Longshore Bar Deposits in a Modern Fluvial-dominated Delta: A Case Study from the Wulan Delta, Demak, Central Java, Indonesia

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ABSTRACT

The Wulan Delta is located about 30km NE of Semarang city, at the northern coast of Central Java. The delta began to develop in Quaternary with sediment being supplied by the Wulan River. In the last ten years, a longshore bar deposit has been developing at the northern to northeastern part of the delta, reflecting a change in depositional style from a river-dominated delta to a more wave/ longshore current-dominated system.

Field work was done recently to determine the stratigraphic pattern, lateral distribution, sand geometry, and the origin of these longshore bar deposits. This included core sampling, sedimentological description and lithology correlation. Forty core samples were taken and 34 out of the 40 cores were used in correlation and interpretation. Qualitative analyses (granulometry) were then conducted on the cored sand deposits to get the sorting, skewness and kurtosis values.

The longshore bar deposit of the Wulan Delta was formed by longshore currents that reworked sediment material to the shoreline and deposited sands laterally around the river mouth. Sediment transport dynamics influenced saltation swash and backwash, which are interpreted from the presence of swash cross-stratification as a characteristic of deposition in the foreshore area. The longshore bar deposit was deposited progressively seaward due to rapid sediment influx from up-river and limited accommodation space. The geometry of the sand deposits was measured for three segments of longshore sand bars. At STA LSB 1 it is 2773m long, 830m wide and 0.75m thick. At STA LSB 2 it is 1082m long, 272m wide and 0.5 m thick; and at the last station it is 1276m long, 374m wide and 1m thick.

Keywords: *Eocene, erosion, sea-level changes, sediments, South China Sea, subsidence, unconformity, uplift, Tertiary.*

INTRODUCTION

The Wulan Delta is located in the northern coastal area of Central Java. Administratively, the delta is located in Wedung District, Demak City, approximately 30km NE of Semarang City (Figure 1). The delta began to develop in Quaternary and currently it covers an area of approx. 25 km². Sediments deposited in the delta are supplied by the Wulan River, which transports abundant detritus of sedimentary and igneous rocks origin from the Kedung Ombo Boyolali and the Muria Mountain. In the last 40 years, the Wulan Delta has prograded rapidly towards the Java Sea.

The morphology of the Wulan Delta resembles an elongate or "bird foot" shape, which is typical of a delta formed by fluvial processes as the dominant force in delivering sediment material. Starting in 2010, sand deposits that grow laterally began to form around the river mouth section. The sand bar became wider by 2015 and still continues to widen, forming a NE-SW-oriented longshore bar.

Longshore bar deposits are rarely associated with a fluvial-dominated delta system, such as those found in the Wulan Delta. The longshore bar deposit of Wulan Delta is formed as a result of longshore current transporting sediments backward to the land. Waves are constantly moving from deeper water in the open ocean across the shelf to the shore zone; there, they eventually break and become translated into wave swash and longshore currents (Boggs, 2006). The sand deposit is distributed laterally away from the river mouth, isolating an area that is separated from the open sea, forming a lagoon setting.

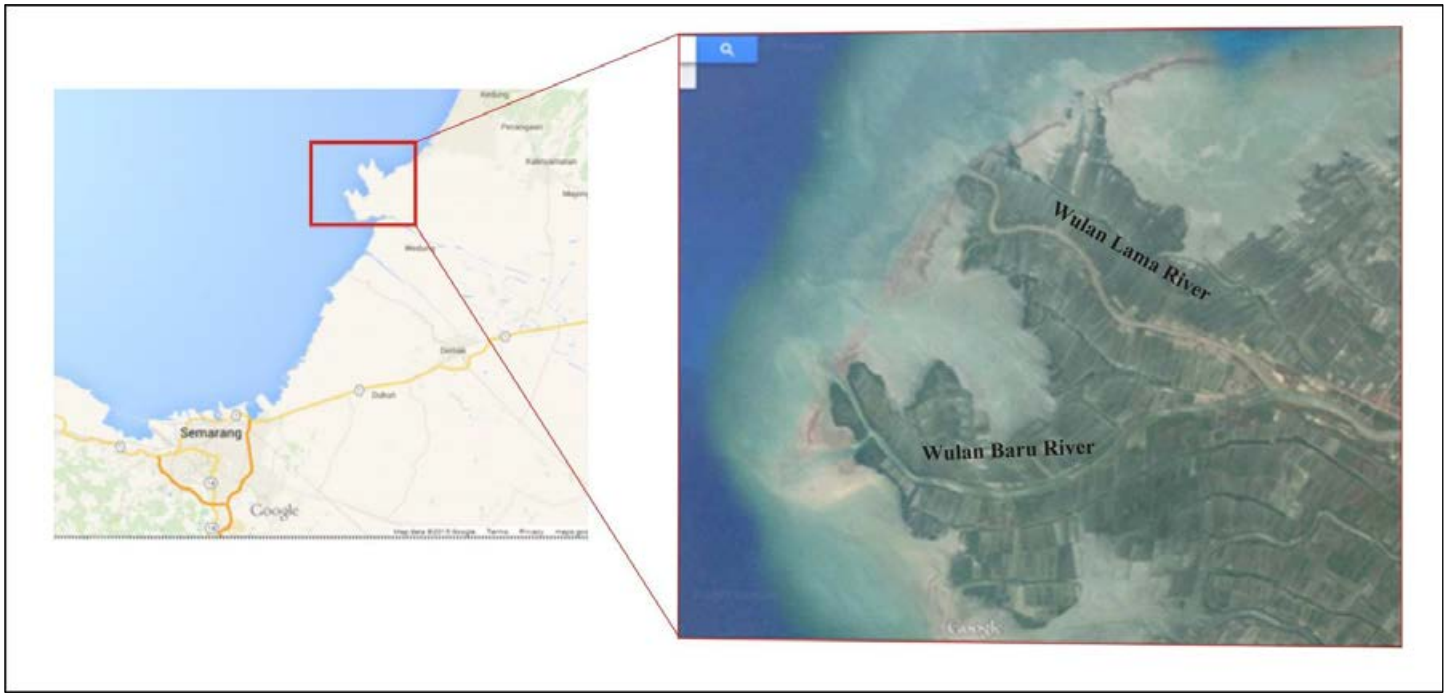


Figure 1. *Location map of study area (taken from Google Maps, 2015).*

In this article we will discuss about the vertical and lateral successions of this longshore bar deposit and build a 3D model of its sand deposition and geometry. We aim to provide a 3D model of longshore bar geometry in a fluvial dominated delta system, which potentially can be used as an analogue for oil and gas reservoirs of similar palaeodepositional environment.

METHODOLOGY

The focus of this research is on the longshore bar deposit located at the mouth of the Wulan Lama river (Figures 2, 8). The methodology used in this study consists of three main parts namely field work, satellite (LANDSAT) imagery analysis and quantitative analysis of sediment grains (granulometry analysis).

The field work includes field observation and description, longshore current measurements and core sample acquisition covering 3 longshore bar deposits. In this article, the longshore bar deposits are named LSB 1 to LSB 3 and the location of core samples is shown on Figure 2. The cores were acquired from 10 line sections across the backshore, foreshore, and shoreface and each line has 3-4 core samples. In total, 40 core samples were acquired around the river mouth of the Wulan Lama Delta system and 34 out of 40 cores were used in analyses and interpretation. The cores were taken from various depositional settings including longshore bar, mouth bar, point bar, and tidal bar deposits and their lengths vary from 70 – 135 cm.

The satellite image analysis was done by using LANDSAT images acquired in 1975, 1997, 2002, 2008, 2013, and 2015 (Figure 3). The Landsat image analysis was aimed to compare sediment deposits at the Wulan Delta in the years of when the images were acquired. Stratigraphic data from core samples were used in supporting the satellite image interpretation.

The granulometry analysis was aimed to get data on skewness, kurtosis, sorting, and the type of sediment. In addition, the granulometry data of each core sample will be used as supporting data for the distribution of sand in the longshore bar deposit.

RESULTS AND DISCUSSIONS

LANDSAT Aerial Photography Analysis

LANDSAT images (Figure 3a) show that in 1975 Wulan Delta still had one dominant river system (Wulan Lama River) and there was no longshore bar deposition. Then in the next 20 years, the Wulan Delta grew very fast with numerous sediment influxes and a new river distributary called the Wulan Baru River, developed SW of the Wulan Lama River (Figure 3b). As seen on Figure 3, a W-E-oriented bar began to be deposited NE of the Wulan Lama River by 1997. Since then, additional bars have developed towards the northeast and southwest of the Wulan Lama River from 2002- 2015 (Figures 3c to 3f). In contrast, only small sand bars have developed near the Wulan Baru river mouth as seen from Figures 1 and the 2013 and 2015 images (Figure 3).

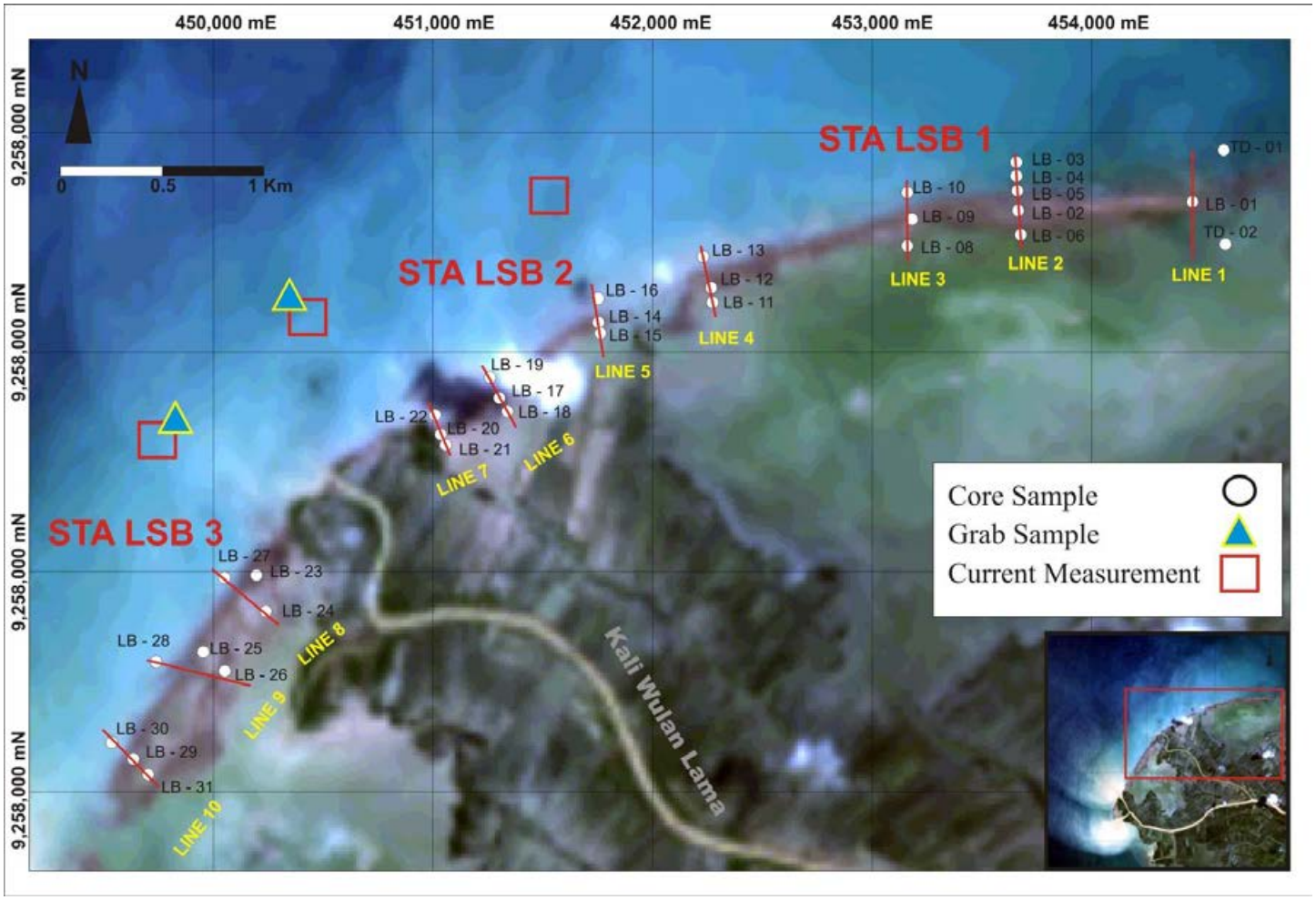


Figure 2. *Scope of study and sample location in the Wulan Lama River using LANDSAT 2015 aerial photography.*

