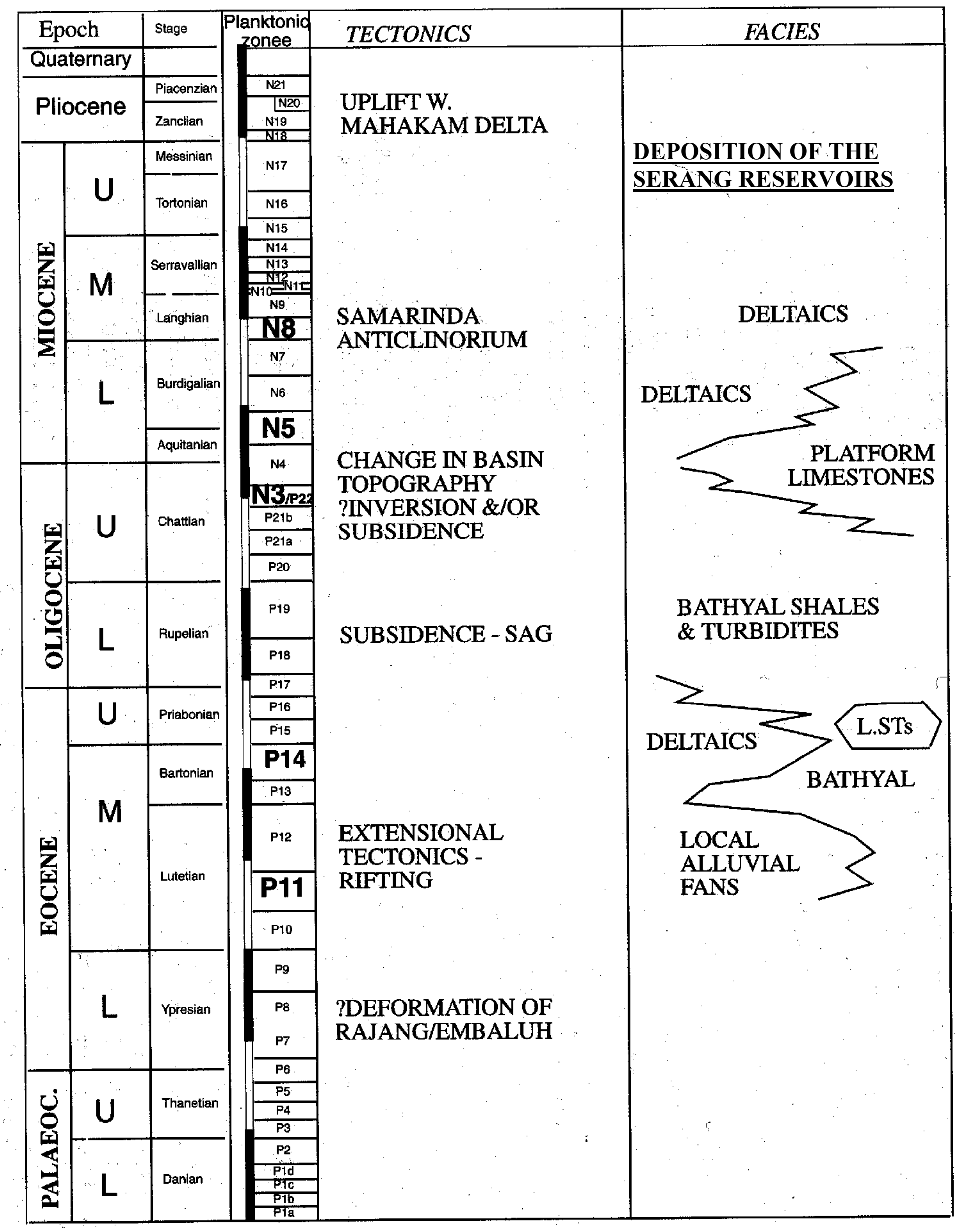


Figure 3.6: Major tectonic and east to west changes of facies associations (called "facies" in the diagram) for the Kutei Basin. The black and white bars represent 5 Ma (from Moss et al, 1997). The formation of the Kutei Basin was during the Middle to Late Eocene. The deposition of the studied interval (underlined) was during late Late Miocene (N 17).

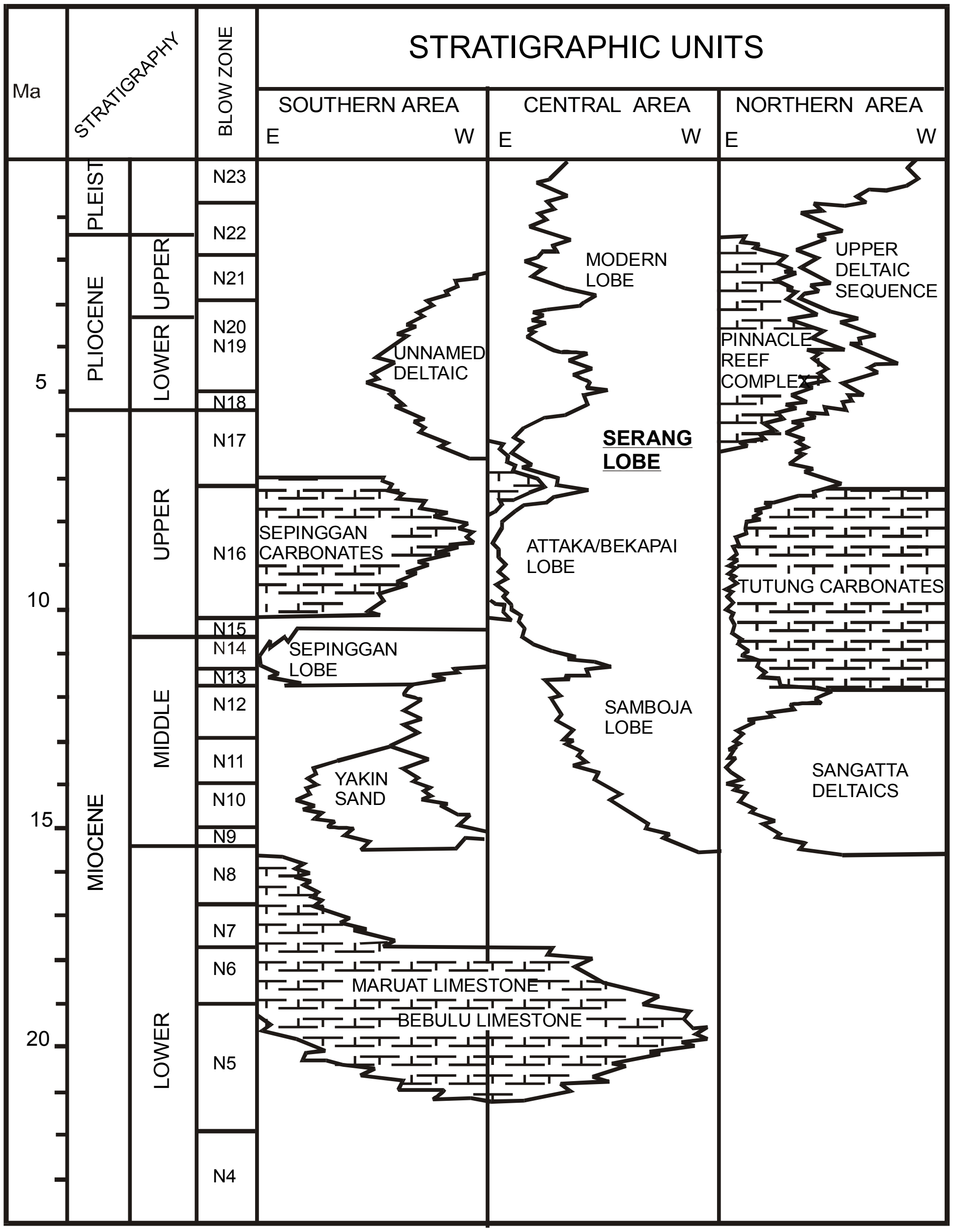


Figure 3.7: Stratigraphic scheme for sand-rich and carbonate-rich sediments in the lower Kutei Basin. The jagged lines represent sand and carbonate sediments. All the sand-rich sediments are deltaic with the exception of the Yakin sands that are probably marine-shelf sand. The Serang lobe is underlined (from Van de Weerd and Armin, 1992).

Mahakam Delta, whereas the Sepinggan Delta is located south of the Mahakam Delta. The deposition in the Serang Field was during the development of the northern lobe of Sequence 4. Figure 3.8 illustrates the paleogeographic evolution of the Upper Miocene deltaics. The following summary is after Snedden et al (1996):

- During 9.0-10.5 Ma Sequence 1 was developed. Two major depocenters developed: southern and northern. The southern lobe probably derived from the proto-Mahakam Delta. The northern lobe probably derived from a northern extension of the Mahakam distributaries, with contributions from the Sangatta Delta system (Figure 3.7a).
- During 8.2 - 9.0 Ma Sequence 2 was developed. The lobes shifted inboard, resulted in the retreating of the shelf margin position of the northern lobe landward, and the moving of the southern lobes seaward (Figure 3.7b).
- During 6.3 – 8.2 Ma Sequence 3 was developed. Shelf margin wedge was well developed in the central portion of the shelf because of a lowering rate in relative sea-level fall. Depositional thick was formed as the shelf-margin moved seaward; however, the sand is only limited to the updip portion of the wedge. The shelf-margin outbuilding resulted in the most seaward development of the shoreline. The southern lobe was shifted landward as a compensation for the seaward shift of the shoreline (Figure 3.7c).
- During 5.5-6.3 Ma Sequence 4 was developed. The northern and southern lobes moved to the north and south respectively. Carbonates were well developed in the central portion of the basin where there was no clastic deposition. The proto-Sepinggan Delta may also contribute sediments in the deposition of southern lobe.

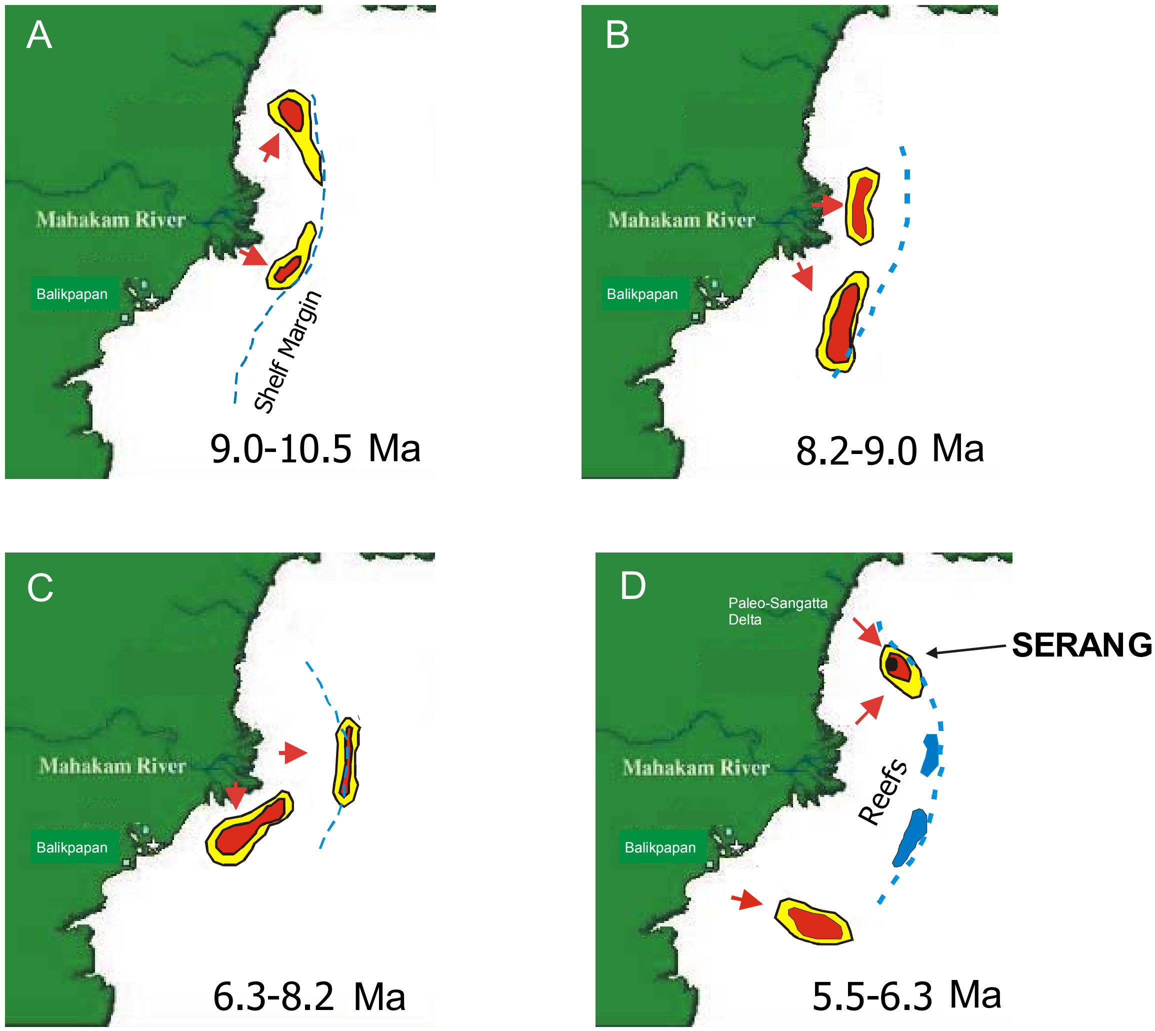


Figure 3.8: Maps of four depositional sequences in Upper Miocene Mahakam Delta (modified from Snedden et al., 1996). The reservoirs of the Serang Field were developed during late Late Miocene (5.5-6.3 Ma) with reservoir provenance either from southwest (paleo-Mahakam Delta) or northwest of the study area (paleo-Sangatta Delta).

Each depositional sequence was interrupted by periods of compressional deformation, uplift and erosion. Progradiation of deltaic sediment may have contributed to the inversion by the mechanism of diapirism (Ott, 1987) or growth faulting (Chambers and Daley, 1995). Sediment supply has been variable with time. Intervals of rapid sedimentation correspond to periods of uplift and erosion of older sediments (Allen and Chambers, 1998). The deltaic sediment deposition is still continuing to the present day, results in the deposition over 8 km thick of deltaic sediment that prograde over 200 km eastward (Hamilton, 1979) (Figure 3.4).

3.6 Petroleum system of the Kutei Basin

Tectonics and sedimentation in the Kutei Basin control the petroleum system of the Basin. All producing oil and gas fields are concentrated in the Lower Kutei Basin, whereas the Upper Kutei Basin contains none. The barren nature of hydrocarbons in the Upper Basin resulted from the extensive uplift and erosion in that region during the deltaic progradation in the Lower Basin (Satyana et al., 1999). All the oil and gas fields are located in the Samarinda Anticlinorium-Mahakam Foldbelt. The Serang Field is located in the northeast part of the Foldbelt.

Accumulations of hydrocarbons in each field in the Lower Kutei Basin have migrated from a proximal kitchen that is located in the downdip synclinal area of the field (Satyana et al, 1998). The hydrocarbons migrated laterally updip for a maximum distance of 10 km to accumulate in anticlinal traps (Paterson et al., 1997). Wells that are located 10-20 km from the kitchen have a big risk to be a dry hole (Duval et al., 1992).

The source rocks of the Mahakam Delta petroleum system are lower delta plain coals and delta front/ prodelta organic mudstones. The source rocks are parts of the Miocene Balikpapan Formation (Duval et al., 1992). The Paleogene section is overpressured and believed to be too deep to contribute petroleum accumulation. The post Miocene interval is located below the oil window (Peters et al., 2000). The intersection between coaly delta plain sediments and the thickest sediments in the kitchen is the best area for hydrocarbon generation (Duval et al., 1992).

Hydrocarbons are trapped in deltaic sandstone reservoirs of the Balikpapan Formation (Middle Miocene) and Kampung Baru Formation (Upper Miocene-Pleistocene) (Satyana et al., 1998). Seals are provided by intraformational mudstones. The oil fields in the Mahakam Delta petroleum system generally are faulted, whereas gas and condensate fields are not. This phenomenon may results from easier escape of gas in fault traps compared to the more viscous oil (Armin et al., 1994).

A geochemical-sequence stratigraphic model for the Mahakam Delta and Makassar Slope (Peters et al., 2000) is shown in Figure 3.9. This figure illustrates the hydrocarbon accumulation pattern and oil window maturity based on geochemical-sequence stratigraphic analysis. The highstand kitchen refers to the coastal plain coals source rocks that were deposited during highstand. The lowstand kitchen refers to the coaly mudstone source rocks that were deposited during lowstand. Hydrocarbon accumulation in offshore fields mainly migrated from the highstand kitchen. On the contrary, hydrocarbon accumulation in onshore field generally migrated from the lowstand kitchen.

The generation and migration of hydrocarbons in the Kutei Basin started in the Late Miocene. Tectonics also influenced the oil generation by fracturing the source rock that in turn aided the hydrocarbon expulsion from the source rock (Ferguson and McClay, 1997). Peak oil accumulation has occurred since Late Pliocene. Trapping mechanism took place from the Middle Miocene to Plio-Pleistocene.

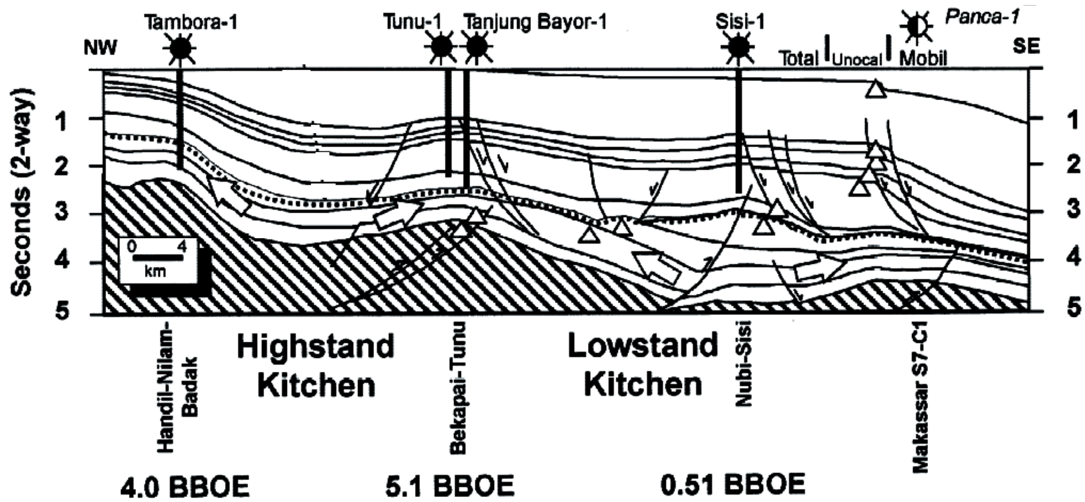


Figure 3.9: A geochemical-sequence stratigraphic model for the Mahakam Delta and Makassar Slope. White arrows indicate present day hydrocarbon migration, whereas triangles indicate shelf break during specified depositional intervals. The Serang Field is not located within the cross section (from Peters et al., 2000).

CHAPTER 4

CORE STUDIES: DESCRIPTIONS AND INTERPRETATIONS

4.1 Introduction

The purpose of this chapter is to document the cores with text and graphics and propose the interpretation for the depositional environments. There are ten depositional environments interpreted from the cores: (1) prodelta, (2) transgressive coastal plain to lagoon (calcareous mudstone), (3) lower delta front, (4) delta front bar, (5) tidal flat, (6) interdistributay bay, (7) distributary channel, (8) delta plain marsh and swamp, (9) fluvial/distributary channel, and (10) crevasse splay and crevasse channel. The log response of the corresponding cored intervals was used as analogs to facilitate the interpretation of depositional environments of non-cored intervals. Because it is hard to recognize the interpreted depositional environments in non-cored interval, in the cross section some depositional environments were lumped. For example, floodplain, delta plain marsh and swamp, and crevasse splay and crevasse channels in the cross sections were classified as overbank. When it is thin and hardly recognized in cross section scale, in some cases the interdistributary bay also classified as overbank. Because the prodelta and lower delta front are hard to be differentiated based on log pattern only, the prodelta is classified as lower delta front in the cross section.

Cores are available from SA-2RD, SA-5 and SA-3RD2 wells. Because the well names were changed as the Serang Field developed, the core name and the well log name are different. The well log name for SA-5 cores is SA-2, whereas the well log name for SA-3RD2 cores is SA-3. The well log name for SA-2RD cores is SA-2RD1. In core study the core names were used, whereas in log correlation the well log names were used. Location of cored wells can be seen in the base map at Figure 2.1. In cross sections, the

SA-2RD1 well is located at cross section 2-2' and C-C', the SA-2 is located at cross section 2-2' and A-A', whereas the SA-3 is located at cross section 1-1' and A-A' (Plated 2-3).

In this study cores were divided into lithologic Units, called "Units" hereafter. Each Unit represents a depositional event. Most of the Units are separated by sharp boundaries that are represented by scour surfaces; however, some Units have gradational transitions because of gradual changes in grain size or biomixing. Each Unit represents a facies. A facies is defined as a body of rock that is characterized by a particular combination of lithology, physical and biological structures and gives an aspect different from the body of rock above, below and laterally adjacent (Walker, 1992). Nine facies were recognized in this study. Each facies was defined by distinctive lithology, physical and biological structures, and texture. The naming of facies was done by using a simple abbreviated code that is designed as follows:

- Capital letter – rock type
- Small letter – physical, biogenic structure and mineralogy

Table 4.1 lists abbreviation code for facies used in this study. These codes were used in the naming of facies as listed in Table 4.2. For example, cross-bedded sandstone was coded as Sx and laminated to burrowed mudstone was coded as Mlb.

Groups of facies that are genetically related to one another and have some environmental significance built up facies associations. The facies associations found in the cores are interpreted to represent the environments listed above.

In this chapter the cores are described per cored interval and interpretation of depositional environments is discussed. In total there are six cored intervals, two each from three wells. The cored intervals were used to calibrate log response of the equivalent interval. The log responses of cored intervals in turn were used as log analogs in predicting the depositional environments from non-cored interval.

Sketches of the cores with descriptions, gamma ray log response, and interpretation of depositional environment are in Plates 1a-1f. Because the cored wells are deviated, the core depth presented in the plates is different from the log depth presented in the cross section. The cored depth presented in Plates 1a-1f is in measured depth, whereas the log depth presented in cross sections (Plates 2-3) was converted to true vertical depth.

Below is the description followed by interpretation of each core. An attempt to understand the relation between interpreted depositional environment and its log response is discussed in the log response section. Some cored intervals can be interpreted in two or more ways, therefore some alternative interpretations are offered.

Table 4.1:Abbreviation codes for facies

Rock type	
S	Sandstone
M	Mudstone
SM	Upward-fining from sandstone into mudstone
Physical and biogenic structures, and mineralogy	
l	Parallel-laminated
x	Cross-bedded
r	Ripple-bedded
w	Wavy-bedded
m	Massive
b	Burrowed to bioturbated
t	Rooted
c	Calcareous
o	Coal / Carboniferous

Table 4.2: Nine facies recognized in this study and their inferred processes

Facies	Abbreviation	Remark	Inferred processes
Coal, carbonaceous mudstone and rooted mudstone	Mo	Coal / carbonaceous mudstone	Period of starvation, insitu accumulation of vegetation rising water-table
	Mt	Rooted mudstone	Period of starvation, suspension deposition in poorly drained area
Burrowed to bioturbated mudstone	Mb	Burrowed to bioturbated mudstone	Suspension deposition, low sedimentation rate, normal marine salinity
	Mpb	Parallel-laminated mudstone, partially burrowed	Suspension deposition, prolonged non-deposition, normal marine salinity
	Mwrb	Wavy- to ripple-laminated, partially burrowed mudstone	Alternating suspension and traction deposition (suspension is more dominant), unidirectional current, marine water influence
Mudstone, parallel to ripple and wavy-laminated	Mp	Parallel-laminated mudstone	Suspension deposition
	Mr.	Ripple-laminated mudstone	Alternating suspension and traction deposition (suspension is more dominant), unidirectional current
	Mw	Wavy-laminated mudstone	Alternating suspension and traction deposition (suspension is more dominant)
	Mow	Parallel- to wavy-laminated mudstone	Suspension deposition with traction influence
Sandstone, burrowed to bioturbated	Sb	Burrowed and bioturbated sandstone	Low sedimentation rate or prolonged non-deposition, normal marine salinity
Sandstone, cross-bedded	Sx	Cross-bedded sandstone	Traction transportation by unidirectional-bidirectional current
	Sxr	Cross-bedded to ripple-laminated sandstone	Traction transportation with a waning of energy
	Sxp	Cross- to parallel-bedded sandstone	Traction transportation with high current energy
	Sxpr	Cross-bedded to parallel-bedded and ripple-laminated sandstone	Traction transportation with a waning of energy
	Sxm	Massive to cross-bedded sandstone	High velocity current transportation, velocity current
	Sxpm	Cross- to parallel-bedded sandstone with massive appearance	Traction transportation with high current energy, fast sedimentation rate
Sandstone, cross-bedded, partly burrowed	Sxb	Cross-bedded sandstone, partially burrowed	Traction deposition in normal marine salinity environment
	Sxpmb	Cross- to parallel-bedded sandstone with massive appearance, partly burrowed	Traction transportation with high current energy, fast sedimentation rate, prolonged non-deposition, marine-water influence
Sandstone, wavy to ripple-laminated	Sr	Ripple-laminated sandstone	Alternating suspension and traction deposition (traction is more dominant), unidirectional current
	Spr	Parallel- to ripple-laminated sandstone	Suspension deposition with traction influence
	Swr	Wavy- to ripple-laminated sandstone	Alternating suspension and traction deposition (traction is more dominant)
Calcareous mudstone	Mc	Calcareous mudstone	Deposition during transgression or diagenetic product

4.2 SA-2RD cores

SA-2RD cores have a total thickness of 145.6 ft. The cores represent two cored intervals: 8651.0-8742.0 ft and 8196.4-8251.0 ft. These cored intervals were previously studied by Art Trevena in 1996. At the same time, Emiliano Mutti also studied the cored interval 8651.0-8742.0 ft. They have different opinions about the interpretation of depositional environments represented the cores. After personally doing the core study, alternative interpretations are offered for both intervals, as discussed below. The core description is subdivided into composite Units based on combinations of facies that represents a facies association or series of facies associations that are genetically related.

4.2.1 Cored interval 8651.0-8742.0 ft

This cored interval is subdivided into twenty-six Units that reflect four depositional environments: (1) prodelta, (2) lower delta front, (3) fluvial/distributary channel, and (4) crevasse splay /crevasse channel Because the prodelta and lower delta front deposits are genetically related and have a transitional boundary, they will be described together. The sketch of core for this interval can be found in Plate 1a. The distributary / fluvial channel and crevasse splay / crevasse channels represents short-term cycle 1A in the studied interval, whereas the prodelta and lower delta front is located below the short-term cycle 1A.

4.2.1.1 Units 1-2: Prodelta to lower delta front

These Units are described together because they represent a continuous shallowing-upward deposition, with a gradational contact. Unit 1 is from 88729-8742 ft. Unit 2 is from 8720.5-8729 ft.

4.2.1.1.1 Description

The lower part of Unit 1 consists of burrowed mudstone with traces of lamination. The burrowing is more intensive at the upper 3 ft. Trace fossils found in this Unit are *Thalassinoides, Teichichnus, Planolites, Asterosoma*, and possibly *Zoophycus.* Siderite nodules are present at the lower 9 ft. This Unit locally contains coal laminae. In the upper 6 ft, the mudstone contains intercalation of very fine sandstone laminae.

Upward, Unit 1 grades into Unit 2 that consists of burrowed muddy sandstone with remnants of wavy and parallel lamination. The bioturbated muddy sandstone is biomixed and poorly-sorted. Around 8723.3 ft and 8725.5 ft calcareous shells and siderite nodules are present. In this Unit, mudstone content gives dark brown color, whereas sandstone content gives white color. Trace fossils present in Unit 2 are *Thalassinoides, Planolites,* and *Asterosoma.* Shells are abundant around 8725 ft. The upper part of Unit 2 seems less compact. A zone that is more unconsolidated and darker in color occurs near the top of Unit 2 at 8722-8722.5 ft. This Unit is capped by a compact diagenetic concretion at 8721.5-8722 ft that is separated by a scour surface from the sandstone of Unit 3.

4.2.1.1.2 Interpretation

Overall, the trend from Unit 1 into Unit 2 represents continuous shallowing-upward deposition in prodelta to lower delta front environments. The laminated mudstone that is disrupted by burrowing and bioturbation (Unit 1) records a slow rate of deposition from suspension below normal fair-weather wave-base that is later disrupted by organisms. Presence of burrowing indicates slow sedimentation rate and normal marine salinity. Trace fossil assemblages indicate that the depositional environment preferable for Units 1-2 is in a fully marine environment below normal fair-weather wave-base. Because Unit 1 is dominated by mudstone whereas Unit 2 is dominated by fine-grained sandstone, it is interpreted that Unit 1 was deposited in deeper environment than Unit 2.

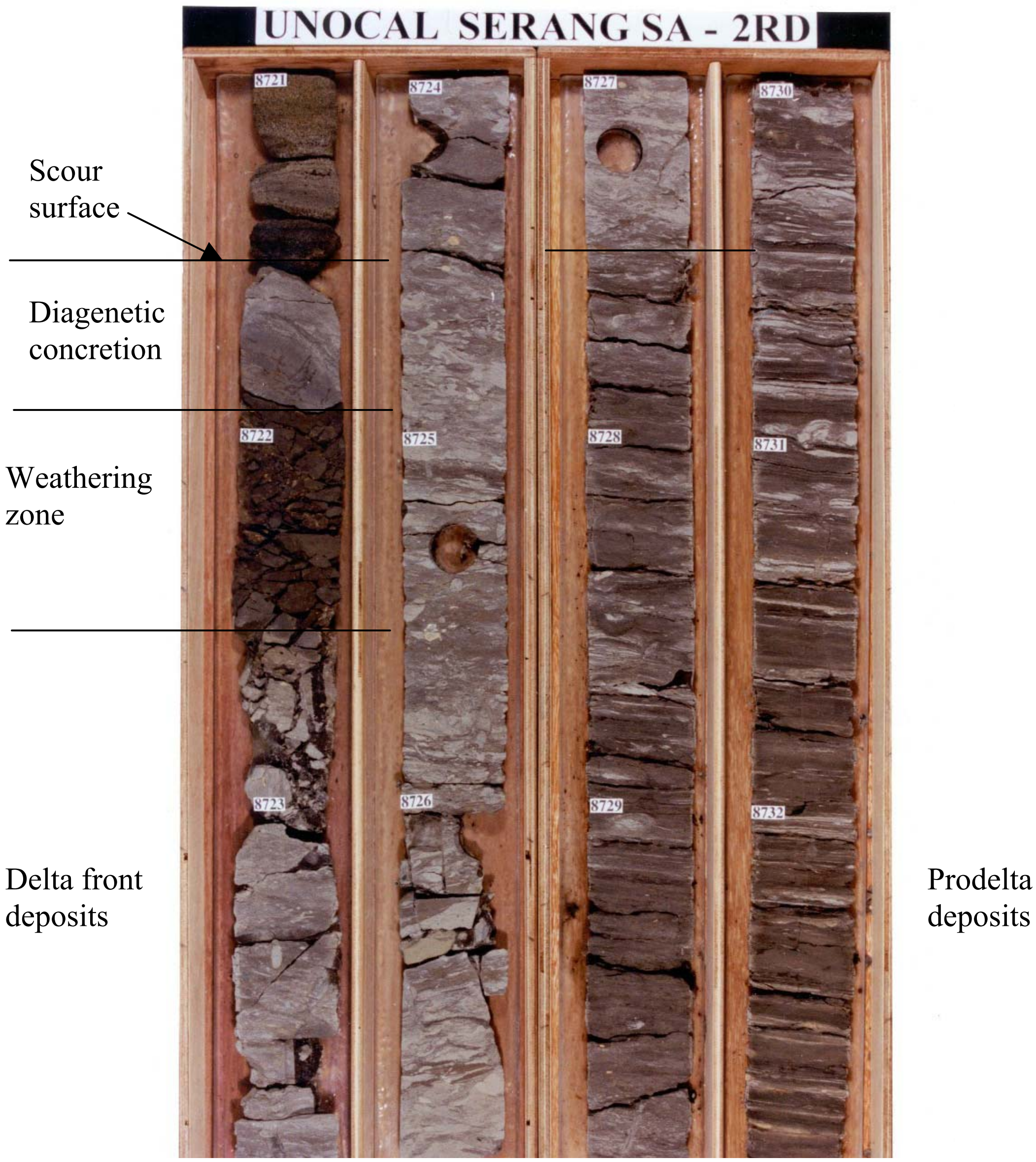


Figure 4.1: The erosional contact between bioturbated sandstone (Unit 2) and cross-bedded to parallel-bedded sandstone (Unit 3) at 8721.5 ft. A diagenetic mineral concretion occurs at 8721.5-8722 ft. A darker, unconsolidated zone that is interpreted as a weathering zone occurs at is 8722-8722.5 ft, just below the diagenetic mineral concretion. The contact between bioturbated sandstone (Unit 2, interpreted as delta front deposits) and bioturbated mudstone (Unit 1, interpreted as prodelta deposits) is picked at 8727.5 ft.

Burrowed sandstone with traces of wavy and parallel lamination that is biomixed with mudstone (Unit 2) may represent episodic fluvial deposition. The episodic deposition reflects seasonal outflow conditions at river mouths. This kind of sedimentary deposit may take place in a low-energy delta front. The presence of shells also supports this interpretation because shells are abundant in this environment.

The upper part of Unit 2 shows evidences of paleosol. It is possible that the scour surface between Unit 2 and Unit 3 actually is a sequence boundary if there was a significant missing time during the formation of paleosol.

4.2.1.2 Units 3-14: Fluvial/distributary channel

These Units are described together because they are genetically related and represent one facies association. The Units can be subdivided into 3 parts that represent different sedimentary structures: Units 3-5, Units 6-12, and Units 13-14. Each Unit is separated by scour surfaces.

4.2.1.2.1 Description

Units 3-5 (at 8709.25-8721.5 ft) consists of cross-bedded sandstones. Units 6-12 at 8692-8709.25 ft consist of cross-bedded sandstones that grade upward into ripple-laminated sandstone with an upward-fining trend. Units 13-14 at 8687-8692 ft consist of ripple- to wavy-laminated sandstone and mudstone.

Units 3-5 are dominated by cross bedding. Mud clasts are present locally at 8711-8712 ft. Coaly materials are present locally at 8713-8714 ft. The sandstone contains light oil stain that gives a dark brown color. Part of the sandstone that does not contain oil stain is light gray. The base of Unit 3 is parallel-bedded. The base of Unit 4 consists of subangular to subrounded granules and pebbles of quartz, chert, and rock fragments. The top of Units 4 and 5 have massive appearance.

Units 6-12 consist of cross-bedded sandstones that change upward into ripple-laminae. The cross-bedded sandstone is brown, while the ripple-laminated, finer-grained sandstone is white. Carbonate cement gives white color in the ripple-laminated sandstone. Ripple lamination is not preserved in Units 8 and 11. Rare burrows are present in the upper part of Units 10 at 8696-8697 ft. Very fine-grained sandstone with climbing ripple lamination is present in Unit 12 at 8692.5-8693.5 ft.

