HOW DID CHANNEL SYSTEMS SURVIVE HIGH SEA LEVEL PERIODS? NEW SEDIMENTOLOGICAL INSIGHTS FROM OUTCROP, MODERN ANALOGUE AND SUBSURFACE DATA IN THE LOWER KUTAI BASIN, E. KALIMANTAN

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ABSTRACT

It is generally assumed that fluvial depositions reached their peak in low sea level conditions and that high sea levels were generally considered as a period of neglected breaks in sedimentation and thus were ordinarily interpreted to be associated with an abandonment phase. In contrast, our recent findings from outcrop and subsurface data in the Lower Kutai Basin, East Kalimantan has revealed a complex response in the channel-fill development stages within relatively high sea level periods (either authigenic or allogenic factors). Evidence has shown that some channels certainly "survived" the abandonment period.

A three km detailed transect was measured through several road cuts and coal mines in the Samarinda Anticlinorium area. The well log, FMI, pressure analysis and core petrographic analyses permit an assessment of the subsurface pattern. The integrated biostratigraphy data (foraminifera, nanno-plankton and palynology) are used to synthesize the regional marker. This study also benefitted from unmanned aerial vehicle (UAV) mapping, which created a high resolution (1-3 cm precision) 3D digital outcrop model (DOM). To complete the final perspective view, the recent channel deposits in the Mahakam Delta and Balikpapan bay are also used as a comparative model. These entire measurements and intensive amount of information are synthesized into the integrated geological model.

We identify three typical depositional models of highstand channels due to their specific responses at the channel upper boundary, namely: i) drowned fluvial channel, ii) backfilled/keep-up channel and iii) fluvial channel to shoreface rejuvenation. This study also reveals new insights about the sedimentary processes and facies geometries in the Lower Kutai basin. This unique phenomenon was affected by (a) a large tidal prism area that covers the entire delta systems and (b) a short (40-45 km.) fluvial to shelf sedimentation conduits, combined with (c) relatively high sedimentation fluxes. This type of sand has been long overlooked and currently become recognized as a new bypassed oil reservoir. This new insight is noteworthy toward the re-assessment of the geological model.

Keywords: *transgressive channel, analog study, Mahakam Delta, drone*

INTRODUCTION

The Mahakam delta is a notable example of a mixed tide and river dominated delta (Galloway, 1975, Allen, 1979, Storm et al., 2005, Boyd et al., 1992, Husein and Lambiase, 2013). The modern Mahakam delta system is considered as a low wave-energy, mixed tidal (semi-diurnal tidal with mean range of 1.2 meters and maximum amplitude of 2.8 meters) and fluvial (average river discharge of 8x106 Mm3/yr) dominated delta (Combaz and De Matharel, 1978, Allen, et al., 1979). The early studies by Allen et al., 1976, Allen and Mercier, 1988, state that this delta delivers significant terrigenous material into the tide dominated coastal area, thus the interplay between the fluvial and tidal processes are essential to determine the final facies product.

The delta system drains a total catchment area of 75,000 km^2, with a 2,000 km^2 area manifested as the sub-aerial delta (Gastaldo et al., 1993, Cibaj, 2014). The late Quaternary stratigraphy study in the shelf records the high cycle of relative sea-level changes; demonstrated in the fast interplay between the fluvio-deltaic and shallow marine sedimentation processes (Roberts and Sydow, 2003). The studies of the recent depositional system (Gastaldo, et al., 1993, Storms et al., 2005, Husein and Lambiase, 2013, Riadi and Lambiase, 2015) shows that in the present time, the fluvial discharge is several times smaller than in the past and the delta is nearing abandonment by dominant tidal and wave processes. The specific conditions which have shown the overall interplay between river, tide and wave action are also common and observed elsewhere in many age periods such as in Mesoarchean Moodies Group in

South Africa (Eriksson et al., 2006), Cretaceous McMurray Formation in Canada (Musial et al., 2012) and Tertiary Taishu Group, Southwestern Japan (Nakajo, 1998).

Our study characterizes the facies and stratigraphy of the shallow marine and deltaic sequence from outcrops around the Sangasanga, Samarinda and Semberah areas and compares them with the subsurface data and modern depositional processes. This field study is required to fill the knowledge gap about the detailed succession and stratigraphic stacking pattern, geometry and sandstone reservoir heterogeneity. Our study aimed to see the similarity between surface and subsurface data and to find a typical succession that is distinguishable in the subsurface for a better reservoir geometry prediction.

The Sangasanga Field has been producing for more than 120 years. The field development was commenced by the drilling of LSE-01 well in 1897 by Dutch BPM. This oilfield could be considered as one of the oldest fields in the South East Asia, however the significant remaining reserves in Balikpapan Formation are confined in the deltaic-shallow marine facies, thus a detailed facies association recognition and correlation is needed to settle yet-to-find additional reserves in previously overlooked oil zones.

