Modern Fluvio-Lacustrine System of Lake Singkarak, West Sumatra and Its Application as an Analogue for Upper Red Bed Fm. in the Central Sumatra Basin

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ABSTRACT

Paleogene synrift fluvio-lacustrine rocks in western Indonesian basins are viable and prolific petroleum plays. However, due to active tectonics and confined environment, reservoir distribution and geometry of these Paleogene rocks are highly complex. In order to better understand and identify stratigraphic relationships and facies geometries in Paleogene synrift reservoirs, a field study on analogous modern alluvial-fan and axial-fluvial deltas in Lake Singkarak has been performed by investigating data from various elements of the depositional system. The results of this study illustrate how an integration of grain texture, faunal analysis, depositional facies, and stratigraphic stacking patterns in a modern depositional environment can characterize the complexity of reservoir geometry, reservoir quality and their distribution, both laterally and vertically.

This study focuses on modern sediment of Sumpur axial-fluvial delta and Malalo alluvial fan delta in the northern part of Lake Singkarak, West Sumatra Province. Seven depositional facies were recognized in the Sumpur axial-fluvial delta including fluvial, upper and lower distributary channel, subaqueous distributary channel, mouth bar, shoreline, and abandoned delta. From a sand quality and facies geometry perspective, the lower distributary channel, subaqueous distributary channel and mouth bar facies are associated with the most favourable reservoir potential. The Malalo alluvial-fan delta can be subdivided into four depositional facies including upper, middle, lower, and subaqueous fan facies. The highest reservoir quality exists in the lower and subaqueous fan facies. These two deltaic systems exhibit that the highest quality reservoirs occur in the more distal setting and their distribution in the axial-fluvial delta is more regionally extensive than it is in the alluvial fan delta.

The model from Lake Singkarak was then compared to Paleogene reservoirs in "NAT" Field, Central Sumatra Basin. The field produced hydrocarbons from synrift deposits within Upper Pematang Group. The comparison was done with an objective to use Lake Singkarak as the analog depositional model for the Upper Pematang Group.

Keywords: *Lacustrine Delta, Alluvial Fan Delta, Synrift Play, Central Sumatera Basin, Modern Analogue, Lake Singkarak.*

INTRODUCTION

Paleogene synrift lacustrine fan/delta deposits in western Indonesia basins have been recognized as having high reservoir potential (e.g. Noeradi et al., 2005; Eubank and Makki, 1981). In the Central Sumatra Basin for instance, lacustrine fan/delta reservoirs have been explored and produced sporadically even though its reservoir characteristics, both geometry and quality, is still inadequately understood (Waren et al., 2015). Similarly, this lack of understanding also occurs in the Ombilin Basin, which has promising exploration targets in the synrift deposit (Noeradi et al., 2005). It is believed that synrift lacustrine fan/delta reservoirs in both basins will play an important role in the future.

Lake Singkarak, which is situated in West Sumatra, Indonesia (Figure 1a), is known as a pull-apart basin that is filled by synrift deposits (Bachtiar et al., 2015). This basin provides useful information as an analogue in understanding synrift reservoirs to improve subsurface analysis in the Central Sumatra, Ombilin and/or other basins. Furthermore, Lake Singkarak deposits have also been considered to contain hydrocarbon potential for exploration targets (Koning, 1985).

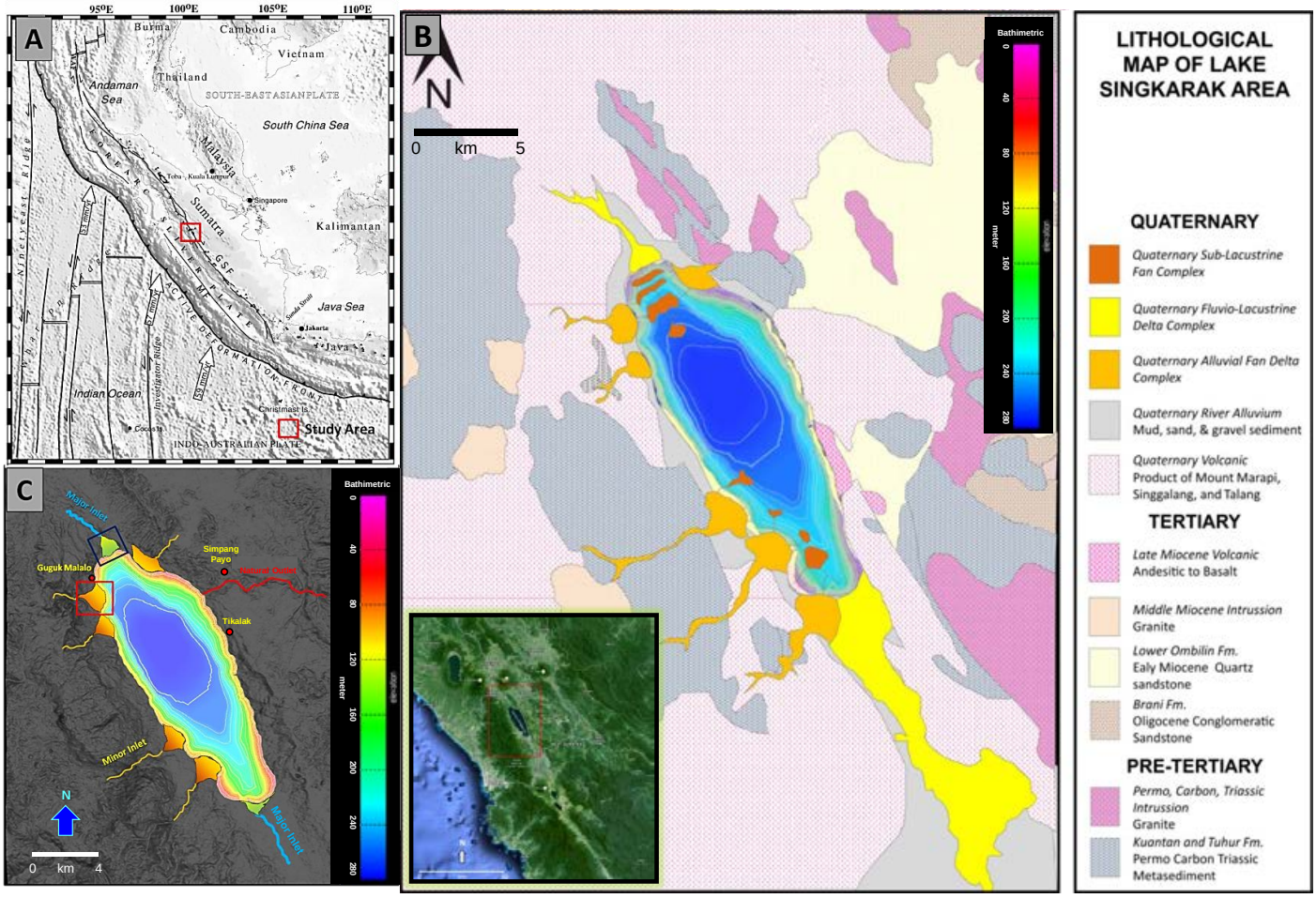


Figure 1. *General geological aspect of Lake Singkarak. a) Regional tectonic of Sumatra Island highlighting Sumatra Fault System (Sieh and Natawidjaja, 2000); b) Lithological map, recent sedimentology facies study, and bathymetry of the Singkarak Lake (modified from Kastowo et al., 1996, Silitonga and Kastowo, 1995, Bachtiar et al., 2015, Puslit-Limnologi, 2001 cited in Emelia, 2009), inset map West Sumatra area satellite image showing north-west and south-east lineaments; c) Location of Sumpur Axial Fluvial Delta, Malalo Alluvial Fan Delta, and other lobate systems in the Singkarak Lake.*

Numerous regional studies on Lake Singkarak have been conducted since 1961 (e.g. Verstappen, 1961; Tjia, 1970; Zen, 1971; Koning, 1985; Sieh and Natawidjaja, 2000; Aydan, 2007; Bachtiar et al., 2015). The most recent study provided sedimentology facies model that includes alluvial fan, braided river, meandering river, fan delta, shoreline, lacustrine delta, shallow lacustrine, and shelf-slope lacustrine facies (Bachtiar et al., 2015) (Figure 1b). This facies subdivision becomes the foundation for regional understanding of the Lake Singkarak synrift system. However, detailed analysis on reservoir geometry and quality is still unexplored. In order to obtain a better understanding of how each reservoir facies distributes in such lacustrine delta or more commonly known as axial fluvial delta and alluvial-fan delta environments, detailed analysis on modern systems in both environments have been performed. Axial fluvial delta will be represented by Sumpur Delta which is located in the northern part of Lake Singkarak. Meanwhile, Malalo Delta represents alluvial fan delta, located to the southwest of Sumpur Delta (Figure 1c). These two deltas share a common thing, which is genetically a border fault-related delta. Although the accommodation space of these deltas is mainly controlled by border fault movement, the deltas' position to the fault is significantly different. The Malalo Alluvial Fan Delta (MAFD) is formed in the highest fault-throw area and perpendicular to the border fault, while the Sumpur Axial Fluvial Delta (SAFD) is created at the fault-tip area and parallel to the fault. The difference led to distinctions of accommodation space or basin geometry and sediment-filling in each delta.

GEOLOGICAL SETTING

Lake Singkarak is located in the intermountain area of the Bukit Barisan Mountains (Koning, 1985), 364m above sea level (Azhar, 1993 cited in Emelia, 2009). The lake is bounded to the north and south by Mount Marapi and Mount Talang volcanoes, respectively. The eastern and western borders of the lake are comprised of a range of uplifted basement blocks, granitic intrusions and Tertiary-Recent volcanic deposits (Silitonga and Kastowo, 1995; Kastowo et al., 1996). The lake has two main inlets from the Sumpur River and Sumani River while the natural outlet is the

Ombilin River (Aydan, 2007) (Figure 2). There is an artificial outlet supporting a hydroelectricity project which becomes the major outlet today, located in the Guguk Malalo area at the western part of the lake (Aydan, 2007).

Tectonics and Structure of Lake Singkarak

Lake Singkarak is located in a pull-apart basin situated between the Sianok and Sumani segments of the Sumatran strike–slip fault system (Bellier and Sebrier, 1994 cited in Sieh and Natawidjaja, 2000) (Figure 2). The slip is right-lateral with 23km of separation (Sieh and Natawidjaja, 2000). This full-graben rift basin is also known as a part of the Ombilin Basin (Koning, 1985). The lake is oriented in NNW-SSE direction, elongate with a length of 18km, width of 8km, and maximum water depth of 268m (Puslit-Limnologi, 2001 cited in Emelia, 2009). The area remains tectonically active today as evidenced by major earthquake activities within the last decade (Aydan, 2007).

Along the lake boundary, the Sumatran strike slip fault system consists of a series of minor normal faults which are parallel to the NNW-SSE regional fault trend (Sieh and Natawidjaja, 2000). Sediments are transported across the normal fault scarps where they form various lobate systems (fans or deltas) (Figure 1c). However, there are several normal faults in the area of extension which are believed to provide steep slope as the host for sub-lacustrine fan deposit (Bachtiar et al., 2015; Puslit-Limnologi, 2001 cited in Emelia, 2009).

Previous regional studies have indicated that the normal faults act as a major control in creating accommodation space for sedimentation (Sieh and Natawidjaja, 2000; Bachtiar et al., 2015). Three types of delta including alluvial fan delta, axial fluvial delta and sub-lacustrine fan delta developed in Lake Singkarak and their entry points are controlled by the presence of faults. Axial fluvial delta is interpreted occurs at the fault tip region. On the other hand, alluvial fan deltas usually developed where relay ramp occurs along the boundary fault margin. However alluvial fan delta in Lake Singkarak is the present day configuration and it is currently controlled by single fault.

Stratigraphy

The Singkarak Lake is surrounded by lithologic units that consist of Pre-Tertiary metasediments and intrusive volcanics, Tertiary extrusive, Quaternary extrusive volcanics and Recent alluvial deposit (Figure 1b). The Pre-Tertiary package appears as the basement of both Ombilin (Koesoemadinata and Matasak, 1981) and the Singkarak Lake rift basins.

The Tertiary extrusive package is a volcanism product during Miocene (Silitonga and Kastowo, 1995). The Quaternary extrusive volcanics were deposited by surrounding volcanic activities (Zen, 1970 cited in Aydan, 2007). Recent sediments of alluvial deposit are currently filling Lake Singkarak as synrift deposits. The Pre-Tertiary, Tertiary, and Quaternary rocks become the provenance of recent sediments that are filling in to the lake.

Pre-Tertiary

The Pre-Tertiary rocks are exposed in the north-western, western, and eastern part of Lake Singkarak. These rocks can be distinguished into meta-sediment and intrusive lithologic units from Mergui Microplate, ranging from Carboniferous to Cretaceous in age (Pulunggono and Cameron, 1984). The meta-sediments consist of marble, phyllite, slate, and quartzite which were originated from Kuantan Formation (Silitonga and Kastowo, 1995; Kastowo et al., 1996). The intrusive rocks are characterized by Triassic-Cretaceous granite and granodiorite intrusions (Silitonga and Kastowo, 1995; Kastowo et al., 1996).

Tertiary

Tertiary extrusive outcrop is exposed in the eastern part of Lake Singkarak near the Tikalak village. These extrusive volcanics consist of andesitic-basaltic character as a result of lava flow and hypabyssal intrusions in Miocene age (Silitonga and Kastowo, 1995).

Quaternary

The Quaternary extrusive volcanics of Ranau Formation (van Bemmelen, 1949 cited in Koesoemadinata and Matasak, 1981) are exposed in the north-western, south-western and eastern parts of the graben system. These Quaternary extrusive volcanics consist of tuff and laharic flows. The provenance of Ranau Formation around Lake Singkarak area is from materials produced by volcanic activities including Mounts Marapi, Singgalang, Tandikat in the north and Mount Talang in the south (Zen, 1970 cited in Aydan, 2007).

Recent

Lake Singkarak is in a regression phase today as indicated from the presence of lake-terrace outcrop in Simpang Payo village to the north-east of Lake Singkarak (Fletcher and Yarmanto, 1993). Currently, this regression phase influences recent sediment filling processes that majorly creates a progradational stacking pattern.