Units 13-14 show an overall upward-fining pattern from rippled to wavy-bedded fine-grained sandstone to ripple-laminated mudstone. They are moderately-sorted and medium brown in color. These Units are separated by scour surfaces. Coaly zones occur in Unit 13. The coaly zones are thin, less than 0.5 inch thick, and located at 8688.25, 8688.4 and 8688.8 ft.

4.2.1.2.2 Interpretation

Previous core study done by Trevena (1996) interpreted the Units described above as distributary channel deposits. In his report, he also mentioned an alternative interpretation by Emiliano Mutti who interpreted the lithology as deltaic shelfal lobes deposited by hyperpicnal density underflow in 30-50 m water depth during a catastrophic flood.

The sandstones of Units 3-12 are obvious in every well in the Serang Field. Based on the well log response of the sandstones, the upward-fining trend is in wells that are located in the southern part of the Serang Field. Other wells tend to have blocky log pattern. Te sandstones can be interpreted as fluvial channel deposits that have a meandering pattern.

The presence of burrows and mud drapes in Unit 10 indicates decreased sedimentation rate and occurrence of marine water influence. The decreasing amount of fluvial energy was substituted by tidal influence. The presence of mud drapes and burrows in Unit 10 may indicate distributary channel because they represent tidal influence and marine water environment; however, those features may also be found in fluvial channel with a waning of fluvial energy. Burrows can also be produced in fluvial channels with marine water intrusion. Because there is not enough evidence to review whether the channel is distributary channel or fluvial channel, Units 3-12 is classified as a fluvial/distributary channel deposit.

The cross-bedded sandstones (Units 3-5) are interpreted to be deposited in a high-energy condition. Cross bedding structures that change upward into ripple lamination and the upward-fining trend in Units 6-12 indicate the waning of fluvial energy. The presence of mud drapes may represent the waning of fluvial energy or tidal influence during the deposition of the sandstones.

The presence of several cross-bedded to ripple laminated sandstones (Units 6-12) that are separated by scour surfaces indicates pulses of deposition. To the top, the degree of rock preservation increases. In the lower Units (Units 3-5) only cross bedding is preserved, whereas in upper Units (Units 6-10) ripple lamination is also preserved. Units 13-14 that are finer grain and ripple-laminated may indicate abandonment channel fill or interdistributary bay deposits.

The presence of coal laminae in Unit 14 indicates that this Unit was deposited near swamp/marsh. Those areas are restricted of sediment supply. Possibly this Unit was deposited in interdistributary bay or abandoned channel environment.

4.2.1.3 Units 15-18: Crevasse splay and crevasse channel

These Units are described together because they represent facies associations that are genetically related. Each Unit is separated by scour surfaces.

4.2.1.3.1 Description

The trend from Units 15-18 shows an overall increase in grain size. Each Unit has an upward-fining pattern that is capped by coal layers. These Units create an overall upward-coarsening pattern. Sedimentary structures found in each Unit are cross bedding that change upward into ripple bedding. The trend from Units 15-18 shows more dominant cross bedding over ripple bedding. The sandstones that built up these Units are moderately-sorted and brown.

4.2.1.3.2 Interpretation

The interpreted depositional environments for Units 15-18 are crevasse splay and crevasse channel. Several upward-fining patterns that give an overall upward-coarsening pattern suggests the presence of pulses of deposition that are accompanied by an increase in transportation energy. Lack burrows and bioturbation may indicate rapid deposition and fresh water environment. Coal laminae that are located at the top of each Unit indicate abandonment phase in episodic deposition.

This composite Unit is subdivided into crevasse splay (Units 15-16) and crevasse channel (Units 17-18) deposits based on the grain sizes and sedimentary structures. Crevasse splay has finer grain and dominated by ripple to wavy bedding, whereas crevasse channel has coarser grain and dominated by cross bedding (Figure 4.2).

4.2.1.4 Units 19-26: Fluvial/distributary channel

Units 19-26 are described together because they are genetically related and deposited in the same depositional environment. Each Unit is separated by scour surfaces.

4.2.1.4.1 Description

The Units consist of medium- to very coarse-grained sandstone, poorly to moderately-sorted, dominated by planar cross-bedding, and light brown. Trough cross bedding occurs at Unit 19. In Unit 22 the cross bedding is not clearly shown. Parallel-bedded to massive structure is more obvious. Scour surfaces separate each Unit. Subangular to subrounded pebble-size clasts of quartz, chert, and other rock fragments are abundant in some of the scour surfaces. Two inches of coal fragment occurs in the scour surface at 8673.3 ft. The sandstones in Units 19-26 are oil-stained, which gives a dark brown color.

4.2.1.4.2 Interpretation

Emiliano Mutti interpreted the sandstone at 8651.0-8742.0 ft as a shelfal delta lobe deposits (Trevena, 1996); however, there is a lack dewatering structures that usually found in gravity flow deposit. The upward-coarsening sandstone associated with coal laminae may indicate crevasse splay deposit, and multiple upward-fining trends of the sandstones provide additional evidence that the sandstones are likely to be channel deposits. The sandstones are interpreted as amalgamated fluvial channel deposits based on the following reasons.

Units 19-26 consists of individual Units with an upward-fining trend that are separated by scour surfaces. The degree of preservation of sediments in these Units is low. It is indicated by uniform sedimentary structure (i.e., only cross bedding is preserved). This fact suggests that these Units were deposited in a high-energy system, with low accommodation-to-sediment supply rates.

Based on the grain sizes, sedimentary structures, abundance of scour surfaces, and vertical and lateral continuation of the sandstone, Units 19-26 are interpreted as multistory channel fill. Because the sandstones are coarse-grained and absent of marine influence evidences, such as burrows and mud drapes on cross beds, it is possible that they are fluvial channel deposits. The interpretation of fluvial channel deposit is similar to previous interpretation by Trevena (1996); however, distributary channels with high sediment supply can create that kind of deposit. Therefore the sandstones were classified as fluvial/distributary channel deposits.

The amalgamated sandstone that is obvious in every well probably was produced by meandering channels that switched laterally. The upper part of the deposit, which consists of finer grains, is eroded. On the other hand, the coarser grain portion is preserved.

Alternatively, the sandstones probably were deposited in braided fluvial channel or braided delta environments. Braided channel environment can create laterally continuous coarse-grained sandstone bodies because these systems have high-energy and have a tendency to scour the channel floor and erode the upper part of the previous channel deposit (Miall, 1996). The interpretation of braided channel deposit can be considered as something unique, as there is no braided channel nor braided delta analog found in the modern Mahakam Delta system; however, it does not mean that the interpretation of braided channel and braided delta deposits are impossible, as delta morphologies always evolve through time (Bhattacharya and Walker, 1992).

4.2.1.5 Log Response

Calculation of core-to-log depth correction was done by correlating the grain size changes in core with the log patterns. Abrupt increase in grain size at the contact between fluvial/distributary channel and lower delta front deposits and upward-coarsening pattern of crevasse splay / crevasse channel deposits were used as parameters in calculating core-to-log depth correction because they are easily recognized. The core-to-log depth correction gives a result of + 1 ft, which means that the core interval 8651.0-8742.0 ft is equals to log depth 8652.0-8743.0 ft. This result is similar to the core-to-log depth correction calculated by Trevena (1993).

Figure 4.3 shows the relation between log response and interpreted depositional environments gained from core study in interval 8651.0-8742.0 ft. The log signatures of each interpreted depositional environment in this cored interval can be described as follows:

1. Prodelta to lower delta front deposits have serrated gamma ray pattern. Gamma ray readings of lower delta front deposits are lower compared to those of prodelta deposits because of their more abundant sand content.

Figure 4.2: Crevasse channel deposits that are characterized by cross-bedded sandstone, overlain by ripple-laminated sandstones and capped by coal (at 8677.7-8685 ft). Each deposit is separated by coal layers that indicate abandonment phase of crevassing. Coal layers can be found at 8677.7, 8680.5, 8681.8, 8682.2, 8683.2, 8683.7, and 8684.2 ft (arrows).

2. Fluvial/distributary channel deposits are characterized by sharp base, low gamma ray response. When the abandoned channel fills are preserved, fluvial/distributary channel deposits have an upward-increasing gamma ray log pattern. On the other hand, they are characterized by an overall blocky log pattern when the abandoned channel fills are not preserved.
3. Crevasse splay and crevasse channel deposits have an overall upward-decreasing gamma ray log response.

4.2.2 Cored Interval 8196.4-8251 ft

This cored interval is subdivided into sixteen Units. The facies associations in this cored interval are interpreted to reflect three depositional environments: (1) interdistributary bay, (2) marine-influenced fluvial/distributary channel or estuarine channel, and (3) fluvial/distributary channel. This cored interval represents short-term cycle 2B in the cross section (Plates 2-3). The sketch of core descriptions for this cored interval is in Plate 1b.

4.2.2.1 Units 1-5: Fluvial/distributary channel

These Units are described together because they are genetically related and deposited in the same environment. The composite Units consist of five individual Units that are separated by scour surfaces.

4.2.2.1.1 Description

Units 1-3 (8243-8252 ft) consist of medium- to fine-grained sandstone that are parallel-laminated to trough cross-bedded. The sandstones are medium gray and carbonate-cemented. Coaly particles define the laminations. At 8246.3-8246.4 ft and 8250.3-8250.6 ft the sandstones are not carbonate-cemented and contain oil stain. Subangular to subrounded mud clasts up to two inches in size are present at the base of

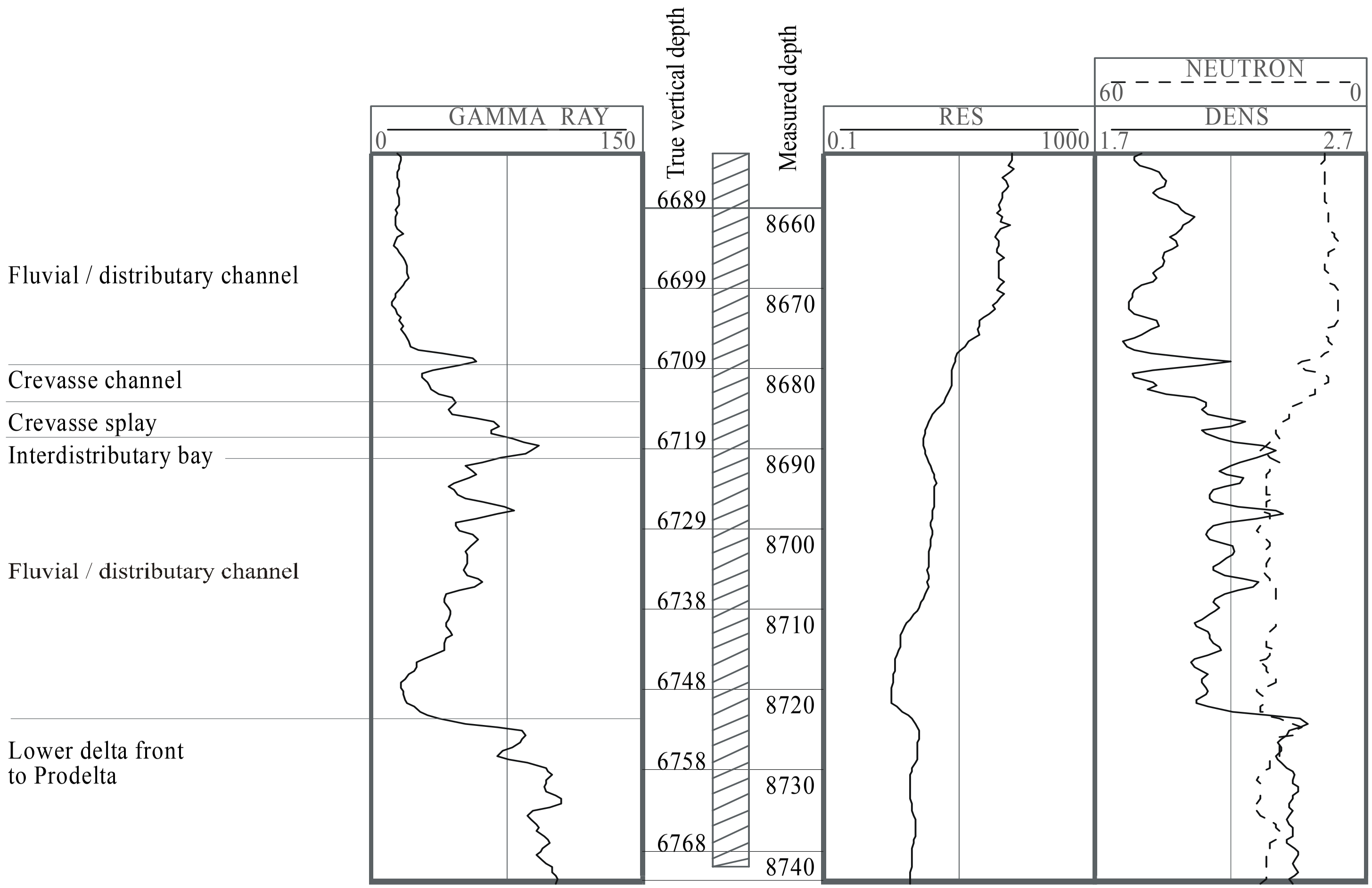


Figure 4.3: Log response of cored interval 8651-8742 ft and the interpreted depositional environments. The depth presented here is referred to log depth, not to core depth. There is +1 ft correction for core-to-log depth calculation.

Unit 2 at 8248.1-8248.6 ft. Within the clasts, coaly particles up to a half of inch are present locally.

Unit 4 is fine- to medium-grained sandstone, moderately-sorted, parallel-laminated to planar cross-bedded. Coaly particle-defined the laminations. Unit 4 is dark brown because of the oil stain. At 8240-8240.5 ft the sandstone is carbonate-cemented.

Unit 5 is 10.5 ft thick, medium- to fine-grained sandstone, moderately-sorted, and has massive appearance with locally parallel lamination and cross-bedded structures. The lower 1.5 ft of Unit 5 is unconsolidated; therefore, the sedimentary structure and scour surfaces in the lower part of Unit 5 is hard to be recognized.

4.2.2.1.2 Interpretation

Units 1-5 are interpreted as fluvial/distributary channel deposits. These Units consist of high-energy traction current deposits. Finer grain deposits with lower flow regime structures such as ripple lamination are not preserved in these Units. The Units lack marine-influence signatures, such as the presence of mud drapes and burrows.

Parallel-laminated to trough cross-bedded nature of Units 1-3 indicates high-energy traction current deposit. Units 1-4 shows an overall upward-fining trend that is interrupted by scour surfaces. During the deposition of Units 1-4 there were pulses of deposition, each shows a waning of energy that is indicated by upward-fining trend.

The log response of the same stratigraphic interval in other wells shows that the carbonate-cementation that is indicated by a kick in low gamma ray and high resistivity only occurs in some wells (e.g., SA-2RD1 and SA-23PH wells). It is interpreted that the carbonate-cemented sandstone only occurs locally around SA-2RD well. The carbonate-cementation results in lower reservoir quality, as its presence reduces the porosity and permeability of the sandstones.

The massive appearance of Unit 5 may indicate that the deposition of this Unit was very fast; therefore, the primary sedimentary structure was not preserved.

4.2.2.2 Units 6-15: Marine-influenced fluvial/distributary channel or estuary channel

Units 6-15 are described together because they are genetically related and deposited in the same environment. Each Unit is separated by scour surfaces.

4.2.2.2.1 Description

These Units can be grouped into three parts based on the occurrence of *Ophiomorpha* burrows. Unit 6 at 8215-8228.5 ft has a massive appearance and *Ophiomorpha* burrowed. Units 7-12 at 8209.5-8215 ft is trough cross-bedded without *Ophiomorpha* burrows, while Units 12-15 at 8204-8209.5 ft is trough cross-bedded and *Ophiomorpha* burrowed (Figure 4.3).

Unit 6 is medium- to fine-grained sandstone, moderately-sorted, has massive appearance, locally parallel-laminated and cross-bedded. *Ophiomorpha* burrows occur at 8217-8220 ft. The characteristics mentioned above are similar to the characteristic of Unit 5, except that Unit 6 is burrowed while Unit 5 is not. The sandstones are dark brown because of oil stains.

Units 7-12 consist of medium- to fine-grained, trough cross-bedded sandstones. These Units are 1-3 ft thick and separated by scour surfaces. Unit 8 and Unit 11 have bi-directional paleocurrent directions (Figure 4.4).

Units 13-15 in general have the same characteristics as Units 7-12, with an addition that these Units are *Ophiomorpha* burrowed and have an upward-fining trend. Soft sediment deformation structure occurs at Unit 13 at interval 8028.24-8029 ft.

4.2.2.2.2 Interpretation

Trevena (1996) interpreted Units 4-15 as delta front bar deposits. His interpretation of delta front bar deposits is based on these arguments: (1) upward-coarsening pattern of the sandstone, especially in interval 8235-8244 ft, (2) occurrence of possible swaley or hummocky cross stratification in interval 8214-8217 ft, (3) presence of *Ophiomorpha* burrows in the upper part.

This study argue that Units 4-15 are fluvial/distributary channel deposits with marine influence or estuarine channel deposits instead of delta front bar deposits because of the following reasons:

1. As seen in the core description that is supported by the log response of this well, there is no obvious upward-coarsening pattern. Unit 4 that is finer-grained seems to be a product of waning of energy of the deposition of Units 1-3 instead of a beginning of deposition of delta front bar; moreover, the gamma ray log response tends to have a blocky pattern instead of upward-decreasing pattern (Plate 1b).
2. The possibly swaley cross stratification that Trevena (1996) proposed is more likely a parallel-laminated structure in unconsolidated sandstone. Hummocky and swaley cross stratification is hard to be recognized in core.
3. The Units seem too sandy and too thick to be a delta front bar deposit.
4. If the series of Units 4-15 represent delta front deposits, there should be a flooding surface between Unit 3 and Unit 4, and the correlation of this flooding surface candidate to adjacent wells is difficult. The log response in all the wells in this interval shows a blocky pattern that more likely for the channel interpretation.
5. The *Ophiomorpha* burrows are not necessarily created in delta-front setting. Estuarine channel or fluvial/distributary channel with saltwater wedge can also produce a favorable environment for organisms to live and disrupt the sediment.

The Units described above lack characteristics of distributary channel deposits, such as upward-fining in grain size accompanied by mud drapes. Units 4-15 are dominated by cross bedding. This fact indicates that the sediments were deposited under high sediment supply, either as fluvial or distributary channel deposits.

The modern Mahakam delta has a salt wedge in the lower reaches of the distributary, which extends upstream more than 20 km from the channel mouth (Allen and Chambers, 1998). It is also possible that in the Miocene the salt wedge may extend upstream up to the lower reaches of fluvial channel. The interpretation of fluvial origin with marine influence for the burrowed sandstone is similar to the Buttenworth et al. (2001) interpretation for the same type of sandstone in Nilam Field, Kutei Basin. Alternatively, the sediment was deposited as estuarine channel fill. In this setting, fluvial deposits are mixed with marine-influenced channel. The high sedimentation rate from the river and saltwater condition of the estuary may also produce cross-bedded sandstone with burrows.

The occurrence of burrows in Unit 6 and Units 13-15 indicates that during the deposition of Unit 4-15 the water salinity was good for organisms to live. Possibly there was marine water intrusion to the depositional environment, which made a favorable condition for the living of organisms. The rare and restricted type of ichnofacies that is dominated by *Ophiomorpha* probably resulted from a high-energy depositional system, which could be a constraining factor for burrowers. The absence of *Ophiomorpha* burrows in Units 7-12 may indicate an increase of sedimentation rate that created an unfavorable condition for them to live.

4.2.2.3 Unit 16: Interdistributary bay

This Unit is described separately because it represents a distinctive facies association compared to that of the Unit below.

4.2.2.3.1 Description

Unit 16 consists of dominantly parallel-laminated to wavy-bedded mudstone with isolated ripples and local burrows. The lower part of Unit 16 is characterized by interlaminated of wavy-bedded mudstone with fine-grained sandstone. Mud content results in dark brown color, whereas sand content results in white color. Thin medium sandstone (approximately 1 inch) signifies the lower boundary of Unit 16 (Figure 4.5).

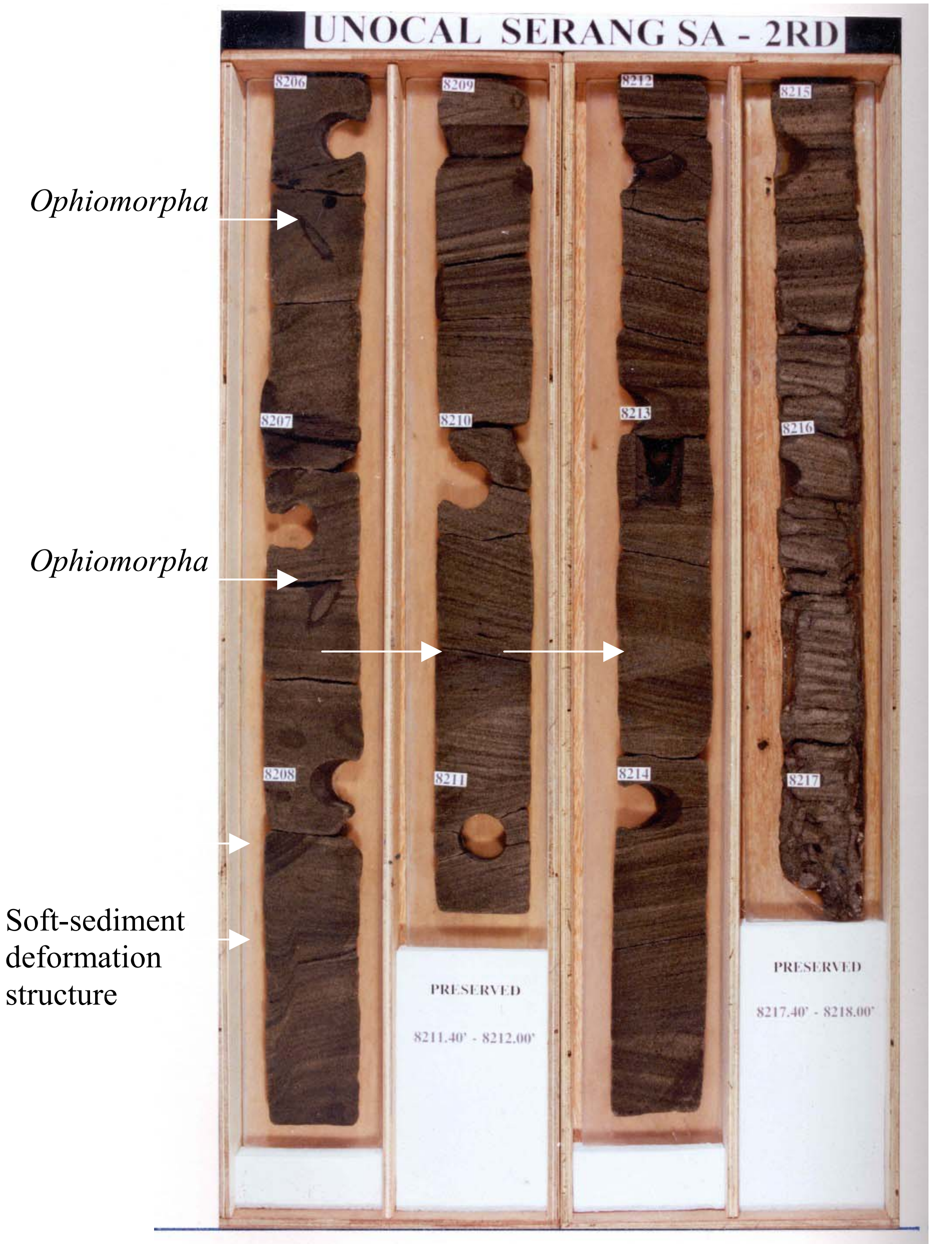


Figure 4.4: Trough cross-bedded sandstones that are burrowed in the upper part. *Ophiomorpha* burrows occur around 8206.5 ft and 8207.5 ft. Note that the cross bedding is bi-directional around depth 8213.7 ft, 8210.7 ft. and 8208.25 ft (arrows without explanation). Soft sediment deformation structure or very large burrow occurs at 8208.5-8209 ft.

Burrows in this Unit are vertical to oblique and mostly filled with sand. Large clay-pelleted burrow (5 inches long and 1.5 inches wide), possibly are *Teichichnus* that were produced by shrimp or crab, are located at 8197-8197.8 ft and 8198.8-8199.5 ft (Figure 4.5). Another type of burrow present is *Thalassinoides.*

4.2.2.3.2 Interpretation

The interpreted depositional environment for the laminated to wavy-bedded mudstone is interdistributary bay or lagoon. Parallel-laminated to wavy-bedded mudstone indicates low-energy depositional environment. The presence of burrows (including shrimp or crab burrow) indicates that the salinity of the environment is favorable for organisms. The isolated ripples may indicate the presence of tidal influence during the deposition of Unit 6.

The thin medium sandstone that is located at the lower part of Unit 6 (Figure 4.5) possibly is transgressive lag deposit that signifies a transgressive surface of erosion.

4.2.2.4 Log Response

Calculation of core-to-log depth correction for cored interval 8196.4-8251 was done by correlating the grain size changes in the cores with the log patterns. A thin carbonate cemented zone at 8240 ft and abrupt grain size change from medium- to fine-grained fluvial/distributary sandstone with marine influence or estuarine channel deposits into interdistributary bay mudstone at 8204.8 ft were picked as parameters in calculating core-to-log depth correction. The thin carbonate cemented zone creates a low gamma ray kick in the log response that is easily can be recognized (Figure 4.6, Plate 1b). The core-to-log depth correction gives a result of +1, which means that cored interval 8196.4-8251 ft equals to log interval 8197.4-8252 ft. This correction is similar to core-to-log depth correction previously calculated by Trevena (1993).

Figure 4.5: Interdistributary bay deposits (at 8196.4-8203.8 ft). Medium-grained sandstone marks the boundary between *Ophiomorpha* burrowed sandstone below (at 8203.8-8206.0 ft, interpreted as fluvial/distributary channel with marine influence or estuary channel deposits) and laminated to wavy-bedded mudstone above. Note the presence of large burrows (possibly *Teichichnus*) at 8197-8197.8 ft and 8198.8-8199.5 ft.

Figure 4.6 shows the relation between log response and interpreted depositional environment gained from core study in cored interval 8196.4-8251 ft. The log signatures of each interpreted depositional environments in cored interval 8196.4-8251.0 can be described as follows:

1. Fluvial/distributary channel deposits have low gamma ray readings with blocky and upward-increasing pattern. The carbonate content in fluvial/distributary channel deposits results in high resistivity and high density. A low kick in gamma ray at 8240 ft results from a thin carbonate cemented zone.
2. Marine-influenced fluvial/distributary channel or estuarine channel deposits have a blocky log pattern with low gamma ray readings below and upward-increasing gamma ray pattern above. The upward-increasing pattern is displayed possibly because of the increase of mud content. The boundary between marine-influenced fluvial/distributary channel or estuarine channel (Units 6-15) and fluvial/distributary channel below it (Units 1-5) is hard to recognize in log because they both have blocky log pattern with low gamma ray readings.
3. Interdistributary bay deposits are characterized by moderate to low gamma ray readings.

4.3 SA-5 cores

The total thickness of cores in the SA-5 well that were studied is about 144 ft. the SA-5 cores were previously described by Siemers (1993). In general, there are similarities in the interpreted depositional environments of Siemers (1993) and those of this study (Table 1.1). Below is the description for each cored interval. The description is subdivided based on combination of facies that represents a facies association or series of facies associations that are genetically related.

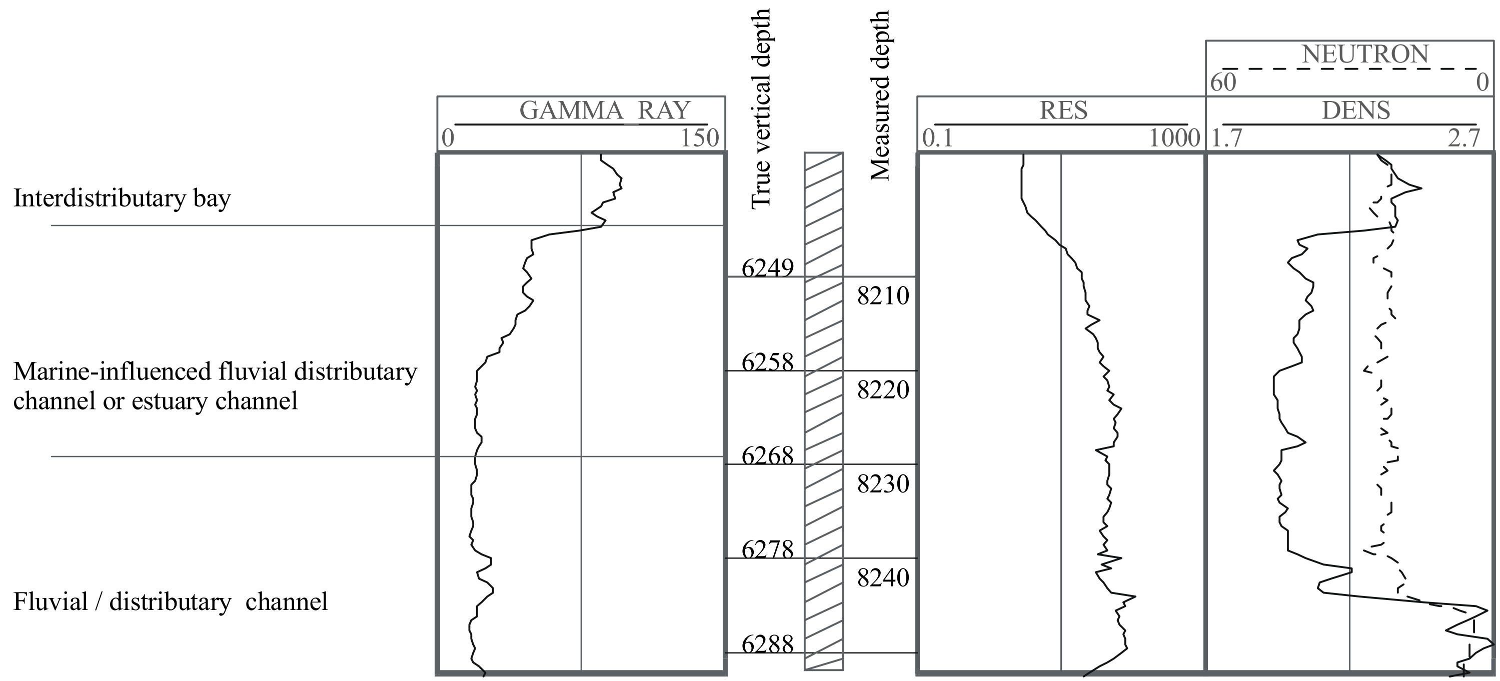


Figure 4.6: Log response of SA-2RD cored interval 8196.4-821 ft and the interpreted depositional environment. The depth presented here is referred to log depth, not to core depth. There is +1 ft correction for core-to-log depth calculation.

4.3.1 Cored interval 6950-7032 ft

This cored interval is subdivided into sixteen Units. The facies associations in this cored interval are interpreted to reflect five depositional environments: (1) lower delta front, (2) delta front bar, (3) interdistributary bay, (4) marsh/swamp, and (5) fluvial/distributary channel. This cored interval represents short-term cycle 2B in the cross section (Plates 2-3). The sketch of core descriptions for this cored interval is in Plate 1c.

4.3.1.1 Units 1-2: Fluvial/distributary channel and interdistributary bay

These Units are described together because they are genetically related and have a gradational transition. No scour surface observed at the boundary of these Units.

4.3.1.1.1 Description

Unit 1 consists of fine-grained, wavy- to ripple-laminated sandstone that changes upward into ripple-laminated mudstone. Unit 1 forms an upward-fining trend and records a transition from flaser to lenticular bedding. The sandstone is moderately well-sorted and beige, whereas the mudstone is dark gray.

Unit 2 consists of 2 ft of burrowed to bioturbated mudstone. Burrows and bioturbation disrupt the primary sedimentary structure of this Unit; however, some traces of lamination are still preserved. Trace fossils found are possible *Thalassinoides* and *Skolithos.*

4.3.1.1.2 Interpretation

Units 1-2 are interpreted as an inactive or upper part of fluvial/distributary channel deposits that grade upward into interdistributary bay deposits. The upward-fining pattern and transition from flaser bedding into lenticular indicate that Unit 1 was deposited under a condition of waning of energy. The waning of energy continues up to the deposition of the burrowed mudstone (Unit 2). The burrows indicate marine water influence and slow rate of deposition. Traces of parallel-laminated structure indicate suspension deposition, possibly Unit 2 was deposited in interdistributary bay environment.

4.3.1.2 Unit 3-4: Transgressive coastal plain to lagoon

These Units are described together because they are genetically related and represent a continuous deposition. The lower boundary of Unit 3 is gradational, whereas the upper and lower boundaries of Unit 4 are sharp.

4.3.1.2.1 Description

Unit 3 consists of thin, laminated mudstone with upward-coarsening pattern. Unit 3 is separated from Unit 2 based on its more massive appearance because of its less heterogeneous mineral composition, lack bioturbation, and lighter color.

Unit 4 consists of calcareous mudstone or calcite-cemented mudstone (Figure 4.7). The calcareous mudstone is fine-grained, dark gray in color, and possibly contains dolomite. Personal communication with Art Saller (2002) suggested that Unit 4 is calcareous mudstone.

4.3.1.2.2 Interpretation

Units 3-4 represent a continuous deposition during transgression. The association f Unit 3 with thin calcareous mudstone above it (Unit 4) indicates that Units 3-4 probably were deposited during transgression. The energy responsible for the deposition of Unit 3 is marine-derived energy.

Based on log character in the same stratigraphic interval, the calcareous mudstone is also found in other wells (for examples SA-4, SA-6, SA-22, and SA-29 wells, Plates 2-3). The calcareous mudstone does not look like a diagenetic product (Art Saller, 2002, personal communication). The disappearance of the thin calcareous mudstone in some wells is probably because it was eroded. Another possibility is that the sedimentation in those wells took place near the locus of deposition, which in turn inhibit carbonate production.

4.3.1.3 Unit 5: Lower delta front

This Unit is described separately because it represents a distinctive facies association compared to those of Units above and below it.

4.3.1.3.1 Description

Unit 5 consists of fifteen feet of laminated, fossiliferous mudstone that is burrowed to bioturbated at the top. *Asterosoma, Terebellina*, and possibly *Rosselia* are present. Shell fragments are present at 7004.5-7005 ft. The basal contact with Unit 4 is sharp, whereas the upper contact with Unit 6 is preserved and not displayed on core. The mudstone is brown in color, and has a darker color (carbonaceous) in the upper 4 ft. Siderite nodules are commonly found in the middle part of this sequence, at 7011-7018 ft.