Core Description and Lithostratigraphy Correlation

Stratigraphic correlation was done by connecting similar lithofacies in every core sample from the same line section. The lithofacies identification was facilitated by recognising different patterns of sediment from bottom to the top of each core (Figures 4, 5, 6). From the results of core sampling and field descriptions, five lithostratigraphy units have been interpreted in the study area: tidal sand-mud, interdistributary bay mud, lagoonal mud, offshore mud, and longshore bar sand deposits (Figure 7a-c).

a) Tidal sand-mud

These deposits are characterised by the alternation between mud layers and very fine sand layers. Mud drapes like flaser or lenticular laminations found in tidal deposit are located at the bottom of the unit. Bioturbation formed by burrowing organisms also occur in the sampled cores. Tidal sand-mud deposits seen in the core samples are usually about 10-20cm thick.

b) Interdistributary bay mud

Interdistributary bay deposits are characterised by a very thick mud layer without alternations with sand layers. Organic materials such as plant roots, trunk, leaf and mollusk shells are often found in these deposits. Inter-distributary bay mud deposits are seen in the lower part of the core samples and their thickness is about 40-80cm.

c) Lagoonal mud

The lagoon deposits are isolated from the open sea by barrier sand in front of them and the barrier sand in this case is the longshore bar deposit. The lagoon deposits usually are found in the upper part of the core samples. These deposits are characterised by muddy sand to mud and their thickness based on core samples taken in the backshore area is about 20 cm. The lagoon deposits laterally interfinger with the longshore bar deposits.

d) Offshore mud

Offshore mud deposits are sediments of dominantly mud grain size from the offshore zone. In the study area these sediment are found far from the shoreline and were taken by using a grab sampler from water depth of about 2-3m. Based on its stratigraphic position, offshore mud is interpreted as the oldest lithofacies onto which the longshore bar deposits developed.

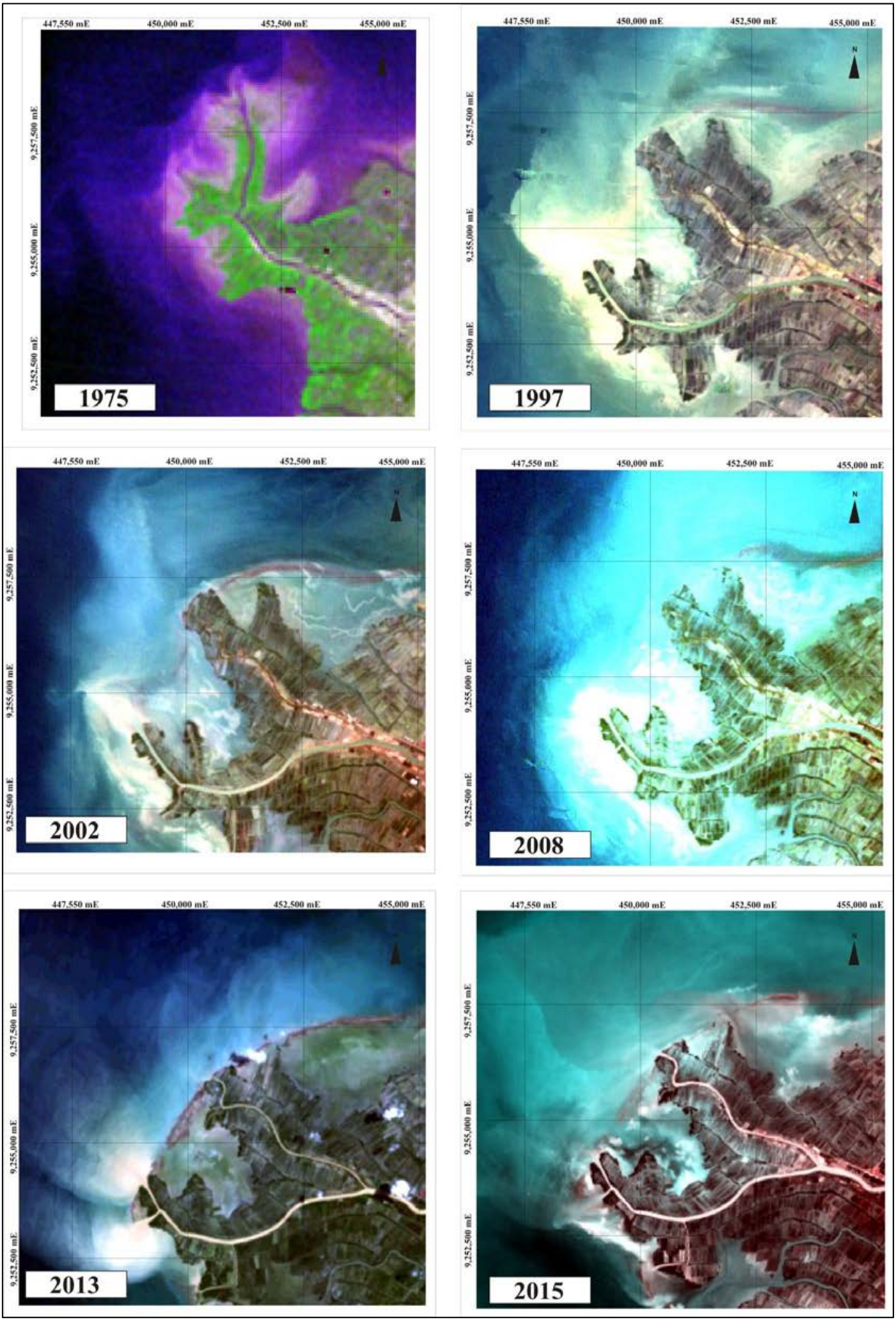


Figure 3. *Comparison of Wulan Delta since 1997, 1997, 2002, 2008,2013, and 2015 from LANDSAT aerial photography (USGS, 2015).*

e) Longshore bar

The longshore bar deposits are characterised by very fine sand to very coarse sand that show a coarsening upward pattern. Observed sedimentary structures include parallel lamination and swash-cross stratification, which is of low angle cross-stratification. The sand laminations are sometimes black because they contain heavy minerals such as hematite, hornblende, and magnetite. The longshore bar deposits are seen in the upper part of the cored samples and they usually overlie tide-influenced sand-mud and inter-distributary bay mud deposits.

Current Measurements

Current measurements were done by the Lagrange Method, to obtain direction and velocity of the currents that affect longshore bar deposition around the Wulan Lama River mouth. The measurements were done in different locations and each location consists of three measurements. The measured currents were analysed by using rose diagrams to see their dominant directions. The results from 5 locations are summarised on Table 1.

The dominant directions of the longshore currents are northwest - southeast and northeast-southwest. East of the Wulan Lama river mouth (Figure 1), the longshore current trend is northwest - southeast, while west of the Wulan Lama river, the currents tend to be oriented in northeast-southwest. These current directions controlled the orientation of the longshore bars where they are spread in a northeast-southwest direction, perpendicular to the direction of the river flow.

Granulometry Analysis

Granulometry analysis was performed for four depth intervals of each core sample. The depth intervals are 0-10, 30-40, 60-70, and 90-100 cm (Figure 8). Sediment grain size distribution maps were then created for each depth interval, which has its own characteristics of grain size distribution (Figure 9). Based on the cross plot of grain size distribution with cumulative probability, it is found that the hydrodynamic transport in the longshore bar is dominated by saltation (Figure 10) and the dominant sand deposit is beach sand (Figure 11).

STA LSB 1 has an overall coarsening upward succession, with muddy sand at the base, from 90-100 cm, overlain by very fine sand, changing gradually to medium to coarse sand (Figure 4, 11). At the STA LSB 2, the grain size of the sediment also changes gradually upward from mud to sand (Figures 10 and 11). Mud deposit is widespread and covers almost all regions at the STA LSB 2. In interval 60-70 cm at the STA LSB 1 and LSB 3, the sand deposits begin to spread in the same interval at the STA LSB 2, the sands also begin to deposit laterally (Figure 12), which characterises deposition of the longshore bar. In interval 60-70cm at the STA LSB 3, the mud becomes less dominant, unlike those in the same interval at the STA LSB 2.

Development of the Longshore Bar Deposit

During the initial stage of delta development, the sediments were delivered dominantly by Wulan Lama River as it built the delta out towards the sea (Figure 3a). The Wulan Baru river system was less dominant in building the Wulan Delta at the time and its flood plain was still small and narrow. Within the next 20 years, the Wulan Baru river system developed significantly and delivered sediment that covered up its vast flood plain (Figure 3b). The length of Wulan Baru River was approximately similar to the length of Wulan Lama River when measured from distributary channel point as seen on 1975 and 1997 LANDSAT images.

Sand and other sediment transported by the Wulan River were initially deposited near the river mouth. The sediment accumulation became thicker and then they were spread laterally towards both side of the Wulan Lama river mouth. This sedimentation process from 2002 – 2015 was unlike the processes in 1975 until 1997, and reflects a change from river-dominated deposition to marine (longshore current) deposition.

No	X	Y	Direction (NE)	Length (m)	Time (s)
1	450156	9256272	225	5	24
2	450365	9256434	210	5	40
3	450579	9256674	165	5	28
4	450905	9256792	160	5	35
5	451006	9256866	144	5	30

Table 1. *Direction of longshore current in the Wulan Delta.*

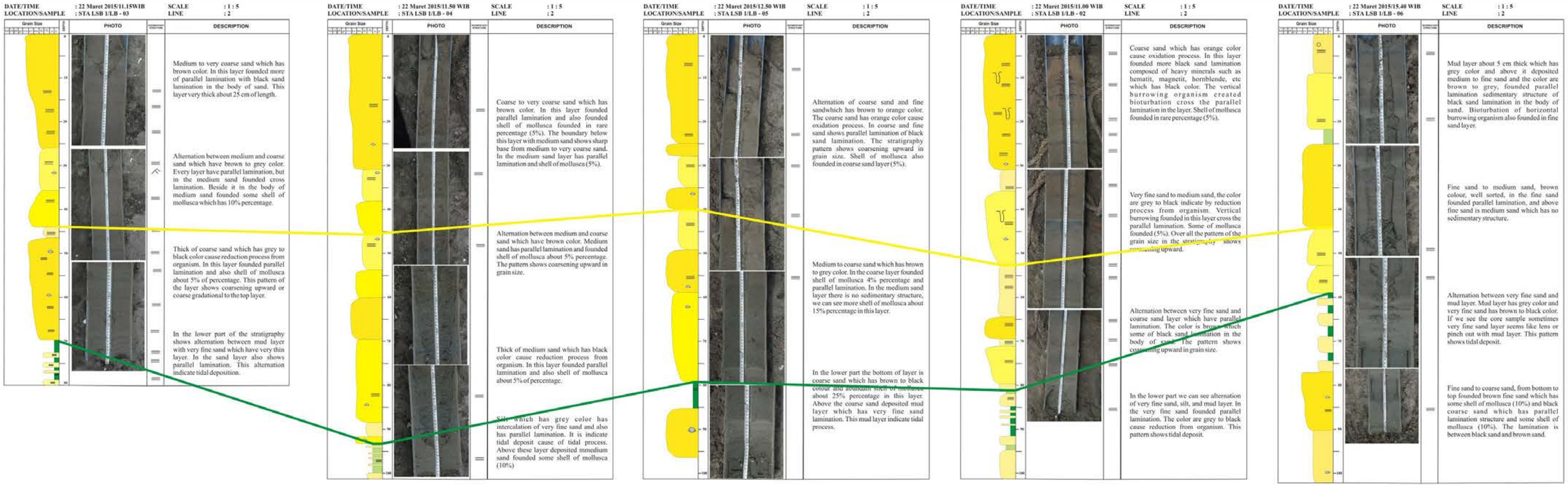


Figure 4. *Core samples description in the STA LSB 1 line 2 shows In the lower part deposited Tidal sand-mud which found in thin layer about 20 cm alternation sand and mud layer and the upper part deposited longshore bar deposited which has coarsening upward pattern.*