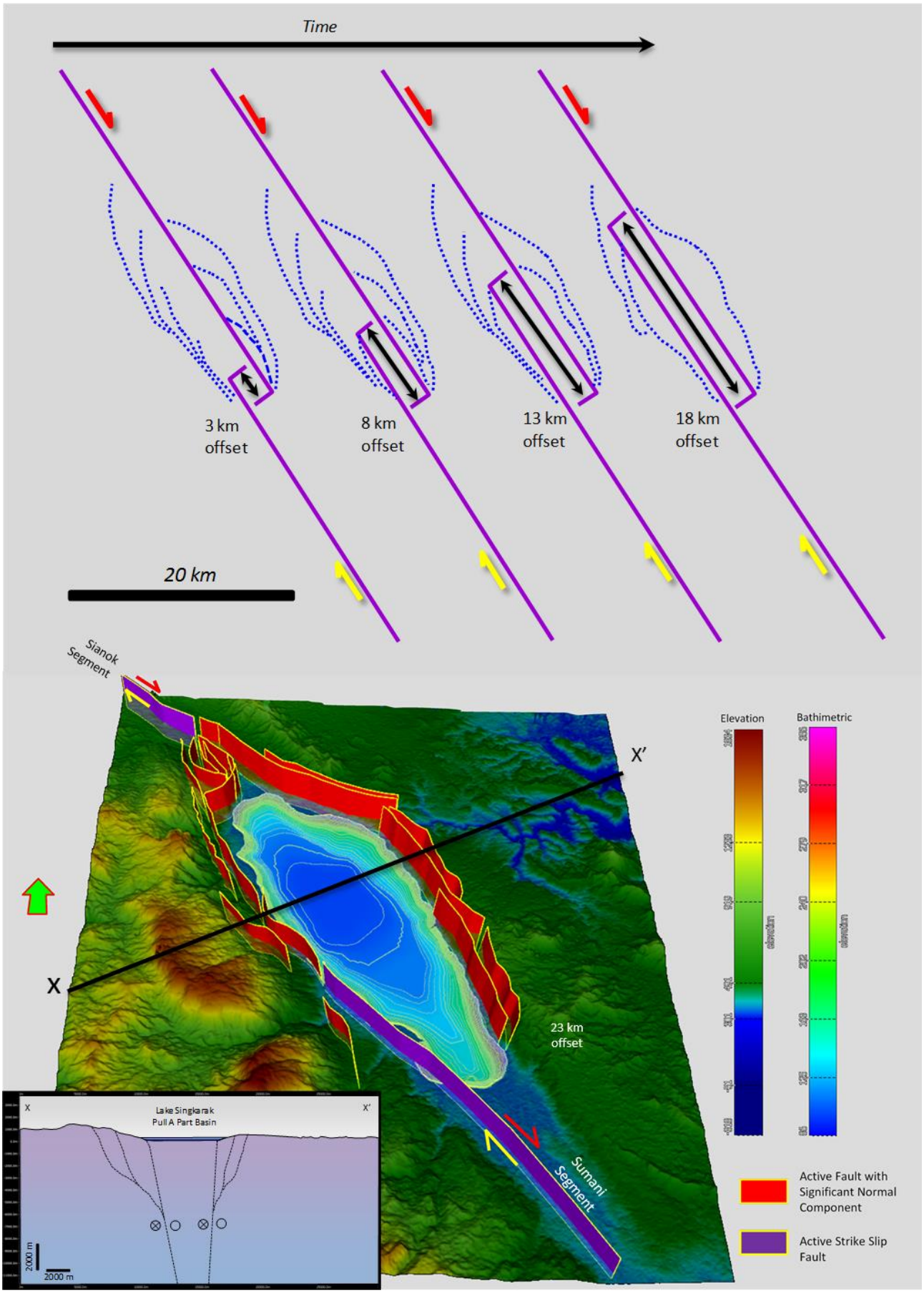


Figure 2. *Neotectonics with bathymetry of Lake Singkarak (modified from Sieh and Natawidjaja, 2000 and Puslit-Limnologi, 2001 cited in Emelia, 2009).*

The recent sediments consist of siliciclastic deposit of alluvium containing cobble to clay size materials. Further understanding of sediment facies and its geometry distribution in both alluvial fan delta and axial fluvial delta is the main object of this research. These understandings will be earned by combining sedimentological process and its related fault activities.

Provenance of Sumpur Axial Fluvial and Malalo Alluvial Fan Deltas

The sediments filling the SAFD and MAFD are sourced from metamorphic rocks of the Kuantan Formation, Triassic-Cretaceous granite intrusion and Quaternary extrusive volcanics of Ranau Formation. These sediment sources are located in the north-western part of the lake (Figure 1b).

DATA & METHODOLOGY

The following methods are used to characterize reservoir potential within axial fluvial and alluvial fan deltas of the Lake Singkarak: (1) Delta morphology interpretation from satellite image combined with aerial photos by using a drone. (2) Sediment texture analysis and depositional facies interpretation of recent sediments from river bed sampling, river mouth coring, surface trenching and offshore grab samplings to describe various facies characters in both environments. In order to support the facies characterization, faunal analyses were also performed. (3) Facies geometry mapping by integrating bathymetry data from offshore sampling points and facies data points to illustrate the distribution of potential reservoirs.

SUMPUR AXIAL FLUVIAL DELTA (SAFD)

Axial rift drainage and its associated deltas have received more attention than other types of rift drainage and are commonly thought to play a dominant role in rift-lake filling (LeFournier, 1980; Lambiase and Rodgers, 1998 cited in Cohen, 1990). In the Singkarak Lake, Sumpur River is the largest axial drainage system. A smaller one axial drainage has also developed at the south-western part of the lake. The other major axial stream is known as Sumani River that acts as the Singkarak Lake inlet and is located in the south-eastern part of the lake. The SAFD is located in the northwestern end of the lake in Sumpur Village (Figure 1c).

Morphology

The SAFD is classified as a fluvial-dominated delta, as a product of Sumpur River activities which flows as an axial drainage system. This type of delta typically has elongate to irregular lobate areal geometries (Galloway and Hobday, 1996). Its geometry is about 675m long and 515m wide (Figure 3). The delta progrades axially in the sense of parallel to the NNW-SSE faults. The positions of axial rivers and their deltas are constrained by basin structure (specifically, geometry of adjacent border-fault systems) to a greater extent than those rivers that enter the lake laterally (Cohen, 1990).

The Sumpur River, a single major trunk stream in SAFD, holds mean stream gradient about 0.7° which is similar with the famous Lake Tanganyika's axial streams (Ruzizi and Nemba River basins) [Cohen, 1990]. Although SAFD system has similarity on the slope gradient of its axial stream with the Tanganyika Lake, its size differs significantly, with only 10% of the Ruzizi system. The SAFD system gradient is significantly increased as the river entering the lake basin to ±21° as indicated from the cross-stratification angle which is observed on core sampling in the river mouth area (Figure 3). In addition, it is also supported by bathymetry slope that was constructed from offshore grab sampling points in front of the river mouth area, which show gradient ranging from 18° to 20°. The understanding of basin morphology across the axial delta system will influence the construction of depositional facies and its distribution.

Depositional Facies

There are four main depositional facies association that can be observed in the SAFD (Figure 4). They include: (1) Alluvial Plain facies association that contains Fluvial Channel facies (FC), (2) Delta Plain facies association which consists of Upper Distributary Channel facies (UDC) and Lower Distributary Channel facies (LDC), (3) Delta Front facies association that consists of Subaqueous Distributary Channel facies (SDC) and Mouth Bar facies (MB), and (4) Shallow Lacustrine facies association, consisting of Shoreline facies (SH) and Abandoned Delta facies (ABD).

Fluvial Channel Facies (FC)

The FC facies developed along the alluvial plain area overlying ancient prograding SAFD system. The FC is characterized by straight to slightly sinuous channel geometry, containing cobbles to pebbles with occasionally boulder clasts in a sandy matrix. This grain-supported facies shows poorly sorted fabric, sub-rounded to rounded grain shape, and low sphericity (Table 1). Additionally, observed polymic fragments include metamorphic rocks, granite, and volcanic rocks (pyroclastic). The width of the Sumpur River is 22m at the northern part of the research area, and gradually increases to 36m towards the delta plain (Figure 4).



Figure 3. *Sumpur Axial Fluvial Delta geometry and morphology. a) Satellite image, b) Drone image of river-mouth area in strike-section view, c) Drone image of river-mouth area in dip-section view.*

Upper Distributary Channel Facies (UDC) and Lower Distributary Channel Facies (LDC)

The Distributary Channel facies occur in the upper delta plain where the Sumpur River disperses into four distributaries (Figure 4). These distributaries reflect different geometry which has been produced by its level of flow activities. The most active distributary is also the widest, ranging from 18m to 45m while the three other less active distributaries are only 6m to 15m. There are several intra-distributary plains located between the distributaries. It is characterized by the presence of fine-grained sediments and is covered by vegetation.

The distributary channel in SAFD is divided into two facies based on its unique character (geometry, grain size distribution and sorting), which consists of Upper Distributary Channel Facies (UDC) and Lower Distributary Channel Facies (LDC). In general, the UDC still reflects a low sinuosity, larger grain size, and poorer sorting compared to the LDC (Figure 4).

The UDC is composed of 50% pebble clasts and 35% granules combined with very coarse sands. The proportion of cobble clast size is lower than it is in the FC. This inter-locking grained facies shows poorly sorted fabric, rounded to sub-rounded grain shape and high sphericity (Table 1). Polymic fragments are also observed as in the FC. In the most active distributary, a sand bar developed well and the geometry of this bar is 44m wide and 172m long. A core was taken from this facies to analyse the sand bar characteristics (Figure 5). A typical fining upward facies succession has been recovered and from bottom-up it includes imbricated granule clast as the scour base that gradually changes to cross-stratified, coarse to medium grained sands. The texture analysis indicated poor to moderately sorted fabric, sub-rounded grain shape and high sphericity.

The LDC is composed of dominantly pebbles to coarse grained sands and occasionally finer grained (medium to silt grained) sands. The main difference between this facies and other two previous facies (the FC and the UDC) is straight river geometry, smaller grain size, and moderate-well sorted fabric. Eight cores have been taken to illustrate the LDC characteristics. Based on the cores, the LDC can be subdivided into two unique lithofacies (Figure 5). The first is cross-bedded pebble to coarse sand lithofacies, holding poor to moderate sorted fabric, sub-angular grain shape and high sphericity. This lithofacies is generally deposited as composite stacking facies in the channel axis area (Figure 6).

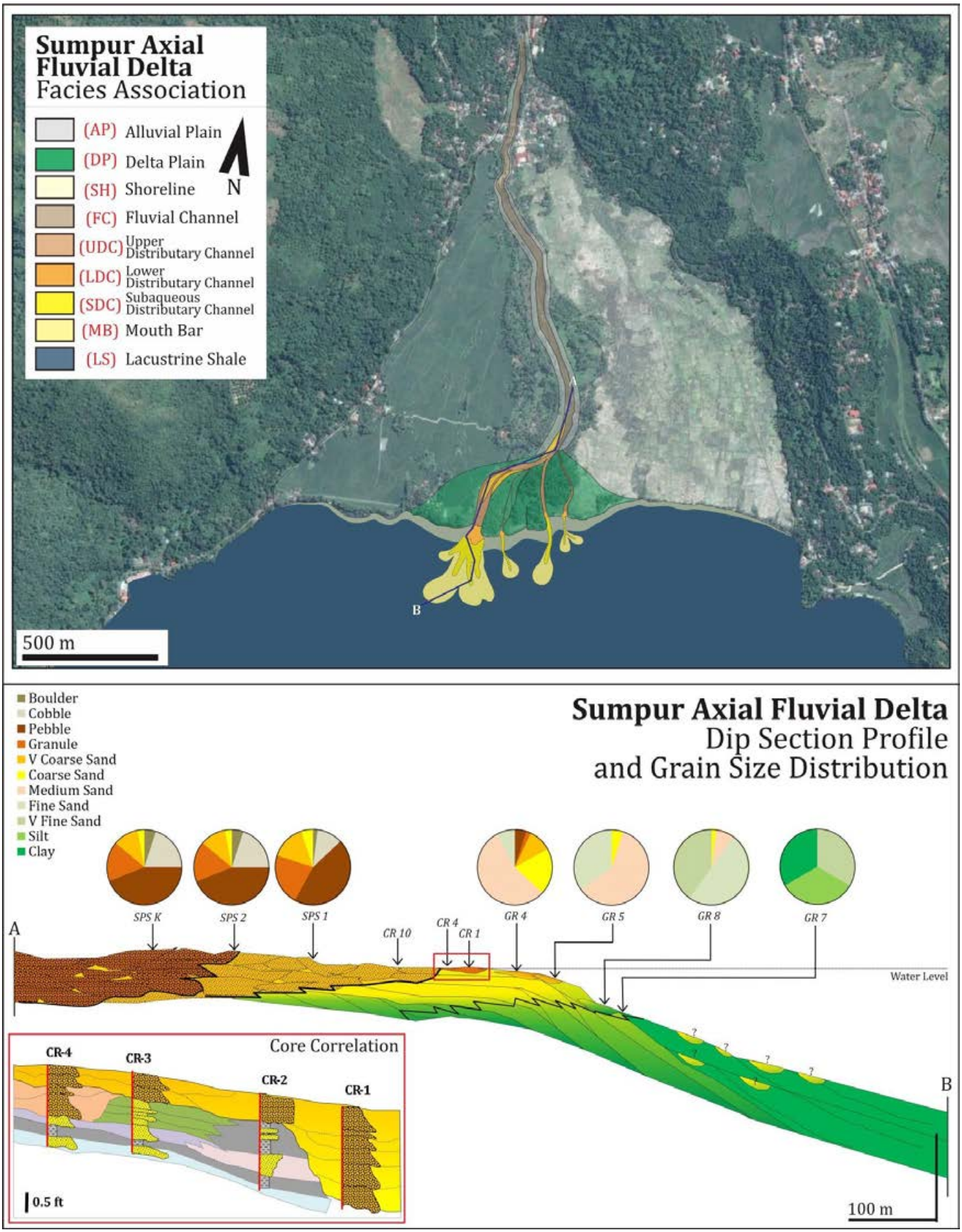


Figure 4. *Regional facies map of Sumpur Axial Fluvial Delta and its dip-section profile.*