4.3.1.3.2 Interpretation

Unit 5 is interpreted to be deposited in lower delta front/prodelta. The lamination and trace fossil contents indicate suspension deposition with low sedimentation rate in a fully marine environment below normal fair-weather wave-base. The occurrence of carbonaceous material content at the upper part of Unit 5 indicates that the depositional environment of Unit 5 is not far from the source of the carbonaceous material (swamp/marsh). The siderite nodules may be a post depositional diagenesis product.

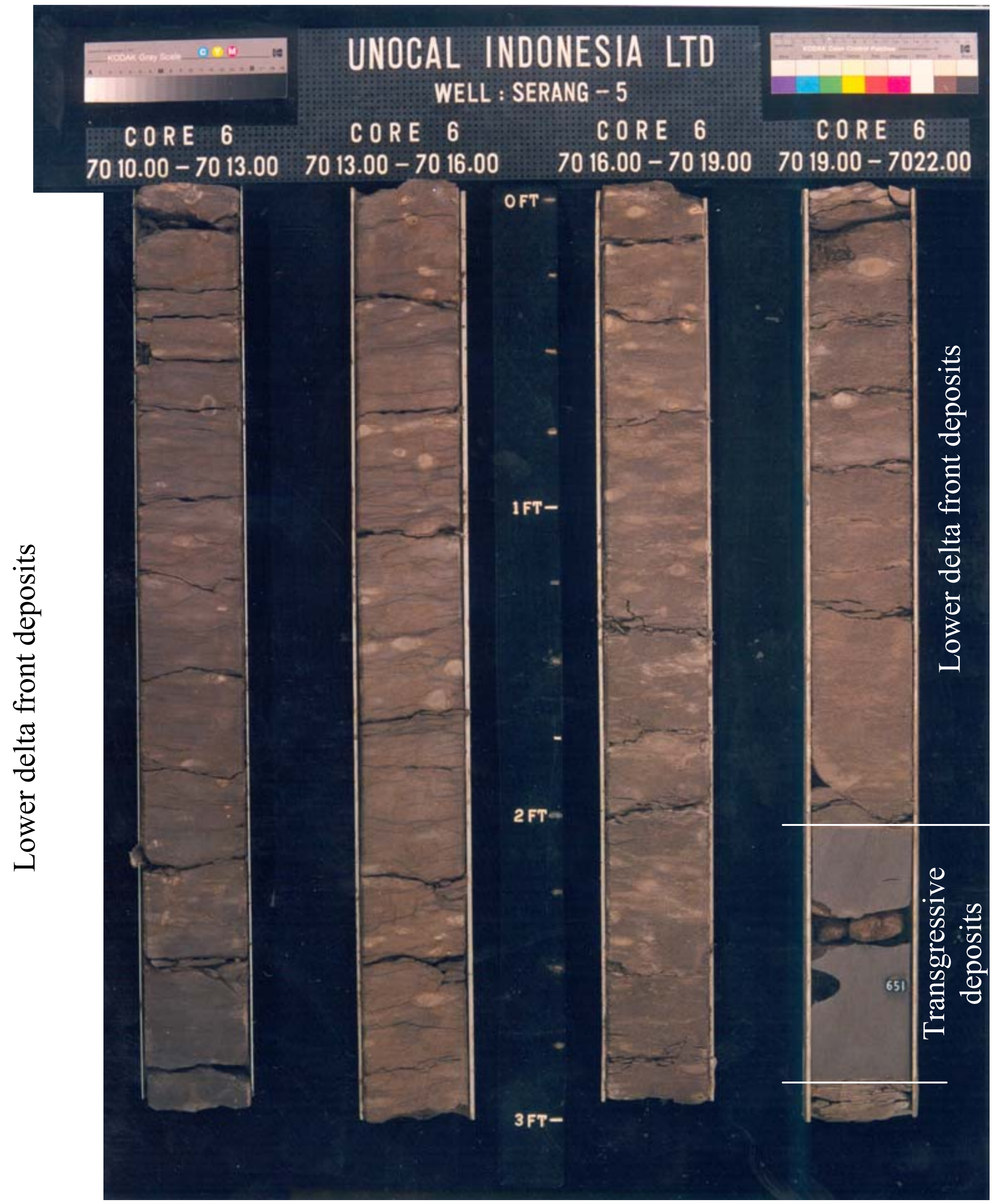


Figure 4.7: Thin calcareous mudstone (Unit 4) at 7021.1-7021.9. This Unit has sharp upper and lower boundaries and is interpreted as a transgressive deposit. Overlying this Unit is lower delta front deposits (Unit 5).

4.3.1.4 Unit 6: Delta front bar

This Unit is described separately because it represents a different facies association compared to that of Units above and below it.

4.3.1.4.1 Description

Unit 6 consists of laminated, highly burrowed to bioturbated, poorly-sorted, sandy mudstone that has an upward-fining trend. This Unit is abundant of trace fossils. Trace fossils found in Unit 6 are *Zoophycus, Planolites, Terebellina, Teichichnus, Asterosoma,* and possibly *Diplocraterion.* Sedimentary structures were highly disrupted by burrows and bioturbation (Figure 4.8); therefore, the primary sedimentary structure of this Unit cannot be recognized. Unit 6 is poorly-sorted and has gray and brown mottled tone. The lower boundary of Unit 6 is preserved and not displayed on core, whereas the upper boundary of Unit 6 with Unit 7 is sharp.

4.3.1.4.2 Interpretation

The interpreted depositional environment for Unit 6 is delta front bar. The sedimentary structures of this Unit indicate that the deposition of Unit 6 took place during a low sedimentation rate, which allows burrowing to keep pace with the sedimentation. Trace fossil contents indicate that this Unit was deposited in shallow-marine setting. Probably this Unit was deposited in a subaqueous environment with normal marine salinity condition such as tidal channel, delta-front bar, or estuarine. Based on its sandy nature, intensive burrows and bioturbation, and association with Units adjacent to it, Unit 6 is interpreted as delta front bars.

4.3.1.5 Units 7-8: Lower delta plain and marsh/swamp

Units 7-8 are described together because they represent two depositional environments that are genetically related. The Units are not separated by a scour surface.

4.3.1.5.1 Description

Unit 7 consists of thin, parallel-laminated, dark brown carbonaceous mudstone and barren of bioturbation. Unit 8 consists of coal. Both Units have a total thickness about 1 ft. The upper and lower boundaries of these Units are sharp (Figure 4.8).

4.3.1.5.2 Interpretation

The laminated, carbonaceous mudstone (Unit 7) and coal (Unit 8) represent a period of starvation. The laminated mudstone that is barren of bioturbation represents suspension deposition in a starving basin. The carbon content indicates that the depositional environment is close to the source of carbonaceous material, probably in lower delta plain. Coal of Unit 8 represents deposition from insitu vegetation in restricted clastic input environment, more likely in swamp or marsh.

4.3.1.6 Unit 9: Delta front bar

This Unit is described separately because it represents a distinctive facies compared to those of Units above and below it. The contact with Unit 8 is sharp but non erosional whereas the contact with Unit 10 is gradational.

4.3.1.6.1 Description

Unit 9 is fine-grained sandstone that is highly burrowed and poorly-sorted because of biomixing. Traces of wavy-laminated structure are observed in this Unit. Overall Unit 9 has an upward-fining trend. The lower contact with Unit 8 is erosional (Figure 4.8). The upper contact with Unit10 is gradational. The biomixing gives mottled tone of light brown and dark gray. Possibly *Zoophycus* and *Terebellina* dominate the trace fossil content.

4.3.1.6.2 Interpretation

Unit 9 is interpreted to be deposited as delta front bar based on its sandy nature, high intensity of burrow and bioturbation, and trace fossil associations. Those features indicate that this Unit was deposited under low-energy and slow rate of deposition in shallow-marine setting. Alternatively, this Unit may have been deposited in tidal channel or estuarine enviromnents.

4.3.1.7 Units 10-13: Lower delta front

Units 10-13 are described together because they are genetically related and deposited in the same environment. Overall the Units have gradational contact.

4.3.1.7.1 Description

Unit 10 consists of mudstone that is burrowed to bioturbated and dark gray to brown. The burrows and bioturbation produce mottled tone. *Asterosoma,* possibly *Zoophycus, Thalassinoides,* and *Terebellina* burrows are present. Upward, the mudstone grades into bioturbated fine-grained sandstone (Unit 11) that is poorly-sorted because of biomixing. Unit 12 is dark gray calcareous mudstone or probably calcite-cemented zone. The thickness of Unit 12 is 2 ft. Unit 13 is laminated mudstone that contains some siderite nodules and possibly bioturbated. This Unit has an upward-fining pattern. The contact between carbonate and laminated mudstone is uneven. It is probably a scour surface.

4.3.1.7.2 Interpretation

The interpreted depositional environment for Units 10-13 is lower delta front. The abundance of burrows and bioturbation in Units 10-11 indicates that those Units were deposited with slow rate of deposition in normal marine salinity environment. The trace fossil associations indicate that the depositional environment of Unit 10 is in shallow-marine, possibly in lower delta front. Unit 11 possibly is a flood deposit that was deposited as delta front bar. The calcareous mudstone (Unit 12) possibly is a diagenetic product. Alternatively it is transgressive mudstone deposit. Based on log response, the calcareous mudstone is found in adjacent wells and other wells that are located in the southern and northern field margins (SA-7, SA-16, SA-19, and SA-31 HZ wells, see cross section C-C' at Plate 2). The disappearance of calcareous mudstone in other well may be caused by erosion, as this Unit in other wells is truncated by channel deposits.

The lack bioturbation in Unit 13 can be caused by the fresher water environment or more rapid rate of deposition. The uneven contact between Unit 12 and Unit 13 resemble a scour surface. The presence of a scour surface between Unit 12 and Unit 13 indicates that the rate of deposition of Unit 13 is relatively rapid that in turn inhibit bioturbation.

4.3.1.8 Units 14-16: Fluvial/distributary channel

Units 14-16 are described together because these Units are genetically related and represent the same depositional environment. Each Unit is separated by scour surfaces.

4.3.1.8.1 Description

Unit 14 is medium- to fine-grained sandstone with trough cross bedding to parallel-lamination that grade upward into mudstone with ripple- to wavy-lamination. This Unit is medium brown to light gray and lightly oil-stained. It is rubble at the lower 2.5 ft (at 6968.2-6971 ft).

Unit 15 is mudstone with wavy- to ripple-lamination. Coaly material defined the laminations. The Unit is light gray to beige. Because the Unit is cemented, the color reflects cement color instead of the original color. The lower part of this Unit is sandier and creates a scour surface with Unit 14.

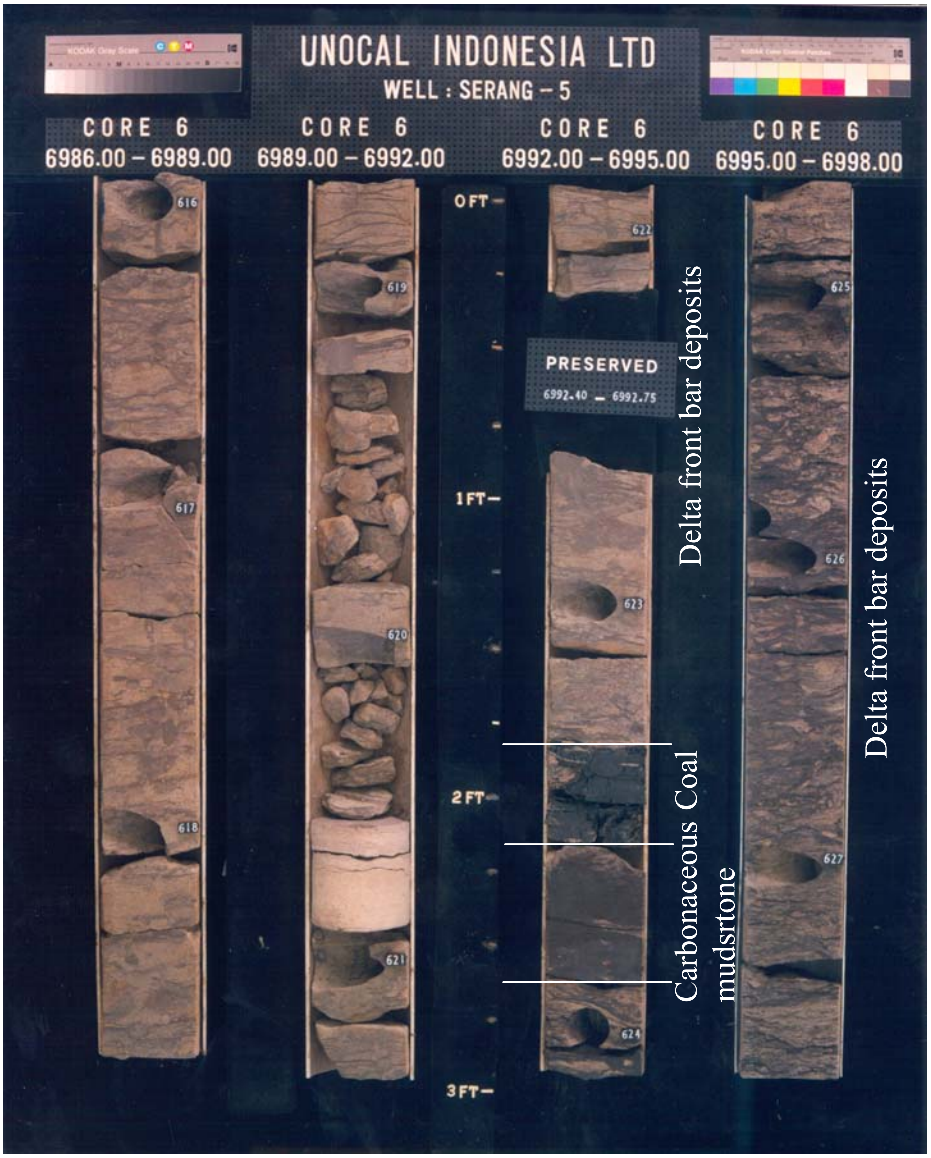


Figure 4.8: Thin coal (at 6993.8-6994.2 ft) and carbonaceous mudstone (at 6994.2-6994.8 ft). Because the coal is thin, gamma ray tool cannot record the radioactivity of coal. Therefore this coal is not marked by a kick of low gamma ray readings (Figure 4.9). The Units above an below the coal and carbonaceous mudstones are bioturbated to burrowed sandstones and sandy mudstones that are interpreted as delta front bars.

Unit 16 is medium-grained sandstone that is massive or possibly cross-bedded. The sandstone is heavily oil-stained. It is not clear whether this sandstone is cross-bedded or massive because there is no big contrast in the grain color, partially because of oil stain content.

4.3.1.8.2 Interpretation

The interpreted depositional environments for Units 14-16 are fluvial/distributary channels. The cross-bedded sandstones (Unit 14) indicate moderate to high current velocity during their sedimentation. They were deposited from bedload transport that is developed by the migration of megaripple (Reineck and Singh, 1975). The transition from medium- to fine-grained, cross-bedded sandstone into fine-grained sandstone and mudstone with wavy bedding structure indicates a waning of energy of transportation. The presence of a scour surface between Units 15 and 16 indicates that there was a pulse of deposition in between their deposition.

The cross-bedded to massive sandstone (Unit 16), if it is a massive sandstone, indicates a rapid sedimentation rate during the deposition of the sandstone. The presence of scour surfaces indicates that Units 14-16 consists of stacking channel deposits.

4.3.1.9 Log Response

Calculation of core-to-log depth correction was done by correlating the grain size changes on cores with the log patterns. Carbonaceous mudstones are marked by a distinctive low kick in gamma ray pattern. This pattern was used as parameter in calculating the correction. The core-to-log depth correction for interval 6950-7032 ft is approximately + 3 ft. This correction gives an approximate log depth for this core about 6953.0-7035.0 ft. The core-to-log depth correction gives the same result as that of Siemers (1993).

Figure 4.9 shows the relation between log response and interpreted depositional environment for cored interval 6950-7032 ft. The log signatures of each interpreted depositional environment in this cored interval can be described as follows:

1. Fluvial/distributary channel deposit has an upward-increasing gamma ray pattern. This pattern suggests the upper part of fluvial/distributary channel deposit.
2. Interdistributary bay deposit is characterized by low gamma ray readings that indicate high mudstone porpotion.
3. Transgressive coastal plain to lagoon deposit (calcareous mudstone) is characterized by a kick of low gamma ray pattern, low sonic, high density and low neutron readings. Those patterns resulted from calcareous content.
4. Lower delta front deposit has serrated pattern with high gamma ray, low resistivity, and high sonic readings.
5. Delta front bar has blocky pattern with medium gamma ray readings and higher gamma ray readings than those of fluvial/distributary channel.
6. Lower delta plain swamp/marsh deposits are characterized by a kick in high gamma ray, high resistivity, high sonic, low neutron and low density readings. This pattern is different compared to that of other cores that is characterized by a kick in low gamma ray. The high gamma ray readings probably because of the thin nature of the coal (0.5 ft) that cannot be read by the gamma ray tool.

4.3.2 Cored interval 6555.0-6615.0 ft

This cored interval is subdivided into seventeen Units. Facies associations in this cored interval are interpreted to represent the following depositional environments: (1) tidal flat, (2) distributary channel, and (3) swamp or marsh. This cored interval represents intermediate-term cycle 3 in the cross section. The sketch of core description for this cored interval can be found in Plate 1d.

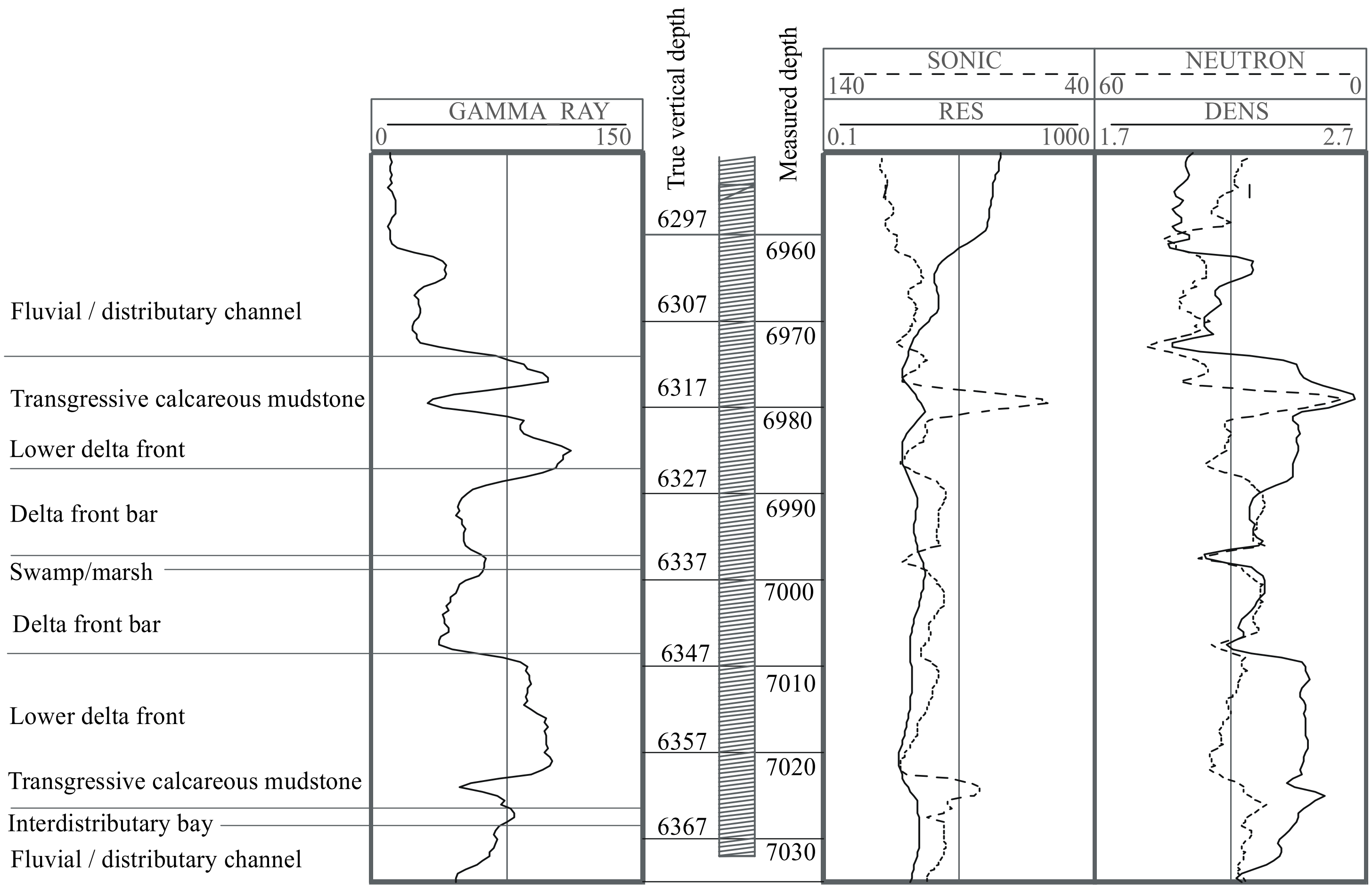


Figure 4.9: Log response of SA-5 cored interval 6950-7032 ft and the interpreted depositional environments. The depth presented here is referred to log depth, not to core depth. There is +1 ft correction for core-to-log depth calculation.

4.3.2.1 Units 1-7: Distributary channel

Units 1-7 are described together because they are genetically related and represent the same depositional environment. Each Unit is separated by scour surfaces. These Units consist of an overall upward-fining sequence.

4.3.2.1.1 Description

These Units are characterized by the abundance of volcaniclastic fragments. Units 1-4 that are located at 6604-6615 ft consist of medium- to coarse-grained, cross-bedded to parallel-bedded sandstones. The sandstones are moderately- to poorly-sorted and light brown in color. Subrounded pebble-sized clasts (0.4 mm in average, up to1.5 cm) are present at the scour surfaces. The clasts composed mainly of lithic grains of volcanic, sedimentary and metamorphic rocks, quartz, and feldspar.

Unit 5 is medium- to fine-grained sandstones, light brown in color, moderately- to poorly-sorted. This Unit records a change of sedimentary structure from cross bedding and parallel bedding below into ripple-lamination above. The boundary between Unit 5 and Unit 4 is a scour surface with subrounded pebble lag deposits. The clasts are composed mainly of lithic grains of volcanic, sedimentary and metamorphic rocks, quartz, and feldspar.

Unit 6 is fine-grained sandstone, parallel-laminated to ripple-bedded, with coaly-material defined lamination. The sandstone is moderately-sorted and gray to dark gray. The base of Unit 6 consists of medium-grained sandstone resting on a scour surface.

The upper part of the composite Unit (Unit 7, at 6592-6598 ft) consists of medium-grained sandstone with massive appearance and possible parallel-bedded structure. The sandstone is moderately- to poorly-sorted and light brown in color. The sandstone is organized into discrete beds that are separated by thin, brown, mudstone interlayers.

4.3.2.1.2 Interpretation

Units 1-3 are interpreted as parts of distributary channel deposits. The multiple scour surfaces indicate that these Units consist of multistory channel deposits. The cross-bedded sandstone (Unit 1) indicates deposition in moderate to high current velocity. The transition into laminated to rippled sandstone (Unit 2) which has finer grain size indicates a waning of current energy. Unit 2 is probably a part of transitional to inactive channel fill. The presence of medium-grained parallel-bedded sandstone (Unit 3) indicates a deposition in upper flow regime. The abundance of volcaniclastic fragments in the sandstones gives evidences that there was a volcanic activity during the deposition of the sandstone.

The association of the channel deposits and coal of Unit 9 (to be discussed later) may indicate that the deposition of the sandstone was in area that is easily drowned with water during transgression. Therefore, it is more likely that the deposition of the sandstones in this interval took place in a distributary channel setting instead of fluvial channel.

4.3.2.2 Unit 8-9: floodplain and swamp or marsh

Units 8 and 9 are described together because they are genetically related. The contact between these Units is non erosional.

4.3.2.2.1 Description

Unit 8 consists of sandy mudstone that is rooted and has an upward-fining trend. The mudstone is 2 ft thick and dark brown. Unit 9 consists of 2 ft thick of coal.

4.3.2.2.2 Interpretation

The rooted sandy mudstone and coal bed represents a period of starvation during channel abandonment. The rooted sandy mudstone is interpreted as a floodplain deposit, whereas the coal may represent swamp or marsh deposit.

4.3.2.3 Units-10-15: Distributary channel

These Units are described together because they are genetically related and represent the same depositional environment. Each Unit is separated by scour surfaces.

4.3.2.3.1 Description

These Units are characterized by the abundance of volcaniclastic fragments. The lower part of these composite Units (Units 10-13, at 6573-6577.5 ft) consists of medium- to coarse-grained sandstone with lamination to cross bedding. The sandstones are moderately- to poorly-sorted and light brown. No pebble-size clasts observed on the scour surfaces.

The upper part of these composite Units (Units 14-15, at 6590.5-6577.5) consists of medium-grained sandstones that upward fining into mudstone. The sandstones are parallel-bedded. At Unit 14 the sandstones change upward into sandy mudstone with laminated to ripple-bedded. At Unit 15 the parallel-laminated sandstone changes upward into rooted sandy mudstone that is yellowish (Figure 4.10).

4.3.2.3.2 Interpretations

Units 10-15 are interpreted as distributary channel deposits. Multiple scour surfaces within the Units indicate multistory channel deposits. The lower portion of these Units (Unit 10-13) represents active channel deposit. Units 14-15 possibly represent a transitional, upper inactive portion of channel fill deposits, as these Units are characterized by an upward-fining pattern.

The presence of roots at Unit 15 represents a pause in deposition. The upward-fining pattern in this Unit partly is related to weathering process. The yellowish color of sandy mudstone is possibly a diagenetic feature that resulted from kaolinitic alteration associated with acidic fluids derived from compacting peat (Allen and Chambers, 1998).

The association of these deposits with coal above and below indicates that the deposition of the sandstone was in area that is easily drowned with water during transgression. Therefore it is interpreted that the deposition of the sandstones in this interval took place in a distributary channel environment.

4.3.2.4 Units 16: Swamp or marsh

This Unit is described separately because it represents a different depositional environment compared to Units above and below it.

4.3.2.4.1 Description

This Unit consists of 1.2 ft thick of coal that has a sharp contact with the Unit above and below it (Figure 4.10).

4.3.2.4.2 Interpretation

The coal was deposited in swamp or marsh when there was a shut down of fluvial-derived sediment supply.

4.3.2.5 Units 17: Tidal flat

This Unit is described separately because it represents a different depositional environment compared to that of the Units above and below it.

4.3.2.5.1 Description

This Unit consists of laminated sandy mudstone that is grayish brown in color (Figure 4.10).

4.3.2.5.2 Interpretation

This Unit is interpreted to be deposited in tidal flat environment. Deposition of this Unit possibly during transgression, as this Unit is represented by an overall upward-increasing pattern on gamma ray log response.

4.3.2.6 Log Response

The core-to-log depth correction is calculated by comparing the position of coal of Unit 5 in core and log. The core-to-log depth correction for cored interval 6555-6615 ft is about + 1 ft, hence the cored interval is located at log depth 6554.0-6616.0 ft. This calculation matchs with the core-to-log depth correction calculated by Siemers (1993).

Figure 4.11 shows the relation between log response and interpreted depositional environment gained from core study in cored interval 6555-6615. The log signatures of each interpreted depositional environments in this cored interval can be described as follows:

1. Distributary channel deposits have a blocky followed by upward-increasing gamma ray log pattern. The blocky pattern might represent the active channel fill, whereas the upward-increasing pattern might represent the transition to inactive channel fill.
2. Coal is characterized by a kick of low gamma ray, high resistivity, high sonic, high neutron and low density pattern. The coal is easily recognized from the overlay of high neutron and low density.

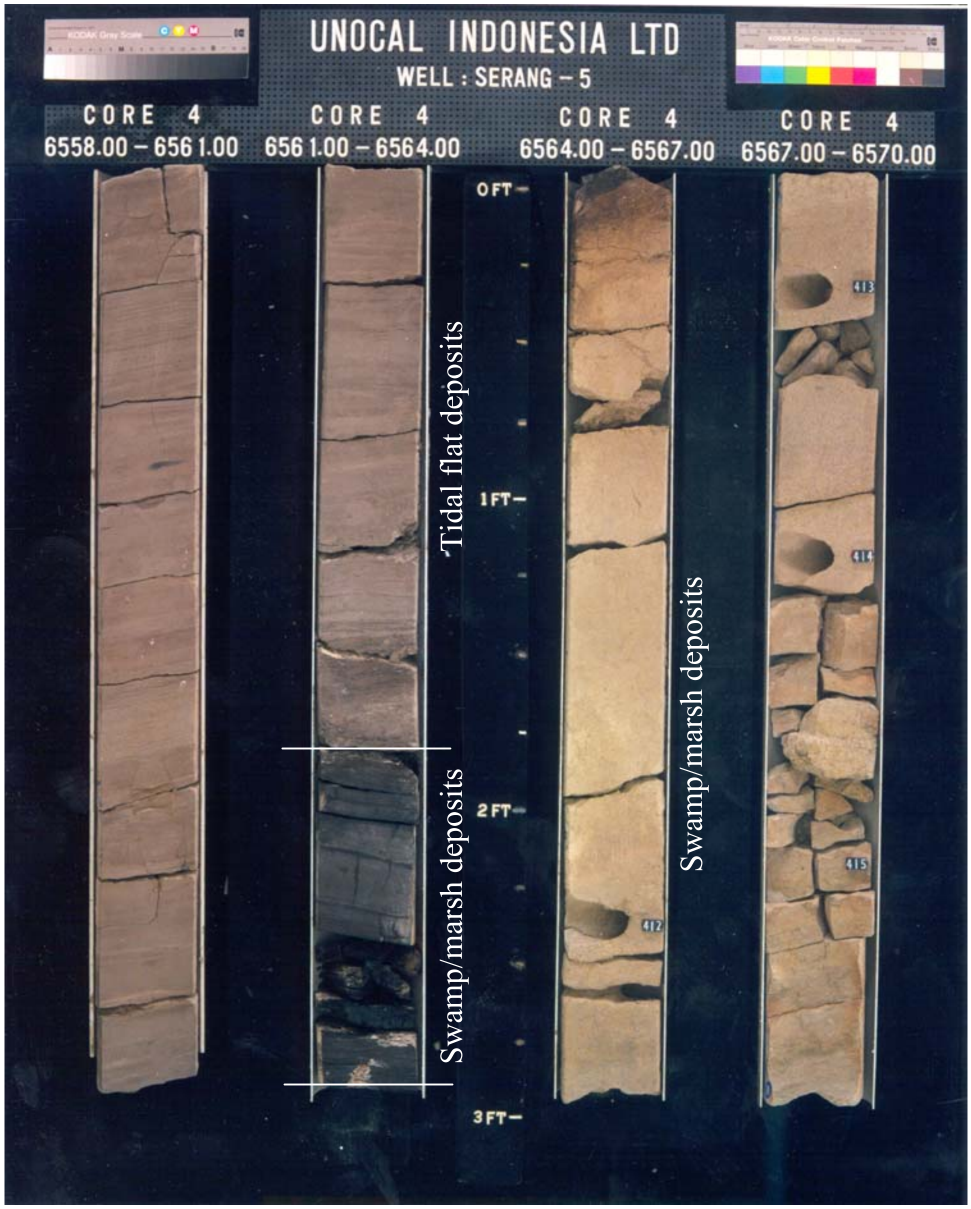


Figure 4.10: Tidal flat deposits at 6558-6563 ft. The tidal flat deposits are overlying carbonaceous mudstone (at 6563-6564 ft) and rooted sandy mudstone (at 6564-6570) that is a product of kaolinitic alteration associated with acidic fluids derived from compacting peat. The rooted sandy mudstone is interpreted as abandoned part of distributary channel.

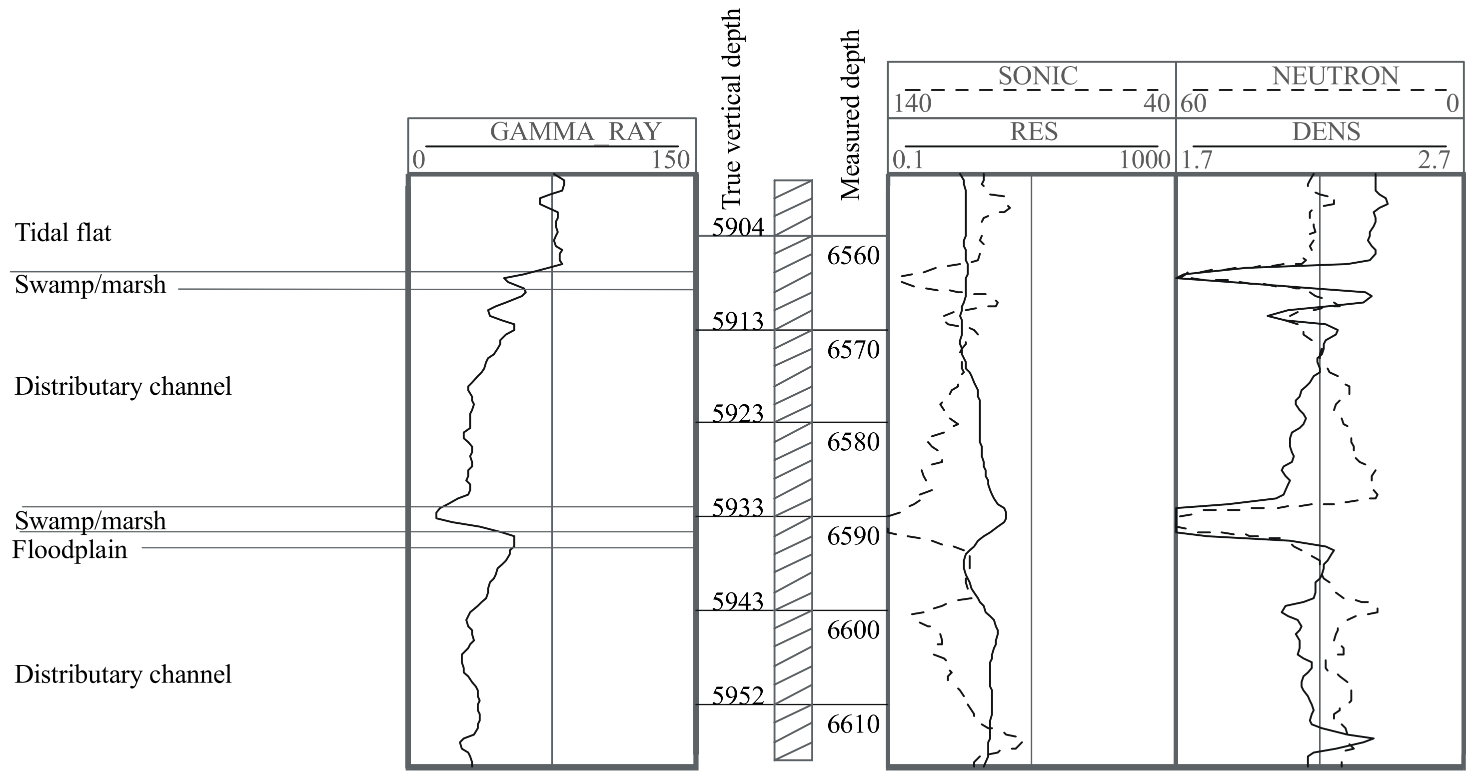


Figure 4.11: Log response of SA-5 cored interval 6555-6615 ft and the interpreted depositional environment. The depth presented here is referred to log depth, not to core depth. There is +1 ft correction for core-to-log depth calculation.