Figure 5. *Core samples description in the STA LSB 2 line 5 shows In the lower part deposited Interdistributary bay mud which has thick mud layer and the upper part deposited longshore bar deposited, LB-15 shows in the upper part deposited lagoon mud.*

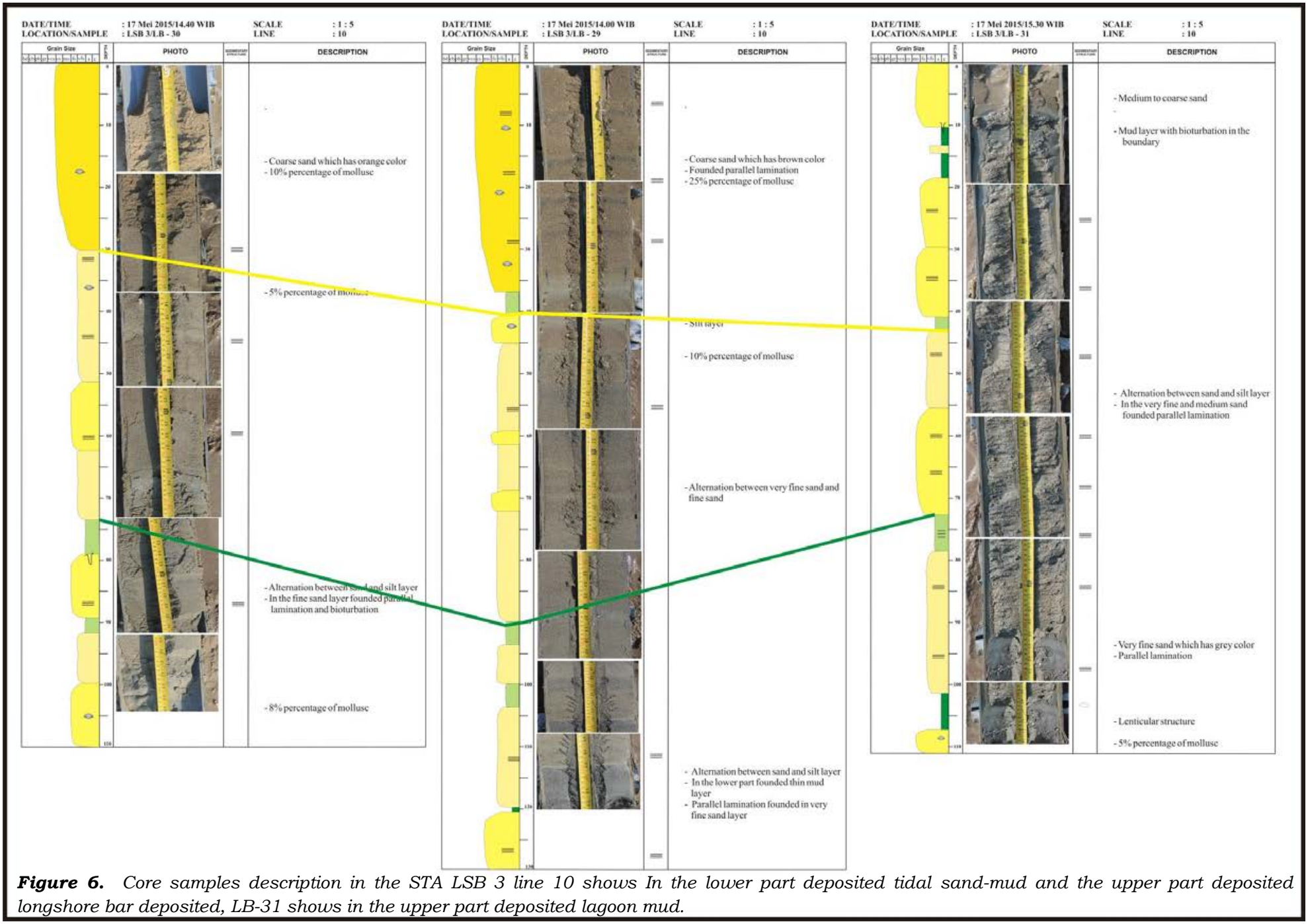


Figure 6. *Core samples description in the STA LSB 3 line 10 shows In the lower part deposited tidal sand-mud and the upper part deposited longshore bar deposited, LB-31 shows in the upper part deposited lagoon mud.*

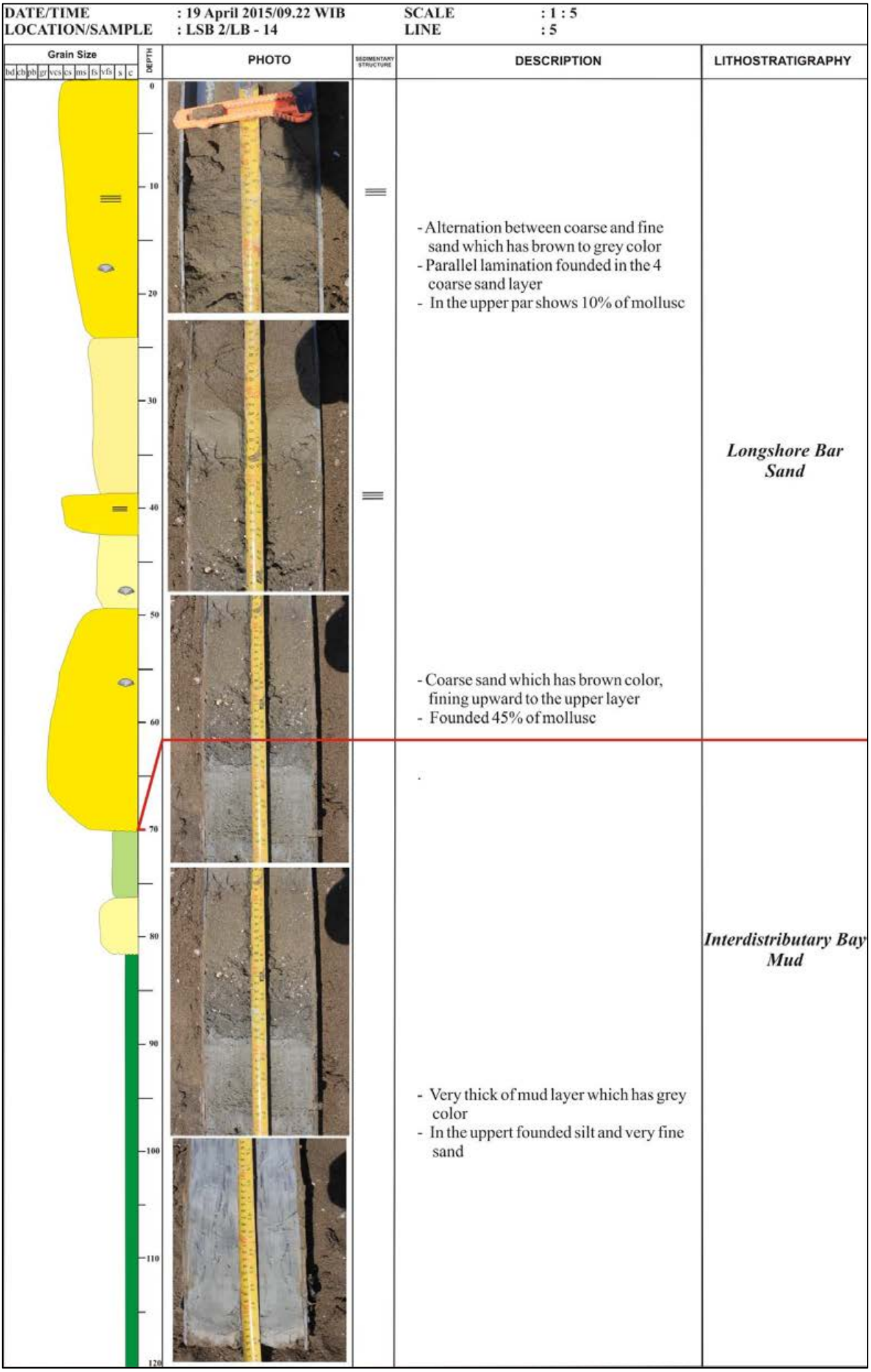


Figure 7a. *Core samples description shows different facies changes vertically, LB-14 core sample has Interdistributary Bay Mud in the lower part then longshore bar deposited above it.*

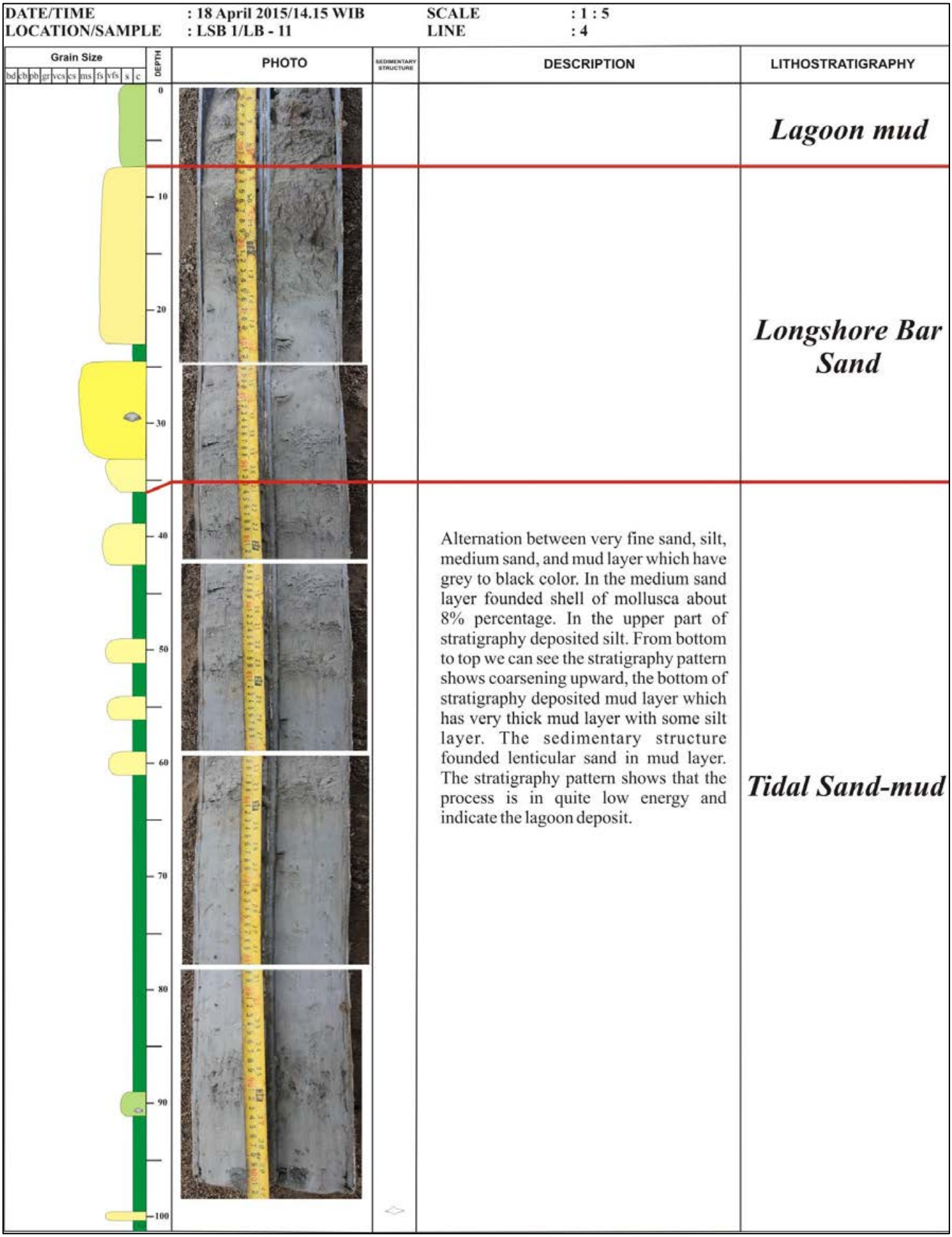


Figure 7b. *Core samples description shows different facies changes vertically, LB-11 shows Tidal Sand-mud in the lower part and longshore bar deposit lies tidal sand mud deposit then in the upper part deposited Lagoon Mud.*