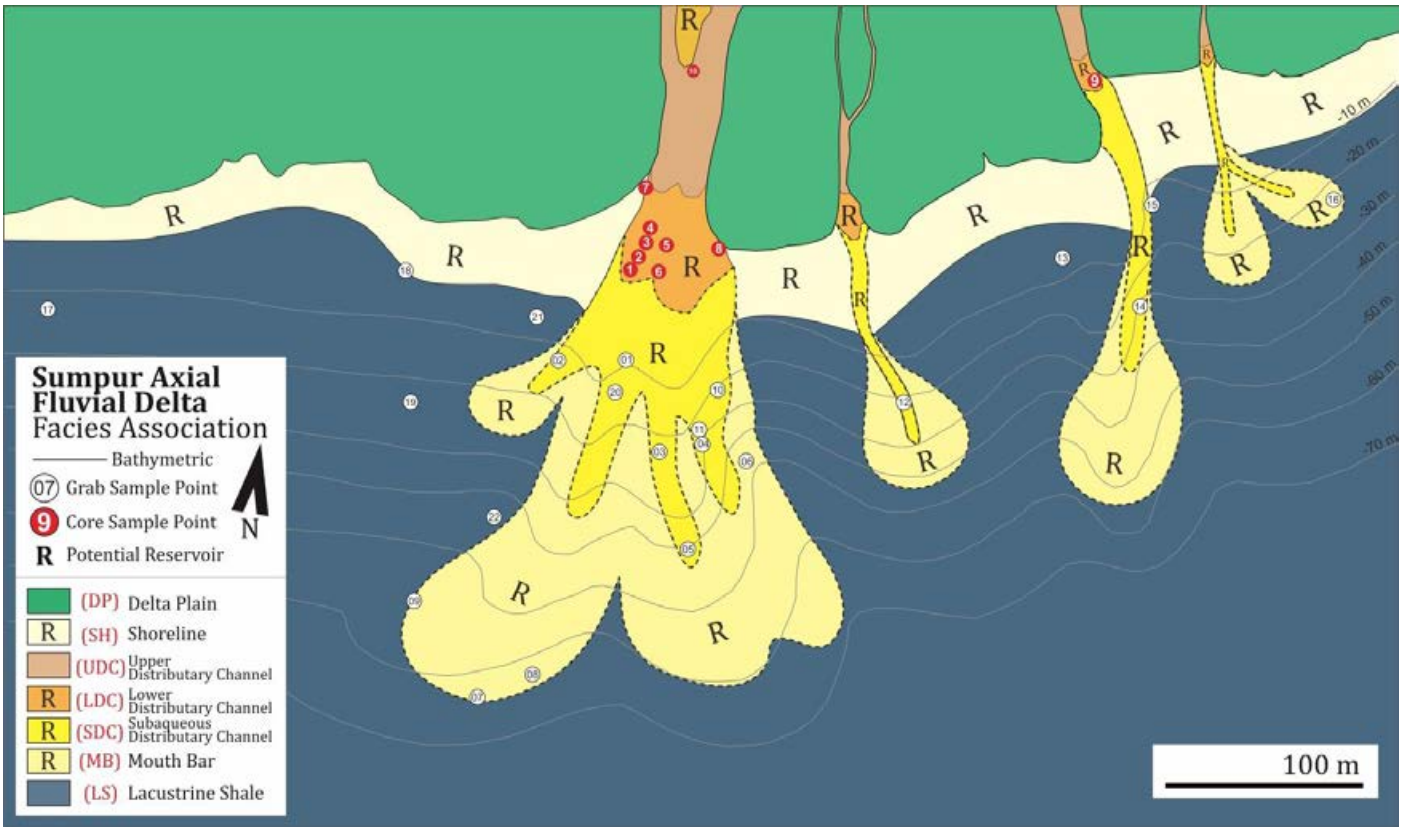


Figure 5. *Sumpur Axial Fluvial Delta facies map focusing on near shore area. It also shows coring job location and grab sampling data points.*

The second lithofacies is cross-bedded medium to very fine grained sands, occasionally with silt at the top of this lithofacies. This lithofacies is represented by well to moderate sorted fabric, sub-rounded grain shape and high sphericity, and is commonly deposited in the channel margin area. During the flooding season, silts are deposited and cover the channel margin area. Abundant carbon materials from plants are present in one of the cores.

Subaqueous Distributary Channel Facies (SDC)
The SDC is a continuation of the distributaries and it develops below the lake level from the river mouth to offshore area, ranging approximately from 100m to 120m toward the lake basin (Figure 5). To enhance the understanding of the SDC geometry and distribution, grab sampling were performed in the offshore area. Eleven grab sample descriptions indicate coarse to medium grained sands, well sorted fabric, sub-rounded to sub-angular grain shape, and high sphericity (Table 1).

Mollusc's faunal analysis was also performed in three grab samples. The SDC is a suitable habitat for gastropods class such as Brotia, Melanoides, Thiara, whereas it is less favourable for Bellamya (Figure 7). These faunal analyses indicate a habitat which has clear water flowing and an oxygen rich environment, in a sand to gravel substrate. The geometry of the SDC is dominantly controlled by the activity of the distributaries channel influx. In other words, the most active distributary will generate larger SDC. In SAFD, the SDC geometry can be subdivided into two types: (1) Multiple channels of 90m wide and 120m long, specifically each channel is 20m wide; and (2) Single channel of 15m wide and 110m long (Figure 5).

Mouth Bar Facies (MB)
As the SDC flows to the offshore, sediments are discharged to the lake basin and are accumulated as MB (Figure 5). The MB accumulation ends in the prodelta area and inter-fingers with lacustrine shales. Several grab samples are utilized to understand the geometry and characteristics of this facies. Four grab sample descriptions show fine to medium grained sands, very well sorted fabric, sub-rounded to sub-angular grain shape, and high sphericity (Table 1). The MB grain size gradually changes to finer-grained as water depth and distance from the SDC feeder increases. The geometry of the MB is controlled dominantly by the activities of SDC influx (LDC and SDC). To illustrate that, multiple SDCs will develop multiple MB lobes, while a single MB is created by a single SDC (Figure 5). In SAFD, the most active distributary has developed multiple lobes of MB which have geometry of 180m wide and 120m long. There are two single lobes of MB from less active distributary influx with geometry of 60m wide and 100m long. These MB lobes are separated by lacustrine shale that may indicate poor connectivity between each MB.

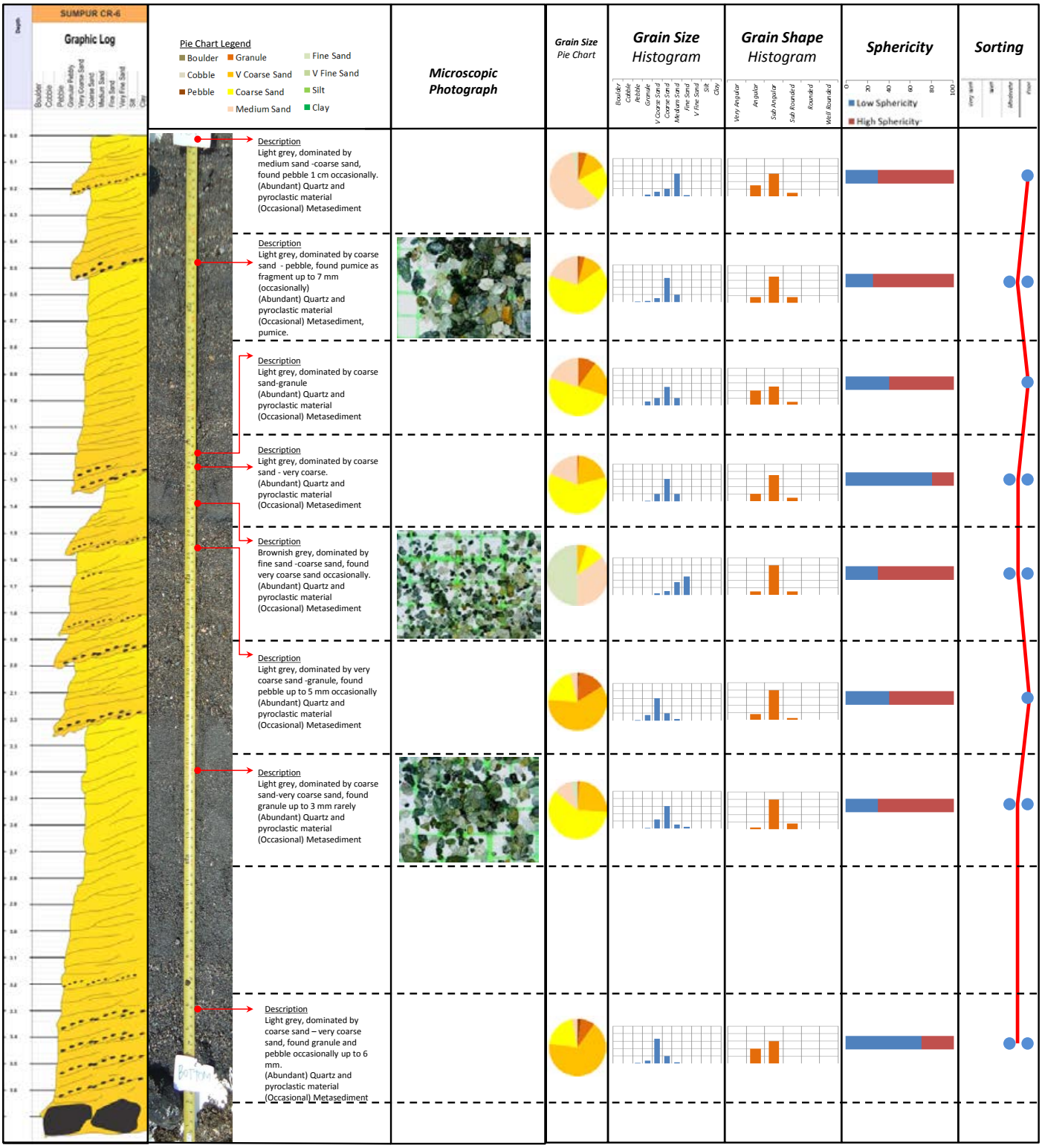


Figure 6. *Core description of CR-6 that is located in the channel axis of Lower Distributary Channel in Sumpur Axial Fluvial Delta.*

Shoreline Facies (SH) and Abandoned Delta Facies (ABD)

The SH develop along the shore of SAFD (Figure 4). There are two different types of SH that can be observed in the system. The first is the shoreline associated with active distributary, which extends to the side of the SDC. It is represented by dominantly fine grained sands, occasional granule to pebble clasts, moderate sorted fabric, sub-angular grain shaped and high sphericity. The second is, the shoreline associated with abandoned distributary/delta. It is characterized by fine grained intercalation with medium grained sands, well sorted, sub-rounded grain shape, and high sphericity. These sediments character is a product of reworking abandoned distributary/delta deposit by wave activities.

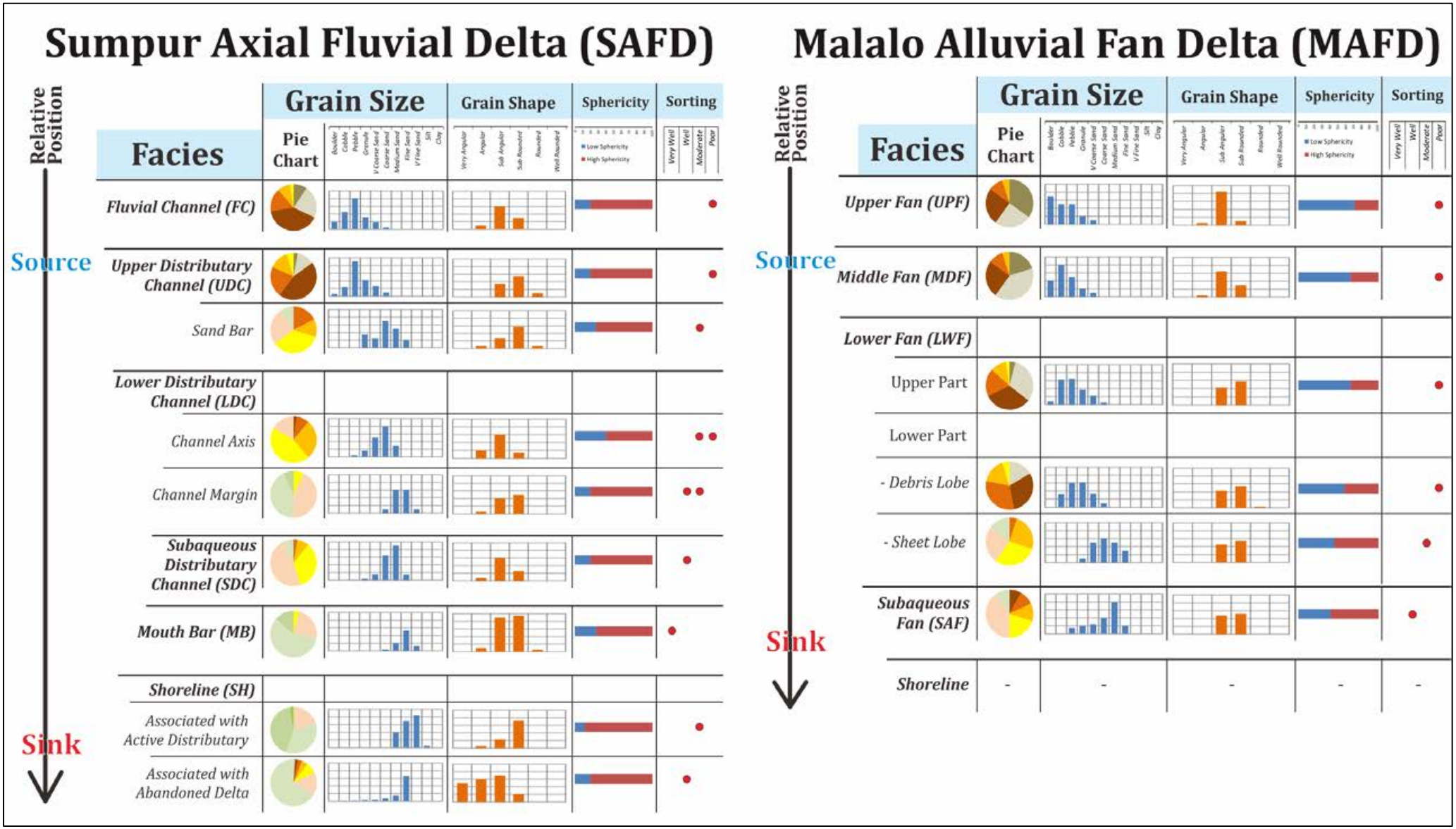


Table 1. *Median value of sample description in Sumpur axial fluvial delta and Malalo alluvial fan delta.*