3. Tidal flat deposits have a moderate gamma ray pattern. In other wells, tidal flat deposits have an overall upward-increasing gamma ray pattern, indicating the transgressive nature of tidal flat deposits.

4.4 SA-3RD2 cores

The total thickness of the SA-3RD2 cores that were studied is about 102.5 ft. The cores can be divided into two cored intervals: 7601.0-7662.0 ft and 6587.0-6628.5 ft. Below is the description and interpretation of each interval, followed by the explanation of the relationship between core and log response.

4.4.1 Cored interval 7601.0-7662.0 ft

This cored interval is subdivided into twelve Units. Facies associations in this cored interval are interpreted to represent two depositional environments: (1) lower delta front, and (2) delta front bar or distributary channel. Stratigraphically this cored interval is located below the study interval. In order to get more data to calibrate log response with core, this cored interval was also studied. The sketch of core description is in Plate 1e.

4.4.1.1.1 Description

Units 1,3, and 5 consist of very dark gray, laminated, burrowed to bioturbated mudstone that contains abundant siderite nodules in the lower 4.5 ft. The mudstone contains benthonic foraminifers. Trace fossils found in these Units are *Thalassinoides*, *Planolites,* and possibly *Terebellina* The mudstone grades upward into burrowed to bioturbated, very fine-grained calcareous sandstone (Units 2,4,6) that forms upward-coarsening pattern and has a mottled tone of light brown and dark gray. The sandstones are poorly-sorted because of biomixing. *Thalassinoides, Planolites, Asterosoma,* and possibly *Terebellina* are found in the sandstones.

4.4.1.1.2 Interpretation

The interbedded mudstone/sandstone sequence that is burrowed and bioturbated shows evidence of slow suspension deposition in a saltwater environment. Trace fossil associations indicate fully marine environment below fair-weather wave-base. The biomix of sand and mud that is resulted from the burrowing/bioturbation produced the gradual contact between the mudstone and thin sandstone.

4.4.1.2 Unit 7: Distributary channel or delta front bar

This Unit is described separately because it represents different depositional environment from that of Units above and below it. The lower contact with Unit 6 is a scour surface, whereas the upper contact is sharp but non-erosional.

4.4.1.2.1 Description

Unit 7 consists of fine- to medium-grained sandstone with cross bedding to lamination that is slightly burrowed and oil-stained. This Unit is from 7630-7634.5 ft. At 7633 *Thalassionides* is observed. Oil stain content gives dark brown color in this Unit.

4.4.1.2.2 Interpretation

The interpreted depositional environment for Unit 7 is delta front bar or distributary channel. Cross bedding and rare burrowed/bioturbated nature of this Unit indicates that this Unit was deposited in moderate to high current velocity. The high-energy that can produce this kind of structure could results from flood/storm in delta front setting. Alternatively, the sandstone was deposited in the lower reach of distributary channel. The presence of burrows indicates saltwater condition in delta front environment, or saltwater wedge in freshwater distributary channel environment.

4.4.1.3 Units 8-12: Lower delta front

These Units are described together because they consist of a repetition of two facies that are genetically related: burrowed and bioturbated mudstone (facies Mpb, Units 8, 10, 12) and burrowed to bioturbated sandstone (facies Sb, Units 9,11). The transition from burrowed to bioturbated mudstone into burrowed to bioturbated sandstone is gradational; the transition from burrowed to bioturbated sandstone into burrowed to bioturbated mudstone is more abrupt.

4.4.1.3.1 Description

Units 8, 10, 12 consist of very dark gray, laminated, burrowed to bioturbated mudstone. The mudstone contains benthonic foraminifers. Trace fossils found in these Units are *Planolites,* and possibly *Terebellina.* Siderite nodules are abundant in Unit 10 and Unit 12. Unit 12 is rarely bioturbated compared to other Units; it is more dominated by siderite nodules.

The mudstone grades upward into burrowed to bioturbated, very fine-grained calcareous sandstone (Units 9,11) that forms an upward-coarsening pattern and has a mottled tone of light brown and dark gray. The sandstones are poorly-sorted because of biomixing. *Thalassinoides,* and *Asterosoma* are found in the sandstones.

4.4.1.3.2 Interpretation

The interbedded mudstone and sandstone that is burrowed and bioturbated shows evidences of slow suspension deposition in saltwater environment. The trace fossil associations indicate marine environment below fair-weather wave-base. Biomixing of sand and mud resulted in the gradual contact between the mudstone and thin sandstone.

4.4.1.4 Log response

The core-to-log depth correction is calculated by correlating the grain size changes in cores with the log patterns. Calculation of log to depth correction for this interval gives a result of + 24, which means that the log depth of the interval is 7626-7693. This calculation is similar to that of Siemers (1993).

Figure 4.12 shows the relation between log response and interpreted depositional environment gained from core study in cored interval 7601-7662 ft.

1. Distributary channel / delta front bar deposits have a distinctive lower gamma ray, higher resistivity, and higher sonic values compared to adjacent lithology.
2. Lower delta front deposits have a serrated log pattern with upward-decreasing gamma ray pattern.

4.4.2 Cored interval 6587.0-6628.5 ft

This cored interval is subdivided into six Units. The Units can be classified a facies association that represents fluvial/distributary channel environment. This cored interval represents short-term cycle 2B in the cross section (Plates 2-3). The sketch of core description for this cored interval is in Plate 1f.

4.4.2.1 Units 1-6: Fluvial/distributary channel

These Units are described together because they are genetically related and represent the same depositional environment. Each Unit is separated by scour surfaces.

4.4.2.1.1 Description

Unit 1 consists of medium-grained sandstone with parallel to cross bedding. The sandstone is moderately well-sorted and medium brown because of oil stain. The stratification of this sandstone is difficult to be discerned because of the oil stain. The oil stain is decreasing upward. Interval 6614.5-6614.65 ft consists solely of a mud clast.

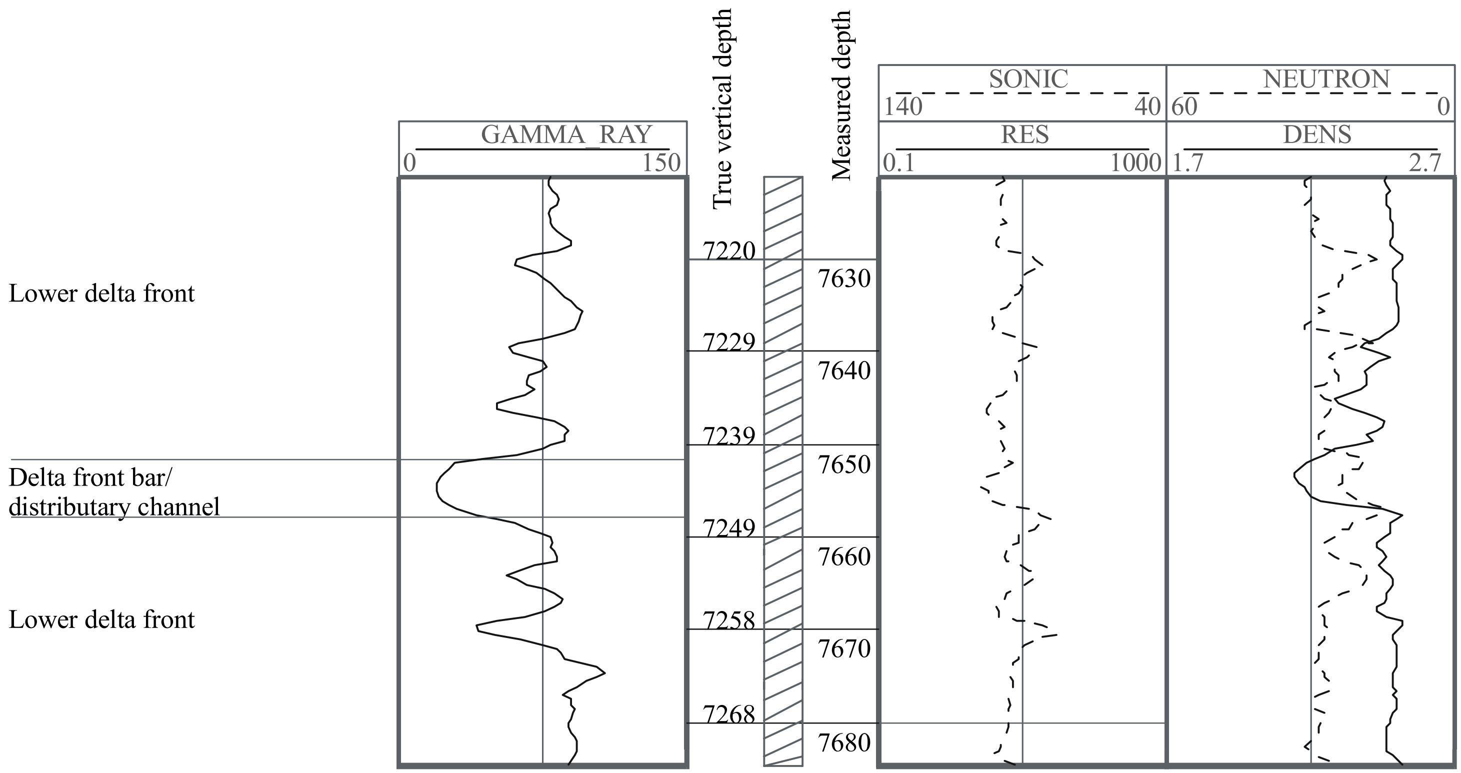


Figure 4.12: Log response of SA-3 RD2 cored interval 7601-7662 ft and the interpreted depositional environments. The depth presented here is referred to log depth, not to core depth. There is +24 ft correction for core-to-log depth calculation.

Unit 2 is medium- to fine-grained sandstone, parallel to cross-bedded with internal laminations and upward-fining trend. Locally coaly material defined laminations. The sandstone is moderately well-sorted and gray in color. Carbon laminae within the laminated structures are present at interval 6608.8-6608.85 ft and 6612.7-6612.8 ft.

Unit 3 consists of medium- to fine-grained sandstone with parallel to ripple laminations. The sandstone is moderately well-sorted and very light brown. Locally coaly materials defined the laminations.

The lower part of Unit 4 consists of medium- to fine-grained sandstone, moderate-angle cross-bedded with internal lamination at the bottom. Upward, the structure changes into parallel and ripple lamination (Figure 4.13). The sandstone is moderately well-sorted and very light gray. Locally coaly materials defined the laminations.

Unit 5 is fine-grained sandstone that is ripple-laminated. The sandstone is moderately well-sorted and very light gray. Locally coaly materials defined the laminations.

Unit 6 consists of very fine-grained sandstone, ripple- to wavy-laminated, and shows upward-fining pattern with a transition from flaser to lenticular lamination. The sandstone is moderately well-sorted, very light gray to light brown in color. Locally coaly materials defined the laminations.

4.4.2.1.2 Interpretation

The interpreted depositional environment for Unit 1-6 is fluvial/distributary channel. Overall the Units represent a waning of energy. There are six pulses of deposition observed within these Units, each are bounded by scour surfaces. Units 1,2,3, and the lower part of Unit 4 represent active channel fills. They consist of medium- to fine-grained sandstone and dominated by parallel to cross bedding. Unit 5,6, and the upper part of Unit 4 represent transitional or inactive channel fill. They consist of fine-grained sandstone with ripple to wavy laminations.

4.4.2.2 Log response

Core-to-log depth correction for the core interval 6587.0-6628.5 ft was done by correlating the changes in grain size on cores with the log patterns. By assuming that the changes in grain size is correlated to gamma ray response and no radioactive materials contained in core, calculation of core-to-log depth correction gives a result of +4, which suggests that the log depth for cored interval 6587.0-6628.5 is 6591.2-6632.5. This result is different from that of Siemers (1993) that suggests a correction of +20 ft.

Based on core-to-log depth correction value above, the log response of the cored interval in its proper depth can be observed as follows:

1. Sandstones that have gamma ray readings more than 60 API are fine-grained, muddy, and ripple-bedded.
2. Sandstones that have gamma ray readings less than 60 API generally are coarser grained, parallel- to cross-bedded.

The 60 API gamma ray value is used as sandstone cut-off value in calculating the net sand in this study because it marks a significant changes in grain size and sedimentary structure as seen on core (Figure 4.13).

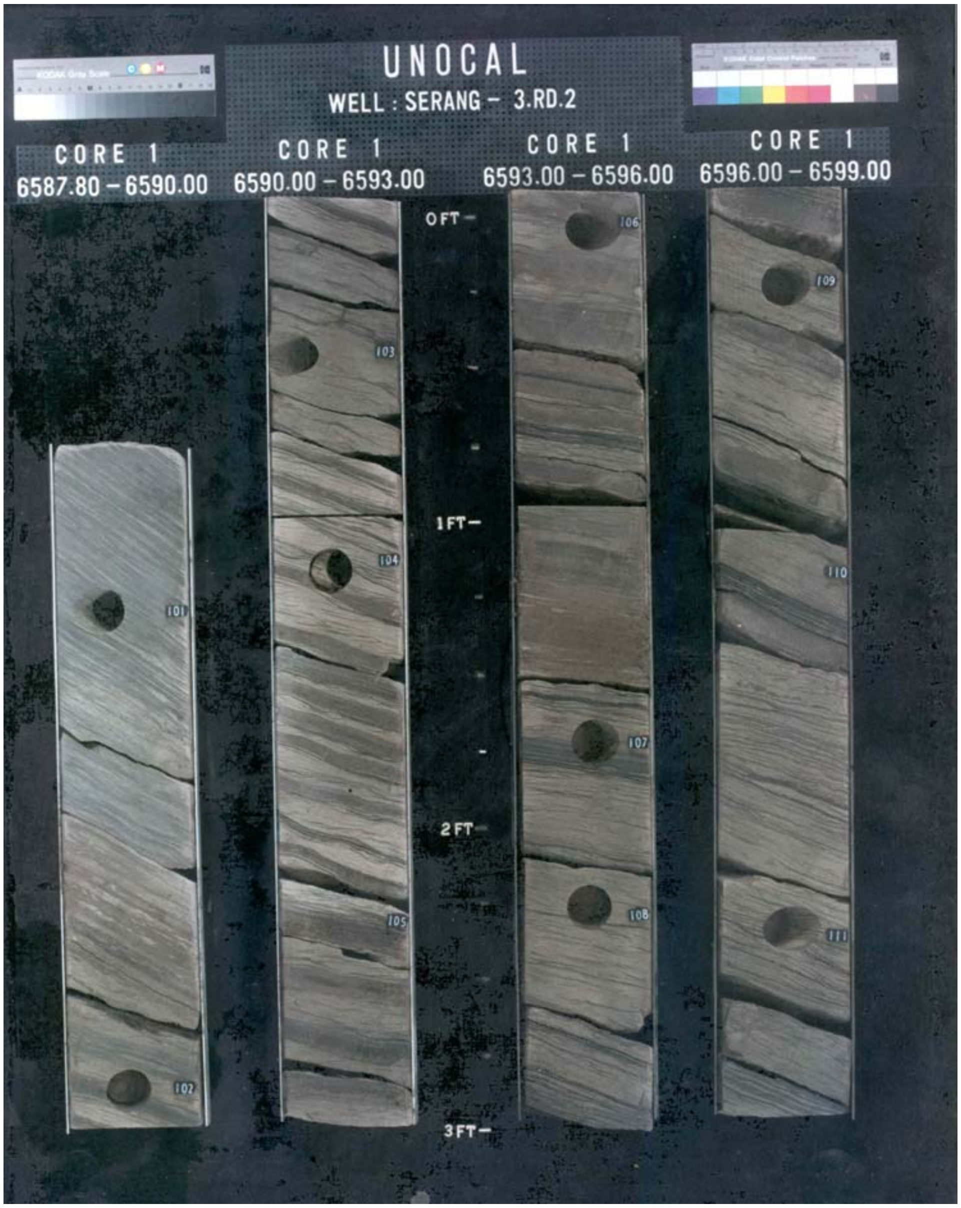


Figure 4.13: Fluvial/distributary channel sandstone with 60 API gamma ray readings at 6596 ft is used as sandstone cut-off in calculating net sand in this study. This sandstone has higher mud content compared to the sandstones below it. The sandstones above 6596 ft are more mud-prone compared to those below 6596 ft.

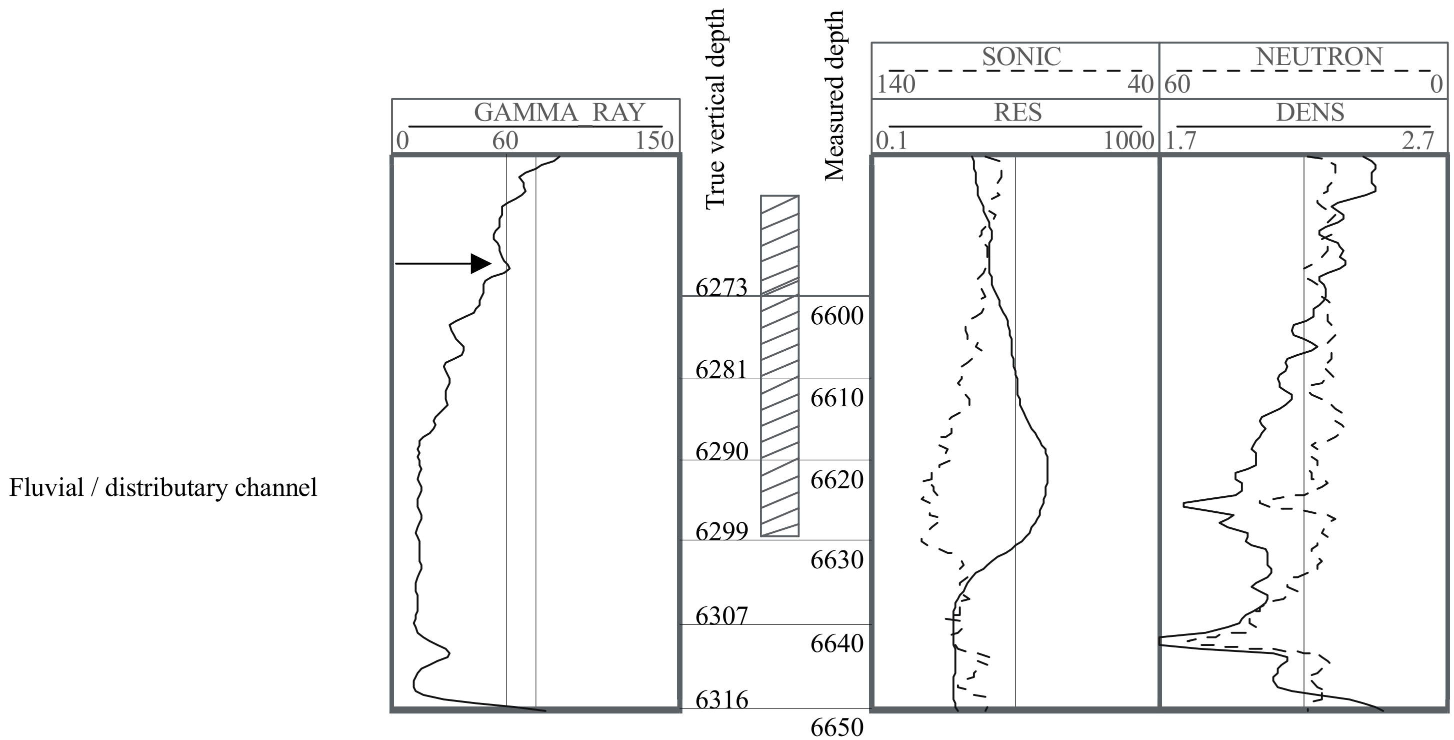


Figure 4.14: Log response of SA-3RD2 cored interval 6587-6628 ft and the interpreted depositional environments. The depth presented here is referred to log depth, not to core depth. There is +4 ft correction for core to log depth calculation. The 60 API value, that is used as the net sand cut-off, is located at 6596 ft (arrow).

CHAPTER 5

SEQUENCE STRATIGRAPHY IN THE SERANG FIELD

5.1 Introduction

This chapter contains the sequence stratigraphic methods used in this study, the analysis of sequence stratigraphy of the Serang Field, and the proposed depositional model. The following discussion on base level is summarized from Busch (1971), Wheeler (1964), and Gardner (1993, 2001a, 2001b).

As discussed in the previous chapter, core study indicates that the sediments were deposited in fluvial-deltaic environments (Plates 1a-1f). Log-core calibrated correlation indicates that the studied interval in the Serang Field reflects several depositional cycles of fluvial-deltaic sediments. The depositional cycles that built up the sediments in the study interval vary in scale.

In this study, two interpretation scenarios are offered: (1) incised valley fills (IVF's), and (2) large freely migrating channel systems; however, only one is described in detail. The cross sections for the selected scenario are on Plates 2-3, whereas the cross sections for the non-selected scenario are on CD.

Before discussing the stratigraphic cycles in detail, an overview regarding the comparison between IVF and freely migrating channels depositional systems is discussed first because the choice of a depositional model (i.e., IVF's or freely migrating channels) will control, in part, how the stratigraphic cycles are subdivided.

5.1.1 Base level

Stratigraphic base level is an abstract, undulatory surface that records the balance of erosional and depositional processes (Wheeler, 1964). Generally a stratigraphic cycle consists of conformable increments of lithologically variable strata that record a complete cycle of base-level fall and rise (Busch, 1971). The cycle includes all strata and stratal surfaces formed during a full base-level cycle and are not limited to any particular depositional environment (Gardner, 2001a). Base-level rise reflects time of increasing accommodation-to-sediment supply ratio, whereas base-level fall reflects time of decreasing accommodation-to-sediment supply ratio (Gardner, 2001a). Accommodation is potential space available for deposition of sediment (Jervey, 1988).

Figure 5.1 graphically shows a base level surface that extends from non-marine to marine environments. The ideal depositional cycle for recognizing the hierarchy of stratigraphic cycles is a single cycle of allogenic transgression and regression. At this scale, facies can be associated genetically and considered as the same set of scales of allogenic forces (Knox and Barton, 1999). Allogenic processes are processes that are extrinsic to the depositional system, whereas processes that are intrinsic to the depositional system are called autogenic processes (Miall, 1996).

A stratigraphic cycle can be divided into a base-level rise hemicycle and a base-level fall hemicycle (Gardner, 1993). A base-level rise hemicycle reflects deposition during relative base-level rise, whereas a base-level fall hemicycle reflects deposition during relative base-level fall. For the following discussions, the base-level rise hemicycle will be referred to as the transgressive phase of base-level cycle, and the base-level fall hemicycle as the regressive phase of base-level cycle.

The turnaround from transgressive phase to regressive phase is a maximum flooding surface (MFS), whereas the turnaround from regressive phase to transgressive phase is an unconformity (lowstand surface of erosion / LSE) and their correlative conformity if the accommodation-to-sediment supply ratio is negative. When the ratio is not negative, the base-level fall-to-rise turnaround is picked at the scour surface that

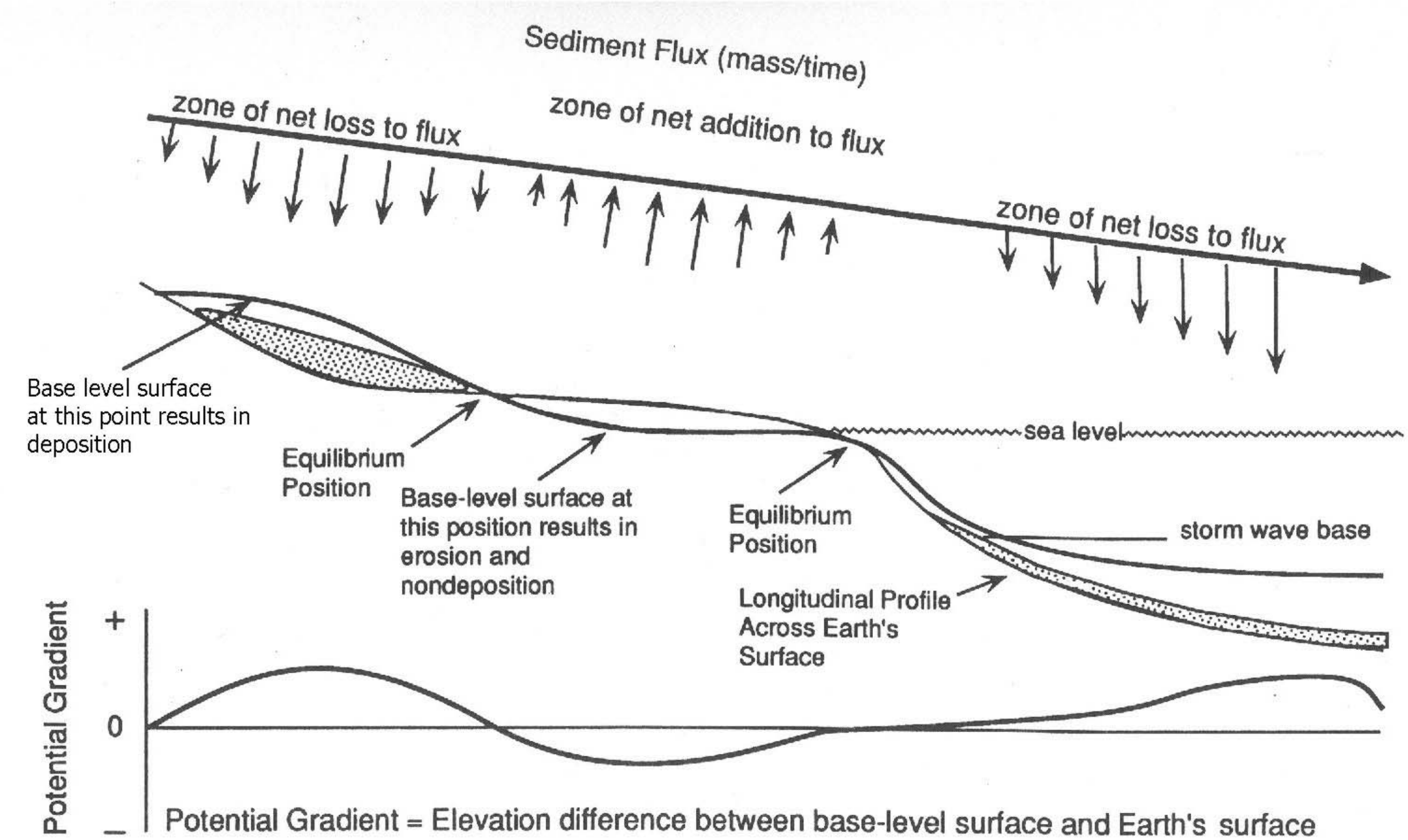


Figure 5.1: Base level surface that extends from non-marine to marine environments. At the zone of net loss to flux, base level surface is located above the ground resulting in deposition, whereas at the zone of net addition to flux, base level surface is located below the ground, resulting in erosion and non deposition (from Gardner, 1993).

reflects erosion and maximum transportation energy. When channel erosion is absent, the base-level fall-to-rise turnaround is picked between regressive deposits (e.g., delta front bar) below and transgressive deposits (e.g., delta plain mudstone) above.

Either an MFS or an LSE can be used as the initial point of a stratigraphic cycle. The use of different transgressive-regressive turnaround points to define stratigraphic cycles can bring different implications for analysis of depositional environments. Using the LSE as the cycle boundary sets transgressive deposits, MFS, and regressive deposits into a genetically related sequence, as promoted by the Exxon group (e.g., Van Wagoner et al., 1990; Posamentier and Allen, 1999). On the other hand, using the MFS as the cycle boundaries groups regressive deposits, LSE, and transgressive deposits into a sequence, as promoted by Galloway (1989).

5.1.2 Stratigraphic hierarchy

The hierarchy of stratigraphic cycle can be scaled as long-term, intermediate-term, and short-term (Figure 5.2). Regardless of the scale, each stratigraphic cycle records a complete base-level cycle that reflects the decrease of accommodation-to-sediment supply ratio to a limit as base-level falls, followed by the increase of the ratio during base-level rise (Wheeler, 1964). The stratal geometry of stratigraphic cycles records short-term and intermediate-term base-level cycles that are superimposed within long-term base-level cycles; therefore, it reflects a cumulative base-level cycle.

Figure 5.2 shows a stratigraphic cycle that uses base-level rise-to-fall turnaround (MFS's) as the initial point of a cycle and the relationship between base level concept and the Exxon depositional sequence. A stratigraphic cycle can be either symmetric or asymmetric depending upon its position along the depositional profile and its stratigraphic position within the stacking pattern of stratigraphic cycles (Gardner, 1993). Generally a stratigraphic cycle is characterized by an asymmetric base-level rise in the coastal plain strata, symmetric cycle in the proximal shallow-marine strata, and asymmetric base-level fall in offshore marine strata.

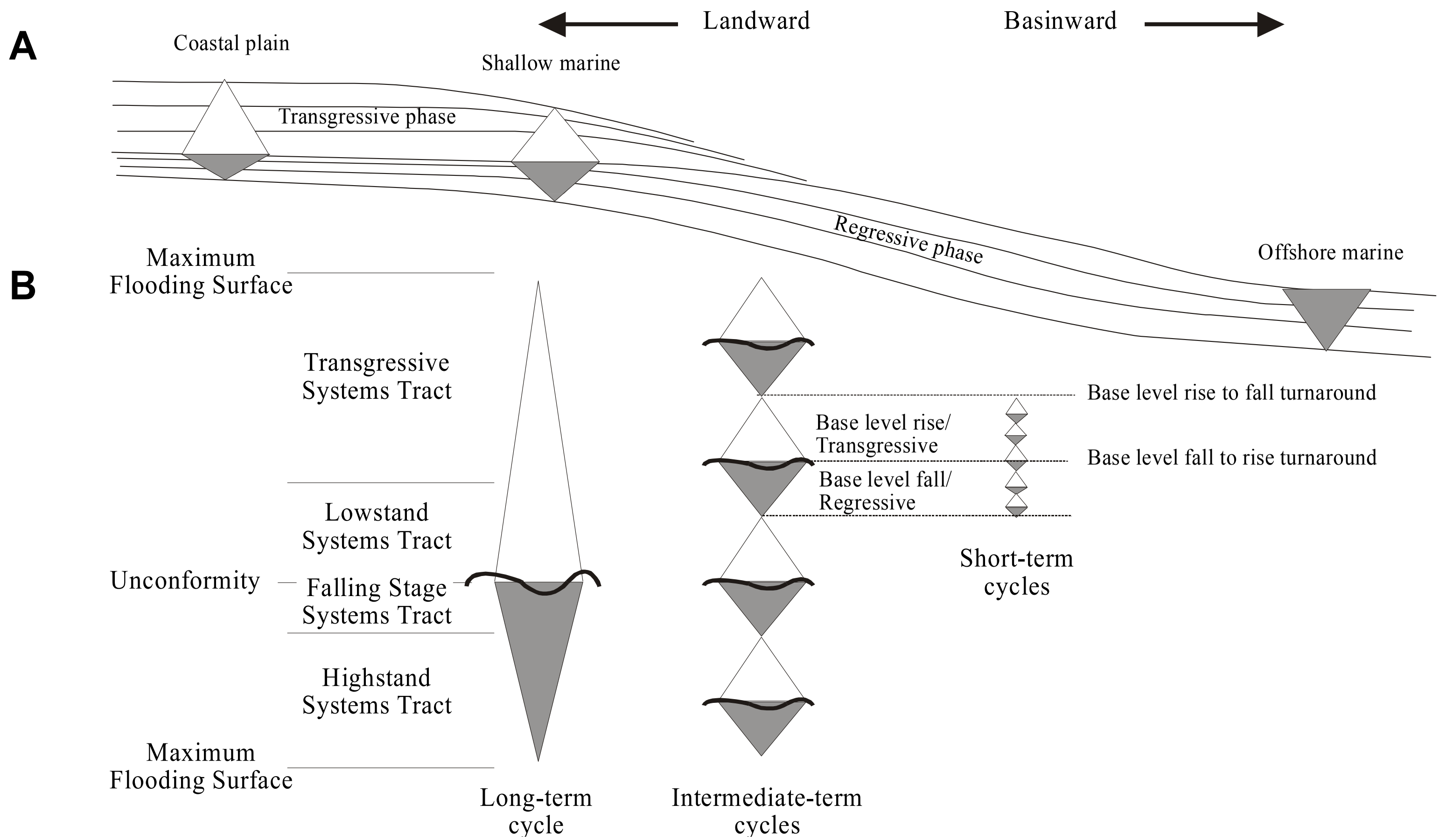


Figure 5.2: A stratigraphic cycle with base-level rise-to-fall turnaround (maximum flooding surface) as the initial point (A). Coastal plain strata are characterized by an asymmetric base-level rise, proximal shallow-marine strata are characterized by symmetric cycle, and offshore marine strata are characterized by asymmetric base-level fall. The relationship of long-term, intermediate-term, and short-term base-level cycle. (B). The cycle consists of transgressive phase (base-level rise hemicycle) and regressive phase (base-level fall hemicycle). The highstand systems tract is deposited during base-level rise, whereas the lowstand and transgressive systems tracts are deposited during base-level fall. The falling stage systems tract is deposited at the base-level rise-to-fall turnaround (Modified from Gardner, 2001a).

A short-term stratigraphic cycle results from a brief marine flooding event. The occurrence of higher frequency base-level cycles superimposed on a lower frequency base-level cycle can result in multiple transgressive-regressive cycles. A higher order unconformity is developed when these cycles involve an episode of relative sea-level fall (Posamentier, 1998). If these cycles do not involve periods of relative sea-level fall, i.e., only involve a slowdown in the rate of relative sea-level rise, the cyclic sedimentation occurs without any associated subaerial unconformities.

A transgressive-regressive succession that developed under the influence of base-level/sea-level cycles are more widely distributed than identical succession produced by variations in sediment flux. Base-level fall is recorded by an upward decrease in accommodation-to-sediment supply ratio, whereas base-level rise is recorded by an upward increase in accommodation-to-sediment supply ratio. Shallow-marine deposits mostly record short-term base-level fall, while fluvial and coastal plain (interfluves) mostly record short-term base-level rise.

5.2 Stratigraphic hierarchy of the Serang Reservoirs

The stratigraphic hierarchy of the Serang reservoirs is arranged as long-term, intermediate-term and short-term. A long-term cycle reflects the trend made by the overall stacking pattern of intermediate-term cycles. An intermediate-term cycle consists of several short-term cycles. Figure 5.3 shows the subdivision of the studied interval into intermediate-term cycles.

Based on the recognition of base level turnarounds, the stratigraphy of the study interval in the Serang Field can be divided into three intermediate-term cycles. Each complete intermediate-term cycle can be subdivided into transgressive and regressive phases. The third intermediate-term cycle records a complete transgressive phase and an incomplete regressive phase (Figure 5.3).