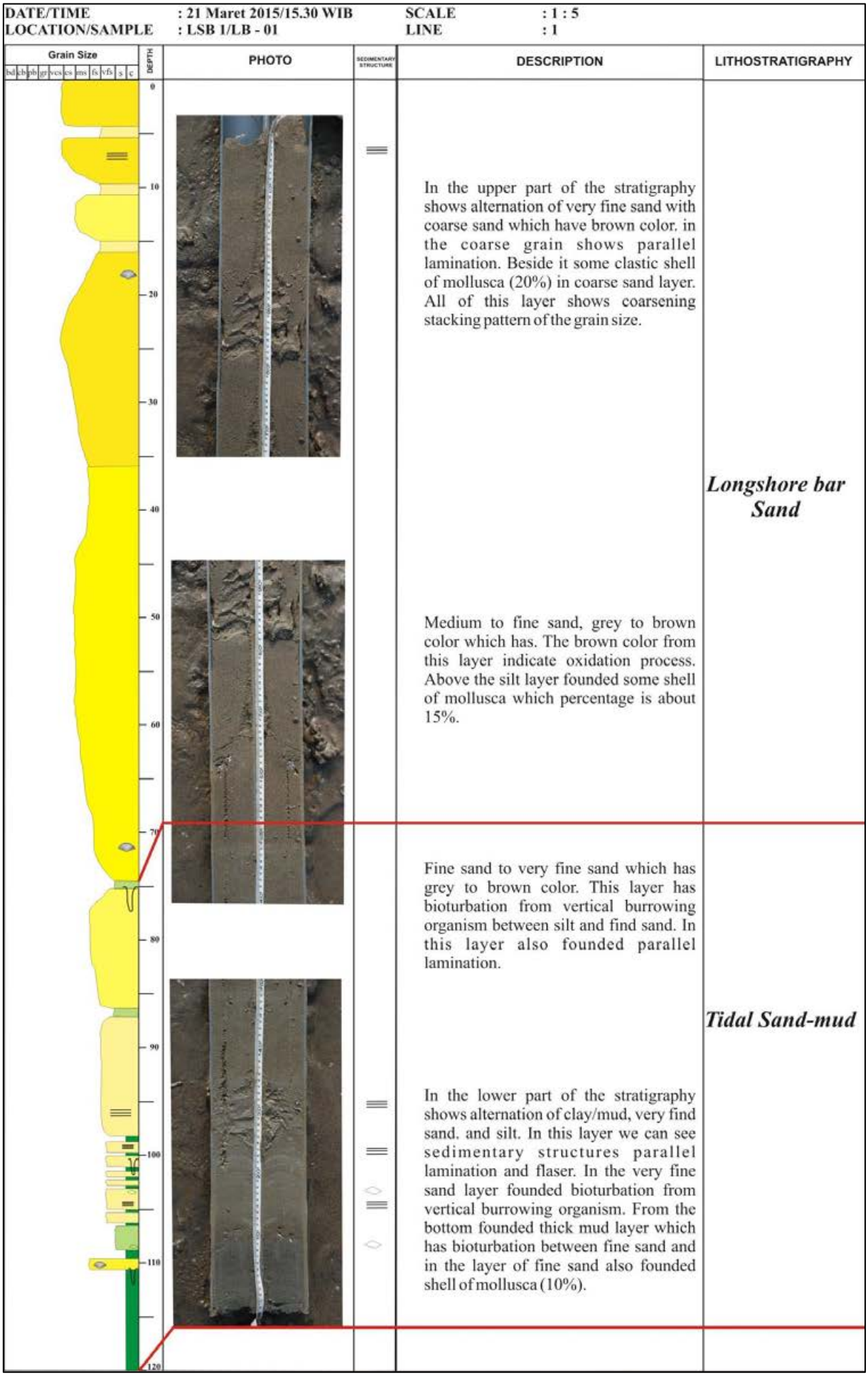


Figure 7c. *Core samples description shows different facies changes vertically, LB-01 shows Tidal Sand-Mud In the lower part and above it lies longshore bar deposit Sand-Mud In the lower part and above it lies longshore bar deposit.*

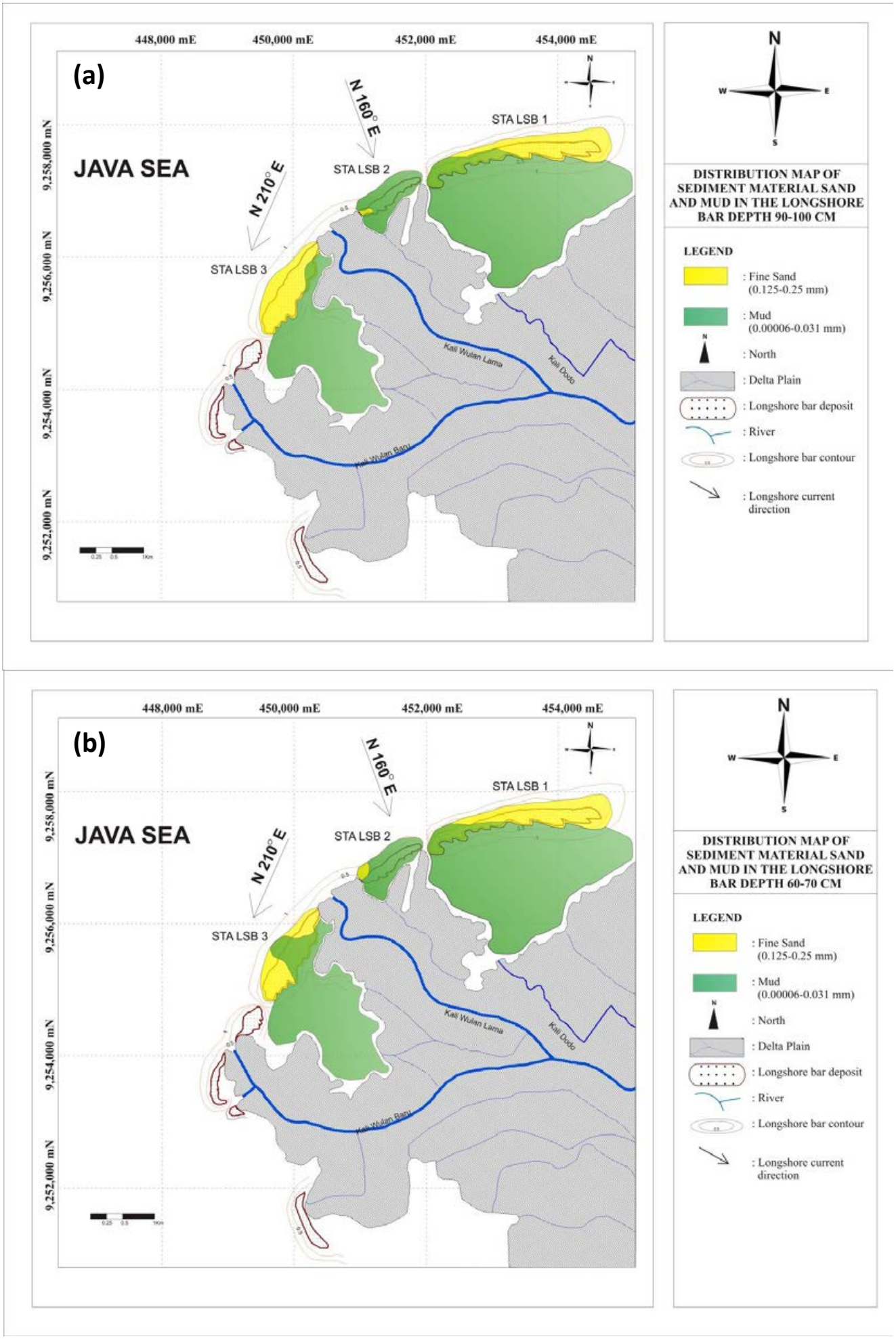


Figure 8a and b. *Grain size distribution of sand and mud of longshore bar deposit in depth interval 90–100 cm (a) 60-70 cm (b).*

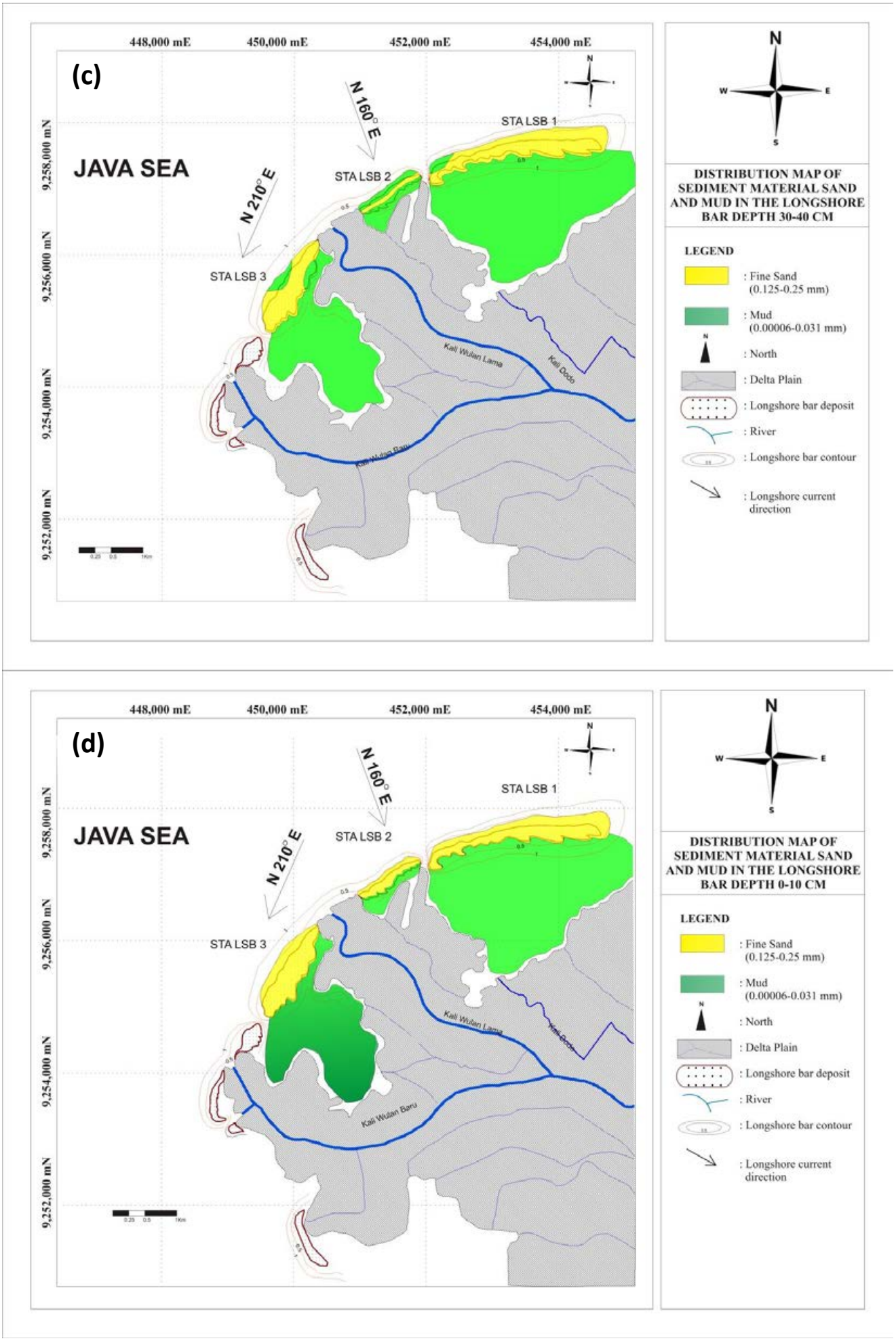


Figure 8c and d. *Grain size distribution of sand and mud of longshore bar deposit in depth interval 30-40 cm (c) 0-10 cm (d).*