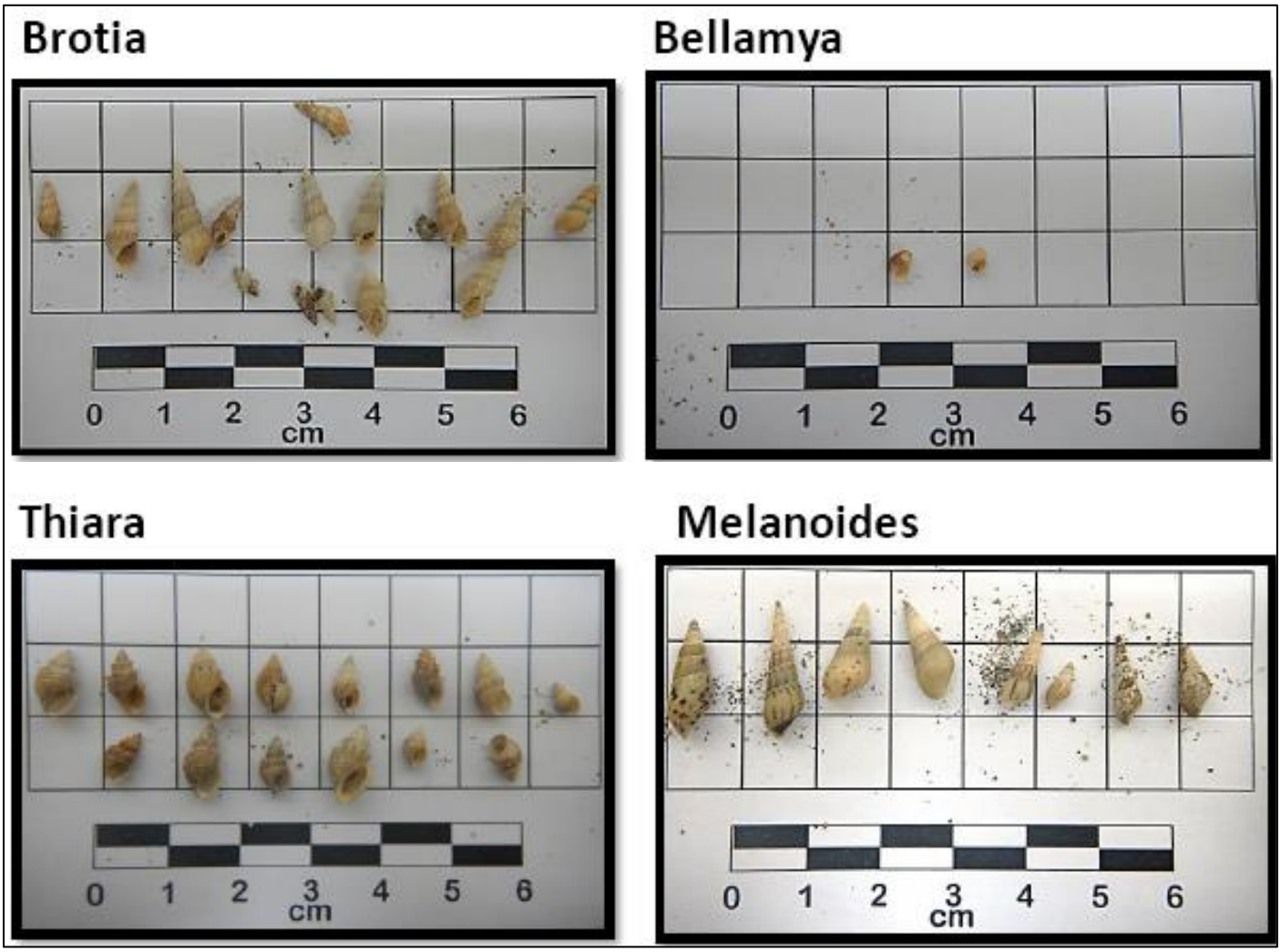


Figure 7. *Faunal analysis that performed in Subaqueous Distributary Channel Facies of Sumpur Axial Fluvial Delta.*

Reservoir Potential and Distribution

We review the reservoir potential of each depositional facies that have been discussed previously although they have not been deeply buried and most likely have not been subjected to significant diagenetic processes. This reservoir potential is determined qualitatively only and is based on lithology, sedimentary textures of each facies combined with its distribution and geometry.

In SAFD, the most favourable reservoir potential occurs in Lower Distributary Channel facies association (LDC, SDC, and MB) (Figure 5). These three facies, coarse to fine grained with moderate to well sorted fabric, are indicating promising ranges of permeability and porosity. Additionally, these facies have a high degree of connectivity which may generate a large reservoir tank. However, the presence of silts in the channel margin area will contaminate the reservoir quality. The less favourable potential reservoir is Shoreline facies which is associated with Abandoned Distributary/Delta but its geometry is limited along the Shoreline. The least favourable potential reservoir is sand Nar in UDC (Figure 5). Even though it appears to be a promising reservoir, its geometry is somewhat localized.

We recognize that the size of potential reservoirs in SAFD, as a snapshot in time, is not economically attractive. To illustrate that, the biggest potential reservoir area is about 64m^2 or 15acres. However, understanding how the modern depositional system is contained within the overall cycle of deposition and its associated reservoir architecture allows for a more robust understanding and delineation of the full potential of this depositional component. The regressive phase of Lake Singkarak had led to progradation of the SAFD. Consequently, the superimposing of a progradational stacking pattern creates an opportunity for targeting a potentially more extensive reservoir within these multiple depositional cycles. Although opportunity may be identified in the SAFD system, an associated risk is recognized as connectivity prediction between the depositional cycles.

MALALO ALLUVIAL FAN DELTA (MAFD)

Alluvial fan delta develops in a border fault where the drainage directly flows down into the lake with short and steep gradient (Cohen, 1990). Several alluvial fan deltas have developed along the western border fault of Lake Singkarak, including MAFD which is the most ideal fan delta to be studied. It is located in the northeast part of Lake Singkarak, approximately 2km to the southwest of Sumpur Axial Fluvial Delta (Figure 1c).

Morphology

The MAFD is irregularly lobate and its geometry is 2.1km wide and 2.3km long (Figure 8). It can be compared with alluvial fan delta systems in Lake Tanganyika to provide a geometric sense about MAFD. Alluvial fan delta systems in Lake Tanganyika have a median maximum length of 2.6km and a mean slope of about 12° for all drainages longer than 1km (Cohen, 1990) which is slightly steeper and longer when compared to MAFD.

The MAFD can be distinguished into four areas based on slope gradient (Figure 9). The areas consist of:

(1) Steep Area, which is located around the fan apex (10° slope, 335m wide, and 815m long)
(2) Moderate Area, which is characterized by 7° slope, 1607m wide and 820m long
(3) Gentle Area, located between end of moderate area to the shoreline (3° slope, 2064m wide and 445m long), and
(4) Steeper Area, which is known as the steepest gradient located between the shoreline to about 150m below lake level (31° slope, 2650m wide and 250m long).

The morphology assessment is crucial to provide preliminary sedimentary facies distribution specifically in the onshore area which most of these sediments have been covered by vegetation.

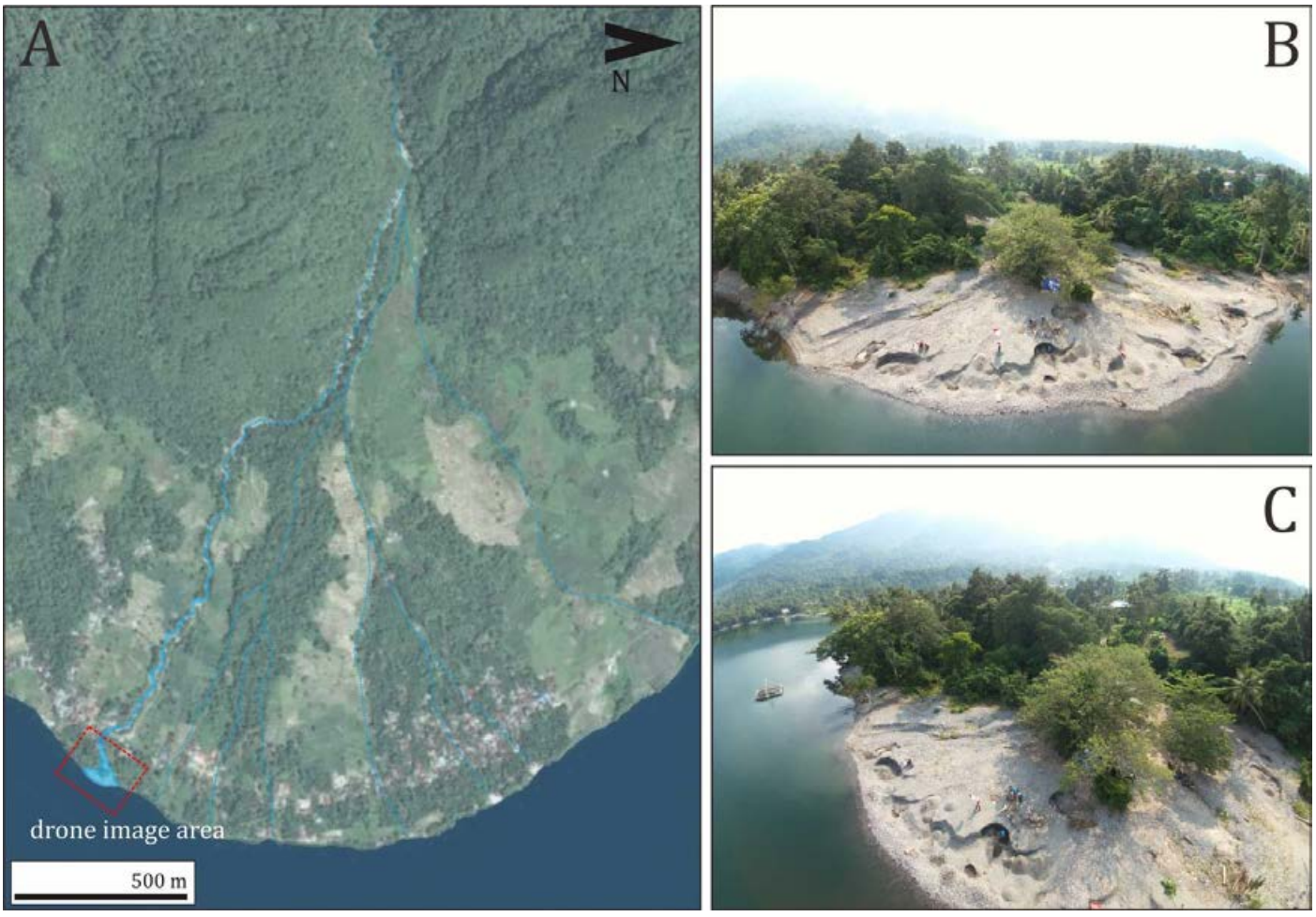


Figure 8. *Malalo Alluvial Fan Delta geometry and morphology. a) Satellite image, b) Three-dimensional image, c) Drone image of river mouth area.*

Depositional Facies

The MAFD is classified as a debris-flow fan based on alluvial fan systems classification from Galloway and Hobday (1996). The sediment characteristics of MAFD show poorly sorted gravels and the surface area of this alluvial fan delta is about 2.4km^2 with 3°-10° surface slope, which allow predominantly debris-flow to take place (Galloway and Hobday, 1996 and Wasson, 1977; cited in Galloway and Hobday, 1996).

There are four main depositional facies association that can be observed in MAFD (Figure 9), which include Upper Fan facies (UPF), Middle Fan facies (MDF), Lower Fan facies (LWF), and Subaqueous Fan facies (SAF). These facies are determined based on sediment characteristics that were observed from the river bed, artificial trenches and offshore data points. In addition, the onshore facies distribution is also guided by morphology interpretation.

Upper Fan Facies (UPF)

UPF develops in the Steep Area (Figure 9). One river bed sample located in the lower part of UPF indicates boulder dominated clasts (boulder size up to 1.3m), poorly sorted fabric, angular to sub-angular grain shape and low sphericity (Table 1). It is expected that facies characteristic in the upper part of UPF near the fan apex tends to be similar but with larger clast size and more angular grain shape. A well-documented example of similar fan facies is in the Van Horn's Proximal Alluvial Fan in Western Texas, United States where most of the proximal fan area is deposited in canyons (McGowen and Groat, 1971). In MAFD, the canyon at the upper part of UPF is 26m wide and gradually decreases down-dip to 17m wide. This canyon facilitates debris-flow process to the lower part of UPF and other more distal settings. Meanwhile, in the lower part of UPF, the facies is more widely-distributed and has geometry of with 335m wide and 260m long (Figure 9).

Middle Fan Facies (MDF)

MDF is found in the Moderate Area where depositional slope is approximately 7°. As slope decreases, larger clasts will be left behind upstream and smaller clasts such gravels are deposited downstream and they cover wider area than the area where the UPF is deposited. The MDF occupies an area of 335m to 1607m wide and 820m long toward the down dip area (Figure 9). Descriptions from eight river bed samples indicate cobble to boulder clast-dominated, poorly sorted fabric, sub-angular grain shaped and low sphericity (Table 1). The percentage of boulder clasts, which are dominant in the UPF, decreases to 20% of total clast composition in the MDF.

Lower Fan Facies (LWF)

LWF is the last facies located nearshore before the lake and is deposited on Gentle Area with 3° of fan surface angle. The LWF has geometry of 1607m to 2064m wide and 445m long toward the shoreline (Figure 9). Generally, the LWF is subdivided into upper and lower LWF based on distinguishable facies characters. Observations on two river beds indicate that the upper LWF is represented by pebble-dominated clasts, poorly sorted fabric, sub-angular to sub-rounded grain shape and low sphericity (Table 1). The lower LWF contains smaller clasts dominated by granule to pebble size, poor to moderate sorted fabric, sub-rounded to sub-angular grain shape, and more mature sphericity (Table 1). This observation was obtained from five artificial trenches in the shore.

The Lower LWF currently acts as the only sediment input into to Lake Singkarak. Consequently a delta shape has developed on that particular location with geometry of 151m wide and 123m long (Figure 10). Understanding of this small delta is critical in order to resolve reservoir potential in an alluvial fan delta setting. As the distance from sediment source increases and steep slope gradient gradually changes to gentle, the debris flow is now associated with sheet flow. It is clearly observed that the facies for this small delta can be separated into two: 1) Debris lobe, and 2) Sheet Lobe.

The Debris lobe facies is characterized by un-stratified gravel size clasts dominated by granule, poorly sorted fabric, sub-rounded to sub-angular grain shape and low sphericity (Table 1), forming two-thirds surface coverage of the total Lower LWF delta area (Figure 10). This facies develops in the central part of the delta which is separated into two distributaries that become the main sediment inlet to subaqueous fan area. Unlike debris lobe, the sheet lobe is characterized by much finer grained sediment that consists of medium to very coarse grains that are deposited in the side of the debris lobes (Figure 10). The geometry of this facies is about 23m wide and 63m long, covering one-third of the area. Based on artificial trenches observation, these facies are deposited unconformably above Subaqueous Fan facies (SAF) (Figure 11).