5.2.1 Selection of cycle initiation point

As previously discussed, both MFS's and LSE's can be used as the cycle initiation point. In order to set the production zone into complete intermediate-term cycles, the LSE's were chosen as the initiation point for intermediate-term cycles because the production zones in the study interval are associated with LSE's; consequently, the definition of a sequence in this study follows the Exxon approach: "a relatively conformable, genetically related succession of strata bounded by unconformities or their correlative conformities" (Mitchum, 1977). The cycle boundaries in this study are erosional surfaces that reflect maximum energy of transportation and may represent either an unconformity or a diastem. In continuous accommodation instead of periods of absence of accommodation, during base-level fall-to-rise turnaround cyclic sedimentation occurs without any associated unconformity (Gardner, 1993).

A complete transgressive-regressive cycle in this study begins at the LSE, transgresses to the MFS, and regresses to subsequent LSE. The LSE's represent a major break in sedimentation and reflect the time of sediment bypass to deeper water. Each cycle initiation in this study reflects the trend of sandstone distribution along a depositional profile. If the LSE's represent an unconformity, prospective are expected sandstones basinward. On the other hand, if the LSE's represent a diastem, prospective sandstones are expected landward.

5.2.2 Long-term cycle

By assuming that the Serang Lobe was formed during 5.5-6.3 Ma (Snedden, 1996), it is interpreted that the duration of the long-term cycle is ~ 0.8 m.y. The long-term cycle may represent third-order cycle (1-10 m.y. duration, Vail et al., 1977).

The changes in channel connectivity, channel geometry, and log-pattern diversity (e.g., serrated, funnel, and blocky log patterns) were used as criteria to identify the trend of long-term cycles in the study interval. As will be discuss later, in the youngest stratigraphic cycle, the channel belts are less interconnected, the sandstone geometry is

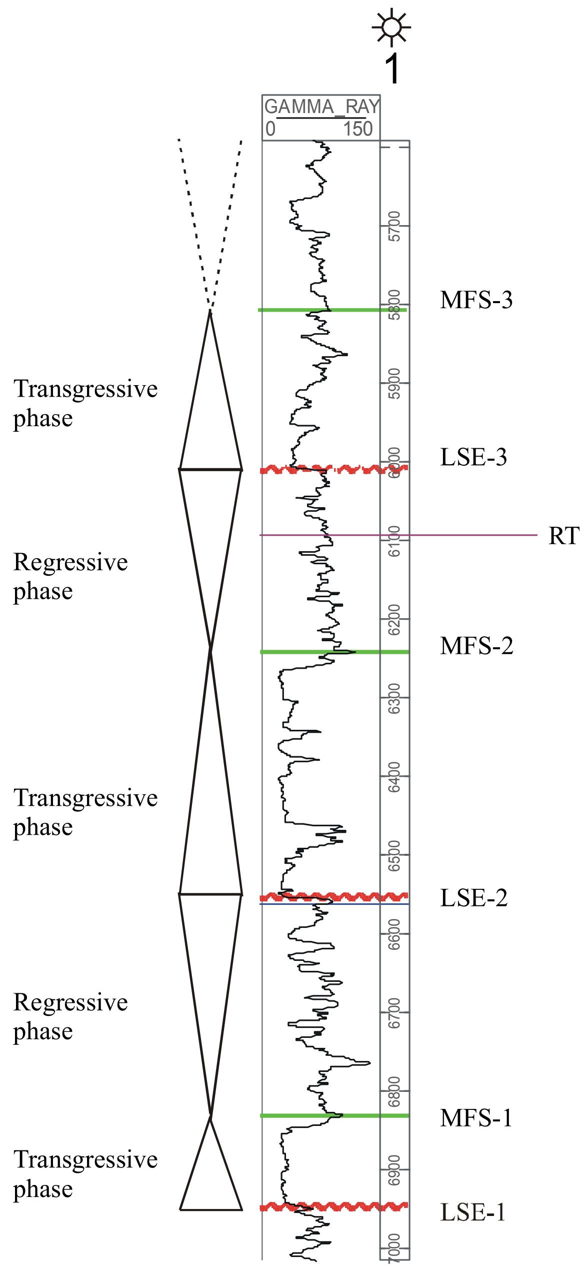


Figure 5.3: Base level turnarounds that were used in subdividing the study interval into intermediate-term cycles. Note that there are three transgressive phases, two complete regressive phases and one partial regressive phase in the study interval. SERANG-1 was used as the reference well because it is not deviated and exhibits the typical trend of intermediate-term cycles in the study interval.

more laterally extensive, and the log-pattern diversity is higher. This trend indicates a long-term base-level rise that resulted from landward-stepping cycles.

5.2.3 Intermediate-term cycles

In this study, the intermediate-term cycles are assumed to be related to a major flooding of the shelf that reflects allogenic processes because the base level turnarounds can be traced constantly on a field scale. The intermediate-term cycles may represent fourth-order cycles (0.2-0.5 m.y. duration, Vail et al., 1977), as there are three intermediate-term cycles within the long-term cycle. MFS's of intermediate-term cycles are assumed to be marine mudstone that overlies regionally abandoned and flooded delta system, whereas LSE's of intermediate-term cycles are assumed to be candidates for unconformity.

For the following discussion, intermediate-term cycle is abbreviated as "IC". The naming of intermediate-term cycles was done by using a numerical code from bottom-up. For example, the first intermediate-term cycle is called IC 1 and the second one is called IC 2.

Three widespread marine mudstones were recognized in the study area (Figure 5.3), and they were considered as major MFS's that reflect regionally abandoned delta systems. Because the study area is only on a field scale (approximately 2 km x 4 km), it is assumed that those major MFS's are regionally correlatable and help define the intermediate-term cycle that reflects a transgressive-regressive cycle of deltaic progradation. The LSE's that were used as sequence boundaries in this study were picked at the base of the amalgamated sandstones beneath MFS's.

The first major MFS (MFS-1) was picked at 6830 ft in the SERANG-1 well. It is located above the lowest / first widespread amalgamated sandstones in the study interval (Figure 5.3). It is characterized by high gamma ray, low resistivity and low density pattern, possibly it is an organic-rich mudstone marker. MFS-1 was assigned as the major

MFS for IC 1. The base of the widespread amalgamated sandstone was chosen as the LSE for IC 1 (LSE-1) (Figure 5.3).

The second major MFS (MFS-2) was picked at 6240 at SERANG-1 well. It is located above the amalgamated sandstones that comprise the main reservoirs of the Serang Field. MFS-2 has the same characteristic as MFS-1 (i.e., low gamma ray, low resistivity, and low density). Based on its log characters MFS-2 was interpreted as organic-rich mudstone. MFS-2 was chosen as the major MFS for intermediate-term cycle 2, and also as the datum for the correlation because it is easily recognized and located at the top of the amalgamated sandstones that are also the main reservoirs of the Serang Field. The base of the highly connected, amalgamated sandstones was picked as the LSE for IC 2 (LSE-2).

The third major MFS (MFS-3) was picked at 6100 ft at SERANG-1 well. It is characterized by an overall upward-increasing gamma ray log pattern below and upward-decreasing gamma ray log pattern above. MFS-3 was also interpreted as widespread marine mudstone that was deposited during the time of maximum sea-level rise. MFS-3 was chosen as the major MFS for IC 3. The LSE that is proposed as a candidate for the unconformity was picked at the base of the thickest sandstone below MFS-3, which is a surface that reflects the maximum energy of transportation.

5.2.4 Short-term cycles

In this study, short-term cycles are regarded as related to minor sea-level fluctuations or lobe switching that reflects autogenic processes. The base level turnarounds of short-term cycles are not necessarily traced on a field scale. MFS's of short-term cycles are assumed as marine mudstone, thin carbonates, or carbonaceous mudstone that overly locally abandoned delta lobes. LSE's of short-term cycles represent a short-lived diastem. The short-term cycles are located within the intermediate-term cycle. The short-term cycles may represent fifth-order cycle (0.01-0.2 m.y. duration, Vail et al., 1977).

For the following discussion, the short-term cycle is abbreviated as "SC". The naming of short-term cycles was done by adding an alphabetical code from bottom-up after the name of the intermediate-term cycle containing the short-term cycles. For example, the first short-term cycle of intermediate-term cycle 1 is called as SC 1A, whereas the second one is called as SC 1B.

5.2.5 The RT marker

An important regional marker within Unocal Indonesia's Northern Offshore Block and Attaka Block, called the RT marker, is located within the study interval (Figure 5.3). Based on petrographic analyses, the marker also corresponds to a marked provenance change in detrital minerals (Siemers, 1993; Trevena, 1993; Tanean, 1996). The sandstones below the RT marker are highly quartzose and contain only minor lithic component (Siemers, 1993; Tanean, 1996), whereas the sandstones above the RT marker contain abundant volcanoclastic fragments and smectite pore linings (Siemers, 1993).

The RT marker is picked at the resistivity kick of the mudstone that is located near a flooding surface around depth 6090 ft in the SERANG-1 well (Figure 5.3). Based on its pattern, the RT marker does not show evidence as a candidate for unconformity. It does not show any evidence of a sharp basal contact nor basinward shift of facies associations. In fact, it indicates a landward shift of facies associations. The hypothesis of unconformity is also not supported by paleontology and vitrinite reflectance data (Trevena, 1993). The changing of sandstone mineralogy above and below the RT marker may be related to the changing of sediment source that is not necessarily related to an unconformity (Siemers, 1993, Trevena, 1993, Tanean, 1996) or an increase of volcanic activity landward of the study area within the same sediment source.

Previous works regarded the RT marker as a transgressive surface that marks an abrupt landward shift of facies associations (Armin et al., 1994). In this study the definition of transgressive surface is different from that of Armin et al. (1994). The RT marker is considered as a good correlation marker that has no stratigraphic significance, neither as an LSE, TSE nor MFS. In this study the stratigraphically significant markers were chosen based on gamma ray logs, whereas the RT marker is picked based on resistivity logs.

5.3 Comparison between freely migrating channel and incised valley fill (IVF) interpretations

Thick, laterally continuous channel deposits that form a sheet geometry may represent: (1) deposition from large river systems that are freely migrating, or (2) deposition from a number of smaller rivers that are confined in a valley (Gardner, 2002, personal communication). Interpretation of whether deposits represent a confined incised valley fill (IVF) or a freely migrating channel system depends on criteria as listed in Table 5.1. IVF interpretation implies that there was a significant base-level fall that created valley morphology, and a major break in sedimentation (unconformity) between the valley fill and the underlying deposit and there was erosion and sediment bypassed to deeper water during the development of the incised valley. On the other hand, the freely migrating channel system interpretation implies that the sandstones were not deposited above an unconformity and there was not much erosion and sediment bypassed to deeper water; most of sediments were deposited landward by fluvial aggradation.

IVF and freely migrating channel models may have different implications in the reservoir heterogeneity of the field. In IVF most of the time is represented by surfaces of erosion instead of rock, and thick sandstones can be result from deposition in lower accommodation (i.e., lower subsidence and high sediment supply condition). On the other hand, in freely migrating channel system most of the time is represented by rocks instead of surfaces of erosion, and thick sandstones can be result from a deposition in higher accommodation (i.e., high subsidence and high sediment supply condition). Based on the IVF model, the distribution of the channel sandstones that act as reservoirs is confined in a valley.

Table 5.1: Comparison of the characteristic of IVF compared to deposits of a freely migrating channel (summarized from Van Wagoner et al., 1990; Wescott, 1993; Posamentier, 1998; and Gardner, 2002, personal communication)

IVF	Freely migrating channel
Allocyclic process (sea-level fluctuation) is the main driving force during the deposition of sediments	Autocyclic processes (fluctuation of sediment supply and subsidence) are the main driving forces during the deposition of sediments
The rate of sea-level fall is greater than the rate of basin subsidence at the depositional-shore line break	The rate of sea-level fall is lower than the rate of basin subsidence at the depositional-shore line break
During sea-level fall rivers incise the shelf and form valley morphology	During sea-level fall rivers adjust to lowered base levels and changes in slope by modifying channel patterns. Lowered base level does not necessarily result in deep incision.
May occur either in a large or small drainage basin	Requires a large drainage basin
Mappable dimension, wider than that of channel	Narrower dimension of channel compared to that of valley
Extensive incision that creates valley morphology	Limited vertical and lateral extent of incision
Anomalously thick, multistory channel deposits hang from the same marker	Stacked distributary channels form multiple horizons and do not hang from the same marker
Confined fluvial system in a valley	Freely migrating fluvial system
Absence of overbank deposits of the same fluvial system outside the valley	Presence of overbank deposits in the interfluves
Well-developed paleosols on interfluves between incised valley	Absence of paleosols on interfluves because the sediments were not subaerially exposed
Encased in middle- to outer-neritic mudstones	Encased in delta-plain to distributary mouth bar deposits
Onlapping of depositional markers within the incised valley fill on to the valley wall	Continuous depositional markers within the channel into the interfluves
Presence of significant basinward shift of facies associations between the valley fills and older deposits	Regular Walther's Law of succession
Implies an unconformity at the base and the wall of the valley	Implies a diastem at the base and the wall of the channel
Implies erosion and sediment bypass to deeper Water	Implies fluvial aggradation, relatively minor erosion and sediment bypass

Thick, amalgamated sandstones are unlikely to be produced by autogenic processes. According to Miall (1996), cycles that are thicker than about 20 m are more likely to be related to allogenic causes, such as high-frequency sequence development or tectonic pulses. Regardless of whether amalgamated sandstones are parts of incised valley or not, they can be developed because there is a tendency for newly formed channels to reoccupy previous channel axes. This tendency results from subtle tectonic influence on local subsidence rates, comparative ease of erosion of sandy deposits of previous channel axes relative to floodplain mud and soil, and the presence of poorly developed levees at the nodes where earlier avulsion occurs (Galloway and Hobday, 1983).

Besides a basinward shift of facies associations, the recognition of unconformities in non-marine settings can be indicated by an increase of channel clustering in non-marine settings (Shanley and McCabe, 1994). Two assumptions are needed for this condition: (1) the rate of accommodation results in distinctive channel-stacking patterns, and (2) the sediment influx was constant (Posamentier, 1998).

Figure 5.4 illustrates the fluvial sequence model that shows the relation between shoreface and fluvial architecture and base level change (Shanley and McCabe, 1994). The diagram shows that a regional surface of erosion with incised valley morphology is developed during base-level fall. During low rates of base-level rise, multilateral, multistory channel fills are deposited. The IVF deposition takes place during a low-accommodation-to-sediment supply condition and confinement within a valley. In this condition, most of the fine-grained sediments within the flood plain are eroded by repeated channel migration, resulting in a relatively widespread, high sandstone

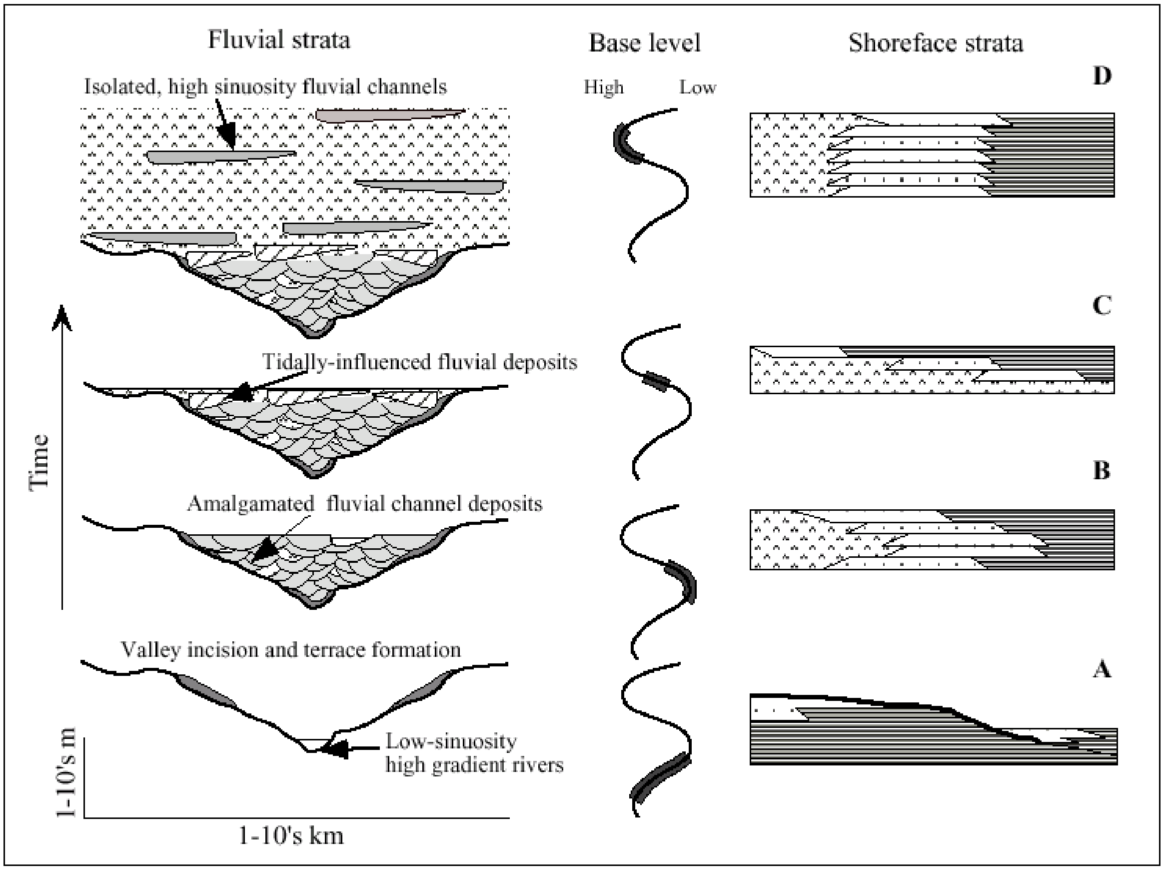


Figure 5.4: Sequence stratigraphic model for fluvial deposits. The model shows the relation between shoreface architecture, fluvial architecture and base level change (from Shanley and McCabe, 1994).

proportion. The mechanism of the changes in relative base level can be caused by fluctuation of fluvial sediment supply of the river, local subsidence, or eustacy.

It is important to note that not all IVF's are sand-prone. The net-to-gross in IVF's depends on the rate of sediment supply relative to rate of accommodation during the backfilling of the valley. If the rate of sediment supply is higher than the rate of accommodation the resulting IVF's are sand-prone, and vice-versa. In the Serang Field case, the rate of sediment supply relative to rate of accommodation is high because the possible valley fill deposits are sand-prone.

Amalgamated sandstones occur at the transgressive phase of IC 1 and IC 2. The amalgamated sandstones resulted from deposition in low rate of accommodation-to-sediment supply ratio. This circumstance can results from freely migrating river with low accommodation-to-sediment supply ratio or by confined deposition in a valley. As discussed in the following sections, the transgressive phases of IC 1 and IC 2 can be considered as IVF's.

5.3.1 Transgressive phase of IC 1

As shown on the cross sections (Figure 5.5, Plates 2-3) the base of the amalgamated sandstones that are located at the transgressive phase of IC 1 conform to a valley morphology. On the field scale the sandstones are obvious and are present in every well that penetrates them. As discussed in Chapter 4, the base of IC 1 is interpreted as an unconformity. If the unconformity creates valley morphology, the IVF interpretation for the transgressive phase of IC 1 is suitable.

The transgressive phase of IC 1 overlies a major basal relief. The sandstones in the northern part generally are thicker than the sandstones in the southern part (Figure 5.5, Plate 2). The thickness of the sandstones is in the general range of 100-120 ft; however, the thickest sandstone is 144 ft penetrated by the SA-4 well and the thinnest is 65 ft penetrated by the SERANG-4 well. The disappearance of the lower sandstone in SERANG-4 well can be interpreted as an evidence of the onlapping of the sandstone onto the margin of the valley (60 ft relief in 2350 m distance, measured from the the SA-22 well). It is shown on Figure 5.5 that the field edge (the SERANG-4 well) does not reach the margin of the valley. This fact indicates that the valley is bigger than the field scale, or alternatively the field was located oblique to the valley. Table 5.2 lists the interpreted condition of the transgressive phase of IC 1 as possible valley fills. Based on the table, the transgressive phase of IC 1 meets all the criteria for IVF.

Regardless of whether the sandstones are part of incised valley or not, there are two hypotheses for the origin of these sandstones: (1) the sandstones were deposited as fluvial-braided channel that changes into meandering to the south, and (2) the sandstones were deposited as mobile migrating fluvial channels or distributary channels that switch laterally and produce multiple channel belts. Were the sandstone deposited as distributary channels, they may have been deposited in a highstand or a lowstand delta. Table 5.3 lists the comparison of the setting needed for the deposition of braided channel and migrating channel. Figure 5.6 shows the possibilities of the depositional setting for the development of the sheet sandstones if they were part of IVF's. The figure shows that the sandstones can be developed as braided fluvial, meandering fluvial, or distributary channel depending upon their position on the depositional profile.

The widely distributed sandstones that form sheet sandstone geometry usually occur in steep gradient, bed-load systems such as braided rivers. Although the braided channel analog has not been found in modern Mahakam Delta, it does not mean that the interpretation of braided channels is not possible because deltaic systems always change through time (Bhattacharya and Walker, 1992). Sheet sandstones can also accumulated in lower-slope and lower energy channels, such as meandering channel systems (Miall, 1980 in Miall, 1996). Were the channels developed in areas of low subsidence rate, the channel deposits would be incised into and superimposed upon each other. In this setting, the preservation of fine-grained overbank deposits is low.

Table 5.2: Interpreted condition of the transgressive phase of IC 1 as IVF's

Criteria for incised Valley fills interpretation	Interpreted condition
Dimension	Wider than the field scale (more than 2x4 km)
Extensive incision that creates valley morphology	Incision is extensive with a large-scale valley morphology (60 ft relief in 2350 ft distance)
Confined deposition in a valley	The channel sandstones were deposited within the valley.
Thick channel fills hang from the same log markers	The anomalously thick, multistory channel deposits (up to 144 ft) hang from the same marker.
Absence of overbank deposits of the same fluvial system in the interfluves	Overbank deposits are absent outside the valley.
Encased deposition in middle- to outer-neritic mudstones	The valley is wider than the field scale; therefore, it cannot be confirmed whether the deposition is encased in middle- to outer-neritic mudstones.
Onlapping of depositional markers within the incised valley fill onto the valley wall	Onlap is indicated by shallower incision at SERANG-4 well.
Basinward shift of facies associations	Basinward shift of facies associations is indicated by fluvial/distributary sediments deposited directly above lower delta front to prodelta sediments.

Table 5.3: Comparison of braided channel and migrating channel depositional system

Braided channel	Migrating channel
Consists of numerous incomplete channel fill, the finer grain portion is truncated, overall blocky shape with numerous sharp contact representing local coarse sand filled scours	Commonly show upward-fining grain size relationship, creating bell-shaped log pattern, locally blocky.
Display rather uniform thickness across the entire sand body with localized deeper sand-filled scoured pods	Display high sinuosity in plan view when the channel is meandering (sinuosity larger than 1.5).
Common in proximal alluvial plain setting	Common in alluvial valleys of river systems and in distributaries where influenced by high tidal ranges or in rivers carrying extremely large coarse bedload sediment.
High width-to-depth ratio, greater than 40 and commonly exceeding 300 (Miall, 1996)	Lower high-to-width ratio. In modern Mahakam River, the channel belt dimension is between 0.5 to 1 km wide and 8 to 13 m deep (Allen and Chambers, 1998)
Steep slope, which result in high-energy transportation.	Gentle slope, low-energy transportation that allow for channel migration.
Abundant of coarse bedload transportation	Predominant of suspended load transportation
Non-cohesive and easily eroded bank	Cohesive and resistant bank
Erratic flooding characteristics	Non erratic flooding characteristics

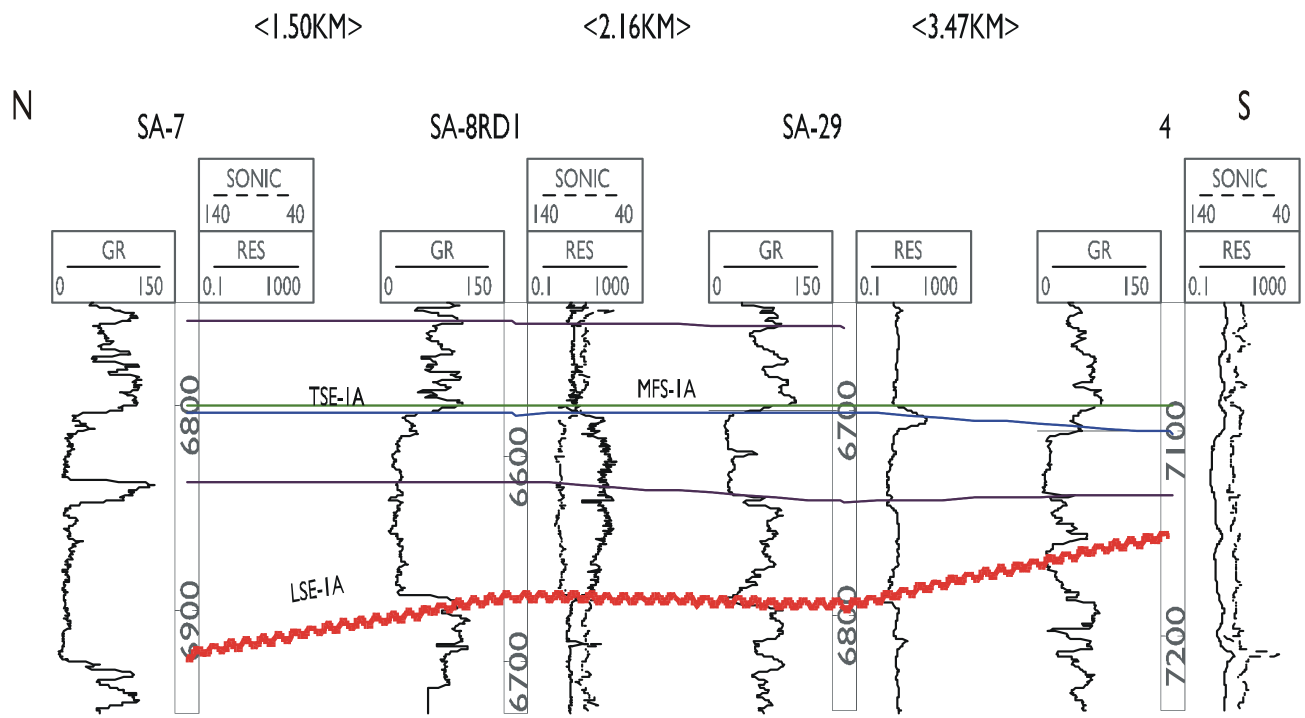


Figure 5.5: A strike-oriented cross section shows the valley morphology at the base of IC-1. Sandstones of SA-7 are thicker, whereas those of SERANG-4 are thinner and truncate an upward-decreasing gamma ray log pattern that is interpreted as a mouth bar. In other wells the sandstone rests on lower delta front deposits that are characterized by serrated log pattern.

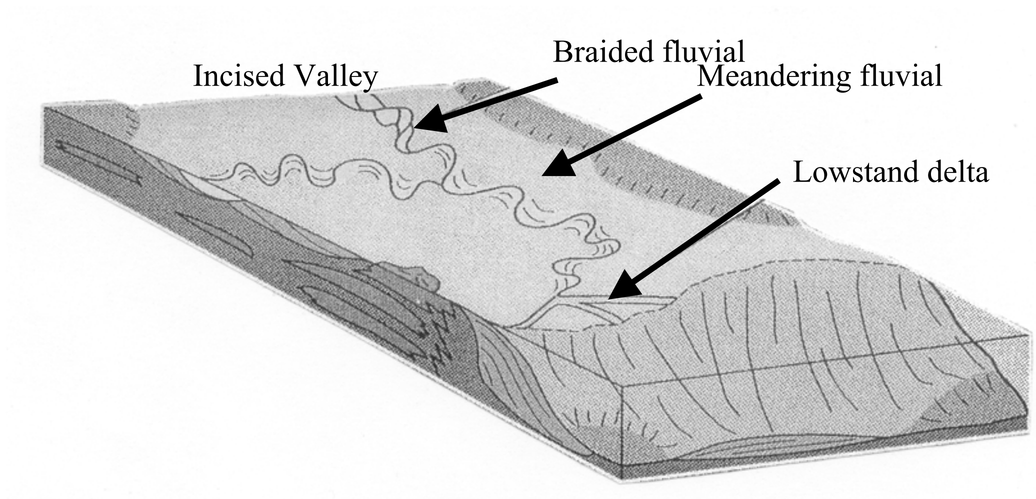


Figure 5.6: The depositional setting of the transgressive phase of IC 1 is interpreted as IVF's (modified from Armin et al., 1994).

5.3.2 Transgressive phase of IC 2

The transgressive phase of IC 2 consists of amalgamated sandstones with sharp base and blocky log pattern (Plates 2,3). The sandstones in the transgressive phase of IC 2 can be interpreted as IVF's (Figure 5.7). The northern part of the study area consists of thicker amalgamated sandstones compared to those of the eastern part. Interfluves was formed at the SA-8 RD well. To the south the amalgamated sandstone changes into delta plain (at SA-2RD1, SA-29, and SA-22) and isolated channels that are interpreted as distributary channels (at SA-19, SA-16 and SERANG-4).

Figure 5.7 shows two scenarios for the strike-oriented D-D' cross section that are produced using two correlation methods: (1) IVF's (Figure 5.8a), and (2) freely migrating channel (Figure 5.7b). In Figure 5.7a correlation markers within the amalgamated channels are discontinuous. Some markers are onlapping onto the possible valley wall. In this correlation style the possible valley morphology controls the confined deposition of channel sandstones. The erosional relief also controls the distribution of overbank deposits of the preceding cycle. In Figure 5.7b, correlation markers are continuous. This correlation style is characterized by changes of facies associations within the correlation markers, which can be considered as time lines, that indicate the nature of freely migrating channel.

As listed on Table 5.5, the transgressive phase of IC 2 can be considered either as IVF's or as freely migrating channels. According to the IVF's scenario, LSE-2 is interpreted as an unconformity that creates major relief (Figure 5.7b). LSE-2 is picked constantly at the base of amalgamated channels, indicating that the amalgamated channels are confined in a valley. To the south LSE-2 truncates delta plain-distributary channel deposits and merges with the base of amalgamated sandstone of the subsequent cycle (LSE-2B).

On the contrary, according to the freely migrating channel scenario, LSE-2 that marks the base of the transgressive part of IC 2 is interpreted as a diastem. LSE-2 changes from the base of amalgamated sandstone in the northern area to the base of delta plain and isolated channels in the southern area (Figure 5.7b).

5.4 Sequence stratigraphy in the Serang Field based on IVF interpretation

This section presents the analysis of the sequence stratigraphy of the studied sediments based on IVF analysis. As discussed in the previous section, the transgressive phase of IC 1 meets all the criteria for IVF, whereas the transgressive phase of IC 2 can be considered either as IVF or as freely migrating channels. In this report the transgressive phase of IC 2 is considered as IVF based on the following reasons:

1. The size of drainage basin of the modern Mahakam River (Figure 3.3) is relatively small and not comparable with that of a major river with large drainage basin.
2. The amalgamated sandstones are anomalously thick and hang on the same stratigraphic marker (MFS-2). This fact indicates that sandstone distribution is confined in a valley.

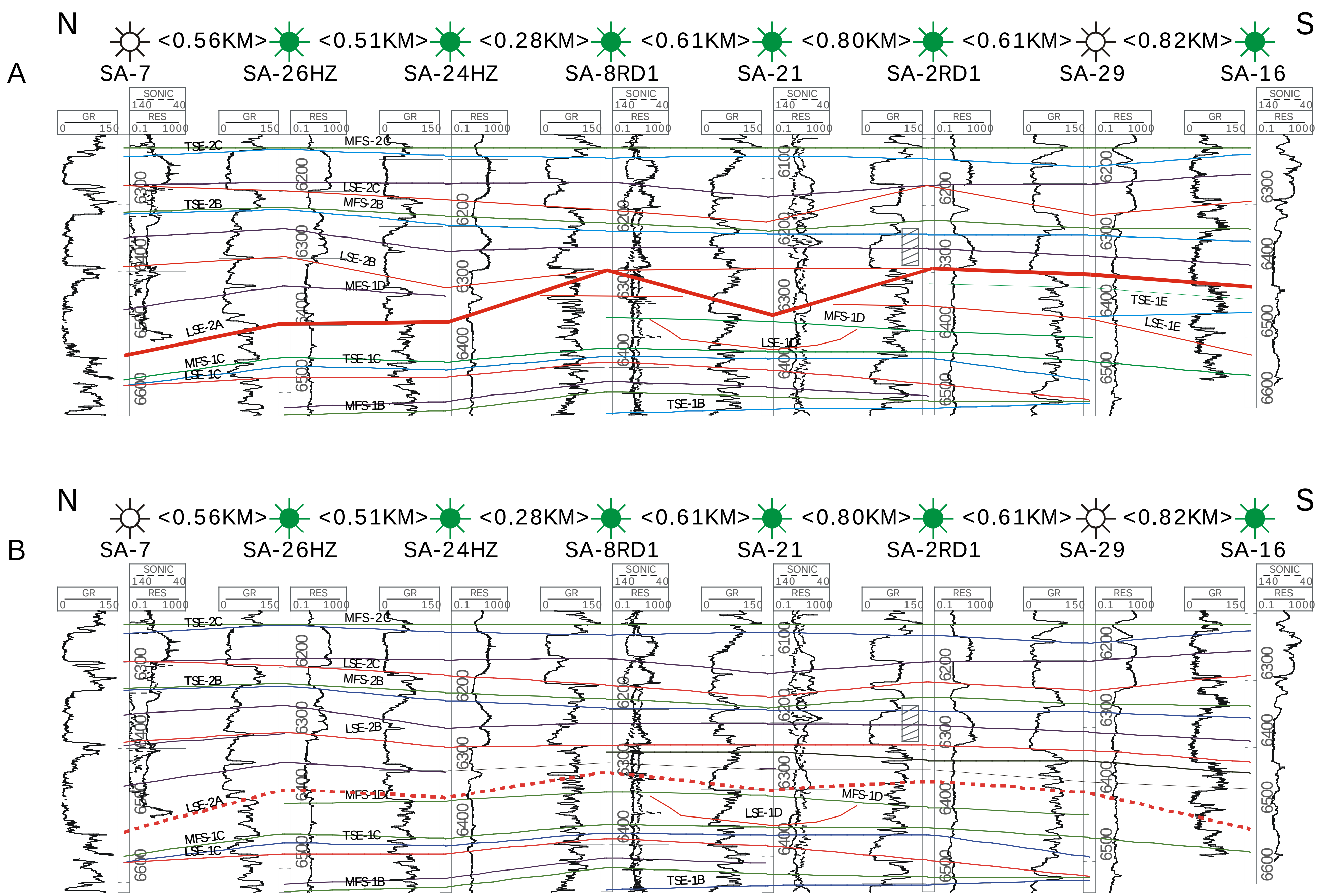


Figure 5.7: An approximately strike-oriented cross section that shows two possible correlation for the transgressive phase of IC 2: IVF (A), and large, freely migrating channel systems (B). In Figure 5.7A the correlation markers within the transgressive phase of IC 2 are discontinuous, whereas in Figure B the correlation markers are continuous. Changes of facies associations are common within the correlation markers in Figure 5.7B.