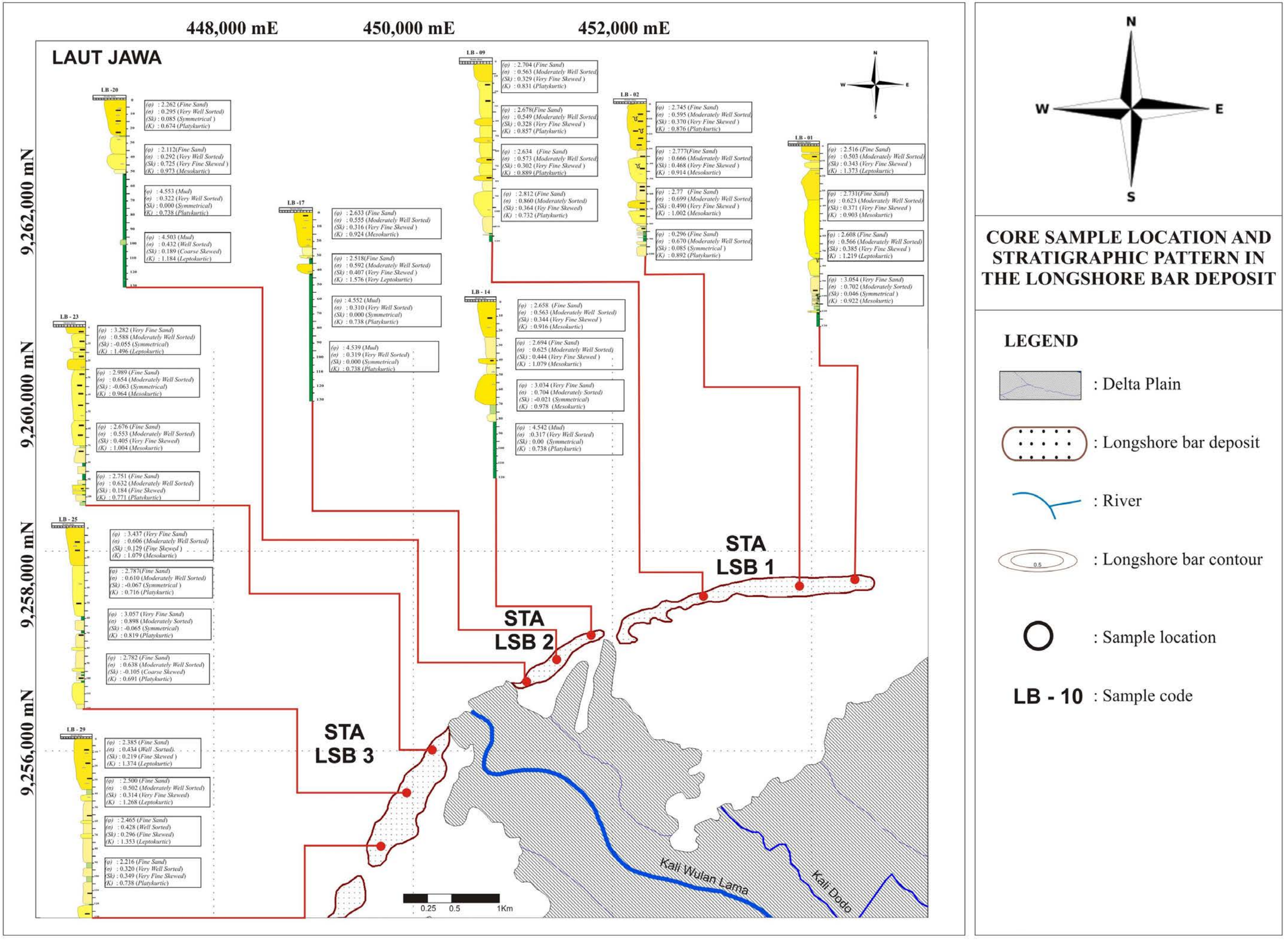


Figure 9. *Granulometry data and stratigraphy each depth interval map.*

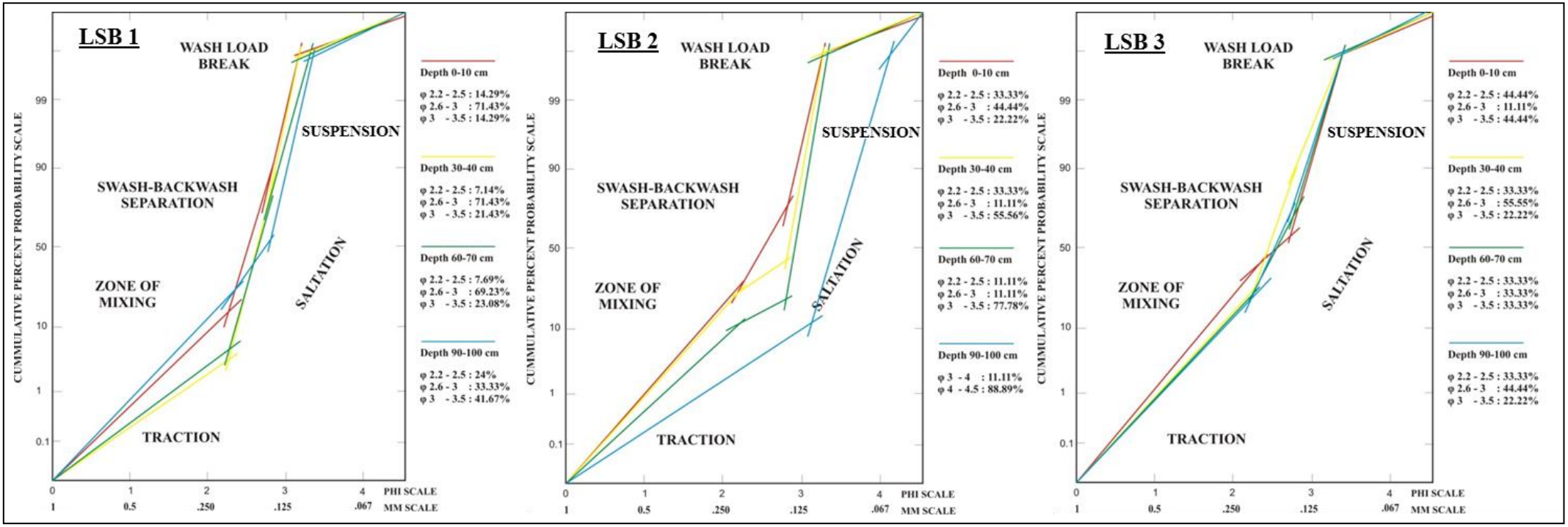


Figure 10. *Relation of sediment transport dynamics to population and grain-size distribution of longshore bar deposit in Wulan Delta (Visher, 1969, cited in Boggs, 2006).*

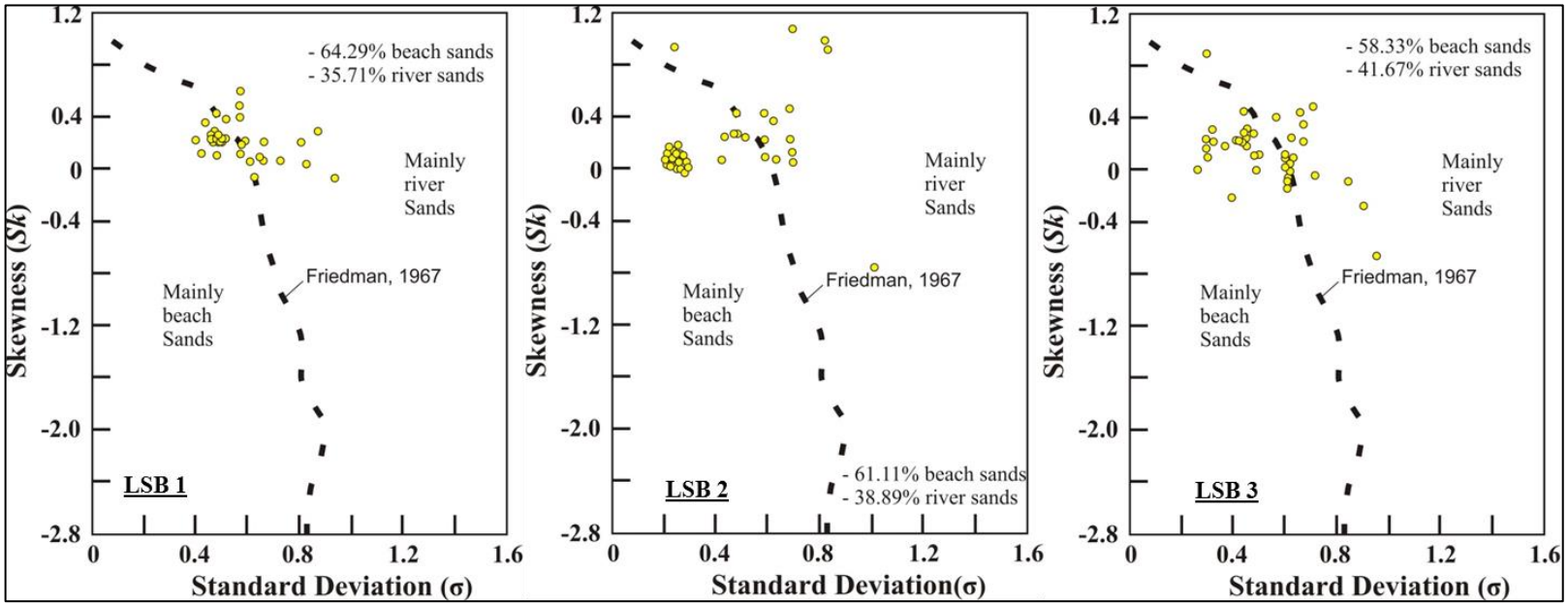


Figure 11. *Grain-size bivariate plot of moment skewness vs moment standar deviation showing the fields in which most beach and river sands plot of longshore bar deposit at Wulan Delta (Friedman, 1967, cited in Boggs, 2006).*