Subaqueous Fan Facies (SAF)

The Subaqueous Fan is a continuation of the Lower LWF delta which is located below the lake level. There are two lobes in the SAF which is dominantly influenced by the presence of distributaries in the lower LWF. The geometry of this facies is about 190 m wide, 105 m long, and 31° subaqueous slope (Figure 9). Six grab samples and four artificial trenches on SAF reveal cross-stratified, medium to coarse grained (sub-rounded to sub-angular grain shaped, and high sphericity) sands.

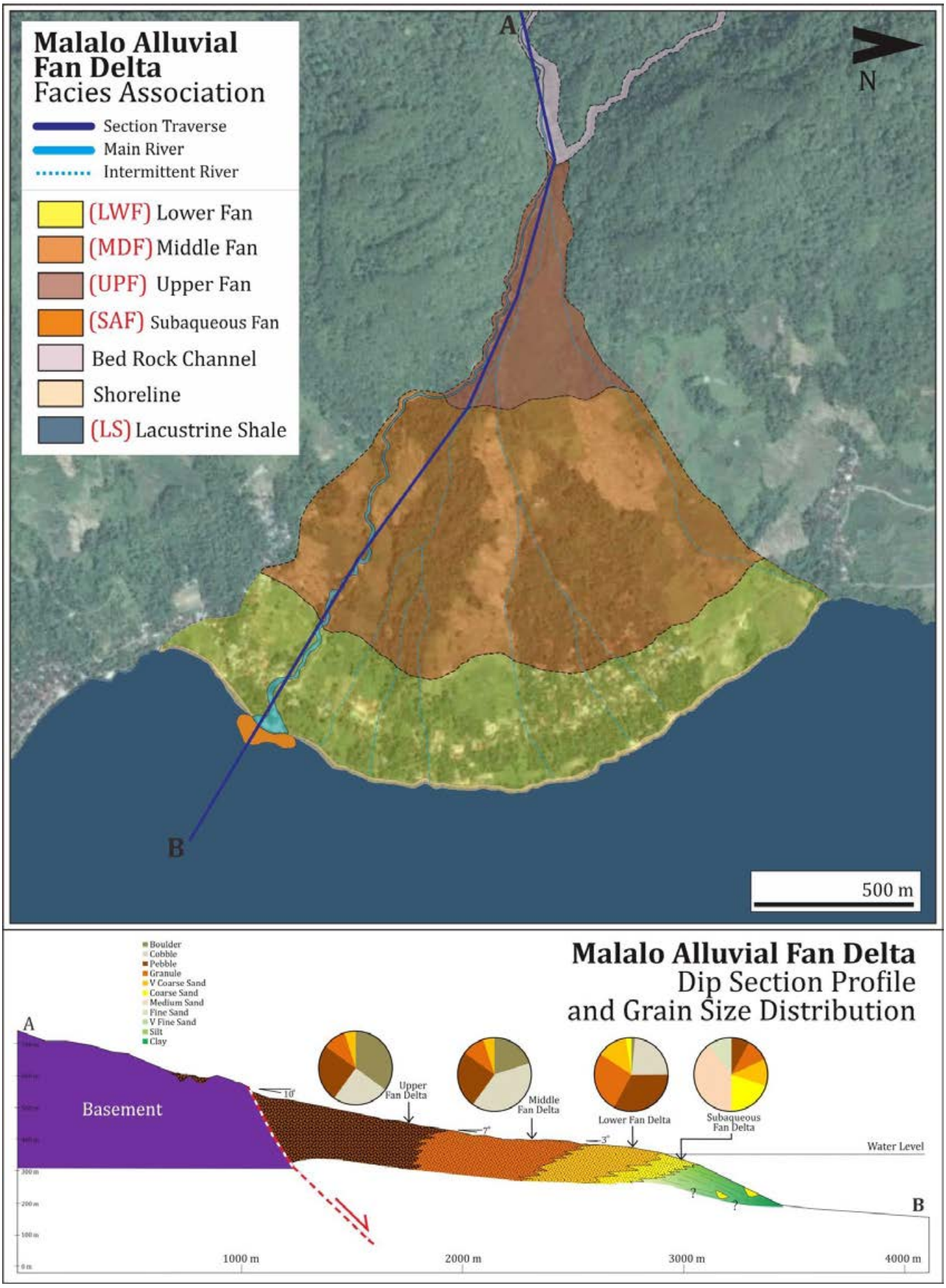


Figure 9. *Regional facies map and a dip section profile of Malalo Alluvial Fan Delta.*

Five other grab samples which are located further from Lower LWF distributaries show silt to clay sediments (Figure 10). This is interpreted as a lacustrine shale deposit which interfingers with the SAF.

Meanwhile, along the coastline with limited sediment influx, wave activity is believed to have taken more important role in depositing sediments. The ancient deposit of MAFD system has been reworked by the wave activity that produced shoreline facies (Figure 9). The geometry and distribution of the shoreline facies was determined by using satellite images and bathymetry data of the MAFD. It is distributed along the shoreline area and is believed that its finer grain size gradually changes into clay size sediment (lacustrine shale) as it enters the deeper basin.

Reservoir Distribution and Proposed Model

Based on facies analysis (Figure 9), sheet sand within lower LWF and SAF are the most favourable potential reservoir in the MAFD. These two facies are medium to coarse grained sands with moderate to well sorted fabric, indicating favourable ranges of permeability and porosity. Additionally, these facies are predicted to have a high degree of connectivity. The less favourable reservoir potential occurs in the Shoreline facies. Its reservoir quality is expected to be moderate and the geometry is fairly limited.

The rest of the facies (UPF, MDF, and Upper LWF) are considered as second priority of potential reservoirs due to their composition which is dominated grain supported of gravel clasts with poor sortation. This characteristic has tendency to produce lower porosity and permeability in the future (Nategaal, 1978 cited in Selley, 2000)

Subsurface reservoir determination in such alluvial fan delta is very challenging. This is mainly because the geometry of reservoirs in this system is usually small (Cohen, 1990). A similar challenge is found in the MAFD system where the most promising potential reservoirs are only associated with a small lower LWF delta.

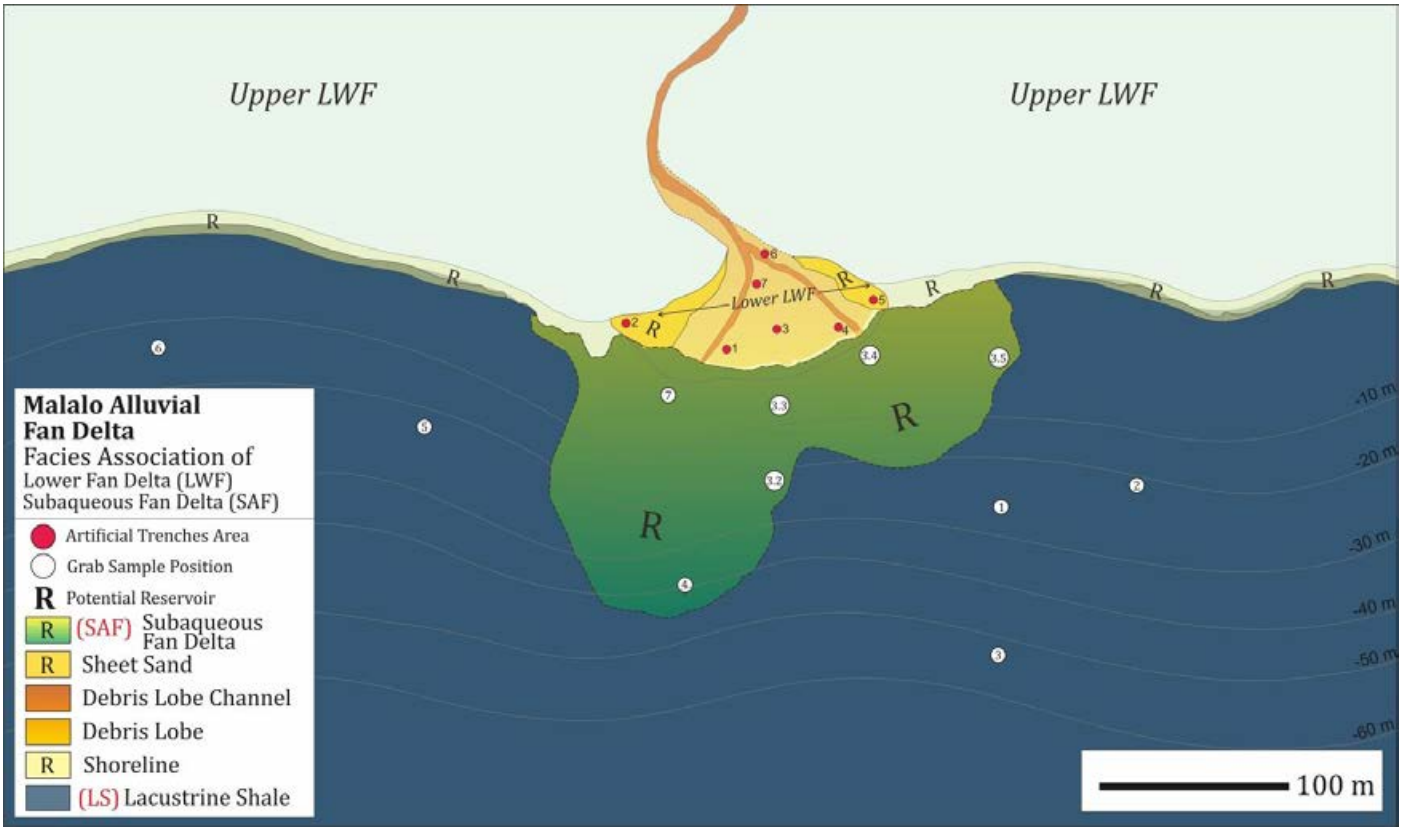


Figure 10. *Malalo Alluvial Fan Delta facies map focusing on near shore area. This map is also completed with artificial trenches location and grab sampling data point.*

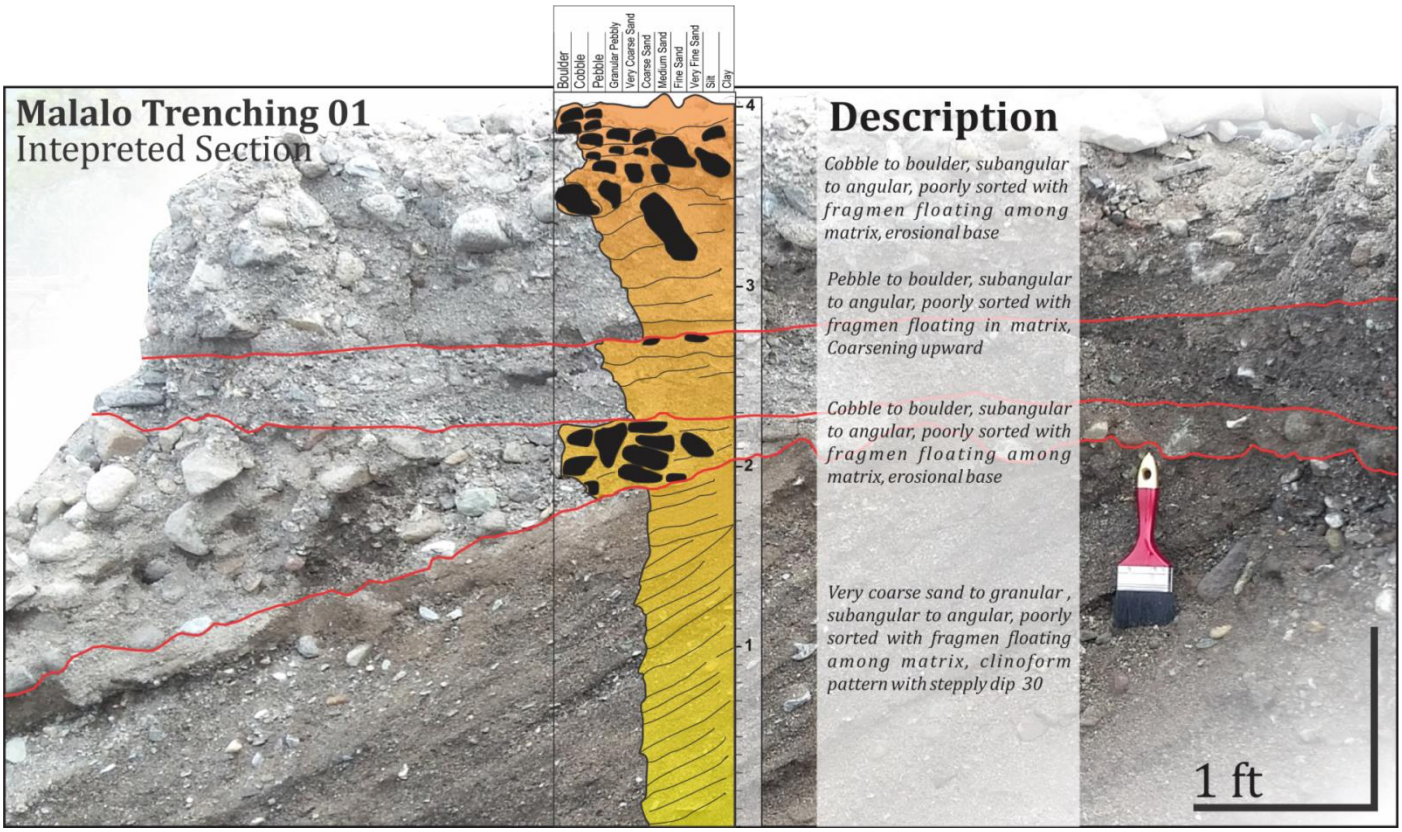


Figure 11. *Sediment description log from one of the artificial trenches located in debris lobe area. Unconformity is clearly observed between Lower Fan Facies (upper part) and Subaqueous Fan facies (lower part).*

DISCUSSION

A proper understanding of depositional cycles and its architectures is essential when working on depositional settings such as Sumpur Axial Fluvial Delta and Malalo Alluvial Fan Delta systems. This knowledge will unlock bigger opportunities by targeting potential reservoirs within and at the proper stages of both environments. The two environments also become the feeders for sublacustrine fans, which have not yet been studied in this research (Figure 12). Further study will be undertaken to explore and evaluate reservoir potential of the sublacustrine fan deposits.