Table 5.4: Comparison between IVF and freely migrating channel interpretations for the transgressive phase of IC 2

Criteria	IVF interpretation	Freely migrating channel interpretation
Dimension	The IVF's are wide on the field scale (2x4 km)	The amalgamated channels only occur at the northern part of the study area. To the south it changes into lower delta plain.
Extensive incision that creates valley morphology	The valley morphology is indicated by low areas in the north and high areas in the south	There are changes of facies associations along strike direction from fluvial/ distributary channel sandstone in the north into delta plain mudstone in the south
Thick channel fills hang on the same marker	Thick channel fills confined in a valley and hang on the same strataigraphic marker	Thick channel fills were deposited unconfined under low accommodation-to-sediment supply (A/S) ratio. Significant increase in A/S ratio above the marker results in easily recognized marker.
Confined fluvial system in a valley	The distribution of amalgamated channels is controlled by valley morphology. High areas consist of delta plain mudstone and coal.	The thick channel deposits were deposited unconfined and laterally migrating. The branching nature of the channel belts indicates that the channels are distributary channel.
Absence of overbank deposits of the same fluvial system outside the valley	Interfluves consist of finer-grained sediments that are deposited in high areas.	Interfluves are characterized by changes of facies associations from distributary channel sandstones into delta plain deposits.
Encased in middle- to outer-neritic mudstones	The deposition is encased in delta plain to delta front sediments	The deposition is encased in delta plain to delta front sediments
Onlapping of depositional markers within the incised valley fill onto the valley wall	The depositional markers of the IVF onlap onto the valley wall	There are changes of facies associations from fluvial/distributary channel in the north into delta front and delta plain to the south. No onlap occurs.
Basinward shift of facies associations	Basinward shift of facies associations is indicated by fluvial/distributary channel above delta front deposits. If the channels are distributary channels (as shown on the net sand maps), the deposition of distributary channels took place later during the backfilling of the valley.	No basinward shift of facies associations occurs. The net sand maps indicate that the channels are distributary channels. The contact between IC 1 and IC 2 does not represent a major hiatus.

3. The incision is wide on the field scale (2x4 km) and creates valley morphology, with a major relief (more than 100 m).
4. Although a basinward shift of facies associations is not clearly shown, the increase of channel clustering may suggest the presence of unconformity at the base of the amalgamated sandstones.

Thick, amalgamated channel sandstones may be developed by a large river that has a large drainage basin. The Miocene paleogeographic setting of the Kutei Basin (Figure 3.1) shows that in the Miocene southwest Kalimantan is a part of Sundaland (Van de Weerd and Armin, 1992; Hall, 1995; Moss, 1997). If the drainage basin for the deposition in the Lower Kutei Basin includes the Sundaland, a large river may have been developed. However, this possibility is unlikely based on paleogeogaphic mapping (Ott, 1987; Van de Weerd et al., 1992; Chambers and Daley, 1995). Deposition in the Lower Kutei Basin is interpreted from west to northwest of the Mahakam Delta with a drainage basin that includes the Upper Kutei Basin and Central Kalimantan Mountains (Figure 3.3). The size of the drainage basin is relatively small (about 60.000 km^2). Deposition was dominated by a single proto-Mahakam River system, and this pattern does not change to the present day.

Petrographic studies (Siemers, 1993; Tanean et al., 1996) show different mineralogy for the Miocene deltaic sediments. The Late Miocene sediments in the Kutei Basin generally are highly quartzose with minor lithic components, whereas older sediments contain more lithic components. The older deltaic sediments are being sourced from the Rajang Embaluh Groups in the Central Kalimantan Mountains (Figure 3.3) that consist of metamorphosed sediments, whereas the Late Miocene sediments are interpreted as resulting from recycles orogenic provenence of older deltaic sediments (Tanean et al., 1996). The recycles orogenic provenence theory explains the highly quartzose nature of the Late Miocene deltaic sediments and supports the interpretation of west-to-east deltaic progradation with the single proto-Mahakam river system as the main sediment source.

The IVF model is favorable for an area with a subsidence rate that is less than the rate of eustatic fall (i.e., lower accommodation), whereas the freely migrating channel model is favorable for an area with the subsidence rate that is greater than the rate of eustatic fall (i.e., higher accommodation) (Posamentier, 1998). The sedimentation in the Kutei Basin was during high sediment supply and high subsidence rate (Snedden et al., 1996). If the rate of eustatic fall in the Kutei Basin during late Late Miocene is greater than the subsidence rate, and other criteria for IVF interpretation as listed on Table 5.3 are fulfilled, then the IVF model is suitable for the transgressive phases of IC 1 and IC 2.

5.4.1 IC 1

IC 1 can be subdivided in general into 100 ft of transgressive phase and up to 310 ft of regressive phase (at SERANG-4 well). The transgressive phase of IC 1 is located between LSE-1 and MFS-1. The transgressive phase of IC 1 consists of anomalously thick (in a general range of 100-120 ft) amalgamated sandstones that are laterally extensive, wider than the field scale (more than 4 km wide), and form sheet sandstone.

LSE-1 is interpreted as an unconformity. In subsurface data, the contact between IC 1 and underlying deposits is marked by an abrupt increase in grain size that is characterized by a change from low gamma ray readings with blocky log pattern above into high gamma ray readings with serrated log pattern below (Figure 5.5). In core data (the SA-2RD core) it is characterized by coarse-grained, cross-bedded sandstone (interpreted as channel deposit) that erodes bioturbated, fine-grained sandstone (interpreted as lower delta front deposit) (Figure 4.1). Possible diagenetic mineral concretion occurs just below the scour surface. The occurrence of diagenetic mineral concretion below the scour surface indicates that the lower delta front deposits were subaerially exposed, inferring to an unconformity development.

The laterally extensive sandstones that built up the transgressive phase of IC 1 probably consist of multiple channel belts. The thick and blocky nature of the channels is interpreted as a result of deposition during low accommodation-to-sediment supply ratio.

In this condition the channels tend to erode the fine-grained deposits. The SA-2RD cores that penetrates the transgressive phase of IC 1 contains coarse to medium grain sandstone with multiple scour surfaces. It is interpreted that the sandstones consist of multiple narrow channel belts that laterally in communication and create sheet sandstone geometry.

The regressive phase of IC 1 is located between MFS-1 and LSE-2. The channel sandstones of the regressive phase of IC 1 formed as isolated channels that are separated by interfluves. The short-term cycles that built up the regressive phase of IC 1 are muddier compared to those of the transgressive phase.

Figure 5.7 illustrates a cross section through SA-21, SA-2 RD1, and SA-19 wells that shows subdivision of IC 1 into short-term cycles. This cross section is approximately strike-oriented (northwest-southeast). Figure 5.8 shows the net sand map for the transgressive phase of each short-term cycle that built up IC 1. The maps were constructed using 60 API gamma ray value as the net sand cut-off. It is shown that the channel belts of the regressive part of IC 1 (SC 1B, SC 1c, SC 1D and SC 1E) tend to create branching patterns. The pattern suggests that the channels are distributary channels. All these channels are interpreted as distributary channels that were deposited during deltaic progradation.

The net sand map (Figure 5.8) also shows that generally the sediment source was from southwest of the study area. This fact indicates that the paleo-Mahakam River sourced the sediments in the study area. Below are discussions about the distribution of depositional environments in IC 1 and their possible origin. The discussion is for each short-term cycle

5.4.1.1 SC 1A

SC 1A is located between LSE-1A and LSE-2B. The transgressive phase of SC 1A is located between LSE-1 and MFS-1. The regressive phase of SC 1A is located between MFS-1 and LSE-1B (Figure 5.9, Plates 2-3).

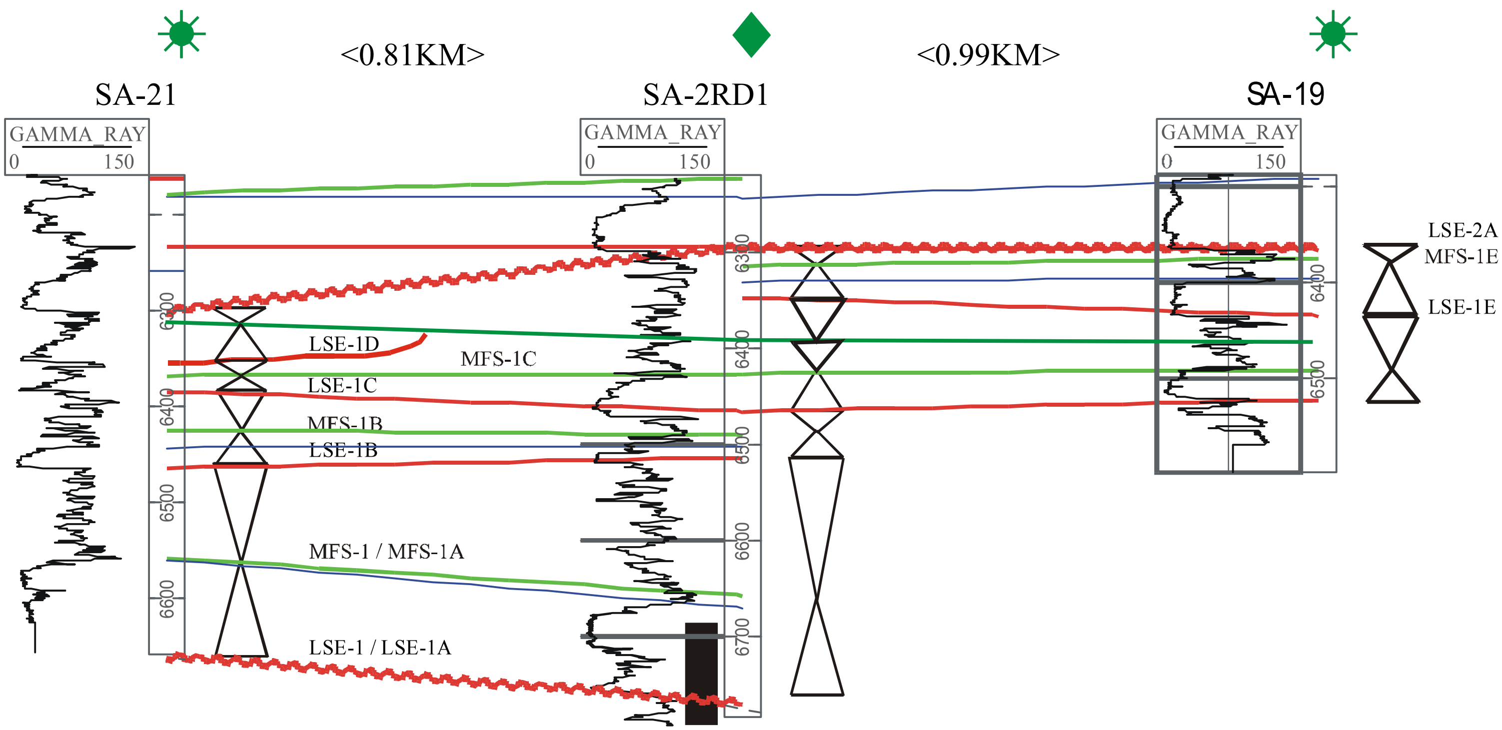
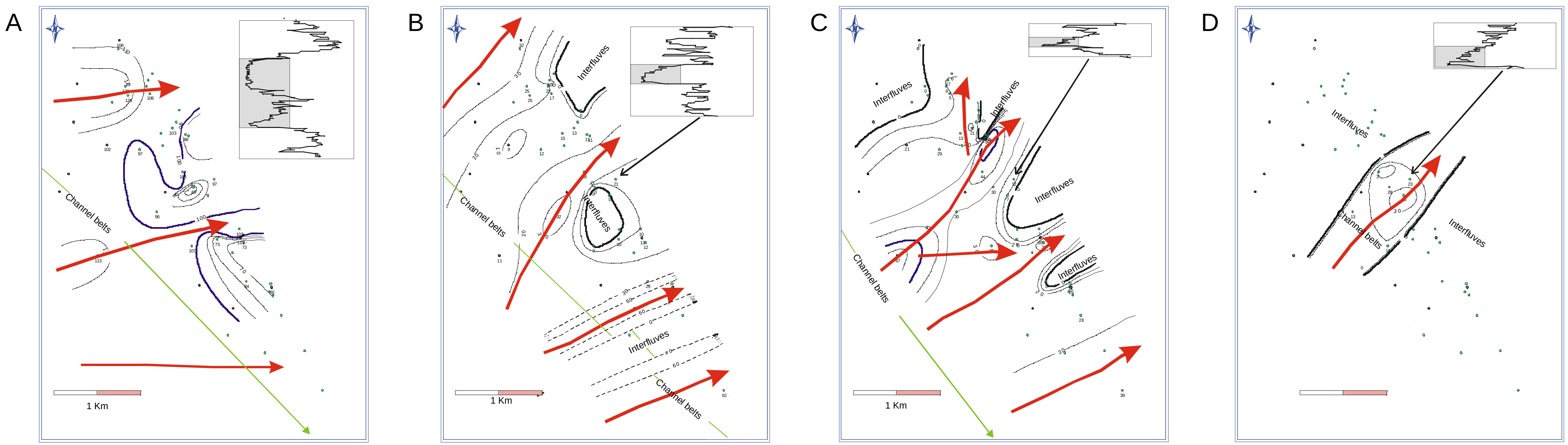


Figure 5.8: Cross section through SA-8RD, SA-21, and SA-2RD1, showing the subdivision of IC 1 into short-term cycles. In this interpretation, SC 1D is missing and represented by a surface in wells SA-8RD and SA-2 RDl.



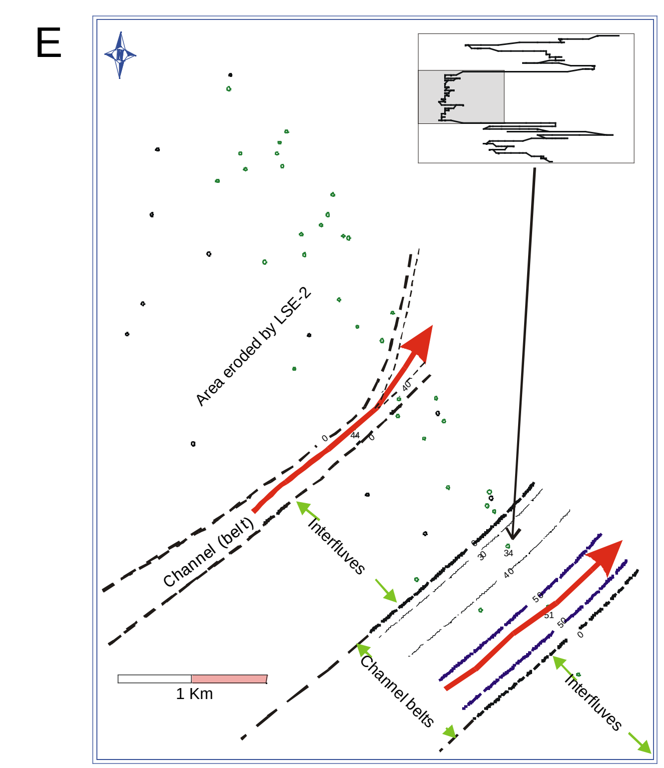


Figure 5.9: Net sand and paleogeographic maps for SC 1A (A), SC 1B (B), SC 1C (C), SC 1D (D), and SC 1E (E). Each map was constructed using net sand cut-off of 60 API gamma ray value. The maps show the branching nature of the channel belts and the southwest sediment source. shaded zones on the log represent gamma ray values less than 60 API used to calculate the net sand. Bold arrows indicate channel belt trends. Dashed contour lines indicate interpreted contour lines in areas that lack data

5.4.1.1.1 Description

The transgressive phase of SC 1A is dominated by thick (in general range of 100-120 ft) amalgamated sandstones that are laterally extensive, wider than the field scale (more than 4 km wide), and form sheet sandstone geometry (Figure 5.5; Plates 2-3). The regressive phase mainly consists of lower delta front deposits and delta front bars. SA-2RD core study indicates that the depositional environment of the sandstones is fluvial/distributary channel.

The middle part of SC 1A is muddier, especially in wells that are located in the southeast part of the study area (Plate 2). The mudstone laterally interfingers with the blocky sandstone (Plates 2-3). At SA-29, mudstone reaches a thickness of 40 ft. The maximum thickness of mudstone in other wells is only up to 20 ft. As observed in SA-2RD core, the mudstones consist of abandoned channel fills that are capped by possible interdistributary bay and crevassse splay/crevasse channel deposits. In general the log response of wells that penetrate the transgressive phase of SC 1A is characterized by low gamma ray readings with blocky log pattern. The abandoned channel fills are characterized by upward-fining patterns, whereas crevasse splays/crevasse channels are characterized by upward-coarsening patterns.

Evidence of incision of older strata, basinward shift of facies associations, and subaerial exposure occurs at LSE-1. In the SA-2RD cores it is indicated by a diagenetic mineral concretion that may indicate paleosol development, a weathering zone, and a scour surface (Figure 4.1). Cores that penetrate the blocky log pattern show abundant scour surfaces that indicate ransportation high-energy. Correlation of markers within the amalgamated sandstone is difficult because the occurrence of mudstones in some wells is not obvious (e.g., in SERANG-1).

In cross sections the transgressive phase of SC 1A creates a major basal relief. As a result, the sediments that were deposited above the scour surface have some local thickening and thinning (Figure 5.5, Plates 2-3) pattern. The sandstone in the northern part generally is thicker than the sandstone in the southern part. The thickness of the sandstone is in the range of 100-120 ft. The thickest sandstone is penetrated by the SA-4 (144 ft), whereas the thinnest is penetrated by SERANG-4 (65 ft).

5.4.1.1.2 Interpretation

The deposition of the transgressive phase of SC 1A was during sediment supply that is higher than the accommodation. This interpretation is based on the facts that (1) the transgressive part of SC 1A is dominated by channel sandstones characterized by blocky log pattern and thus amalgamated, (2) the sediments have low log-pattern diversity, and (3) the occurrence of multiple scour surfaces within the amalgamated sandstones that indicate high transportation energy.

As previously discussed in Chapter 4, the base of IC 1 is interpreted as an unconformity. In logs, the unconformity is marked by a sharp basal contact between blocky, low gamma ray readings above and serrated, high gamma ray readings below. Because the unconformity creates major relief, it is interpreted that the early transgressive deposits of SC 1A are IVF's. The deposition of the sediments was confined in a valley. Table 5.2 shows that the transgressive phase of SC 1A meets all the criteria for IVF's.

The net sand map for the transgressive phase of SC 1A shows that the sandstones were from west of the study area (Figure 5.9a). The source of sedimentation can be from the paleo-Mahakam deltaic lobe that is located southwest of the study area or the paleo-Sangatta Delta that is located northwest of the study area, or from both directions.

The occurrence of continuous mudstone in the southeast part of the field (Figure 5.5, Plate 2) indicates well-developed overbank deposits. This interpretation is supported by core data at well SA-2RD that contains abandoned channel fills that are capped by possible interdistributary bay and crevasse splay / crevasse channel deposits (Figure 4.2). The mudstones are more abundant at the distal part of the study area. The abundance of mudstone may indicate marine influence. Marine influence is supported by cores from SA-2RD cores that exhibit mud drapes and burrows. The increase of floodplain deposits in non-marine strata may indicate the development of a maximum flooding surface basinward (Posamentier, 1998). Therefore, SC 1A may be further subdivided into shorter-term cycles based on the presence of floodplain deposits.

The presence of crevasse splay, crevasse channel and floodplain deposits more likely indicate meandering channels rather than braided channels. There is no data to support the hypothesis that at the time of deposition of the transgressive phase of SC 1A the paleoslope was steep. Based on the data, it is more likely that the deposition of the regressive phase of SC 1A took place under meandering channel under conditions of high sediment supply. The more common marine influence in the southeast part of the study area and the thickening of the sandstone to the north indicates that the locus of sedimentation at that time was in the northern part of the study area.

5.4.1.2 SC 1B

The base of SC 1B is LSE-1B marks channel erosion into SC 1A deposits, whereas the top of SC 1B is LSE-1C. The transgressive phase of SC 1B is located between LSE-1B and MFS-1B. The regressive phase of SC 1B is located between MFS-1B and LSE-1C (Figure 5.8, Plates 2-3).

5.4.1.2.1 Description

The transgressive phase of SC 1B consists of channel sandstones. In some wells the channel sandstones have an upward-fining pattern (e.g., at SA-8RD1 and SA-18HZ wells). Upward, the channel sandstones change into transgressive coastal plain to lagoon deposits that are capped by organic-rich mudstone. The organic-rich mudstone is characterized by high sonic, low density, and high neutron readings. The regressive phase consists of lower delta front deposits and delta front bars that are eroded by subsequent channels.

Figure 5.9b shows the net sand of channel sandstone in SC 1B. There are possibly four channel belts in SC 1B, each separated by zero net sand values that indicate interfluves. The distribution of the channel sandstones is not extensive on the field scale. In the interfluves LSE-1B was picked at the contact between delta front bar and transgressive coastal plain to lagoon deposits. It merged with the TSE-1B.

5.4.1.2.2 Interpretation

The channels are interpreted as distributary channels that prograded across the delta front platform based on the following reasons: (1) the channels are characterized by an upward-fining trend, (2) the channels form a branching pattern that indicates their distributary nature (Figure 5.9b), and (3) the channels are encased in delta front deposits and limited in lateral extent. If the sandstones were interpreted as fluvial channel sandstones, the implication is that there was a major base level fluctuation in a relatively short period of time. On the other hand, interpretation of distributary channel does not require a major base level fluctuation.

In general, sedimentation in the Miocene Mahakam Delta was under high subsidence and high sediment supply (Snedden et al., 1996). Under this condition there is only a small possibility that there were numerous major base level fluctuation created in relatively short period of time during Miocene. The accommodation created by subsidence was followed by high sedimentation, and vice versa, that indicates a balance in base-level rise and fall. Therefore, interpretation of distributary channels, which need smaller base level fluctuations, is favorable compared to interpretation of fluvial channel for the sandstones in SC 1C. Because the channels were interpreted as distributary channels, the contact between SC 1B and SC 1A does not show evidence of a basinward shift of facies associations, and it is regarded as a channel incision instead of an unconformity.

The net sand map (Figure 5.9b) shows that the source of sedimentation for SC 1B was from the southwest of the study area. Therefore, the source of sediments is interpreted from the paleo-Mahakam deltaic lobe that is located in the southwest.

5.4.1.3 SC 1C

The base of SC 1C is LSE-1C that marks channel erosion into SC 1B deposits. The top of SC 1C is LSE-1D. The transgressive phase of SC 1C is located between LSE-1C and MFS-1C, whereas the regressive phase is located between MFS-1C and LSE-1D (Figure 5.8, Plates 2-3).

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5.4.1.3.1 Description

The transgressive phase of SC 1C consists of channel sandstones that are capped by a thin calcareous mudstone, generally less than 5 ft thick. Thick lagoon or estuarine deposits occurs locally in well SA-29. The transgressive calcareous mudstone is characterized by low gamma ray, low sonic, low neutron and high-density readings. Interpretation of transgressive calcareous mudstone is based on cores from SA-5 that penetrates a bed with the same log response. The regressive phase of SC 1C consists of lower delta front, delta front bars, and prodelta or interdistributary bay deposits. The prodelta or interdistributary bay deposits overlie the transgressive calcareous mudstone.

In subsurface data, the channel sandstones generally have a blocky log pattern. Some channels have upward-increasing gamma ray log pattern with sharp basal contact. The thickness of the channel is up to 67 ft. The sandstones are not widespread on the field scale and form a branching pattern. At the interfluves LSE-1C was picked at the contact between delta front bar and transgressive mudstone. LSE-1C merges with TSE-1C at the interfluves.

Figure 5.9c shows the distribution of channel sandstone of SC 1C. Only a few wells penetrate interfluves. The northern part of the study area possibly consists of interfluves solely, as there is no well that penetrates channel sandstone. Interfluves are penetrated by wells SA-7, SA-4, SA-8 RD1, SA-27 and SA-6.

5.4.1.3.2 Interpretation

The channel sandstones are interpreted as distributary channels because: (1) they have an upward-fining trend, (2) they form branching pattern that indicates their distributary nature (Figure 5.9c), (3) they are encased in delta front deposits and limited in lateral extent. The interpretation as to whether the sandstones are fluvial channel or distributary channel deposits affects the interpretation of the base level fluctuation. The occurrence of the transgressive calcareous mudstone just above the channel sandstones indicates a significant transgression over the channel sandstones. Because the contact between SC 1B and SC 1A does not show evidence of a basinward shift of facies associations, it is regarded as a channel incision instead of an unconformity surface.

Figure 5.9c shows the net sand and paleogeographic map of SC-1C. The northern part of the study area consists of interfluves, whereas the southwest part contains channel sandstones. It is more likely that the source of sedimentation for SC 1B was from the paleo-Mahakam deltaic lobe that is located in the southwest.

5.4.1.4 SC 1D

SC 1D is defined at the base by LSE 1D that marks channel erosion into SC 1C deposits. The top of SC 1D is LSE-2. The transgressive phase of SC 1D is located between LSE-1D and MFS-1D. The regressive phase of SC 1D is located between MFS-1D and LSE-2A (Figure 5.8, Plates 2-3). In the northern part, e.g., at SA-7, SA-17, and SA-12 wells, the upper part of SC 1D was truncated by LSE-2 (Plate2). The erosional contact between them forms high relief. In the southern part, SC 1D is overlain by delta plain deposits of SC 1E that changes depositional environment into isolated channels at SA-16 and SA-19 (Figure 5.5).

5.4.1.4.1 Description

The transgressive phase of SC 1D consists of channel sandstones that are capped by thin transgressive calcareous mudstone, less than 5 ft thick. The calcareous mudstone occurs above channel sandstones and does not occur at interfluves. The regressive phase of SC 1D consists of delta front deposits. The transgressive calcareous mudstone is characterized by low gamma ray, low sonic, low neutron and high-density readings. Interpretation of calcareous mudstone is based on cores from SA-5 well (Figure 4.7) that represent strata with a similar log response.

In subsurface data, the channel sandstones generally have an upward-increasing gamma ray log pattern with sharp basal contact. The thickness of channel deposits varies from 33 ft (well SA-19RD2HZ) up to 71 ft (well SA-20). Laterally, the channels are in juxtaposition with interfluves that consist of delta front deposits of SC 1C. In the interfluves, LSE-1D is merged with TSE-1D and MFS-2D. The expression of LSE-1D and TSE-1D in the interfluves is not obvious. For convenience, they were picked at a flooding surface at the same position as MFS-1D.

Figure 5.9d shows the distribution of channel sandstones of SC 1D. It is shown that channel orientation is southwest northeast. Channels in the southwest part are thinner because they were eroded by LSE-2.

5.4.1.4.2 Interpretation

The channel sandstones of SC 1D are interpreted as distributary channel because: (1) they are characterized by an upward-increasing gamma ray log pattern, (2) they have limited lateral extent, (3) their distribution display a branching pattern. There is no basinward shift of facies associations between the delta front deposits of SC 1C and the distributary channel of SC 1D; therefore, it is interpreted that there was no major base level fluctuation during the formation of SC 1D.

The occurrence of transgressive calcareous mudstone that only exists above the channel sandstones indicates that the deposition of transgressive calcareous mudstone was associated with channel sandstone. The transgressive calcareous mudstones can be interpreted as: (1) a thin, transgressive carbonate that was deposited in a shallow-marine setting, and (2) a diagenetic product associated with transgression (calcite-cemented ribbon).

The net sand map (Figure 5.9b) shows a southwest-northeast orientation. This indicates that the source of sedimentation for SC 1D was from the paleo-Mahakam deltaic lobe that is located towards the southwest.

5.4.1.5 SC 1E

The base of SC 1E is LSE-1E that marks channel erosion into the delta front deposits of SC 1D. The top of SC 1E is LSE-2. SC 1E only occurs at the southern part of the study area. In the northern part it is completely truncated by LSE-2. The transgressive phase of SC 1E is located between LSE-1E and MFS-1E. The regressive phase of SC 1E is located between MFS-1E and LSE-2 (Figure 5.8, Plates 2-3).

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5.4.1.5.1 Description

The transgressive phase of SC 1E consists of channel sandstones that change upward into transgressive coastal plain to lagoon deposits. At the interfluves where the distributary channel sandstones are absent, transgressive coastal plain to lagoon deposits of SC 1E overlie the delta front deposits of SC 1D. The regressive phase of SC 1C consists of lower delta front deposits.

In subsurface data (Plates 2-3), the channel sandstones generally have a blocky log pattern with sharp basal contact. The thickness of the channel sandstones is up to 67 ft (at the SA-2 well). The sandstones are isolated and are separated by interfluves. At the interfluves LSE-1E was picked at the contact between delta front bar of SC 1D below and transgressive coastal plain to lagoon deposits above. LSE-1E is merged with TSE-1E at the interfluves. Carbonaceous mudstone / coal that marks the transition from the transgressive coastal plain to lagoon deposits below into delta front deposits above may act as the MFS for SC 1E.

5.4.1.5.2 Interpretation

The channel sandstones of SC 1E are interpreted as distributary channel because (1) they are isolated and separated by interfluves, and (2) they have limited lateral extent (Figure 5.8, Plates 2-3). It is interpreted that there was no major base level fluctuation during the formation of LSE-E. SC 1E is not characterized by basinward shift of facies associations nor an increased in channel clustering. A major base-level fall took place after the deposition of SC-1E. The base-level fall creates a high relief that is similar to valley morphology. The valley morphology is indicated by deeper truncation of LSE-2 the northern part that resulted in the absence of SC-1E in that area.

The net sand map (Figure 5.9e) shows a southwest-northeast orientation. It is interpreted that the source of sedimentation for SC 1E was from the paleo-Mahakam deltaic lobe that is located in the southwest.

5.4.2 IC 2

IC 2 can be subdivided into 260 ft (well SA-22) up to 305 ft (well SA-3) of transgressive phase, and 225 ft (well SA-27 HZl) up to 285 (well SA-29 RD2 HZ) ft of regressive phase. The transgressive phase of IC 2 is located between LSE-2 and MFS-2. The transgressive phase of IC 2 is thicker in the northern area compared to that in the southern area. The transgressive phase of IC 2 consists of stacked, amalgamated sandstones that show multiple incisions.

The regressive phase of IC 2 is located between MFS-2 and LSE-3. The sandstones that built up the regressive phase of IC 2 formed as thick sandstones, up to 100 ft thick, that are encased in delta front to delta plain deposits and separated by interfluves. On the field scale the short-term cycles that built up the regressive phase of IC 2 contain more interfluves compared to those of the transgressive phase. The sandstones of the regressive phase of IC 2 are thick with no obvious mudstone partings.

IC 2 can be subdivided into 5 short-term cycles. The transgressive phase records multiple incision and deposition, and forms three short-term cycles: SC 2A, SC 2B, and SC 2C. Each short-term cycle may represent short-term cycle IVF. Each short-term cycle consists of amalgamated sandstones that pass upward into more mud-prone deposits.

Figure 5.10 illustrates a cross section through SA-1, SA-11, and SA-6 that shows the subdivision of IC 2 into short-term cycles. The cross section is approximately strike oriented (northwest-southeast). The sandstones of SC 2A only exist in the north. The channels of SC 2D and SC 2E only exist in the south. LSE-2 that underlies SC 1A displays a major basal relief (about 100 ft) and creates an undulating surface that is similar to valley incision. LSE-2 is interpreted to be related to major changes in relative base level that may have been caused by eustatic sea-level fluctuation (Figure 5.7a and Plate 2).

As previously discussed, the transgressive phase of IC 2 consists of amalgamated sandstones that are similar to IVF's. The degree of sandstone amalgamation in each short-term cycle that builds up the IVF's is controlled by the rate of accommodation space created that is associated with base level fluctuation. The mechanism of the changes in relative base level can be caused by fluctuation of fluvial sediment supply of the river, local subsidence, or eustatic sea-level fluctuation. The succession in each short-term cycle that built up the transgressive phase of IC 2 is interpreted to be related to minor changes in relative base level that may have been caused by fluctuation of sediment supply or local subsidence. The LSE's of short-term cycles that built up the IVF's (Figure 5.7a, Plates 2-3) show significant erosion. Because the sedimentation of the transgressive phase of IC 2 was during high sediment supply conditions (Snedden et al., 1996), probably the missing time that resulted from the erosion is relatively short.

Therefore, each short-term cycle that is located in the IVF's probably represents channel incision and deposition within the valley that does not represent significant missing time.

The regressive phase of IC 2 contains more mudstone compared to those of the transgressive one. The regressive phase of IC 2 can be subdivided into two short-term cycles, SC 2D and SC 2E. Thick channel deposits occur in the southern part of the study area. They are branching and separated by interfluves. The regressive phase of IC 2 consists of fluvial/distributary channel, floodplain, lower delta plain, delta front bar, lower delta front, and interdistributary bay deposits. Overall, that arrangement reflects deposition during a transgressive-regressive deltaic progradation.

Figure 5.11 shows the net sand map for short-term cycles that built up IC 2. The net sand map shows that generally the sediments source was from southwest of the study area. This fact indicates that the paleo-Mahakam River (or its distributary) acted as the the sediment source for IC 2.

5.4.2.1 SC 2A

The base of SC 2A is LSE-2A that marks the base of stacked, amalgamated channels that built up the transgressive phase of IC 2 (Figure 5.10, Plates 2-3). The top of SC 2A is LSE-2B. SC 2A only records the transgressive phase. No MFS is recognized in SC-2A, probably because it was eroded by LSE-2B.

5.4.2.1.1 Description

The distribution of SC 2A is limited in the northern part of the study area. The sandstones that built up SC 2A are blocky (Figure 5.7a). The amalgamated sandstones pass upward into mud-prone deposits that were interpreted as floodplain deposits.