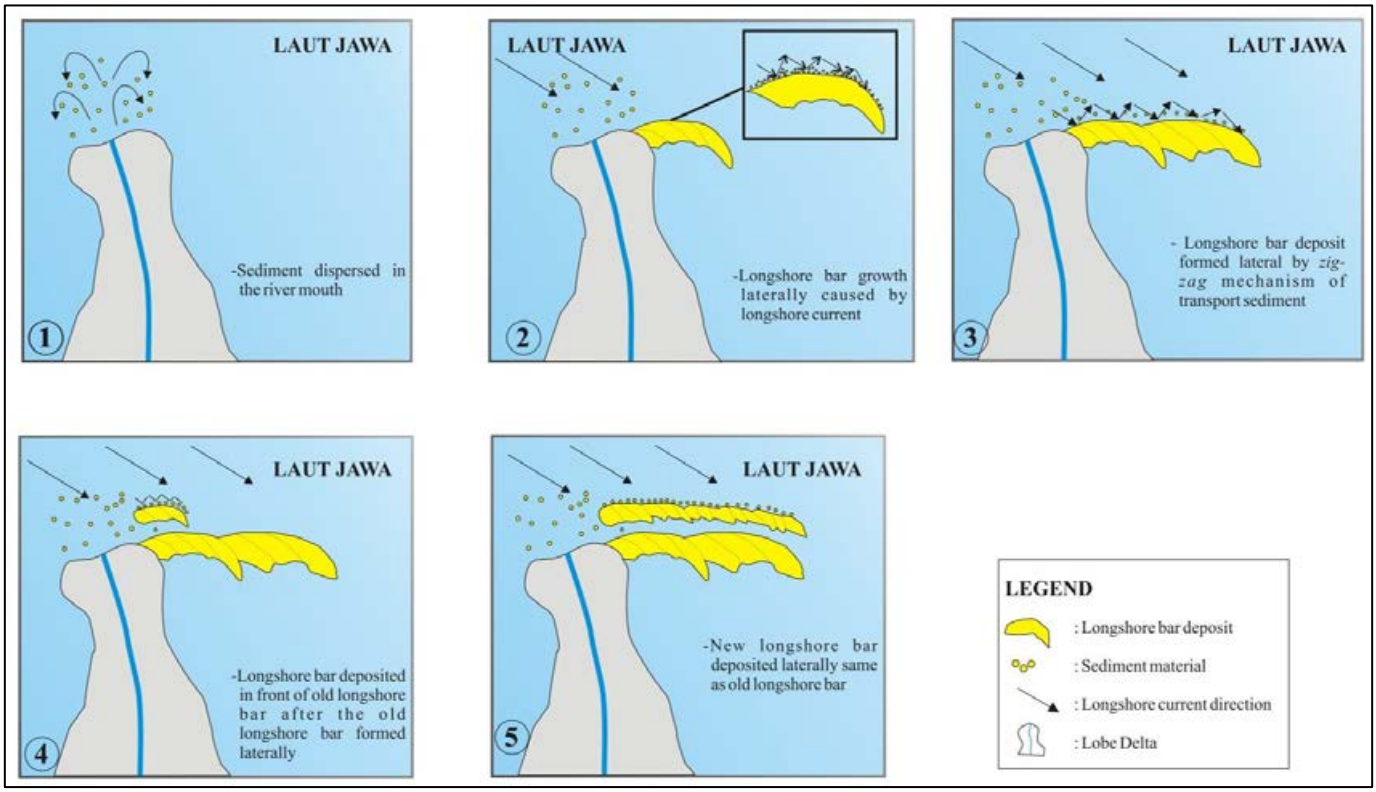


Figure 12. *Lateral distribution of longshore bar deposit in Wulan Delta.*

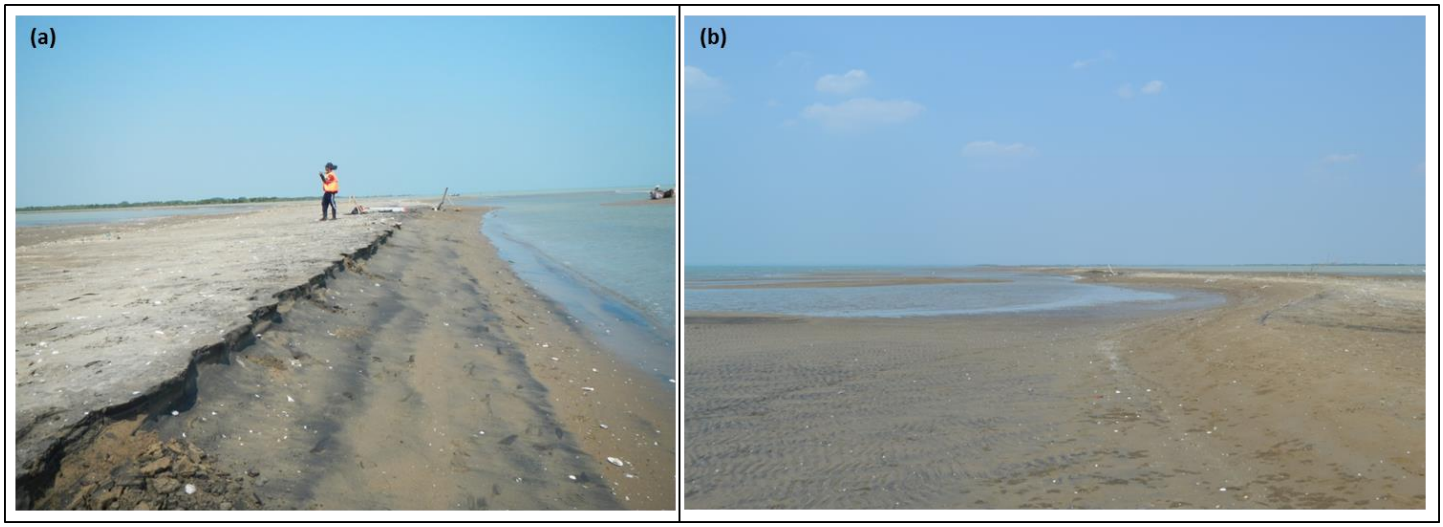


Figure 13. *Longshore Bar Deposit at STA LSB 1 shows the crest of Bar Deposit (a), the longshore bar when Ebb Tide (b).*



Figure 14. *Edge shape of longshore bar at STA LSB 2 (a), new longshore bar deposited in front of the first longshore bar at STA LSB 1 (b).*

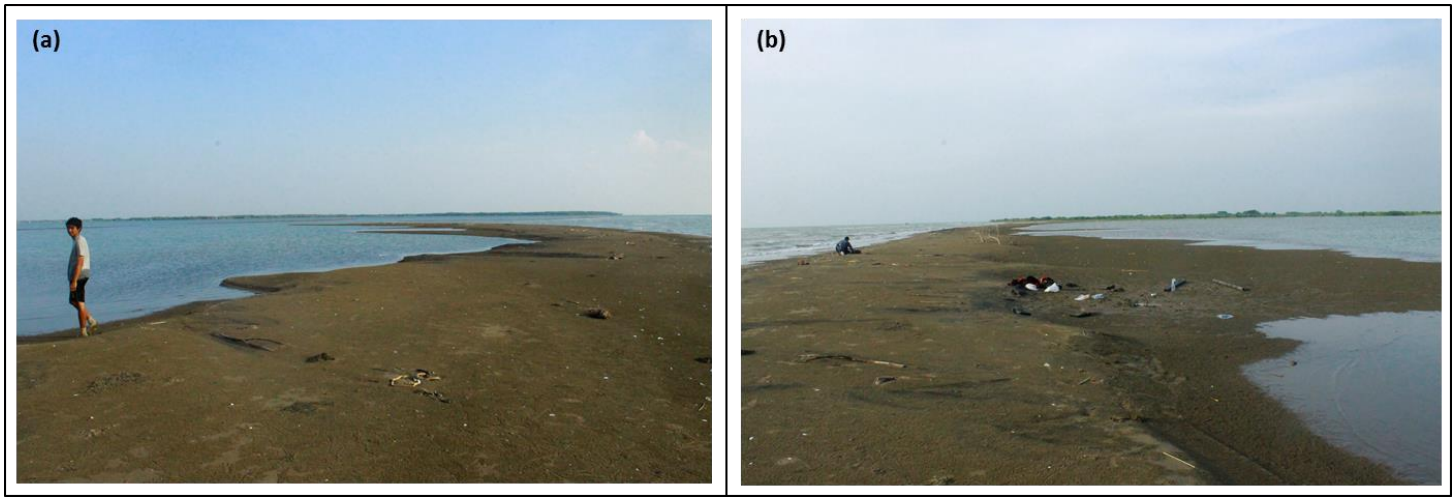


Figure 15. *STA LSB 3 shows shape of longshore bar similar with longshore current direction (a), and longshore bar was deposited by wash over process (b).*

The longshore bar deposit of Wulan Delta has a similar morphological shape to a coastal sand dune with the steeper section at the shoreface (Figures 13, 14, and 15). The youngest longshore bar deposit is oriented in the same direction as the first longshore bar and form the current shoreline. Longshore currents run almost parallel to the shoreline, mostly following the ridge and runnel (bar and trough) system of the beach, and at a few tens of meters to several hundred meters distance, they terminate into rip currents, flowing seaward at right angles to the shoreline (Reineck and Singh, 1980). The deposited materials are progressively older in landward direction. The younger deposits are always piled on the earlier deposits until they come up to surface (Figure 13b) and this process continues to form a dune that migrates towards the shoreface (Figure 12) as the longshore current keeps delivering sediments landward and filling up the limited accommodation space (Figure 16). The longshore bar deposits formed a barrier that impeded sea water flow towards the mainland. In between the longshore bars and the mainland, a relatively quiet and isolated water zone develops as a "lagoon", which is only influenced by tidal processes and sediments are deposited here dominantly by way of suspension. The dominant sediments at this location therefore are clay to silt.

Examination of sedimentary structures in the longshore bar deposit by digging a trench profile resulted in the identification of swash cross-stratification in the deposit (Figure 17). The swash cross-stratification is a sedimentary structure that shows low angle cross stratification at about 15°. Sediment carried by the waves over the berm crest is deposited on the landward side forming layers in the backshore that dip gently landward. These low-angle strata are typically truncated by the foreshore stratification, to form a pattern of sedimentary structures that may be considered to be typical of the beach environment. The backshore area may become colonised by plants and loose sand can be reworked by aeolian processes (Nichols, 2009). The sedimentary structures show the sands prograding to the shoreface in which the parallel lamination overlapped other laminations. This is caused by the deposition mechanism formed in longshore bar, when deposited bedding with a relatively flat angle resulting from the great longshore currents carrying a lot of sediment material in the wash over so that the first sedimentary structures are formed in the form of parallel lamination (Figure 18). As Dabrio (1981) pointed out, when the ridge welds onto the berm, the runnel is filled with sand and vertical accretion of this new part of the berm takes place. The internal structure consists of horizontal or slightly landward-inclined parallel lamination. The newly formed berm is largely emergent and exposed to high-tide swash action under upper flow regime conditions. Backwash erosion cuts the seaward side of the berm, generating seaward-inclined parallel lamination.

The process continuously generated sufficient sediment thickness and surface. Then longshore currents could not reach the backshore of the sediment because sediment become thicker, so that the longshore currents generate back wash erode the sediment in the crest of bar that has formed and deposition over erosion areas. The first stage shows parallel lamination of sands layer then formed inclined parallel lamination to shoreface. The results of the sedimentation process will then be formation in seaward direction (Figure 19).

STA LSB 1 Deposit

The STA LSB 1 is located at the far eastern side of Wulan Lama River mouth. This deposit is the largest of the three longshore bars and it is 2774 m long and 830 m wide. The STA LSB 1 is oldest deposit, being formed when accommodation space was still large and no other deposits were limiting its extension. Four stratigraphic correlation sections namely Lines 1, 2, 3, and 4 were created across the STA LSB 1 (Figure 20). Each line was correlated by joining similar lithostratigraphic facies, which consist of tidal sand-mud, longshore bar sand, and lagoon mud facies.