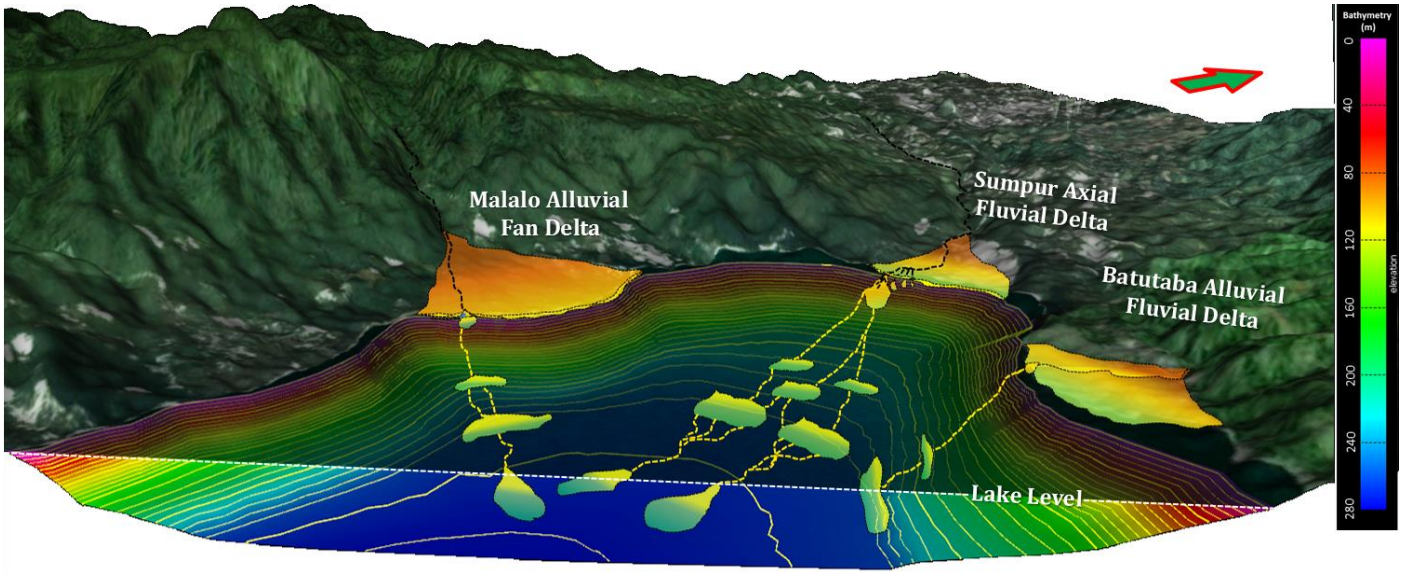


Figure 12. *Three dimensional model of Sumpur Axial Fluvial Delta and Malalo Alluvial Fan Delta. The two deltas are the feeder for various sublacustrine fans.*

APPLICATION IN CENTRAL SUMATRA BASIN ("NAT" FIELD)

A subsurface study focusing on facies model was conducted by Oetary (2016) recently on a field in the Central Sumatra Basin. The facies model resulted from this study is compared to the Lake Singkarak lithofacies in this paper. The objective is to integrate understanding of both surface and subsurface findings with an idea of using the Lake Singkarak as an analogue to part of the field. Here we will summarize the results from Oetary (2016) paper, while for details regarding all methods and interpretation techniques used in the study, the readers are suggested to refer to the original publication.

The study area is located in the North Aman Trough, Central Sumatra Basin (Figure 13) and covers an area of 27 km^2. The field is named "NAT" which stands for North Aman Trough. The reservoir interval of this field is called Upper Red Bed Formation, a member of upper Pematang Group. The Pematang Group consists of various formations that were deposited during synrift tectonic phase (Eubank and Makki, 1981). Synrift deposits usually include lithofacies such as alluvial fan, fan delta, shallow and deep lacustrine, sub-lacustrine fan, and delta facies (Lambiase 1990; Prosser, 1993; Sladen, 1997).

The Upper Red Bed Formation was deposited above the Brown Shale Formation in the Oligocene. Based on Sitohang and Sukanta (1997), sediment in this formation consists mainly of poorly sorted, medium to coarse sands.

Core Analysis

The study done by Oetary (2016) commenced with facies analysis on 119ft of core from the Upper Red Bed Formation. The core shows a coarsening upward stacking pattern and consists of claystone, siltstone, sandstone, to imbricated breccia with occasional laminated carbonaceous materials. Dark shale also occurs within the cored interval. This information indicates that the core had been influenced by two major environments namely onshore slope-related environment and body of water environment. These two environments have produced mass transport and traction-related sedimentary structures and progradational features. There reservoir package was deposited near the border fault during synrift, where alluvial fan to fan delta as the most possible depositional environment of the core (Figure 14). The dark shale in the core may indicate a fan delta setting that was associated directly with lacustrine environment.

Paleodepositional setting interpretation of the core indicates that it was most likely deposited in a Fan Delta. Detailed interpretation was conducted and the core facies were subdivided into: Upper Fan Delta (UPF), Lower Fan Delta (LWF) and Middle Fan Delta (MFD). The Lower Fan Delta (LWF) character in the core shows a lot of similarity to the LWF from surface trenching in Malalo Alluvial Fan Delta (MAFD). Both of them are characterized by coarsening upward successions and dominated by breccia to medium-sand intercalations.

Facies Interpretation and Singkarak Facies Model Integration

Selley (1985) published an ideal facies interpretation workflow that commences with observation to define the geometry, lithology, fossil and sedimentary structure (using paleocurrent as additional data) to build facies and then interpret depositional environment and paleogeography (Figure 15). However, since there is only limited subsurface data in this study, the facies interpretation must be guided by a facies model, a conceptual model or similar case from different areas. In this case, the findings and results from Lake Singkarak are used to guide the subsurface interpretation.

The lithofacies interpreted from core analysis as previously described were then integrated with electro-facies and seismic facies analysis to build facies framework. The result of this interpretation could be defined as geometry input to determine depositional environment and paleogeography (Figure 15). Based on electro-facies analysis, there are two depositional facies within the log interval: fan delta and lacustrine (Figure 16). This depositional facies interpretation was based on log signatures and also guided by facies association concept of synrift depositional environment in the Lake Singkarak. It must be noted that the Singkarak facies model was used for facies association only. The result of electro-facies analysis also supports the seismic facies analysis results and core facies interpretation results.

Seismic facies were determined by characterizing each unit based on the external geometry, internal configuration, continuity and amplitude by using similar workflow applied by Chunchen et al. (2013), Dong et al. (2011), and Veeken (2007). The interpretation was also guided by Lake Singkarak model of facies association. Based on these analyses, there are four depositional environments in the study area, which include fan delta facies, sub-lacustrine fan facies, lacustrine facies and hinge-margin delta facies (Figure 17). This last facies, the hinge-margin delta, is a modified term of lacustrine delta in order to honour its position in tectonically. The lacustrine delta in "NAT" Field is a product of half-graben basin configuration, where the delta is developed on the hinge margin. On the other hand, the Singkarak lacustrine delta is an axial delta system on a full-graben basin configuration.

Therefore, the hinge-margin delta facies as mentioned in the "NAT" field is not present in the Singkarak Model.

Seismic attribute map (RMS amplitude) was made to identify the distribution trend of high amplitude in the study area. In this study, effect of fluid on the amplitude values was neglected. Therefore the high amplitude values indicates sand dominated lithology (Sukmono, 2001), which is confirmed by well-seismic ties. The high RMS amplitudes values on the map are concentrated in the western and eastern part of the study area (Figure 18a). Depositional environment model was constructed by integrating seismic facies map, seismic attribute map, core facies, and electro-facies interpretation (Figure 18b). Based on an overlay of seismic attribute and facies distribution maps, a good correlation between amplitude values and depositional facies can be observed. High amplitude color shows fan delta, sub-lacustrine fan, and delta in the seismic facies.

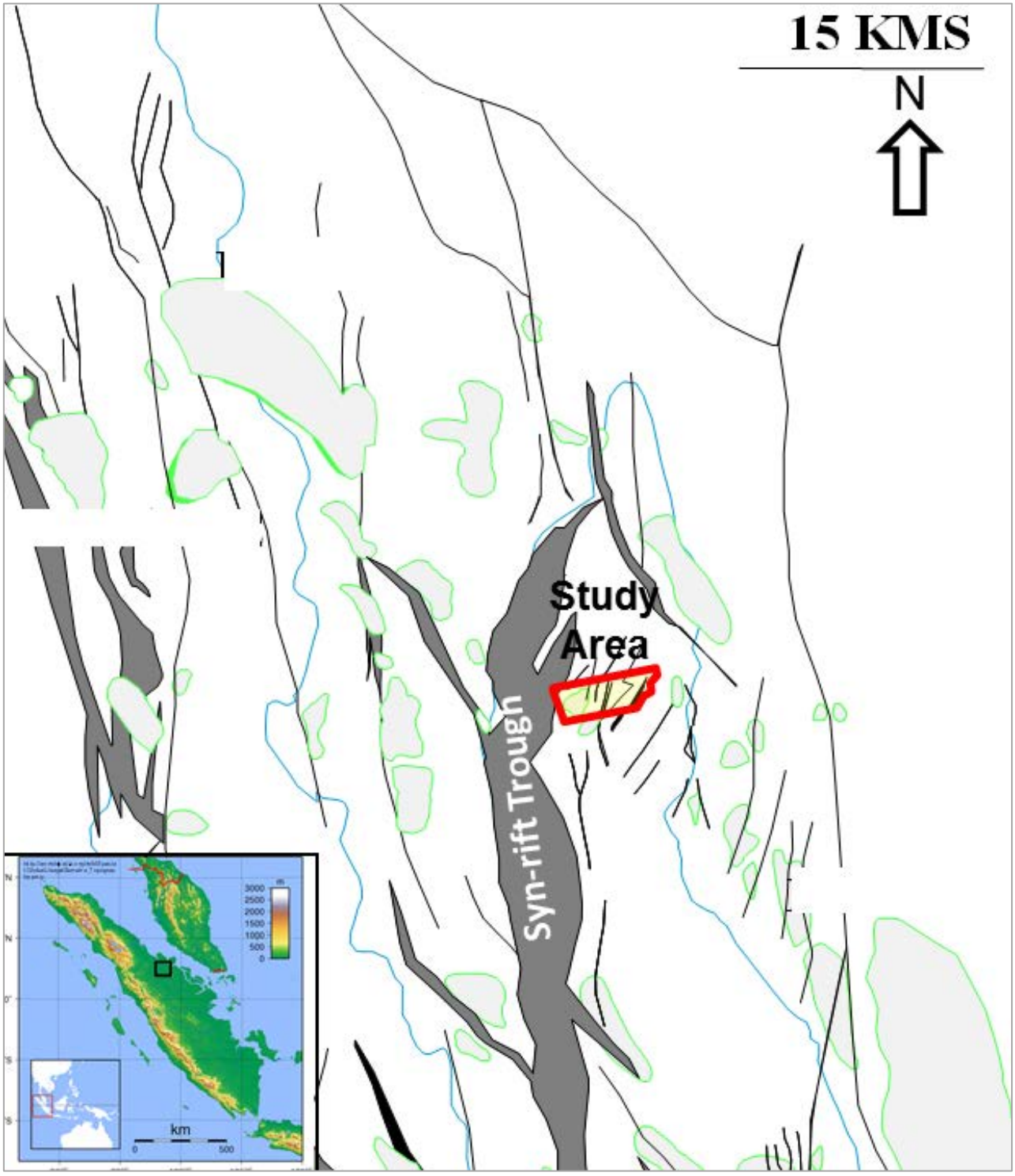


Figure 13. *Location of study area (red polygon), overlain on structural map of Central Sumatra Basin (Modified after Waren et al., 2015).*

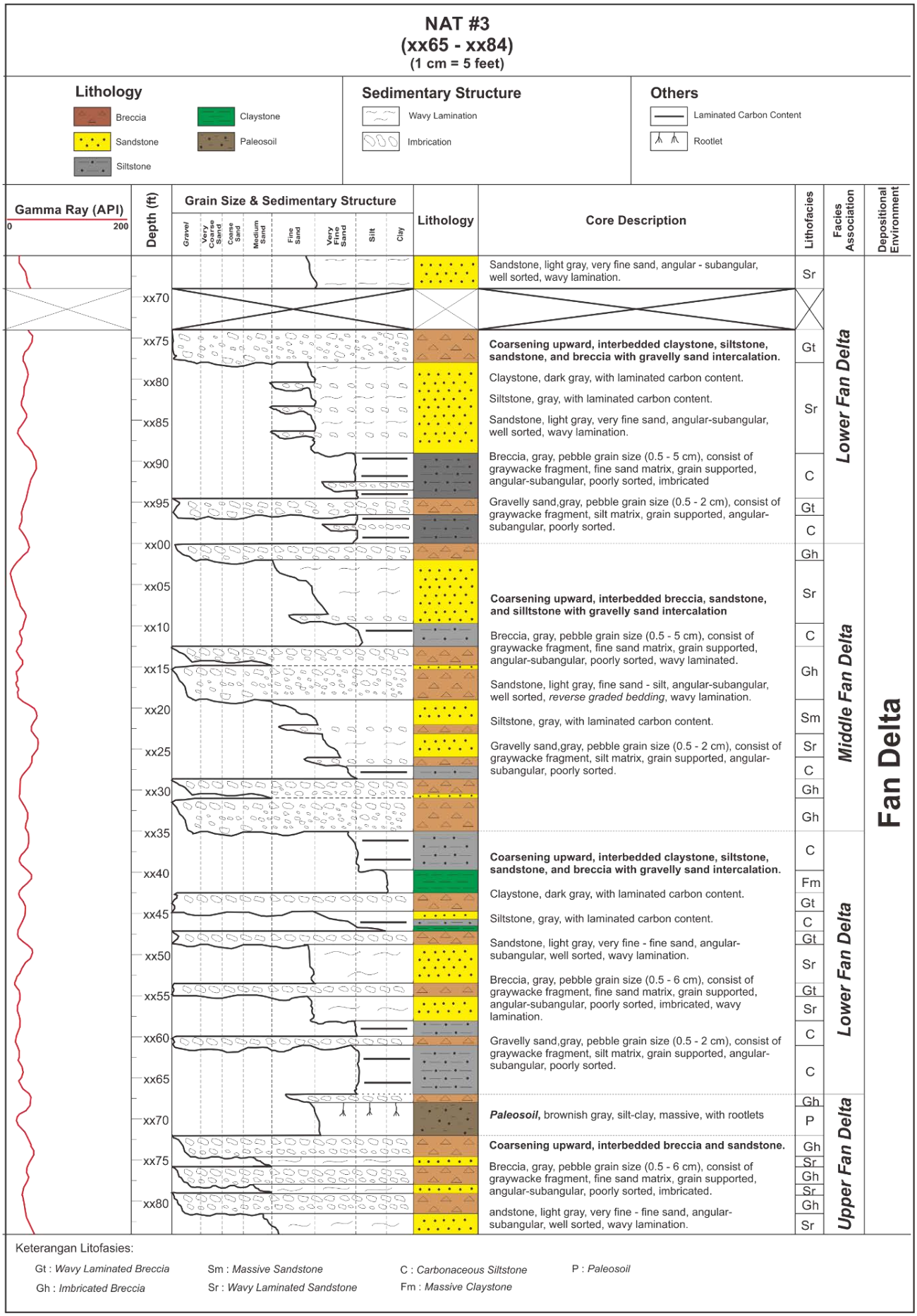


Figure 14. *Core description and depositional environment interpretation from well NAT #3. Lithofacies are subdivided based on Miall (1996).*