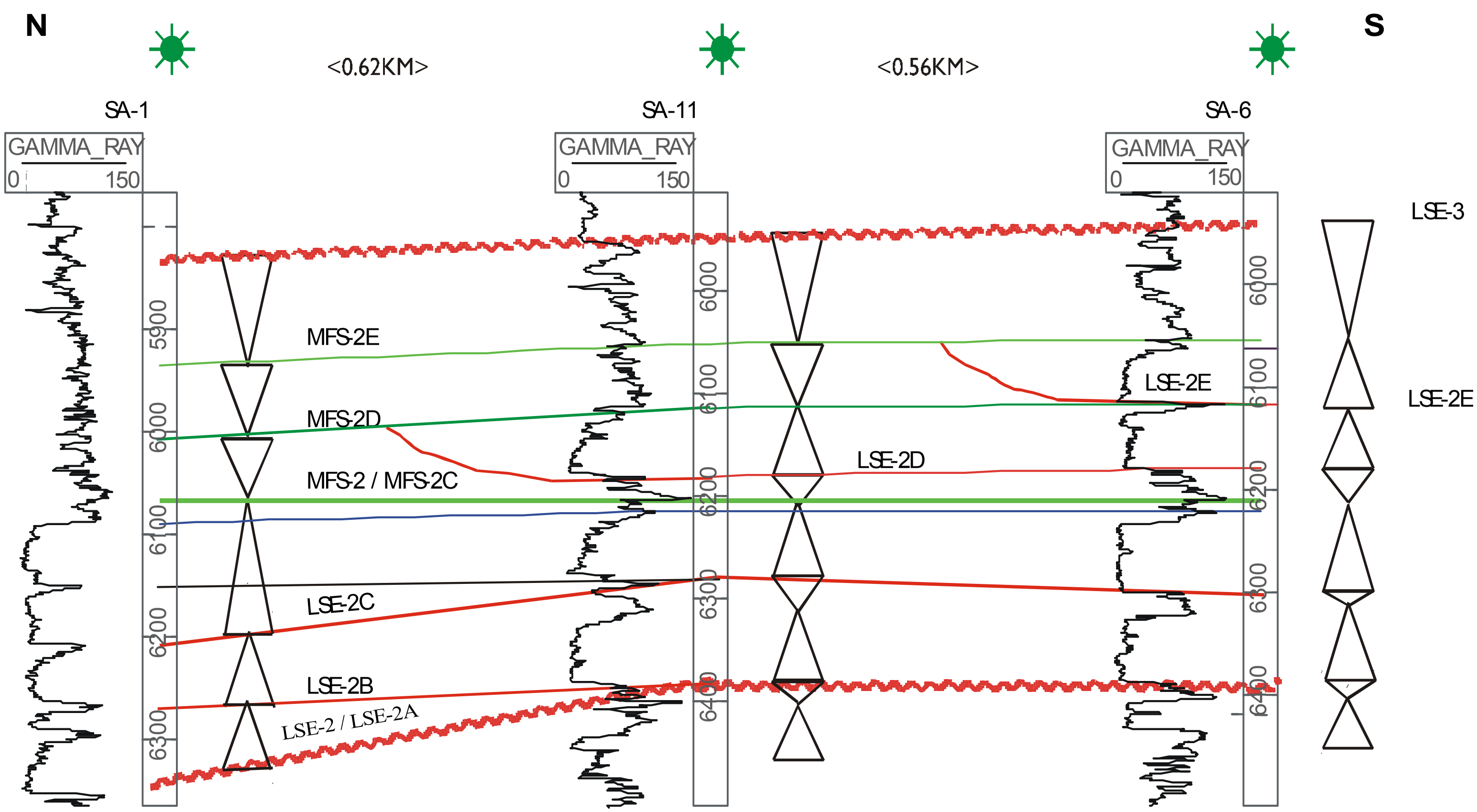

Figure 5.10: Cross section through SA-1, SA-11, SA-6 that shows subdivision of IC 2 into short-term cycles. In the cross section, SC 2D only exists at SA-11 and SA-6, whereas SC 2E only exists at SA-6.

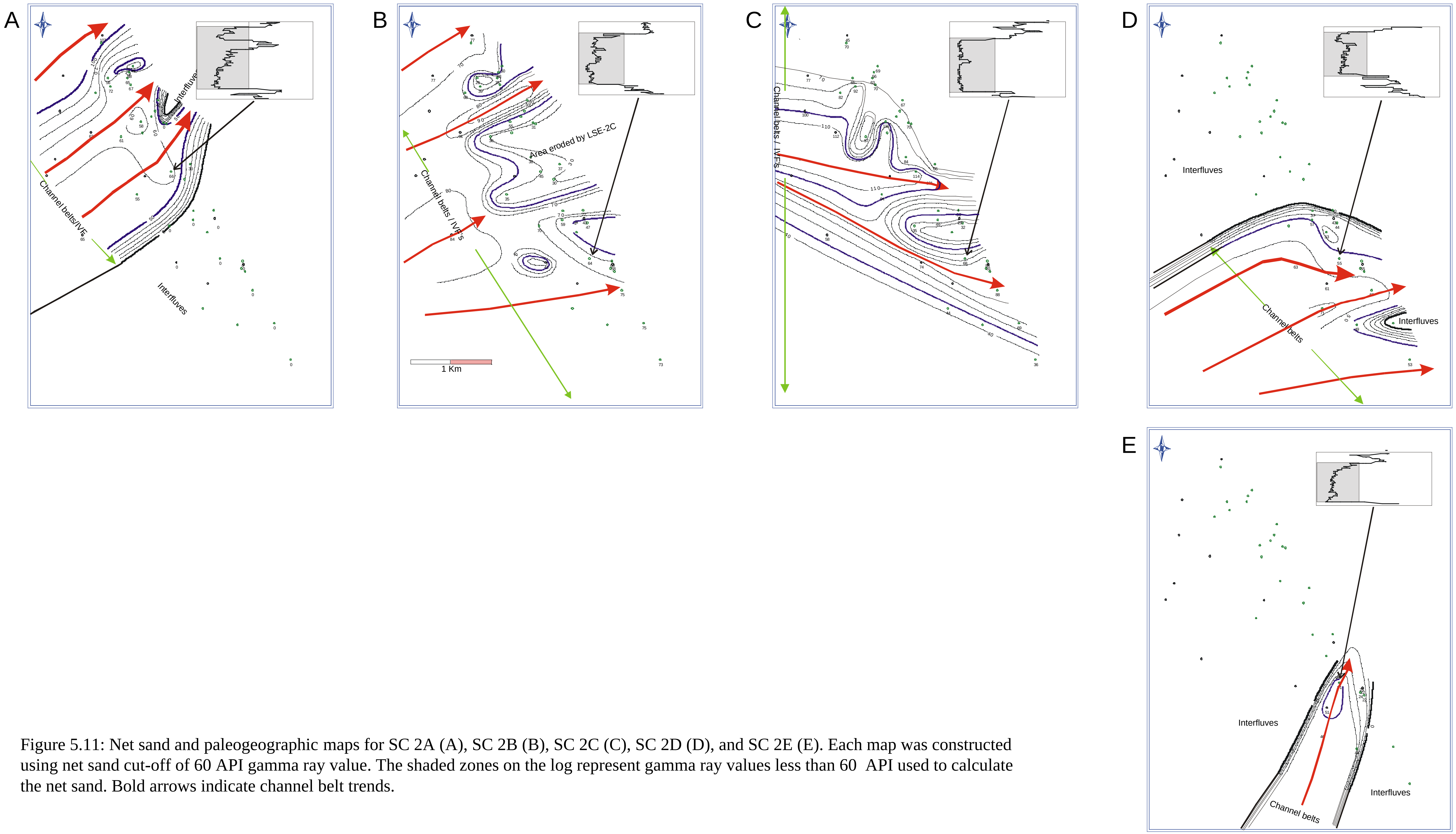

Figure 5.11: Net sand and paleogeographic maps for SC 2A (A), SC 2B (B), SC 2C (C), SC 2D (D), and SC 2E (E). Each map was constructed using net sand cut-off of 60 API gamma ray value. The shaded zones on the log represent gamma ray values less than 60 API used to calculate the net sand. Bold arrows indicate channel belt trends.

Overall, log-pattern diversity is relatively low. Only relatively thin floodplain deposits were preserved. The distribution of floodplain deposits is controlled by the incision of LSE-2B (Figure 5.7a; Plate 2). The absence of mudstones at the top of SC 2A in some wells (e.g., SA-24 HZ) is caused by truncation of LSE-2B.

The surface of erosion that marks the upper boundary of SC 2A is generally shown on logs as a sharp contact between high gamma ray readings of floodplain mudstone and low gamma ray with blocky log pattern of sandstone. In wells where floodplain deposits are absent, the surface of erosion that acts as the upper boundary of SC 2A is marked by a mudstone break in sand-on-sand contact.

Figure 5.11a illustrates the net sand map of SC 2A and the possible paleogeographic setting during the deposition of SC 2A. The map shows that the thick sandstones of SC 2A are only located at the northern part of the study area. The southern part consists of deposits of delta plain and distributary channel.

5.4.2.1.2 Interpretation

The occurrence of thick channel deposits with high sandstone proportions, low log-pattern diversity, and without coal development indicates that the channels were deposited in low accommodation-to-sediment supply ratio. In this setting, the contact between SC 2A and SC 1D is more likely an unconformity. Because the unconformity creates a major relief, SC 1A can be interpreted as IVF. Low accommodation and high sediment supply conditions are not favorable for coal development that requires high accommodation and low sediment supply. As seen in the strike-oriented cross section (Figure 5.7a, Plate 2), the deposition of amalgamated sandstones is possibly controlled by valley morphology because their distribution is confined and only locally occurs in the northern part of the study area.

The dominantly fine-grained floodplain deposits in the upper part of SC 2A reflect relatively high rate of accommodation during floodplain deposition. Short-term base-level rise probably controlled floodplain deposition, as those deposits are more abundant in the upper part of SC 2A. The thin nature of floodplain deposits was possibly caused by erosion of subsequent short-term cycle that created sand-on-sand contacts in some wells. The deposition of the floodplain mudstones is probably related to formation of an MFS basinward, as the formation of thick floodplain can be used as the criteria for an MFS in a non-marine setting (Posamentier, 1998).

5.4.2.2 SC 2B

The base of SC 2B is LSE-2B, whereas the top of SC 2B is LSE-2C (Figure 5.10, Plates 2-3). In the southern part of the study area LSE-2B is located at the same position as LSE-2. The LSE-2B truncated delta front deposits of SC 1E (Figure 5.7a). In the northern part LSE-2B truncate amalgamated channels and mudstones of SC 2A (Figure 5.7a). The transgressive phase of SC 2B is located between LSE-2B and MFS-2B. The regressive phase of SC 2B is located between MFS-2B and LSE-2C. LSE-2C incises SC 2B unevenly, forming valley-like morphology.

5.4.2.2.1 Description

The sandstones that built up SC 2B deposits generally are blocky on the log. Thin sandstones with upward-coarsening patterns were assigned as crevasse splay deposits. Floodplain deposits occur between the sandstones. Overall, log-pattern diversity is more variable compared to that of SC 2A. Beside fluvial/distributary channels, SC 2B also contains floodplain, crevasse splays and crevasse channels, transgressive calcareous mudstones, and delta front bar deposits. Coals were not developed in SC 2B. SC 2B can be subdivided into three sandstone bodies. Two sandstone bodies were regarded as channel fills, whereas the upper sandstone body has marine origin: delta front bar and distributary mouth bar (Figure 5.7a; Plates 2-3).

SA-5 cores (interval 6950-7032 ft, Units 1-2) penetrate SC 2B. Based on core study, the sandstones that built up the transgressive phase of SC 2B are interpreted as fluvial/distributary channel. They do not show shallow-marine influence, such as mud drapes and burrows. Thin transgressive calcareous mudstone was deposited above the sandstone (Figure 5.7a; Plates 2-3). The occurrence of thin calcareous mudstone indicates marine-influence after the deposition of sandstones. MFS-2B is picked above the calcareous mudstone. The calcareous mudstone can also be found in the SA-18HZ and the SA-12RD2. Thick mudstones that probably have a marine origin are found at the top of SC 2B in the SA-2RD1 and the SA-23 PH wells. These mudstones are considered to be an erosional remnant that resulted from LSE-2C truncation.

Figure 5.11b illustrates the net sand map of the transgressive phase of SC 2B. Some thin areas on the map indicate areas where sandstone is thin and areas that have been deeply truncated by LSE-2C, as we can inspect from the cross sections (Plates 2-3).

5.4.2.2.2 Interpretation

The thick channel deposits with high sandstone proportion, low log-pattern diversity, and poor coal development indicate that the channels were deposited in low accommodation-to-sediment supply ratios. Low accommodation and high sediment supply condition is not favorable for coal development that require high accommodation and low sediment supply condition, therefore coal is absent in SC 2B.

Short-term base-level rise brought the environment into a more marine setting that is indicated by the presence of transgressive calcareous mudstone, distributary mouth bar and delta front bar at the upper part of SC 2B. SC-2B is not considered as higher order IVF's because in general LSE-2B that marks the base of SC 2B does not create a major relief.

Figure 5.11b shows the isopach map for the transgressive phase of SC-2b. The channels have a southwest-northeast orientation, indicating that the source of sediment was from southwest of the study area. The thin isopach in the eastern area results from truncation of LSE-2A and from the thinning nature of the channel sandstones basinward.

At the SA-24HZ well, LSE-2B truncates SC 2A deeper; however, this feature is not considered as incised valley of the same order as LSE-2 because the incision is smaller (less than 20 ft) compared to the incision of LSE-2 (up to more than 100 ft). The time missing during LSE-2B incision is considered to be smaller than that of LSE-2. Interpretation of smaller order IVF's for SC 2B can be considered because the LSE-2B creates a significant relief and extensive on the field scale.

5.4.2.3 SC 2C

The base of SC 2C is LSE-2C, whereas the top of SC 2C is LSE-2D. LSE-2C creates a deep incision into SC-2B that is similar to valley morphology. LSE-2D is not areally extensive on the field scale. At the northern part of the study area, where the sandstones of SC 2D are absent, LSE-2D merged with TSE-2D. The transgressive phase of SC 2C is located between LSE-2C and MFS-2C. The regressive phase of SC 2C is located between MFS-2C and LSE-2D.

5.4.2.3.1 Description

The sandstones that built up the transgressive phase of SC 2C generally are blocky. Some of them have upward-increasing gamma ray log pattern (e.g., at SA-21, SA-23 HZ, SA-14 RD2, and SA-3 ST3) that indicates abandoned channel fills. The amalgamated sandstones change upward into interdistributary bay mudstone (as interpreted in the SA-2RD cores) and transgressive coastal plain to lagoon deposits. Overall, log-pattern diversity is relatively low. Most of the wells only penetrate channel deposits that are capped by transgressive coastal plain to lagoon deposits. Wells that are located in the far south (SA-22 and SERANG-4 wells) penetrate delta plain mudstones. Coals were not developed in SC 2C. Sandstone proportion in SC 2C is high. Mudstone deposits consist of floodplain, crevasse splay, and lower delta plain deposits. In general

LSE-2C is shown on log as a sharp contact between high gamma ray readings, which indicates mudstone, and low gamma ray with blocky log pattern that indicates sandstone.

The transgressive phase of SC 2C can be subdivided into four sandstone bodies. The two lower sandstones only occur locally (Plates 2-3). They filled the bottom part of the channel incision. The two upper sandstones are laterally extensive on the field scale. the SA-3RD2 and the SA-2RD cores penetrate SC 2C. SA-3RD2 cores (interval 6587.0-6628.5, Units 1-5) indicate that the sandstones do not show shallow-marine influence, such as mud drapes and burrows. *Ophiomorpha* burrows are present in SA-2RD core interval 8196.4-8251 ft, Units 1-5. As discussed in the previous chapter, the abundance of *Ophiomorpha* burrows indicates marine influence during the deposition of the sandstones. SC 2C is characterized by well-developed interdistributary bay and transgressive coastal plain to lagoon deposits between TSE-2C and MFS-2C.

The regressive phase of SC 2C mostly consists of delta front to lower delta plain deposits. Thin interdistributary bay or prodelta deposits are located above MFS-2C. The regressive phase of SC 2C is thicker in the northern part of the study area. In the southern part of the study area, the regressive phase of SC 2C is thinner because it changes facies associations into distributary channel of SC-2D.

Figure 5.11c shows the net sand map of SC 2C. The thinner nature of net sand in some wells, such as SA-2RD1, SA-23PH, and SA-22, is caused by the changing of facies associations from channel sandstones into floodplain and lower delta plain mudstones.

5.4.2.3.2 Interpretation

The transgressive phase of SC 2C was deposited in high sediment supply that is higher than accommodation space created. This interpretation is based on the thick and sand-prone nature of the sandstones, low log-pattern diversity, and poor coal development. The disappearance of coal in SC 2C is possibly because of the high sediment supply.

The occurrence of *Ophiomorpha* burrows, as found in the SA-2RD cored interval 8196.4-8252.0, is possibly limited to the distal part of the study area, or may only occur locally near the SA-2RD well. The burrows do not occur in the SA- 3 RD2 core interval 6587-6628.5 that is also penetrates SC 2C. The *Ophiomorpha*-burrowed sandstone possibly was deposited in a marine-influence fluvial channel environment. The occurrence of *Ophiomorpha* burrow at the upper part of the sandstones is probably related to the increase of accommodation upward during the channel sandstone deposition, which in turn allowed marine influence to invade landward.

The net sand map (Figure 5.11c) indicates that the source of sediment was from west of the study area. It is not clear whether the sedimentation was from Mahakam deltaic lobe to the southwest or from Sangatta Delta to the northwest of the study area. The thick isopach indicates areas where the channel erodes SC-2B deeper, whereas the thin isopach indicates areas where the channel erodes SC-2B shallower.

LSE-2C creates high relief incision (up to 50 ft at the SA-1 and the SA-27). This feature is not considered to be an incised valley of the same scale as LSE-2 because of the smaller amount of incision compared to that of LSE-2 (up to more than 100 ft) and the missing time because of LSE-2B incision is considered as smaller than that of LSE-2. SC-2C may represent smaller IVF's.

5.4.2.4 SC 2D

The base of SC 2D is LSE-2D whereas the top of SC 2D is LSE-2E. In areas where channel sandstones are absent, LSE-2D is picked at the contact between lower delta front and delta plain deposits. LSE-2E is not areally extensive on the field scale. Organic-rich mudstone that is indicated by low density, high neutron, and high sonic readings is picked as the contact between lower delta front and delta plain.

5.4.2.4.1 Description

In the southern area SC 2D is characterized by fluvial/distributary channel sandstones with blocky log pattern. The channels are thick (up to 80 ft) and branching (Figure 5.11d). Interfluves are developed (at the SA-16) between the channels. In the northern area, where channel sandstones are absent, SC-2D consists of lower delta plain deposits that include thin distributary channels or crevasse channels.

5.4.2.4.2 Interpretation

Based on its thickness, blocky log pattern, and absence of coal development, the channels can be interpreted as fluvial/distributary. The thickness and blocky nature of the sandstones may indicate that the deposition was confined in a valley. The interfluves that occur at the SA-16 well (Plate 2) may indicate either terrace morphology of a valley or the branching nature of the distributary channel.

The channels are thick and amalgamated, and have similar appearance to the IVF's of the transgressive phase of IC-2; however, since the channels have limited lateral extent and the LSE-2D in the interfluves is hard to recognize, it is interpreted that the channel sandstones are not IVF's. The thick and amalgamated channels were probably deposited under increased sediment supply. The thick delta plain deposits in the regressive phase of SC 2D may indicate high subsidence. The Upper Miocene Mahakam deltaic sediments were deposited under such conditions (Snedden et al., 1996).

Figure 5.11d shows that the channel belts are oriented southwest-northeast. This fact indicates that the sedimentation was from the Mahakam deltaic lobe that is located southwest of the study area.

5.4.2.5 SC 2-E

The base of SC 2E is LSE-2E whereas the top of SC 2E is LSE-3. LSE-2E is not areally extensive in the field. At the northern part of the study area, where sandstone deposits of SC 2E are absent, LSE-2E merged with TSE-2E (Figure 5.10 Plates 2-3).

A flooding surface that is located about 3 ft below RT marker, a regional log marker in Mahakam Delta, is chosen as the maximum flooding surface for SC 2E. In areas where channel deposits of SC 2E are absent, TSE-2D is picked at the same position as MFS-2E. The transgressive phase of SC 1C is located between LSE-2E and MFS-2E. The regressive phase of SC 2E is located between MFS-2E and LSE-3.

5.4.2.5.1 Description

The transgressive phase of SC 2D consists of fluvial/distributary channels that are capped by transgressive coastal plain to lagoon deposits. The transgressive phase of SC 2E occurs at the southern part of the study area. Figure 5.22 shows the distribution of channel belt of SC 2E that has a southwest-northeast orientation. The channels are capped by TSE-2E. Thin transgressive coastal plain to lagoon deposits were between TSE-2E and MFS-2E.

MFS-2E was picked at a flooding surface that marks the transition from delta plain and transgressive coastal plain to lagoon deposits into prodelta/interdistributary bay. In interfluves TSE-2E and LSE-2E were picked at MFS-2E because it serves as the best correlation marker. Lower delta plain deposits and overbanks are above prodelta/interdistributary bay deposits.

In contrast with SC 2D, SC 2E records the regressive phase deposits in all wells, which consists of interdistributary bay/prodelta, lower delta plain, and upper delta plain overbanks. The overbanks were eroded by LSE-3.

5.4.2.5.2 Interpretation

Based on the blocky log pattern the channels are interpreted as fluvial/distributary channels. The channel belts of SC 2E are more restricted compared to those of SC 2D. Similar to SC 2D, a valley-like morphology with a relief of up to 80 ft is created. Because the thick channel belts are limited in lateral extent and encased in thick delta plain deposits, they are not considered as IVF's. This indicates that they were deposited under high subsidence and high sedimentation rate.

Different from those of SC 2D, the channel belts of SC 2E do not show a branching pattern. The net sand map (Figure 5.11e) shows that the sediment source was south southwest of the study area, interpreted as from the Mahakam Delta.

The regressive phase of SC 2E is truncated by LSE-3 that creates relatively low relief. There is no obvious basinward shift of facies associations, as the channel sandstones of IC 3 were deposited above upper delta plain /overbank of SC-2E. This indicates that the missing time during the formation of LSE-3 is smaller than that of LSE-2 and LSE-1.

5.4.3 IC 3

The boundary between IC 3 with IC 2 is LSE-3 (Figure 5.10, Plates 2-3), which was picked at the base of the thickest sandstone that records the maximum energy of transportation. The sandstones pinch out laterally and change facies associations into floodplain mudstones. There is no abrupt basinward shift of facies associations between IC 2 and IC 3, as LSE-3 marks a transition from lower delta plain to distributary channel.

IC 3 records a complete transgressive phase and an incomplete regressive phase. The transgressive phase of IC 3 is located between LSE-3 and MFS-3. The regressive phase of SC 2B is started from MFS-3. The top of the regressive phase of IC 3 is located above the studied interval.

5.4.3.1 Description

The channels that built up the transgressive phase of IC 3 are laterally continuous with high width-to-depth ratio, are finer-grained compared to those of IC 1 and 2 (indicated by higher gamma ray readings), and contain well-developed abandoned channel fills and coal. The channel sandstones are volcanoclastic rich (as shown by the SA-3RD2 core), interbedded with coal, and laterally change facies associations into floodplain mudstones.

Above the distributary channels are delta front deposits up to 100 ft thick that are characterized by an overall upward-increasing gamma ray log pattern. The transgressive phase of IC 3 is capped by an MFS that marked the transition from delta front into prodelta environment. At the top of the study interval, carbonates up to 90 ft thick were deposited. At the northern part of the study area, carbonates occurred earlier compared to those of the southern part (Cross section D-D' in Plate 2). There are two carbonate bodies in the northern part of the study area (e.g., at the SA-26 HZ and the SA-31 HZ) that are separated by prodelta deposits.

5.4.3.2 Interpretation

The occurrence of multiple, laterally extensive coals in IC 3 indicate that deposition took place in distributary channels instead of fluvial channels. Coal is well developed in lower delta plain, where the area is drowned by water (Galloway and Hobday, 1983), and more commonly associated with distributary channels instead of fluvial channels. If the sandstones were fluvial channel deposits, there should have been a major sea-level fluctuation that would have brought the depositional environment back and forth from fluvial to lower delta plain in order to deposit the interbedded sandstone and coal. The interpretation of distributary channel is also supported by the muddy nature of the sandstones, which is indicated by relatively high gamma ray readings.

The absence of evidence of basinward shift of facies associations and low relief of LSE-3 may indicate that there was less missing time created by LSE-3 compared to those of LSE-2 and LSE-1. Because there was no absence of accommodation (i.e. the accommodation rate decreased but it was not absent) the deposition was continuous without a major break in sedimentation.

The transgressive phase of IC 3 was deposited during high accommodation-to-sediment supply ratio, as indicated by continuous channels, narrow channel incision, preservation of abandoned channel fills and coals, relatively low sandstone proportion, and high log-pattern diversity. Preservation of abandoned channel fills and coals in sediments that built up IC 3 indicate that channel incisions are not deep, and more time is represented as rock instead of surfaces of erosion.

The occurrence of thick carbonates at the top of the study interval indicates an apparent shut down of sediment supply. Because the carbonates occur earlier in the northern part of the study area, it is interpreted that at the time of the deposition of the carbonate in the north, the locus of ssilisiclastic edimentation was shifted to the south. The shifting of locus of sedimentation creates an environment that is conducive for carbonate growth.

5.5 Depositional model

Two depositional models for the stratigraphy of the Serang Fields are made: (1) depositional model based on IVF's interpretation (Plates 2,3), and (2) an alternative model based on freely migrating channels interpretation (Plates 4,5 on CD). The alternative model is presented in order to emphasize the implications that result from both interpretations.

Each intermediate-term cycle has different characteristics (Table 5.5) that reflect a progressive increase in accommodation-to-sediment supply ratio. The sandstones that built up the transgressive phase of IC 1 contains less continuous markers that indicate less continuous channels, have higher sandstone proportion, lower preservation of abandoned channel fills, no coal development, and low log-pattern diversity. On the other hand, the sandstones that built up the transgressive phase of IC 3 contain more continuous markers

Table 5.5: Comparison of characteristics of transgressive phase of IC 1 to IC 3 deposits that resulted from different rates of accommodation (adapted partly from Gardner, 1993)

IC 1	IC 2	IC 3
More discontinuous channels with high degree of channel connectivity, indicated by less continuous markers	Discontinuous channels, indicated by non continuous markers	More laterally continuous channels, indicated by more continuous markers
Deep channel incision, low preservation of abandoned channel fills	Deep channel incision, low preservation of abandoned channel fills; however, thick abandoned channel fills are developed in some areas (e.g., at the SA-21 well)	Narrow channel incision, high preservation of abandoned channel fills
No coal development	No coal development	Well-developed coal
Contains lowest log-pattern diversity	Contains low log-pattern diversity. Relatively thick overbank deposits are preserved	Contains highest log-pattern diversity. Abandoned channel fills and coal are preserved
Basinward shift of facies associations is indicated by fluvial/distributary channel deposits above lower delta front of older deposits	Basinward shift of facies associations is indicated by fluvial/distributary channel deposits above lower delta front of older deposits	No basinward shift of facies associations occurs. Distributary channel deposits overlying delta plain deposits
More prone to unconformity development. Basinward shift of facies associations is indicated by fluvial/distributary channel	Prone to unconformity development. Unconformity can be inferred from the increase of channel clustering	Less prone to unconformity development. No obvious basinward shift of facies associations occurs.
More time represented by surfaces of erosion instead of rock	More time represented by surfaces of erosion instead of rock	More time is represented by rock instead of surfaces of erosion
Significant sediment eroded, bypassed and deposited basinward	Significant sediment eroded, bypassed and deposited basinward	Fluvial aggradation, more sediment deposited landward

that indicates more continuous channels, lower sand proportion, higher preservation of abandoned channel fills, good coal development, and high log-pattern diversity. The arrangement from IC 1 up to IC 3 reflects a decrease of fluvial bypass, more heterogeneous coastal plain strata, and more time represented by rock instead of surfaces of erosion and non-deposition.

The increase of accommodation rate results from superimposed short-term and intermediate-term base-level cycles within a long-term base-level rise as shown in Figure 5.12. Because the deposition of the transgressive phase of IC 1, IC 2, and IC 3 were superimposed within the transgressive phase of long-term cycle, to the younger stratigraphic cycle the transgressive phase is amplified; More accommodation was created and muddier sediments were deposited. The long-term base-level rise in the Serang Field corresponds to the trend of global sea-level rise during late Late Miocene (Vail et al., 1977), when the Serang reservoirs were deposited.

The superimposed short-term and intermediate-term cycles within a long-term base-level rise results in overall landward-stepping cycles. Landward-stepping cycles are characterized by landward positioned accommodation, which results in increasing aggradation relative to degradation on the coastal plain, and smaller sediment volumes eroded and bypassed to shallow-marine (Gardner, 1993).

Figure 5.13 shows the depositional models for the studied sediments based on (a) IVF model and (b) freely migrating channel model. The two models result in different prediction of sandstone distribution outside the field. Based on the IVF model, there was a lot of erosion and sediment bypass to the deeper water during the deposition of the transgressive phase of IC-2. LSE-2 erodes the deposits of previous short-term cycle and bypasses them to the deeper water (Figure 5.13a).

On the contrary, based on the large, freely migrating channel interpretation there was not much erosion and sediment bypass during the deposition of the transgressive phase of IC-2 (Figure 5.13b). The deposition is controlled by fluctuation of sediment supply. In areas where sediment supply was high, thick amalgamated sandstones were created. On the other hand, areas where sediment supply was low are characterized by abundant mudstones.

Regardless of whether the transgressive phase of IC 2 is interpreted as IVF's or freely migrating channel systems, the changes in sandstone geometry and connectivity and changes in the degree of preservation of rock suggest that the studied sediments were deposited during a long-term base-level rise. The stages of deposition can be summarize as follows:

1. Base-level fall lad to unconformity development at the base of IC 1 (LSE-1), eroding previous sediments, and bypassing and depositing them into deeper water (Figures 5.12, 5.13).
2. Base-level rise backfilled the study area with dominantly channel fills. The deposition was confined in a valley and under a condition of low accommodation-to-sediment supply ratio (Figures 5.12, 5.13). The backfilling sediments were deposited either in fluvial-braided channel or in meandering channel environments. The sediments represent the transgressive systems tract. The source of sediments could be either from a paleo-Mahakam deltaic lobe or the paleo-Sangatta Delta.
3. Subsequent base-level falls deposited several short-term cycles (Figures 5.12) in distributary channel to lagoon, bay, estuary, delta plain and delta front environments. The sediments represent the highstand systems tract (Figures 5.13). The source of sediments was from the paleo-Mahakam deltaic lobe.
4. At the base-level fall-to-rise turnaround (LSE-2) valley morphology was created. Based on IVF model there was a lot of erosion and sediment by pass to deeper water (Figure 5.13a). The erosion represents missing time in the rock record. On the contrary, based on the large, freely migrating channel model the erosion did not represent significant missing time in the rock record (Figure 5.13b).
5. Base-level rise results in deposition of fluvial-deltaic deposits that can be subdivided into three short-term cycles: SC 2A, SC 2B, SC 2C (Figures 5.12,

5.13). The sediments represent the transgressive systems tract. The source of sedimentation was from a paleo-Mahakam deltaic lobe.

6. Subsequent base-level fall deposited two short-term cycles (SC 2D, SC 2E, Figure 5.12) that indicate the progradation of fluvial/distributary channels over delta front platform. The deposition was during highstand systems tract with the source of sediment from a paleo-Mahakam deltaic lobe.
7. Subsequent base-level fall-to-rise turnaround is characterized by less erosion and less missing time than that of LSE-1 and LSE-2 because the deposition was under decreased in accommodation rate instead of absence of accommodation (Figures 5.12, 5.13). No basinward shift of facies associations created. During the base-level fall-to-rise turnaround the distributary channels were deposited above upper delta plain deposits. The source of sediments could be either from the paleo-Mahakam Delta or the paleo-Sangatta Delta.
8. Continuous base-level rise (Figure 5.12) brought the environment into prodelta to delta front setting. An apparent shut down in sedimentation in the study area allowed for carbonate to form at the top of the study interval.

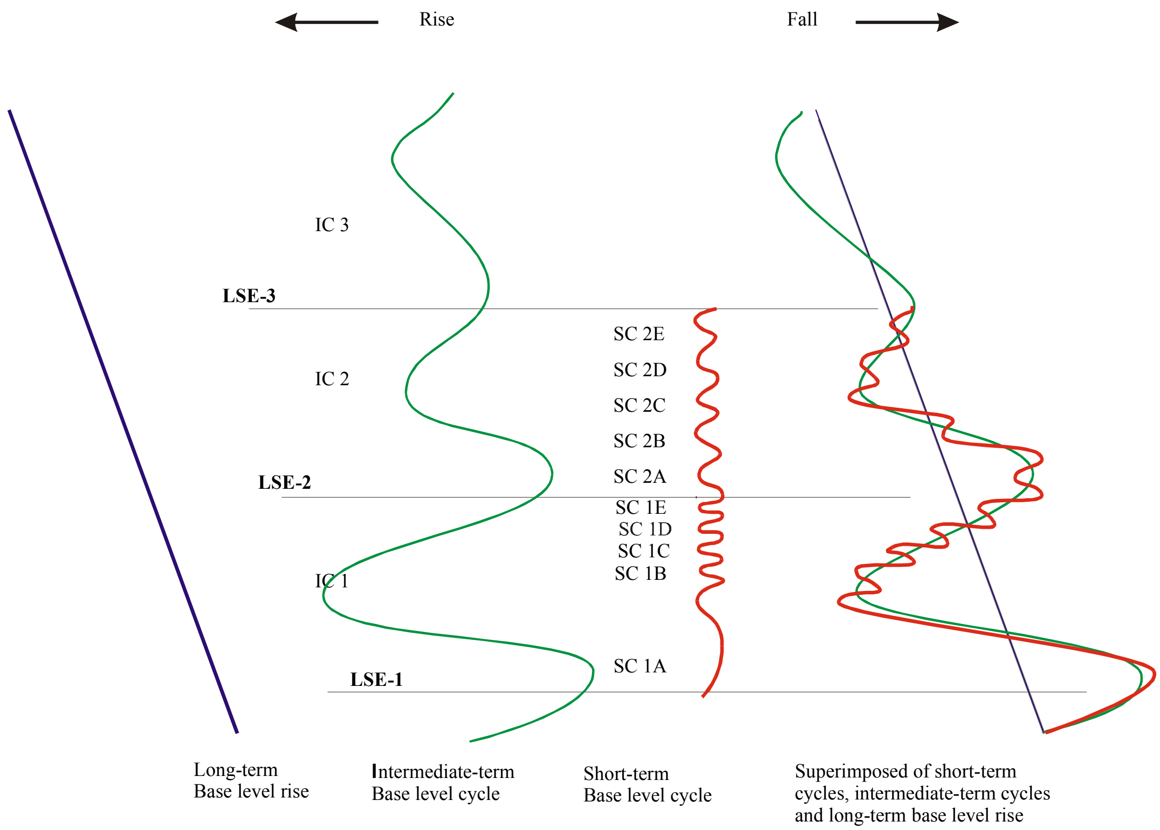

Figure 5.12: Diagrammatic base-level curve that shows the superimposition of short-term, intermediate-term, and long-term base-level cycles in the study interval.