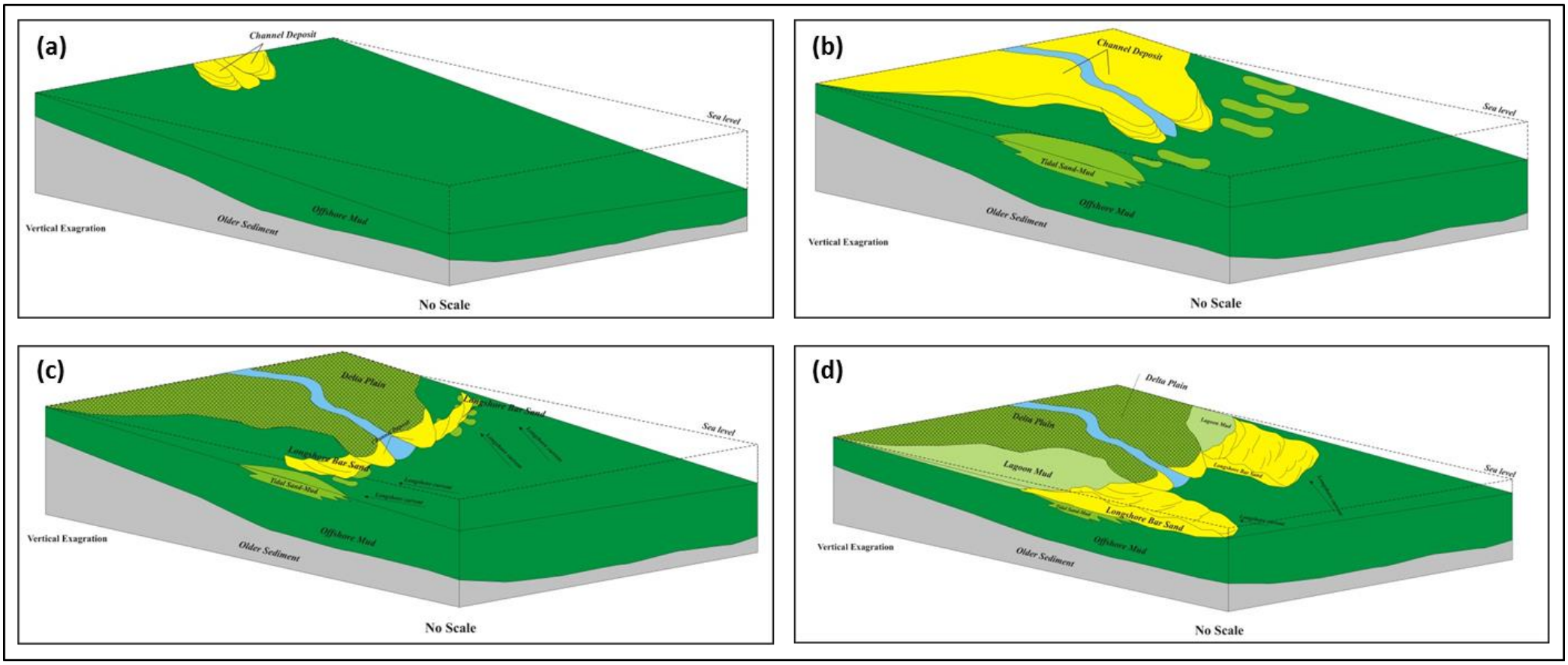


Figure 16. *3D illustration model of depositional system in the longshore bar deposit of Wulan Delta. (a) Early phase of Wulan Delta progradation from Wulan River deposit.; (b) Rapid sedimentation of Wulan River, Tidal Sand-Mud partially deposited.; (c) First Longshore Bar deposited laterally sideways.; (d) The Longshore Bars continuously deposited seaward creates lagoonal setting behind it.*



Figure 17. *Trench profile in the longshore bar deposit at STA LSB 1 showing swash cross-stratification sedimentary structure.*

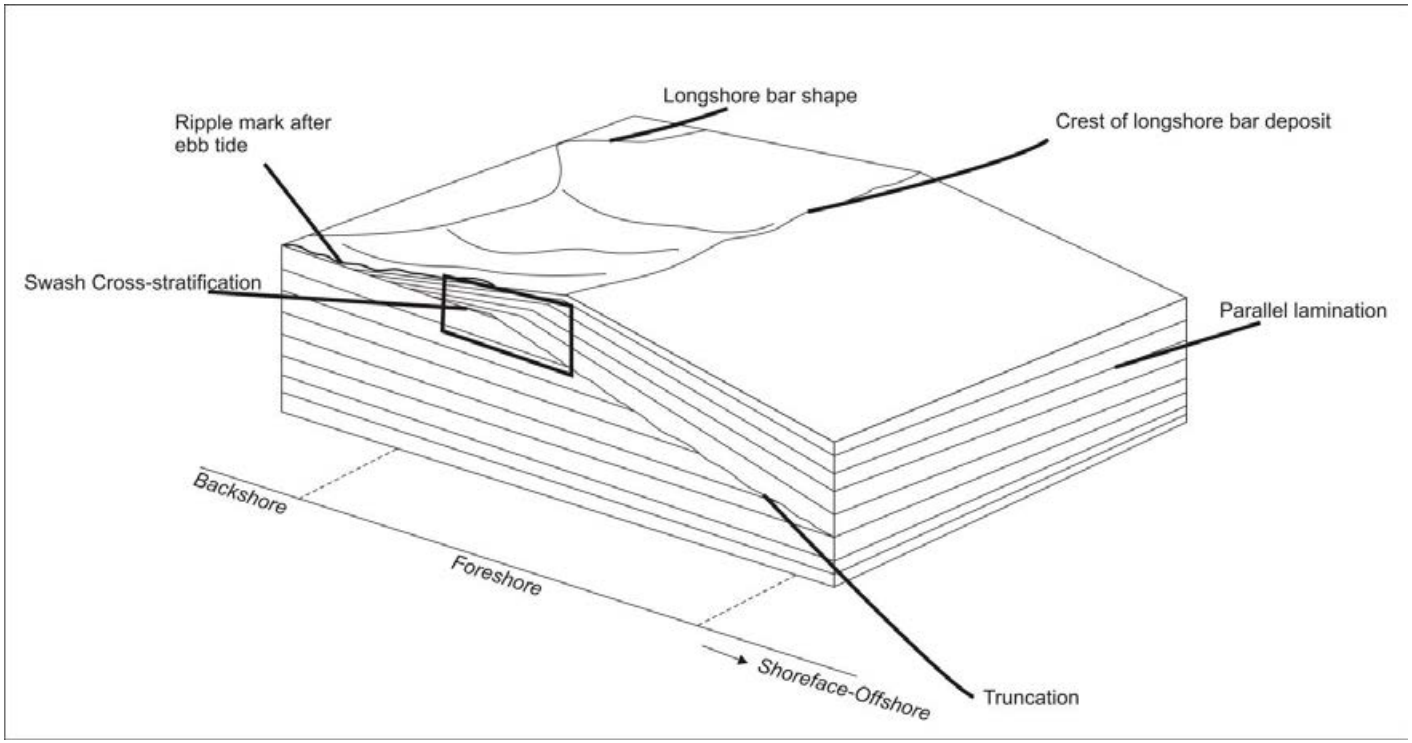


Figure 18. *Model of swash cross-stratification sedimentary structure cross section shows in the other view found only parallel lamination in the longshore bar deposit.*