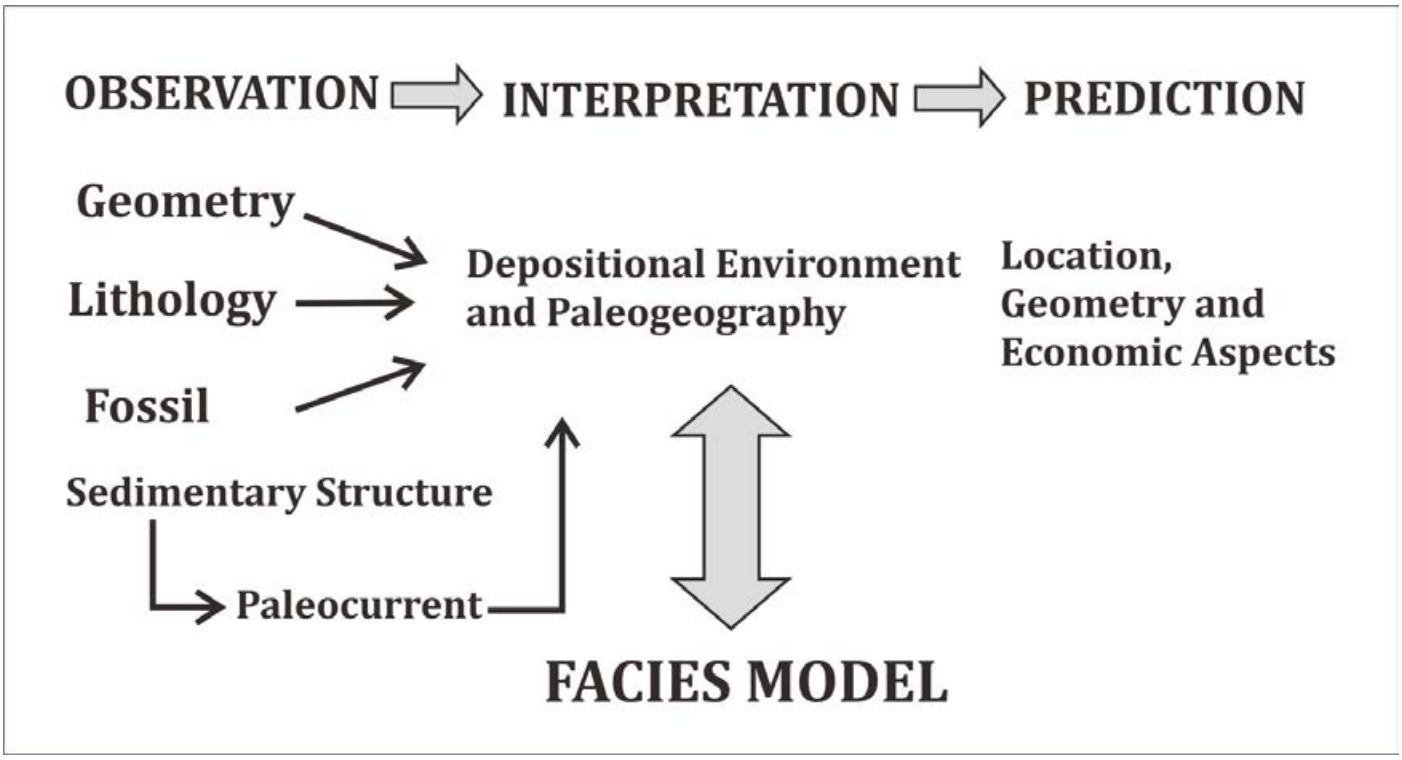


Figure 15. *Conceptual methodology and steps for facies interpretation that includes facies model as reference to produce better interpretation (Selley, 1985).*

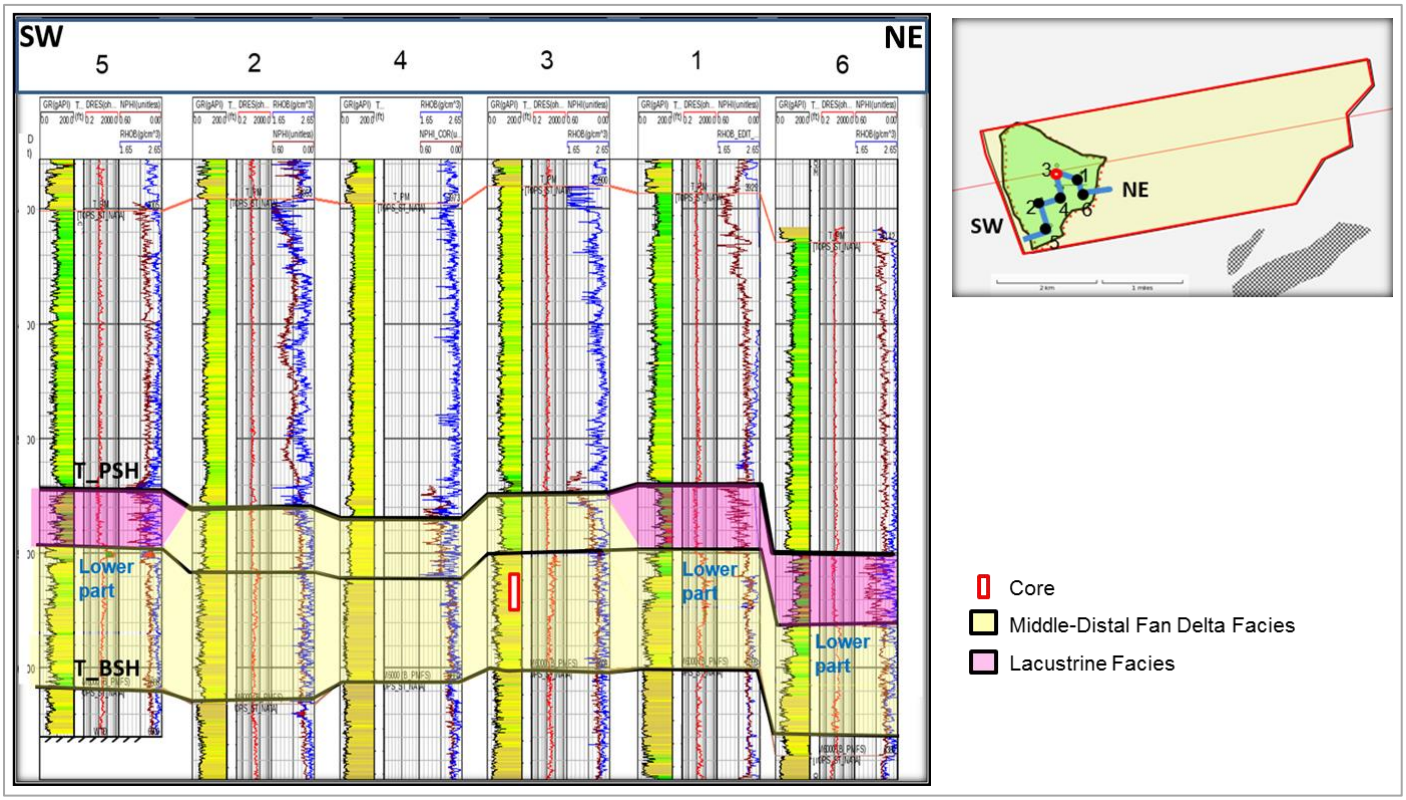


Figure 16. *Stratigraphic correlation from southwest to northeast. The coloured polygons show depositional facies based on electro-facies analysis.*

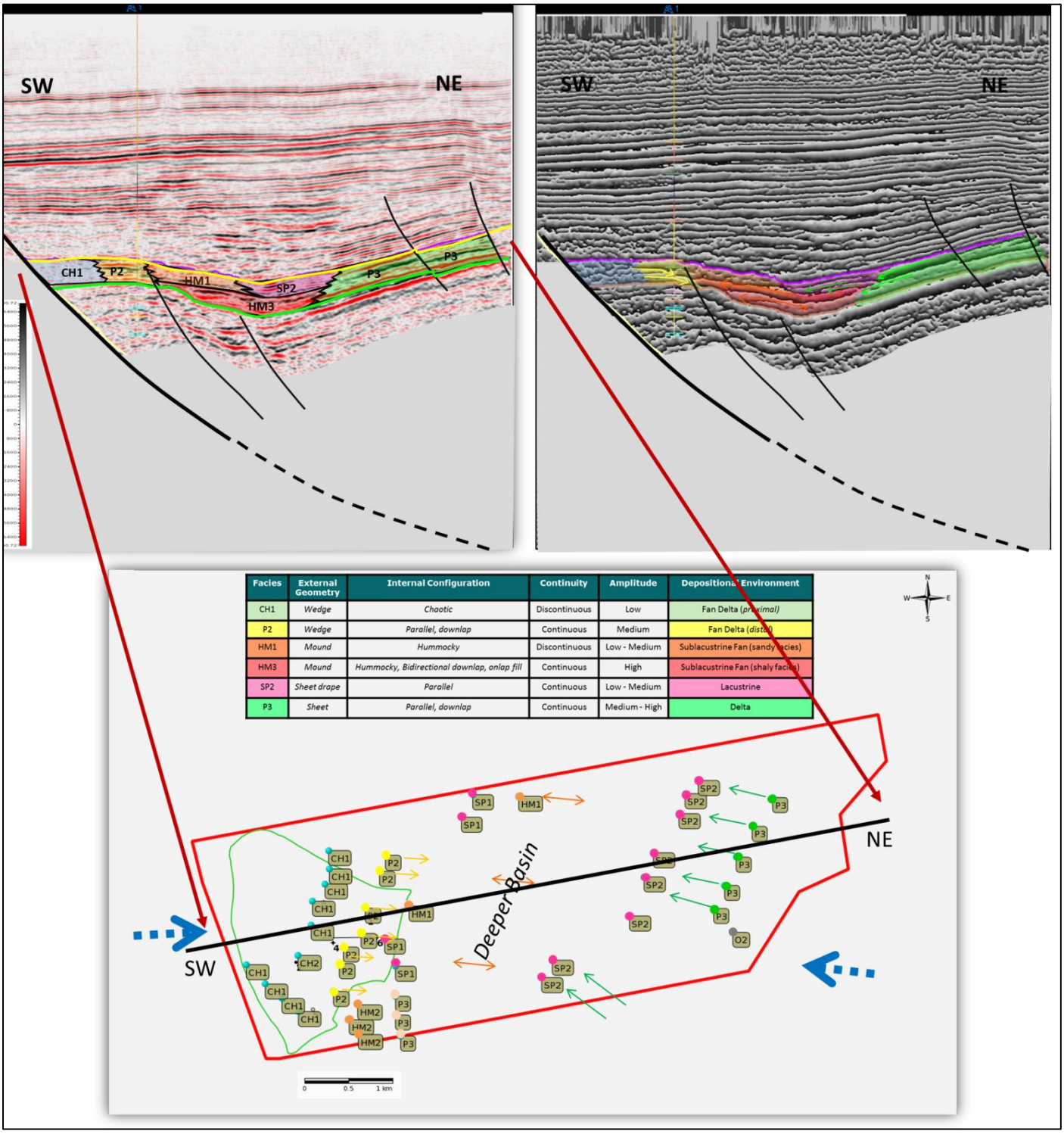


Figure 17. *Three dimension inline seismic bearing SW-NE direction (above) with depositional facies interpretation. Seismic facies map and table of description from each facies are shown on the bottom picture. Coloured dots indicate facies change and coloured arrows indicate downlap or onlap features. The blue arrows at the west of the map shows sedimentation trend (from west and south).*

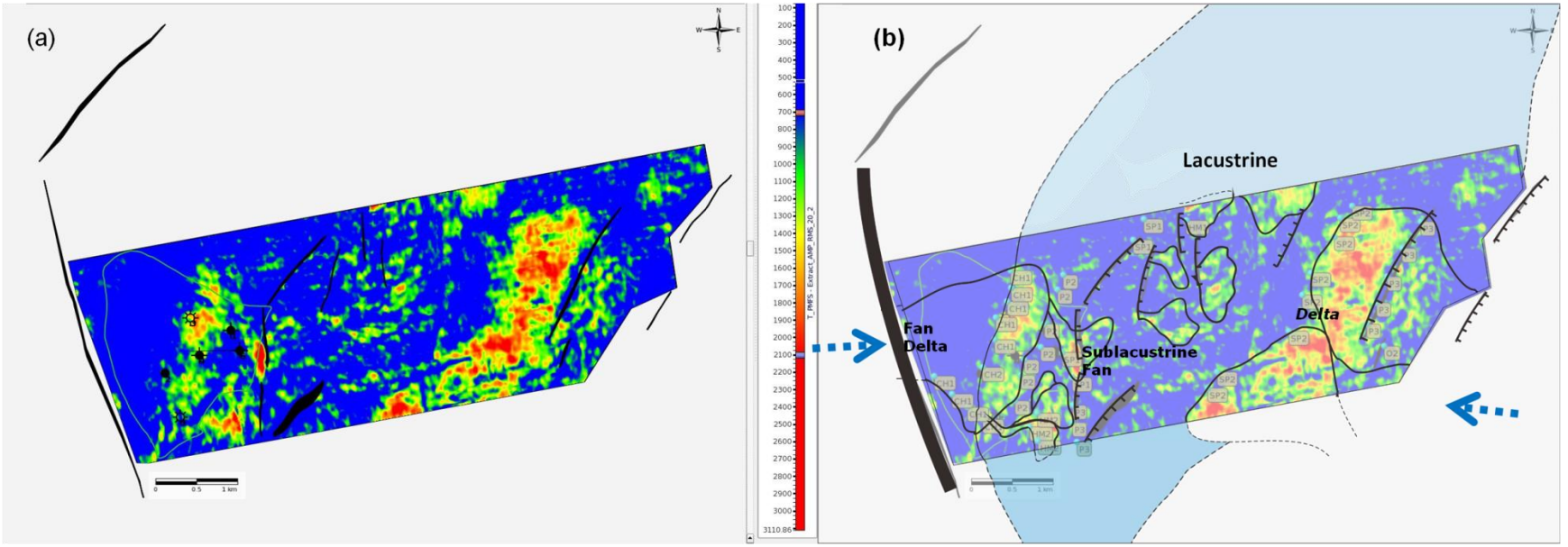


Figure 18. *(a) RMS amplitude map at horizon T_PSH with 20 millisecond seismic window below. Blue color indicates low RMS amplitude values and red indicates high RMS amplitude values. (b) Seismic attribute map overlain with seismic facies map that shows depositional environment model with geometry and distribution interpretation.*