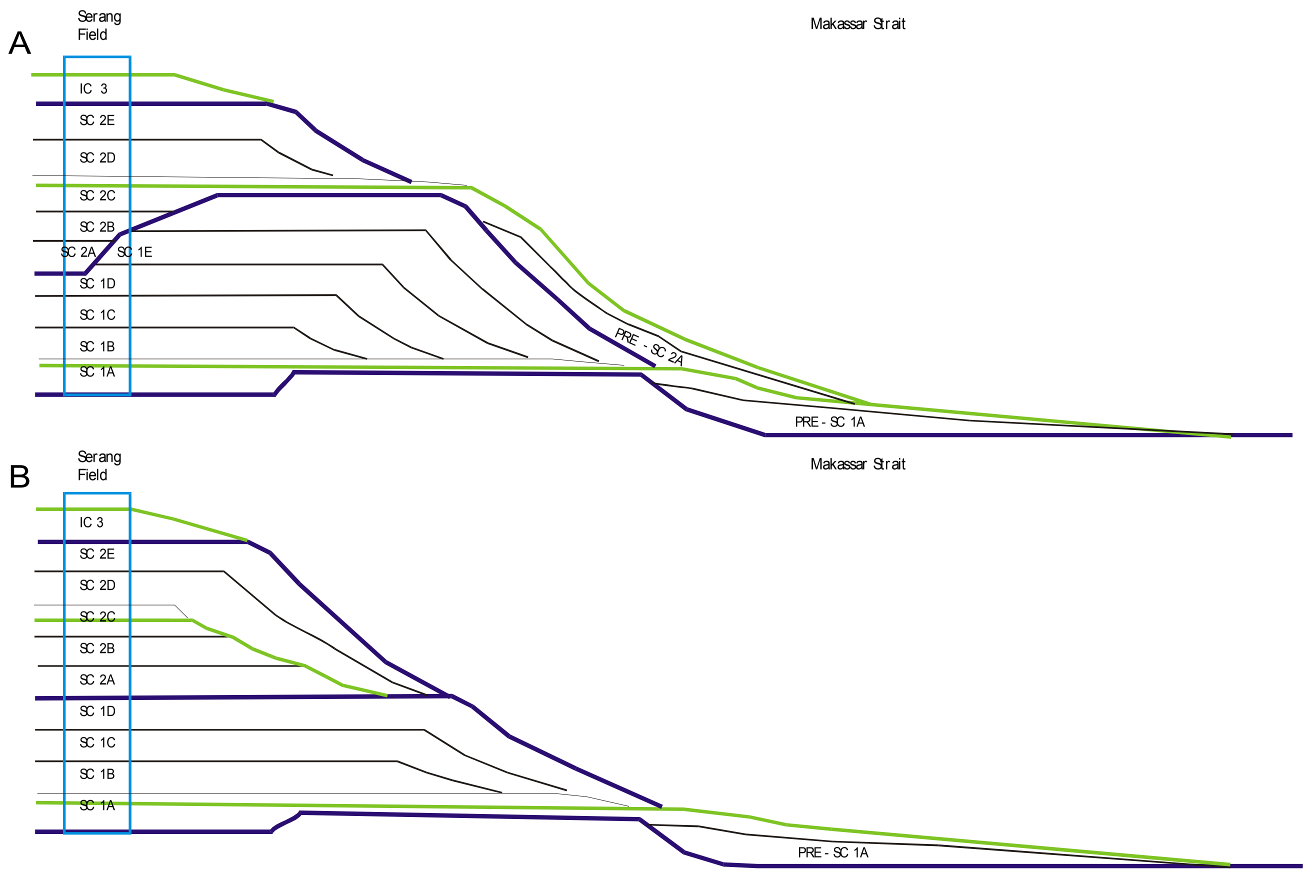

Figure 5.13: Diagrammatic dip-profile depositional model for the Serang Field reservoirs based on IVF's (A) and freely migrating channel systems (B). The IVF model suggests the occurrence of prospective sandstones basinward of the Serang Field that are time-equivalent with the formation of LSE-2. The sandstones resulted from erosion of older deposits and sediment bypass. On the other hand, the freely migrating channel systems model does not suggest the occurrence of prospective sandstones. Bold lines indicate LSE of intermediate-term cycles. Thick gray lines indicate MFS of intermediate-term cycles. Thin lines are related to the deposition of short-term cycles.

CHAPTER 6

SEQUENCE STRATIGRAPHY APPLIED TO RESERVOIR HETEROGENEITY AND SANDSTONE DISTRIBUTION IN THE SERANG FIELD

6.1 Introduction

In this Chapter, the application of sequence stratigraphy to reservoir heterogeneity and sandstone distribution in the Serang Field towards the deeper water is discussed. One of the main aspects of sequence stratigraphy is to predict the sandstone geometries and heterogeneities within time-equivalent successions (Van Wagoner et al., 1990). The reliability of the prediction depends on an understanding of the depositional setting and the position of the reservoir within a stratigraphic cycle.

Sequence stratigraphic concepts can be applied to fluvial reservoirs if base level fluctuations that are related to relative sea-level cyclicity are assumed as the main driving force during the deposition of sediments (MacDonald et al., 1998). The alternation between sandstone-rich channel belt and mudstone rich interchannel interval is controlled by base level fluctuation. During base-level rise, high accommodation rate that is preferable for fine-grained sediment deposition is created. In non-marine environment the formation of thick floodplain mudstones within the IVF's correspond to the formation of maximum flooding surface of short-term cycles basinward. During base-level fall widespread incision produces discontinuous mudstones within sandstone-rich sequences. As previously discussed, interpretation of the position of a sediment body in a long-term cycle has an implication for the prediction of sandstone distributions, either to the landward or basinward from the field.

6.2 Expectation of reservoir heterogeneity

In this report the reservoir heterogeneity of the Serang Field is described qualitatively in terms of the quality and distribution of reservoir rocks (i.e., sandstones), and permeability barrier (i.e., mudstones and valley wall).

Strong water drive is observed in the Serang reservoir, and the amalgamation of sandstones is inferred to create lateral hydrodynamic continuity between wells (Vo et al, 1999); however, the distribution of mudstones within the field may act as fluid flow baffles. Multiple scour surfaces within the amalgamated sandstones caused the disconnected distribution of mudstones that in turn created a discontinuous permeability barrier distribution. The scour surfaces that form the valley wall may act as permeability barriers if they are impermeable because of diagenetic processes.

In the Serang Field, hydrocarbons are accumulated in structurally high areas. Dry holes, as found at the SA-3ST well, were located at the structurally low areas. The reservoirs of the Serang Field are located at ICs 1 and 2. IC 3 is considered as barren because it lacks effective seal development (i.e., it is not directly overlain by a maximum flooding surfaces as in ICs 1 and 2). Because IC 3 is considered as less prospective, the heterogeneity in IC 3 will be discussed only briefly.

The sand-prone reservoirs of IC 1 and IC 2 are characterized by thick pay zones. Laterally discontinuous floodplain deposits separate the pay zones. Marine mudstone capped the reservoirs in IC 1 and IC 2. In some wells channel incision creates sand-on-sand contact (e.g., at SA-1, the SA-27, and SERANG-1 wells, see Plates 2-3); however, were the scour surface of valley and channel incisions are impermeable because of diagenetic processes they may compartmentalize the reservoir. The discontinuous floodplain mudstones and valley walls may compartmentalize the reservoirs; which may influence the later stage of development of the field.

Within the long-term cycle, the trend from the transgressive phase of IC 1 up to IC 3 (Table 5.5) indicates an increase of accommodation-to-sediment supply ratio. This trend indicates that more heterogeneity expected in reservoir of the younger stratigraphic cycle, whereas the older ones tend to be less heterogeneous. The expected heterogeneity within the long-term cycle in increasing order is reservoirs of IC 1, IC 2, and IC 3.

The transgressive phase of IC 1 contains scour surfaces that created sand-on-sand contact. It consists of highly amalgamated fluvial/distributary channel deposits with multiple channel belts and forms sheet sandstone geometry on the field scale (Figure 5.5; Plates 2-3). Core study (at the SA-2RD core) suggests that the scour surfaces within the transgressive phase of IC 1 were not modified by diagenetic processes; therefore, the reservoirs can be considered as in vertical communication. The occurrence of mudstones in the southeast part of the study area (cross section D-D' in Plate 3) suggests an increase of marine influence in the distal part of the study area.

In the regressive phase of IC 1, which is more mud-prone compared to the transgressive phase of IC 1, the distribution of the best reservoir (i.e., channel sandstones) is controlled by channel incision. The channel sandstones are thinner and more limited in lateral extent. They are interpreted as distributary channel based on their limited lateral extent and upward-fining pattern. Laterally the distributary channel sandstones are connected with delta front bars that have lower reservoir quality.

The transgressive phase of IC 2 is sand-prone and dominated by amalgamated channels. The distribution of floodplain mudstones is controlled by overlying channel incision. Because the valley wall may represent a significant subaerial exposure, diagenetic processes may take place along the valley wall. The valley wall and IVF floodplain mudstones may compartmentalize the reservoir.

The regressive phase of IC 2 consists of thick channel sandstones (up to 70 ft thick at the SA-20) that are encased in delta front to delta plain deposits. The distribution of channel sandstones is limited in the southern part of the study area. The thick channel sandstones may suggest the locus of deposition. Laterally the channel sandstones are connected with delta front bars that have lower reservoir quality.

The transgressive phase of IC 3 consists of stacked distributary channels with good preservation of abandoned channel fills and coal. The channels are wide and laterally connected. Vertically they are separated by abandoned channel fills and coal. Because the distributary channel sandstones are not directly overlain by marine mudstone, they lack effective seal development and barren of hydrocarbons.

Within each short-term cycle, the occurrence of sandstones and mudstones is best understood within a sequence stratigraphic framework. Sandstone distribution within each short-term cycle is associated with base-level fall-to-rise turnaround. This pattern is related to the high-energy of transportation during base-level fall-to-rise turnaround that is favorable for deposition of coarse-grained sediments. On the other hand, mudstone distribution is associated with base-level rise-to-fall turnaround. During this time energy of transportation is low. This condition is favorable for the deposition of fine-grained sediments.

As discussed in the previous chapter, IVF and freely migrating channel models may have different implications in the reservoir heterogeneity of the field. In sand-prone IVF's reservoirs the reservoir and permeability barrier distribution are controlled by valley morphology. Because the IVF's of the Serang Field are sand-prone, the IVF model infers that the reservoir within the valley can be considered as having low heterogeneity. It is possible that the uniform production trend and pressure measurement in the Serang Field, besides controlled by the strong water influx, is controlled by the low heterogeneity of IVF's reservoir. On the other hand, in freely migrating channel reservoirs changes of facies associations are more expectable. The multistory sandstones are deposited in an unconfined system and the associated floodplain deposits result in changes of facies associations that in turn create heterogeneity.

6.2.1 Reservoir rocks

In my interpretation, there are three kinds of sediment bodies that act as reservoir rocks in the Serang Field: (1) fluvial/distributary channel sandstones, (2) distributary channel sandstone, and (3) delta front bar. Each sediment body has specific features that can be distinguished one from another, and their occurrence in the Serang Field is best understood within a sequence stratigraphic framework.

As observed in the SA-2RD cores and the SA-5 cored interval 6950-7032 ft, fluvial/distributary channel sandstones are coarse- to fine-grained, moderately well-sorted, and dominated by cross bedding. Multiple scour surfaces within the sandstones, as seen in core, result in truncation of the fine-grained deposits at the channel tops, and amalgamation in turn create vertical continuity for fluid flow. Some parts of the core contain diagenetic carbonates that may contribute to vertical and lateral heterogeneity. Local burrowed intervals, such as the *Ophiomorpha* burrows in the SA-2RD core, and finer-grained abandoned channel fills result in reservoir heterogeneity. The *Ophiomorpha* burrows are expected in the upper part of the channels where more accommodation space was created during the deposition of the sandstones. This situation in turn allows marine influence to invade landward and creates favorable environment for burrowers. As seen in the cross sections (Plates 2-3), the fluvial/distributary channel sandstones are thick and the channel belts are relatively wide on the field scale.

Distributary channel sandstones (the SA-5 cored interval 6555-6615 ft) are dominated by moderately well-sorted, medium-to fine-grained sandstones with an upward-fining trend. Parallel to cross bedding with some scour surfaces are common. Coal and finer grains of the abandoned channel fills that contain mud drapes are well preserved. The abandoned channel fills are progressively finer grained and less permeable upward. It is inferred that during water flood the higher permeability nature of abandoned channel fills towards the bottom, together with gravity force, will pull water down (Lassoter et al., 1986 in Slatt and Galloway, 1994). The abandoned channel fills may also reduce the volumetric calculation. As seen in the cross sections (Plates 2-3), distributary channel sandstones are thinner and narrower compared to fluvial/distributary channel sandstones. Distributary channel sandstones are considered as more heterogeneous compared to fluvial/distributary channel because of their upward-fining trend, mud drapes and bioturbation that may reduce reservoir quality.

Delta front bars are fine-grained, burrowed to bioturbated, and poorly-sorted because of biomixing. All these characteristics result in a poor quality and heterogeneous reservoir. Delta front bars are thin but laterally extensive, although they are considered as secondary reservoirs.

Based on core studies and well log correlation as described above, it is found that the rank of sediment bodies that creates the most heterogeneity and compartmentalization in increasing order is: (1) fluvial/distributary channel, (2) distributary channel, and (3) delta front bar.

Fluvial/distributary channel sandstones occur above the base-level fall-to-rise turnaround unconformity within the early transgressive phase of ICs 1 and 2. The fluvial/distributary channel sandstones are highly connected and characterized by discontinuous markers. This fact indicates that the channel belts consist of several smaller channels that erode finer-grain deposits. The sandstones were deposited in low accommodation-to-sediment supply ratio. In IC 1 the fluvial/distributary channel sandstones form sheet geometry. In IC 2 the sandstones can be subdivided into three short-term cycles, each separated by finer-grain overbank deposits.

Based on their blocky log pattern, the reservoirs of the regressive phase of IC 2 can be considered as fluvial/distributary channels; however, the net sand maps of these reservoirs show branching patterns that are typical for distributary channels. The fluvial/distributary channel reservoirs occur in the regressive phase of IC 2 probably because at the time of their deposition sediment supply was very high.

Distributary channels are abundant in the regressive phase of IC 1. They are encased in lower delta plain and delta front. Distributary channels also occur in the transgressive phase of IC 3 that is characterized by extensive channel belts and continuous markers. The occurrence of distributary channel instead of fluvial/distributary channel deposits at IC 3 indicates more shallow-marine environments. This landward shift of facies associations resulted from the increase of accommodation to the younger stratigraphic cycle.

Delta front bars are common in the regressive phase of intermediate-term cycles. The prograding distributary channels may connect delta front bars and enhance the continuity of delta front bar reservoirs.

Within the short-term cycles, fluvial/distributary channels and distributary channel sandstones occur at the early transgressive phase, whereas delta front bars occur at the regressive phase.

6.2.2 Permeability barriers

Fluid flow through well-connected reservoirs with low heterogeneity depends on the distribution of reservoir baffles that consists of heterolithic deposits. There are four reservoir baffles that may act as permeability barrier in the Serang Field: (1) marine mudstones, (2) floodplain mudstones, (3) valley wall, and (4) mudstone intraclast conglomerates and drapes.

Marine mudstones (e.g., prodelta and interdistributary bay mudstones) that are associated with MFS of intermediate-term cycles (IC’s 1 and 2) serve as the best seal. They act as effective seal because they consist of fine-grained deposits and are relatively thick. The marine mudstones were deposited during base-level rise-to-fall turnaround of intermediate-term cycles, and in general are not incised by channels.

Floodplain mudstones are thought to be the second effective permeability barrier. The occurrence of thick floodplain mudstones is related to formation of MFS of short-term cycles basinward. In non-marine environment the increase of accommodation rate during the formation of MFS’s results in aggradation of the alluvial plain with an upward increase in floodplain mudstone deposition (Posamentier, 1998). Although channel amalgamation has created vertical and lateral communication between wells, floodplain mudstones can compartrmentalize the reservoirs and act as baffles for oil production because they have adequate thickness and lateral extent.

Valley walls may act as effective permeability barrier if they were impermeable. The impermeable nature of valley wall results from diagenetic processes during subaerial exposure; therefore, even in sand-on-sand contact the valley wall may act as permeability barrier.

Laterally discontinuous mudstone such as intraclast conglomerate and intrachannel drape deposits can form partial baffles to vertical fluid flow that reduce effective vertical permeability of the reservoir. The mudstones are thin and not areally extensive; therefore, they are considered as the least effective permeability barrier.

Carbonate-cemented sandstones are diagenetic product and only occur locally within the field. the diagenetic sandstones in SA-2RD cored interval 8196.4-8251 ft are 9 ft thick ,and they may act as effective vertical permeability barrier in the wellbore scale. Because of their diagenetic nature, this study does not consider the carbonate-cemented sandstones in the stratigraphic analysis of permeability barrier.

Based on the characteristics of each permeability barrier described above, the depositional-controlled permeability barriers in the Serang Field are ranked in decreasing order as follows: (1) marine mudstones, (2) floodplain mudstones, (3) valley wall, and (4) mudstone intraclast conglomerates and drapes.

The occurrence of each type of permeability barrier in the Serang Field reservoirs is best understood within a sequence stratigraphic framework. The occurrence of marine mudstones is related to MFS's of intermediate-term cycles. The floodplain mudstones are related to MFS's of short-term cycles. The valley walls are related to LSE's. The mudstone intraclast conglomerate and intrachannel drapes are expected internally within the reservoir.

Although at present the reservoir is thought to be laterally and vertically in communication, the presence of permeability barriers may compartmentalize the reservoirs in the future stage of development. Because the oil column becomes thinner due to production, horizontal drilling seems to be the best choice to develop these reservoirs. Besides considering the fluid contacts, the presence of mudstone partings should be considered in placing horizontal wells.

6.3 Expectation of sandstone distribution outside the field

One important issue regarding sandstone distribution is the possibility of unconformity development during base-level fall-to-rise turnaround. Unconformity development indicates erosion of deposits of the preceding cycle and sediment bypass. During unconformity development, sediments of the preceding cycle are eroded and bypassed to deeper water. As a result, deeper water deposits are time-equivalent with unconformity development. Fluvial channels were deposited later, after the deposition in deeper water. By understanding the depositional setting and the position of sandstones within a stratigraphic cycle, sandstone distribution can be predicted.

As presented in Chapters 4 and 5, the transgressive phase of IC 1 is IVF's. Core study and log correlation show that IC 1 was deposited above an unconformity (LSE-1). The regional stratigraphic study by Armin et al. (1994) shows that this unconformity can be traced across all Unocal Indonesia's Northern Offshore Block and Attaka region. The LSE-1 is marked by a sharp base, overlain by a blocky log pattern above an otherwise serrated log pattern (Figure 5.8). A basinward shift of facies associations was inferred from fluvial/distributary channel deposits above lower delta front deposits (Plates 2, 3). Significant erosion occurred and sediments bypassed to deeper water during the development of LSE-1 (Figure 5.13a). As a result, more sediment stored basinward. There are prospective sandstones basinward that are time-equivalent with LSE-1 development.

The transgressive phase of IC 2 is IVF's. They are regarded as the main reservoir of the Serang Field. IVF's interpretation infers the existence of unconformity at the base of the amalgamated sandstones and backfilling deposition. There was more erosion and sediment bypass and prospective sandstones are expected basinward (Figure 5.13a). Interpretation of IVF's results in a more optimistic prediction of prospective sandstones basinward compared to interpretation of freely migrating channels that does not predict the occurrence of prospective sandstones basinward (Figure 5.13b).

The transition from IC 2 into IC 3 shows continuous deposition from lower delta plain to distributary channel. The missing time during the formation of LSE-3 is smaller compared to that of LSE-1 and LSE-2. At the time of deposition of the sediments of IC 3, time is more represented by rock instead of surfaces of erosion and non-deposition. There were only small amounts of erosion and sediment bypass. It is expected that there is no prospect areas basinward that is time-equivalent with the development of LSE-3 (Figure 5.13a and b).

In order to verify that the erosion that results in unconformity development is not a local event, the unconformity at the base of IVF's of IC 2 in the Serang Field should be found also in adjacent fields that are in the same formation. The Attaka Field is the nearest field from the Serang Field. It is located 12 km south of the Serang Field. The main reservoir of the Attaka Field is assumed as in the same formation as that of the Serang Field; however, they were deposited as different deltaic lobes: the Attaka lobe and the Serang lobe (Van de Weerd and Armin, 1992). If the main reservoir of the Serang Field is underlain by an unconformity, the unconformity should be recognized in the Attaka Field also. Furthermore, the main reservoir of the Attaka Field can be considered as IVF's if they display valley morphology. It is expected that there are prospective sandstones basinward of the Attaka Field.

CHAPTER 7

SUMMARY AND CONCLUSIONS

1. The objectives of this study are to place the late Late Miocene producing reservoirs of the Serang Field, Kutei Basin, Indonesia, into a sequence stratigraphic framework and to provide explanations for reservoir heterogeneity within the field and related sandstone distribution outside the field.
2. The study relied on well logs for correlations and interpretations of the Serang reservoirs. In addition, core studies were performed to to get a reliable interpretation of probable depositional environments, and to obtain log analogs to facilitate interpretation of non-cored intervals.
3. The Serang Field cores studies (Plates 1) were interpreted to exhibit ten facies associations that represents fluvial-deltaic environments: (1) prodelta, (2) transgressive coastal plain to lagoon (calcareous mudstone), (3) lower delta front, (4) delta front bar, (5) tidal flat, (6) interdistributay bay, (7) distributary channel, (8) delta plain marsh and swamp, (9) fluvial/distributary channel, and (10) crevasse channel and crevasse splay.
4. The sequence stratigraphic analysis (Plates 2-3) demonstrates that the Serang Field sediments can be subdivided into three intermediate-term cycles (IC's): IC 1, IC 2, and IC 3. The intermediate-term cycles can be subdivided further into short-term cycles. Overall, these cycles are landward-stepping, and represent a long-term base-level rise.
5. The results show that the main reservoirs of the Serang Field deposited during the transgressive phase of IC 1 and IC 2 as incised valley fills (IVF's) (Plates 2-3). The IVF's of IC 1 form sheet sandstone geometry, whereas the IVF's of IC 2 consist of three short-term cycles that may represent short-term cycle valleys.

6. The result of landward-stepping cycles, younger stratigraphic cycles are expected to have greater reservoir heterogeneity.
7. The occurrence of reservoir rocks and permeability barriers in the Serang Field is best understood within a sequence stratigraphic framework: (1) fluvial/distributary channels are expected at the transgressive phase of intermediate-term cycles, (2) distributary channels and delta front bars are expected at the regressive phase of intermediate-term cycles, (3) marine mudstones are associated with the formation of maximum flooding surfaces (MFS's) of intermediate-term cycles, (4) floodplain mudstones are associated with the formation of MFS's of short-term cycles, (5) valley walls are associated with LSE's, and (6) mudstone intraclast conglomerates and drapes are expected within the transgressive phase of short-term cycles.
8. Reservoir heterogeneity within the Serang Field can be explained in terms of the quality and distribution of reservoir rocks and permeability barriers. The rank of sediment bodies that act as reservoir in decreasing order is: (1) fluvial/distributary channels, (2) distributary channels, and (3) delta front bars. The rank of permeability barrier in decreasing order is: (1) marine mudstones, (2) floodplain mudstones, (3) valley walls, and (4) mudstone intraclast conglomerates and drapes.
9. The general pattern of sediment source of the studied interval was from the paleo-Mahakam Delta, southwest of the study area.
10. Prospective sandstones that are time-equivalent with the formation of unconformity at the base of IVF's are expected basinward of the Serang Field.

REFERENCES

Allen, G.P, 1985, Delta sedimentation: Modern and ancient examples in the Mahakam Delta basin, TOTAL Exploration Laboratory, Pessac, France, unpublished, 50 p.

Allen, G.P., and J.L.C. Chambers, 1998, Sedimentation in the modern and Miocene Mahakam Delta, Indonesian Petroleum Association , Jakarta, 236 p.

Armin, R.A., W. de Boer, S.K. Wiman, and Y. Yusuf, 1994, Stratigraphy, sedimentary facies, and structural evolution in Northern Offshore Block and Attaka Unit, East Kalimantan, Indonesia, with emphasis on sandstone reservoir distribution, Unocal Indonesia Technical Report, unpublished, 28 p.

Bhattacharya, J.P., and R.G. Walker, Deltas, in Walker, R.G., and N.P. James, (eds.), Facies models: response to sea-level change, Geological Association of Canada, p.157-177.

Biantoro, E., B.P. Muritno, and J.M.B. Mamuaya, 1992, Inversion faults as the major structural control in the northern part of the Kutei Basin, East Kalimantan, Proceedings of Indonesian Petroleum Association 21st Annual Convention, p. 45-69.

Busch, D.A., 1971, Genetic units in delta prospecting, AAPG Bulletin, v.55, p.1137-1154.

Butterworth, P., P.J. Cook, H. Dewanto, M. Drummond, U. Kiesow, I.T. McMahon, R.A. Ripple, A. Setoputri, and H.F. Sidi, 2001, Reservoir architecture of an incised valley fill from the Nilam Field, Kutai Basin, Indonesia, Proceedings of Indonesian Petroleum Association 28th annual convention and exhibition, p. 537-555.

Cant, D.J., 1992, Surbsurface facies analysis, in R.G., Walker, and N.P., James, (eds.), Facies models response to sea-level changes, Geological Association of Canada, Ontario, Canada, p. 27-45.

Chambers, J.L.C., and T.E. Daley, 1995, A tectonic model for the onshore Kutai Basin, East Kalimantan, based on an integrated geological and geophysical interpretation, Proceedings of Indonesian Petroleum Association 24th Annual Convention, p. 111-130.

Clark, T., J. Hadiwijoto, B. Zagalai, S. Martinez, and D. Staples, 1994, Serang Field re-evaluation, Proceedings of Indonesian Petroleum Association 23rd Annual Convention, p. 339-354.

Clark, T., M. Turk, J. Hadiwijoto, and Y. Partono, 1999, Serang Field-discovery within a seismic fault shadow, Proceedings of Indonesian Petroleum Association 27th Annual Convention, 19 p.

Cloke I.R., J. Moss, and J. Craig, 1999, Structural controls on the evolution of the Kutei Basin, East Kalimantan, Journal of Asian Earth Science 17, p. 137-156.

Coleman, J.M., and D.B. Prior, 1982, Deltaic Environments of Deposition, in P.A. Scholle and D. Spearing, (eds.), Sandstone Deposition Envrionments: AAPG Memoir 31, p. 139-178.

Doveton, J.H., 1994, Geologic log interpretation, SEPM short course no 29, Kansas, 169 p.

Duval, B.C., Chopin de Janvry, G. Loiret, B., 1992, Detailed geoscience reinterpretation of Indonesia's Mahakam Delta scores, Oil and Gas Journal, 90, p. 67-72.

Ferguson, A., and K. McClay, 1997, Structural modeling with Sanga Sanga PSC, Kutei Basin, Kalimantan: its application to paleochannel orientation studies and timing of hydrocarbon entrapment, Proceedings of Indonesian Petroleum Association: Petroleum systems of SE Asia and Australasia Conference, p. 727-743.

Galloway, W.E., 1989, Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional Units, AAPG Bulletin, v.73, p.125-142.

Galloway, W.E., and D.K. Hobday, 1983, Terrigenous clastic depositional system, applications to petroleum, coal, and uranium exploration, Springer-Verlag, New York, 423 p.

Gardner, M.H., 1993, Sequence stratigraphy and facies architecture of the Upper Cretaceous Ferron Sandstone Member of the Manchos Shale, East-Central Utah, Colorado School of Mines, Golden, PhD dissertation, unpublished, 528 p.

Gardner, M.H., 2001a, Sequence stratigraphy and facies architecture of fluvial-deltaic reservoir analogs: a field guide to selected outcrops of theUpper Cretaceous Ferron

Sandstone Member, Central Utah: Introduction, Colorado School of Mines, Golden, unpublished, 91 p.

Gardner, M.H., 2001b, Sequence stratigraphy and facies architecture of fluvial-deltaic reservoir analogs: a field guide to selected outcrops of theUpper Cretaceous Ferron Sandstone Member, Central Utah: day 3, changes in fluvial architecture related to sediment-volume partitioning in coastal polain and shallow-marine facies tracts, Colorado School of Mines, Golden, unpublished, 74 p.

Hall, R., 1995, Plate tectonic reconstructions of the Indonesian region, Proceedings of Indonesian Petroleum Association 24th Annual Convention, p. 71-84.

Hamilton, W., 1979, Tectonic of the Indonesian Region, US Geological Survey Professional Paper, v.1078, 345 p.

Huffington, R.M., and H.M. Helmig, 1980, Discovery and development of the Badak Field, in M 30: Giant oil and gas fields of the decade 1968-1978, AAPG Special Publication, p.441-458.

Huffington, R.M., H.M. Helmig, 1990, Badak Field-Indonesia Kutei Basin/East Kalimantan (Borneo), in TR: Structural traps III: tectonic fold and fault traps, AAPG Special Publication, p. 265-398.

Jervey, M.T., 1988, Quantitative geological modeling of silisiclastic rock sequences and their seismic expressions, in C.K. Wilgus et al., (eds.), Sea-level changes: an integrated approach: SEPM Special Publication 42, p. 47-69.

Knox, P.R., and M.D., Barton, 1999, Predicting interwell heterogeneity in fluvial –deltaic reservoirs: effects of progressive architecture variation through a depositional cycle from outcrop and subsurface observation, in R.A. Shatzingere and J.F Jordan, (eds.), Reservoir characterization recent advances, AAPG Memoir 71, Tulsa, p. 57-90

Loutit, T.S., J. Hardenbol, P.R. Vail, and G.R. Baum, 1988, Condensed Sections: the key to age determination and correlation of continental margin sequences, in C.K. Wilgus, B.S. Hastings, C.G.S.C. Kendal, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner, (eds.), Sea-.level changes- an integrated approach, SEPM Special Publication No. 42, p. 184-213.

MacDonald, A.C., L.M. Falt, and A.L. Hektoen, 1998, Stochastic modeling of incised valley geometries, AAPG Bulletin, v.82, p.1156-1172.

Mc Clay, K., T. Dooley, A. Ferguson, J. Poblet, 2000, Tectonic evolution of Sanga-Sanga Block, Mahakam Delta, Kalimantan, Indonesia, AAPG Bulletin, v. 84, p. 765-786.

Miall, A.D., 1996, The geology of fluvial deposits: sedimentary facies, basin analysis and petroleum geology, Springer, New York, 582 p

Paterson, D.W., A. Bachtiar, J. Bates, J. Moon, and R. Surdam, 1997, Petroleum system of the Kutei Basin, Kalimantan, Indonesia, Proceedings of the Petroleum Systems of SE Asia and Australasia Conference, p. 709-719.

Peters, K.E., J.W. Snedden, A. Sulaeman, J.F. Sarg, and R.J. Enrico, 2000, A new geochemical- sequence stratigraphic model for the Mahakam Delta and Makassar Slope, Kalimantan, Indonesia, AAPG Bulletin, v. 84, p. 12-44.

Posamentier, H.W., 1998, Sequence stratigraphy concepts and applications, Arco Exploration and Production Technology, Jakarta, Unpublished, 195 p.

Posamentier, H.W., and G.P. Allen, 1999, Silisiclastic sequence stratigraphy, concepts and applications, SEPM Concepts in sedimentology and paleontology #7, Tulsa, 210 p.

Reineck, H.E., and I.B. Singh, 1975, Depositional sedimentary environments with reference to terrigenous clastics, Springer-Verlag, Berlin, 439 p.

Satyana, A.H., D. Nugroho, and I. Surantoko, 1999, Tectonic controls on the hydrocarbon habitats of the Barito, Kutei, and Tarakan Basins, Eastern Kalimantan, Indonesia: major dissimilarities in adjoining basins, Journal of Asian Earth Science 17, p. 99-122.

Schwartz, C.M., G.H. Laughbaum Jr., B.S. Samsu, and J.D. Armstrong, Geology of the Attaka Oil Field, East Kalimantan, Indonesia, Proceedings of Indonesian Petroleum Association 2nd Annual Convention, p. 195-215.

Shanley, K.W., and P.J. McCabe, 1994, Perspective on the sequence stratigraphy of continental strata, AAPG Bulletin, v.78, p. 544-568.

Siemers, C.T., 1992, Sedimentology and petrology of full-diameter cores, Serang No. 3RD2 and No. 5 wells: Report prepared for Unocal Indonesia by P.T. Geoservices, Ltd., Jakarta, Indonesia, unpublished, 6 volumes.

Slatt, R.M., and Galloway, W.E., 1992, Geological heterogeneities, part 6: geological method, in ME 10: Development Geology Reference Manual, AAPG Special Publication, p. 278 - 281

Snedden, J.W., J.F. Sarg, M.J. Clutson, M. Maas, T.E. Okon, M.H. Carter, B.S. Smith, T.H. Kolich, M.Y. Mansor, 1996, Using sequence stratigraphic methods in high-sediment supply deltas: examples from the ancient Mahakam and Rajang-Lupar Deltas, Proceedings of Indonesian Petroleum Association 25th Annual Convention, p. 281-296.

Tanean H., D.W. Paterson, and M. Endharto, 1996, Source provenance interpretation of Kutei Basin sandstones and the implications for the tectono-stratigraphic evolution of Kalimantan, Proceedings of Indonesian Petroleum Association 25th, p. 333-345.

Trevena, A.S., 1996, Description and facies interpretation of conventional cores from deltaic interval in Serang SA-2RD, East Kalimantan, Indonesia, Unocal exploration library, Balikpapan, Indonesia, unpublished, 9 p.

Trevena, A.S., S. Mahadi, S.A. Martinez, Marwoto, Y.J. Partono, S.Sutiyono, 1993, Characterization of Upper Miocene Deltaic Reservoirs at Attaka Field, Offshore East Kalimantan, Indonesia, in C.D. Atkinson, J. Scott, R. Young, (eds.), Clastic rocks and reservoirs of Indonesia, Indonesian Petroleum Association core workshop notes, Jakarta, p. 91-115

Van de Weerd, A., and R.A. Armin, 1992, Origin and evolution of the Tertiary hydrocarbon-bearing basins in Kalimantan (Borneo), Indonesia, AAPG Bulletin, v. 76, p 1778-1803.

Vail, P.R., R.M. Mitchum, and S. Thompson III, 1977, Seismic stratigaphy and global changes in sea-level, Part 2: Relative changes of sea-level from coastal onlap, AAPG Methods in Exploration Series, No. 7, 55 p.

Van Wagoner, J.C., R.M. Mitchum, K.M. Campion, and V.D. Rahmanian, 1990, Silisiclastic sequence stratigraphy in well logs, cores, and outcrops, AAPG Methods in Exploration Series no. 7, 55 p.

Verdier, A.C., T. Oki., and A. Suardy, 1980, Geology of the Handil Field (East Kalimantan-Indonesia), AAPG Bulletin, v. 64, p.399-421.

Vo, D.T, Sukerim, M. Ivanowicz, Syahrani, D. Bouclin, T. Clark, J. Stites, and Y. Partono, 1999, Reservoir modeling asssists operations to optimize field development: Serang Field, East Kalimantan, SPE Journal 59441.

Vo, D.T., S. Waryan, A. Dharmawan, R. Susilo, and R. Wicaksana, 2000, Lookback on performance of 50 horizontal wells targeting oil thin columns, Mahakam Delta, East Kalimantan, SPE Journal 64385.

Wain, T., and B. Berod, 1989, The tectonic framework and paleogeographic evolution of the Upper Kutei Basin, Proceedings of Indonesian Petroleum Association , 18th Annual Convention, Jakarta, 1989, p. 55- 78.

Weimer, R.J., 1992, Presidential Address - Developments of Sequence Stratigraphy: foreland and Cratonic Basins, AAPG Bulletin, p. 965-982.

Wescott, W.A., 1993, Geomorphic thresholds and complex response o fluvial systems – some implications for sequence stratigraphy, AAPG Bulletin V. 77, p. 1208-1218.

Wheeler, H.W., 1964, Base level, lithosphere surface, and time stratigraphy, GSA Bulletin, v.75, p. 599-610.