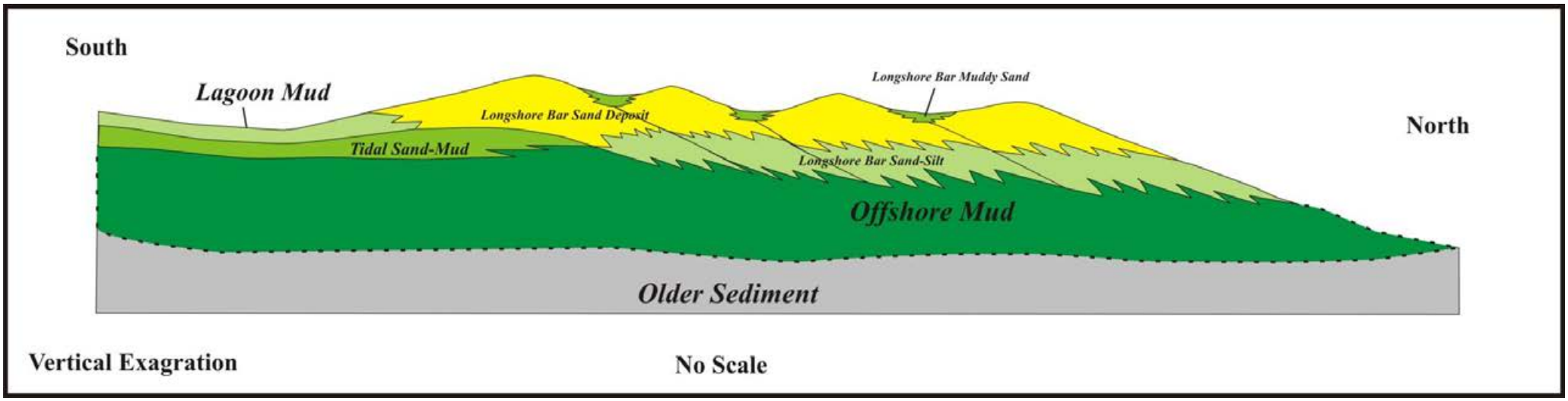


Figure 19. *Longshore bar depositional facies.*

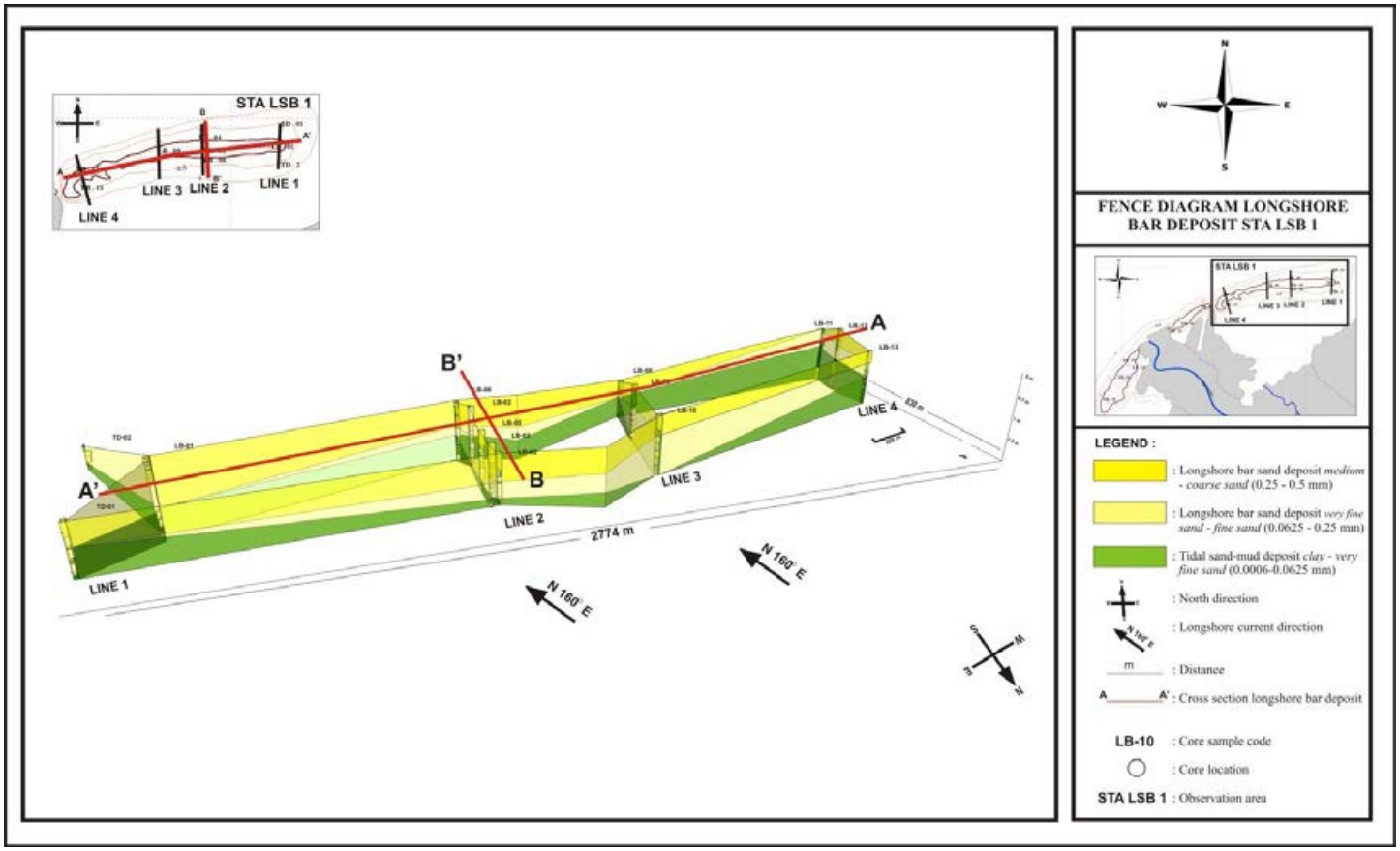


Figure 20. *Fence Diagram of STA LSB 1 deposit.*

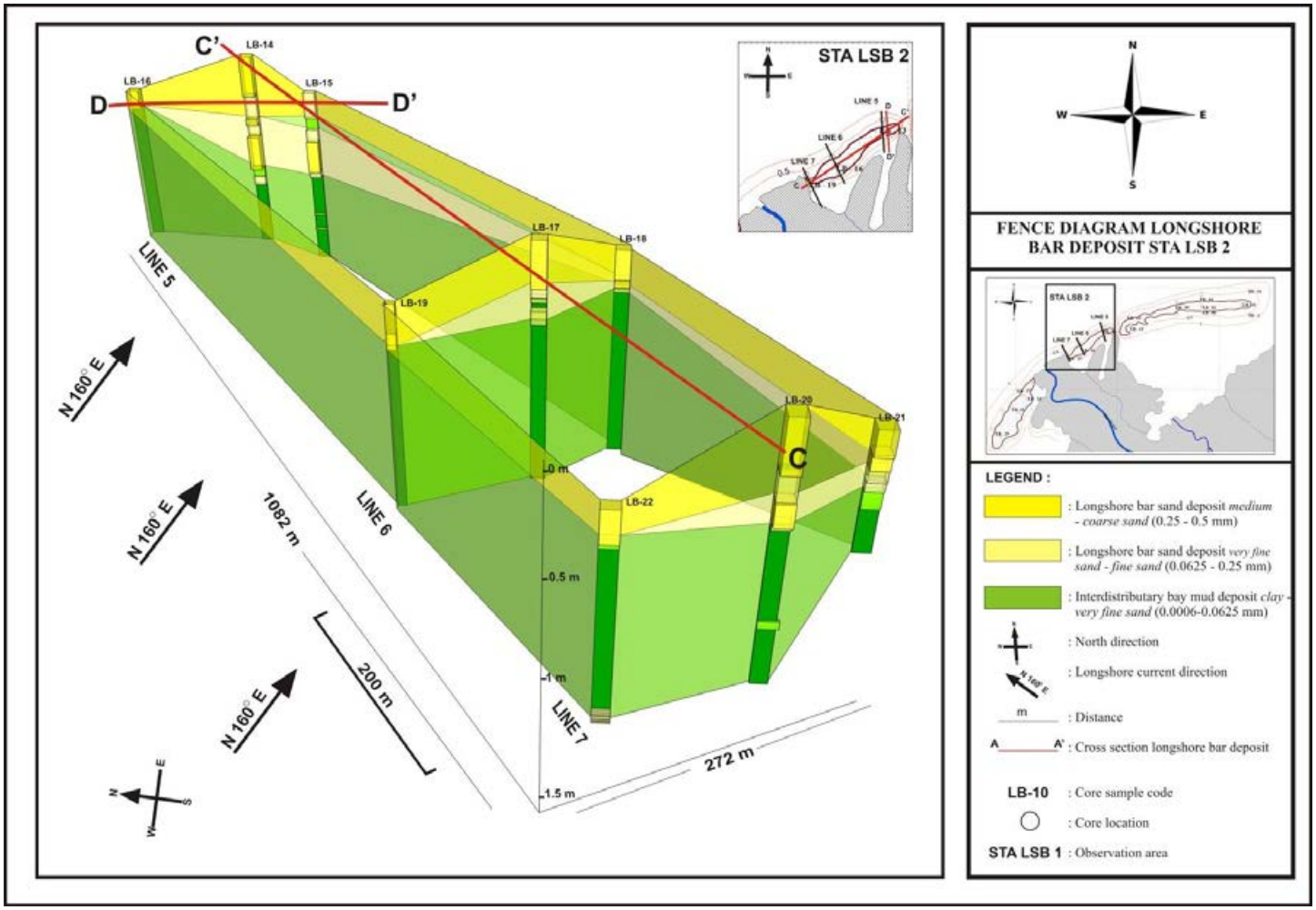


Figure 21. *Fence Diagram of STA LSB 2 deposit.*

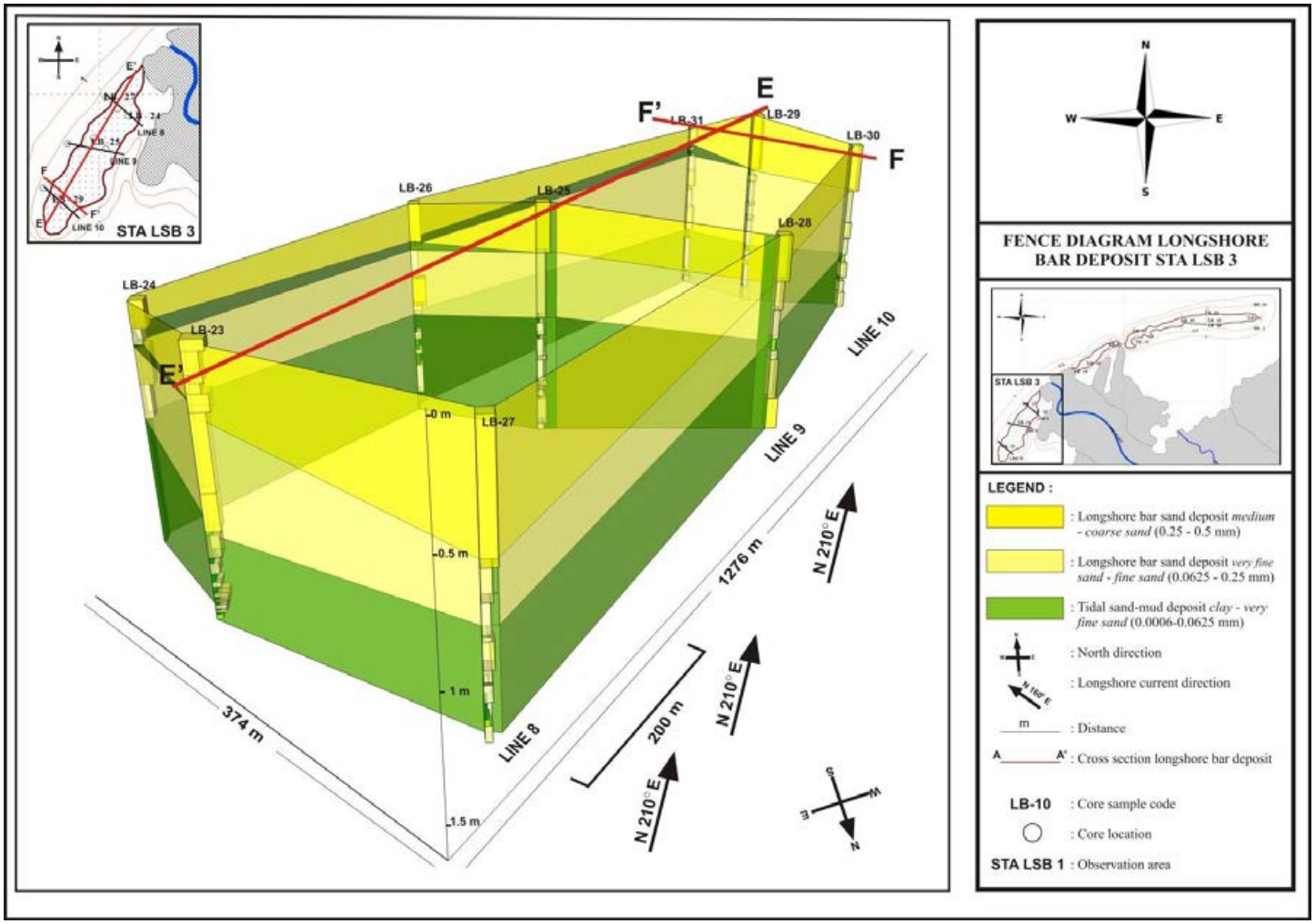


Figure 22. *Fence Diagram of STA LSB 3 deposit.*

The lower stratum comprises tidal deposit, defined by interlaminating sand and mud. The upper stratum comprises longshore bar deposit which was defined by very fine to coarse-grained sand. At the backshore location, the sediments are lagoonal deposits. The sands tend to thicken seaward up to 75 cm, while at the backshore location, the sand thickness is less than 40 cm.

STA LSB 2 Deposit

The STA LSB 2 deposit is located east of Wulan Lama river mouth. This deposit is 1082m long, 0.35 m thick and 272m wide. Three cross sections (Lines 5, 6 and 7) were created to show lithofacies correlation across the STA LSB 2 deposit. The STA LSB 2 deposit has different characteristics from both STA LSB 1 and STA LSB 3 deposit. A mud layer occurs at the bottom part of the STA LSB 2 deposit, while a thin sand layer of less than 1m comprises the upper part. The mud layer is thick and interlaminated mud-sand is rarely seen. The mud contains organic matter such as plant roots and stems. The STA LSB 2 is about 30 cm thinner than the STA LSB 1 and STA LSB 3 deposit. The longshore bar deposit has a calculated sand volume of 103,000 m^3 (Figure 21).

The dissimilarity of sediment stacking pattern in the STA LSB 2 to other longshore bar deposit could be due to its location between two floodplains of a high energy stream that carries clay to very coarse-grained sand materials. The area is called interdistributary bay.

The interdistributary bay environment includes areas of open water within the active delta which may be completely surrounded by marsh or distributary levees but which are more often partially open to the sea or connected to it by small tidal channels (Coleman, 1981). An interdistributary bay is filled by overbank spilling of fine-grained material from the river during flood stages. There is an overall shallowing-upward facies succession, associated with a trend from more marine to more non-marine facies, but commonly without the deposition of thick sands (Walker and James, 1992). Initially, the area was dominated by low energy processes where clays accumulated. The STA STB 2 longshore bar was formed during the past five years when sand materials delivered from Wulan Lama river mouth were reworked and transported to the interdistributary bay location. This process led to deposition of thin sands within the STA LSB 2, which are not observed within the STA LSB 1 and STA LSB 3. As shown on the fence diagram model, the longshore bar deposit overlying the interdistributary bay mud facies starts to thin seaward or towards the shoreface and the lagoon. Accommodation space at the STA LSB 2 longshore bar area is limited.

STA LSB 3 Deposit

The STA LSB 3 deposit is located to the west of Wulan Lama river mouth. This deposit is 1276m long and 374m wide. The longshore bar sand facies within this deposit thins towards the lagoon (Figure 22), but is still quite thick towards the sea/shoreface location. The STA LSB 3 deposit consists of two parallel, NW-SE-oriented longshore bars which are separated by a tidal channel. The parallel bars were deposited in different periods, with the first bar more landward. The first bar began to form between 2008 and 2013 and the second one probably in 2014 (see Figure 3). The tidal deposit between the longshore bars comprises interlaminated clay to fine-grained sands accumulated in low energy environment. This deposit is located in the lower part of the bar, while thick sands dominate the upper part of the STA LSB 3 deposit.

The longshore bar deposit of STA LSB 3 is 100 cm thick and its calculated volume is 432,000 m^3. The area where STA LSB 3 deposits accumulated has limited accommodation space because it is located between two Wulan River distributary channels, so lateral growth of the longshore bars is limited and the sediment are more likely to keep accumulating in seaward direction.

CONCLUSIONS

- The longshore bar deposits of the Wulan Delta accumulated in the last 10 years due to more dominant wave activities that created longshore currents, which eroded and transported sediments supplied by the Wulan river back in landward direction. The longshore currents carry fine-grained sands and distribute them laterally. The longshore bar deposit is approximately 100 cm thick and is located within 300m distance to the shoreface.
- The longshore bar deposits keep migrating seaward because of sediment were constantly supplied by the longshore currents and fill available accommodation space. The width of the bars in the Wulan Delta varies from 273 to 830m. The longshore bars show an overall coarsening upward succession, with offshore mud in the lower part, overlain by tidal sand-mud and longshore bar sand deposits in the upper part.
- The longshore bar deposit in STA LSB 3 is thicker than the other two bars. It is 100 cm thick and was formed by longshore currents that has dominant direction of N210° E. The STA LSB 1 and STA LSB 2 bars were formed by longshore currents that have a dominant N160° E direction.
- The Wulan Delta deposited a longshore bar system starting in 1997 because wave activities now are more dominant than the river flow, so that sediments carried by the river were transported back landward to form longshore bars. It would control both Wulan Lama and Wulan Baru channel less strong to keep prograding sediments seaward. In the early stage from 1975 to 1997 the delta developing its bird-foot style because the river influence dominated over the longshore current and wave action.

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