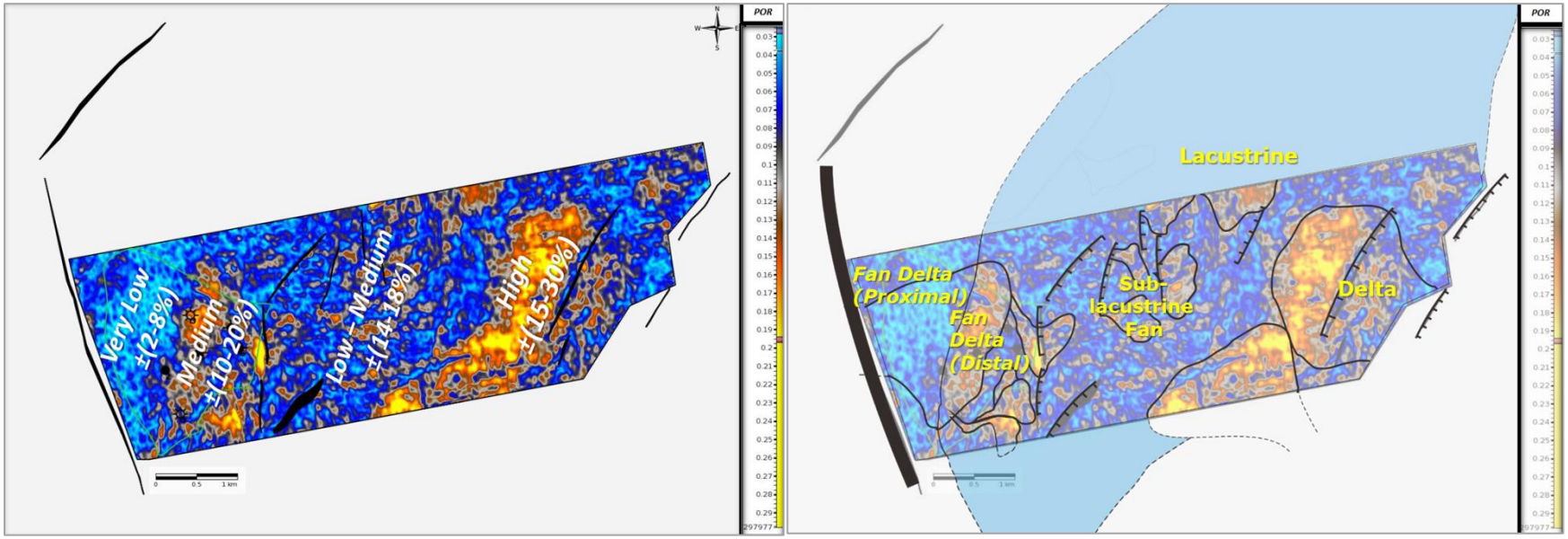


Figure 19. ***(****Left) Porosity map from seismic attribute map at horizon T_PSH to 20 millisecond seismic window below. Blue indicates low porosity and yellow indicates high porosity. (Right) Porosity map overlain by facies map, showing facies with good porosity.*

Facies Property (Porosity) and Reservoir Potential

Porosity values from existing wells were correlated to RMS amplitude values and then were populated to the entire study area to create a porosity map. The methodology to convert RMS amplitude map into porosity map was detailed in Oetary (2016). The porosity map reflects reservoir quality in the study area. This map was then overlain by depositional facies map and it shows that the porosity trend is similar to depositional facies distribution (Figure 19).

In the western part of the study area, the porosity values are very poor (2 – 8%). This area is dominated by poorly sorted, coarse-grained sediments from proximal fan delta. The distal part of the fan delta (with a geometry of ±0.5 x 2km^2), where all of the six wells are located, have good porosity (±10 – 20%), are well sorted and contain finer-grained sediments. In the central part of the area, the porosity is poor (6 – 9%) where it is dominated by lacustrine shale deposit. Isolated good porosity (14 – 18%) area indicates sub-lacustrine fan deposits (with dimension of 0.5 x 0.5km^2). Depositional facies and reservoir potential are summarized on a SW-NE seismic section shown as Figure 20.

COMPARISON TO SINGKARAK MODEL

Based on this study, the facies association model from Lake Singkarak seems to fit and is aligned with certain features observed in the subsurface. This section summarizes specific findings from the subsurface and their comparison with the analogue from Lake Singkarak. Several points that will be included in this discussion are: geometry, internal character and reservoir properties and prospectivity.

Alluvial Fan Delta

The Alluvial Fan Deltas observed in "NAT" Field and the Malalo Alluvial Fan Delta (MAFD) both have irregularly lobate shape and are associated with a border fault. In Lake Singkarak, the Malalo Alluvial Fan Delta (MAFD) has a dimension of 2.1km wide and 2.3km long, whereas the Alluvial Fan Delta in "NAT" Field has a maximum length of about 3km and 2.5km wide. The lithology of both MAFD and "NAT" Field are mostly similar because they are dominated by coarse sediment. Also, the Lower Fan Facies (LWF) of MAFD and "NAT" Field both has the same coarsening upward sequences.

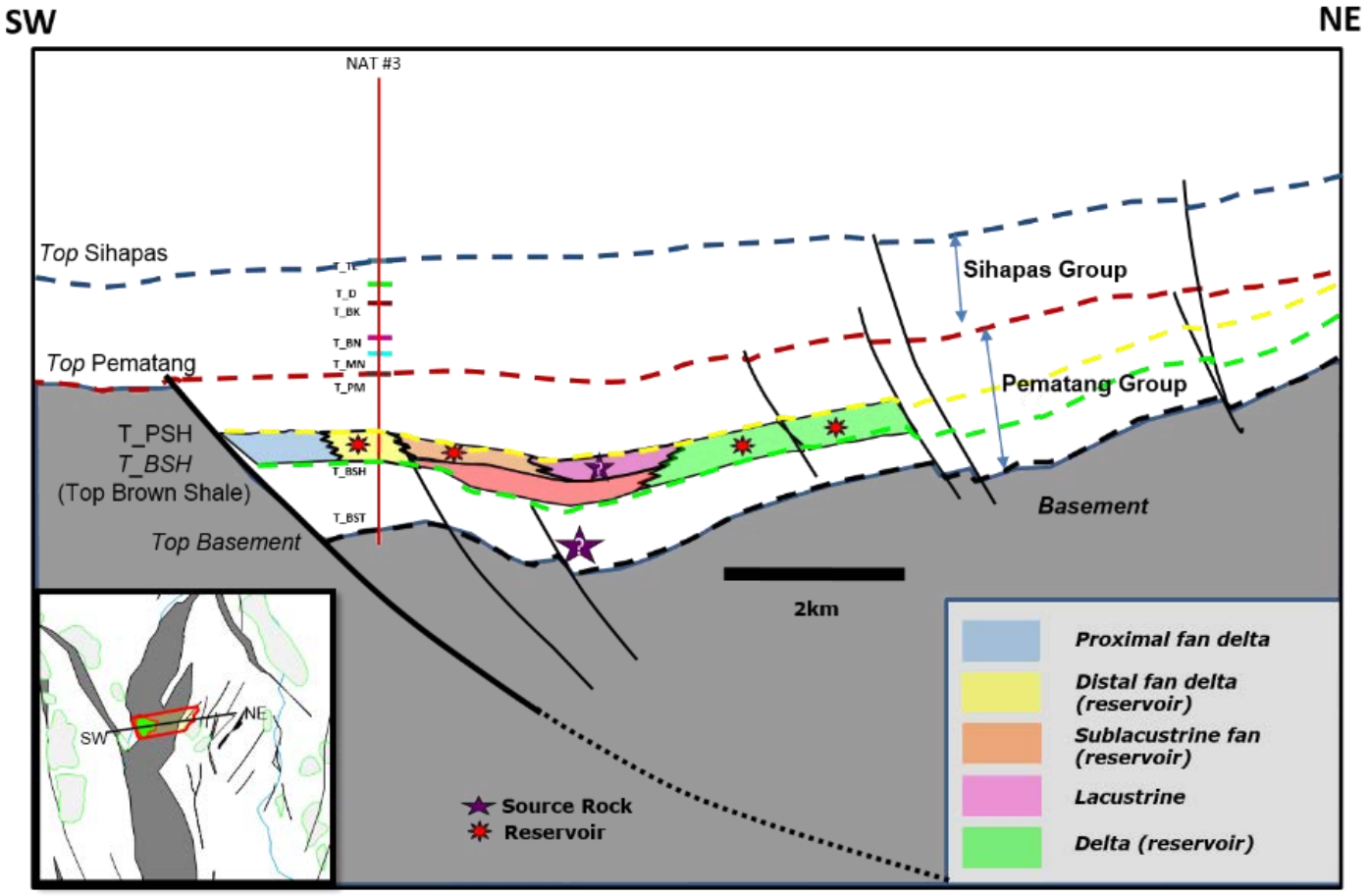


Figure 20. *Reconstruction from seismic line SW-NE direction, showing depositional facies and their potential as reservoir.*

Reservoir properties vary significantly in this kind of depositional environment. Based on surface and subsurface observation, the most favourable reservoir seems to be always located in the distal part, especially within the Lower Fan facies (LWF), Subaqueous Fan facies (SAF) and Sublacustrine Fan. Based on porosity values that were correlated to seismic attribute analysis, both Lower Fan Facies (or in the seismic called as Distal Fan Delta) and Subaqueous Fan facies (SAF) show porosity range from 10% to 20% (Figure 19).

The geometry of LWF commonly shows high degree of continuity, whereas the SAF are found generally in isolated geometry. The Sublacustrine Fan facies has not been described in MAFD because it is inaccessible by the tools that we used in this field work, however it was already discussed conceptually (Figure 12). From seismic attribute, this facies is characterized by isolated geometry with porosity range from 14% to 18%. For the rest of the facies, both Upper Fan facies (UPF) and Middle Fan facies (MDF) are not considered as potential reservoir because from surface observation, these facies are dominated by very coarse sediment with poor sortation. Seismic attribute analysis confirms this finding as these facies generally have low porosity, varying from 2-8% (Figure 19).

Lacustrine Delta

The Lacustrine Delta near "NAT" Field was interpreted from seismic amplitude analysis and none of the wells in the field have actually penetrated it. A comparison was made with Sumpur Axial Fluvial Delta (SAFD) in Lake Singkarak, although the analysis on SAFD focuses on current sedimentation cycle only and its position is not perfectly similar to the location of "NAT" Field's Lacustrine Delta. The SAFD is located at the axial part of the basin while the "NAT" Field's Lacustrine Delta is located at the hinged-margin. In term accommodation space, the hinged-margin area has more space for the delta to spread widely, unlike in SAFD where sediment distribution is limited by fault.

From seismic attribute, the Lacustrine Delta is shown as 2-3km long, homogenous and widely spread lobe. Since this is a small scale observation, its internal character might be really heterogeneous. As previously mentioned in the Sumpur Axial Fluvial Delta (SAFD), the Lower Distributary Channel facies association (LDC, SDC and MB) are the most favourable for reservoir potential since they are characterized by moderately to well-sorted, fine-grained sediment. However, these facies association are geometrically limited in one sedimentation cycle. They need a very good stacking tract to generate a very large reservoir tank. The existence of silt in the channel margin area may contaminate reservoir quality.

CONCLUSION

1. The Sumpur Axial Fluvial Delta (SAFD) is a fluvial dominated delta with elongate to irregular lobate geometry that progrades axially, parallel to NNW-SSE faults. Its depositional facies consist of: Fluvial Channel, Upper Distributary Channel, Lower Distributary Channel, Subaqueous Distributary Channel, Mouth Bar, Shoreline and Abandoned Delta. Based on qualitative and sedimentology-based observation, favourable potential reservoirs are: Lower Distributary Channel Facies Association (Lower Distributary Channel, Subaqueous Distributary Channel, and Mouth Bar Facies), Shoreline associated with Abandoned Distributary/Delta facies and Sand Bar in Upper Distributary Channel facies.
2. The Malalo Alluvial Fan Delta (MAFD) is characterized by an irregular lobate shape and interpreted as a debris-flow fan with geometry of 2.1km wide, 2.3km long, and a slope of 3° to 10° in the onshore part and up to 31° in the offshore part. Its depositional facies consist of: Upper Fan, Middle Fan, Lower Fan and Subaqueous Fan. Based on our interpretation, the Sheet Sand within the lower part of Lower Fan Facies, Subaqueous Fan facies and Shoreline facies are favourable reservoirs with good range of permeability and porosity.
3. Based on subsurface data integration, facies analysis and followed by Singkarak Lake Facies model comparison, there are four depositional facies in the "NAT" field, which include Fan Delta, Sub-lacustrine Fan, Lacustrine and Hinge-margin Delta facies (modified term of Lacustrine Delta).
4. The Alluvial Fan Delta observed in the "NAT" Field matches quite well with the Malalo Alluvial Fan Delta (MAFD). Both of them are irregularly lobate shape and associated with a border fault. The dimension is quite similar (2-3km of width and length) and is dominated by coarsening upward sequences. Based on surface and subsurface observation, the most favourable reservoir seems to be always located in the distal part, especially within the Lower Fan Facies (LWF), Subaqueous Fan Facies (SAF) and Sublacustrine Fan.
5. The Lacustrine Delta in "NAT" Field cannot be compared perfectly with Sumpur Axial Fluvial Delta in Lake Singkarak due to their different settings. The "NAT" Field's Lacustrine Delta is located at the hinge margin and was produced by half-graben basin configuration, while the Singkarak lacustrine delta is an axial delta system on a full-graben basin configuration.

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IAGI Riau Chapter (http://www.iagi.or.id/pengda/) is stand for Indonesian Association of Geologists – Riau Chapter. IAGI Riau is located in Pekanbaru, Riau Province and it focuses mainly on social activities, geological fieldtrips and geological research in Central Sumatra Basin and Ombilin Basin, annualy. This research is fully funded by IAGI Riau itself and supported by its loyal member voluntarily. In this photo (left to right): Willy Paksi, Enry Horas Sihombing, Iqbal Fardiansyah, Faizil Fitris, Habash Semimbar, Endo Finaldhi, Rivdhal Saputra (UGM), Abdullah Talib. Other members who are not included in the photo are: Reybi Waren and Satia Graha. For further information, please contact IAGI Riau at iagi.riau@gmail.com

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