BASIN SETTING

The study area is located in the onshore area of the lower Kutai Basin (Figure 1). The basin is an open embayment facing eastward to the Makassar Strait, bordered by the suture of the early Tertiary Makassar strait rifting the Central Kalimantan High to the northwest, by the Adang Flexure and Paternoster platform and Meratus Mountains to the south and the Mangkalihat High and Sangkulirang Fault to the north (Figure 1). The basin was formed initially by rifting in the Middle Eocene and subsequently filled by syn-rift sedimentation as well as carbonate until early Miocene.

This succession was folded and created the Samarinda anticlinorium (Figure 2), which became the paleotopography for the younger fluvio-deltaic sub-sequence of the Kutai Basin (Tanean et al., 1996). The Mahakam River has started to incise -

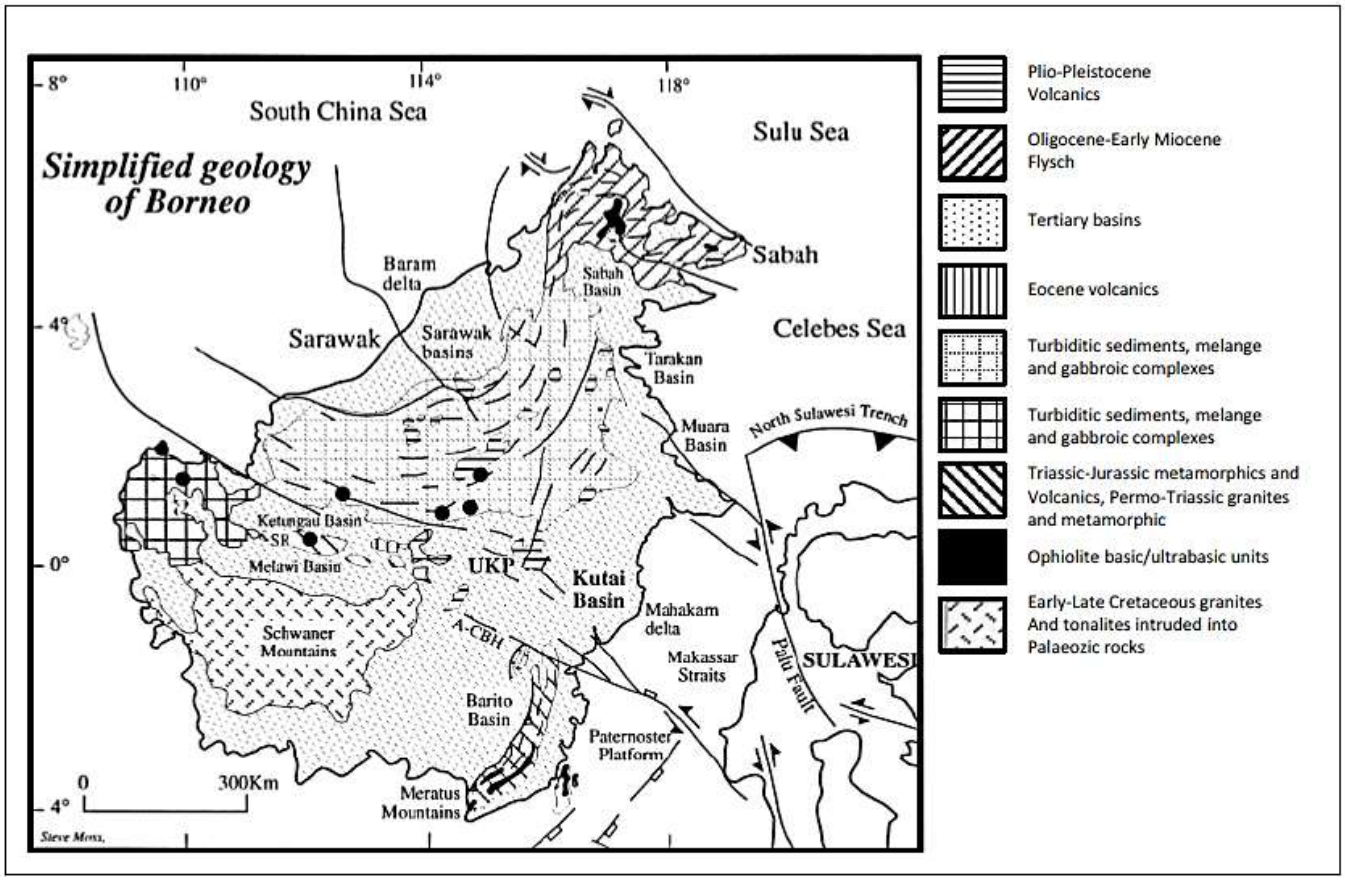


Figure 1. *The regional overview of the Lower Kutai Basin area (after Moss and Chambers, 1999)*

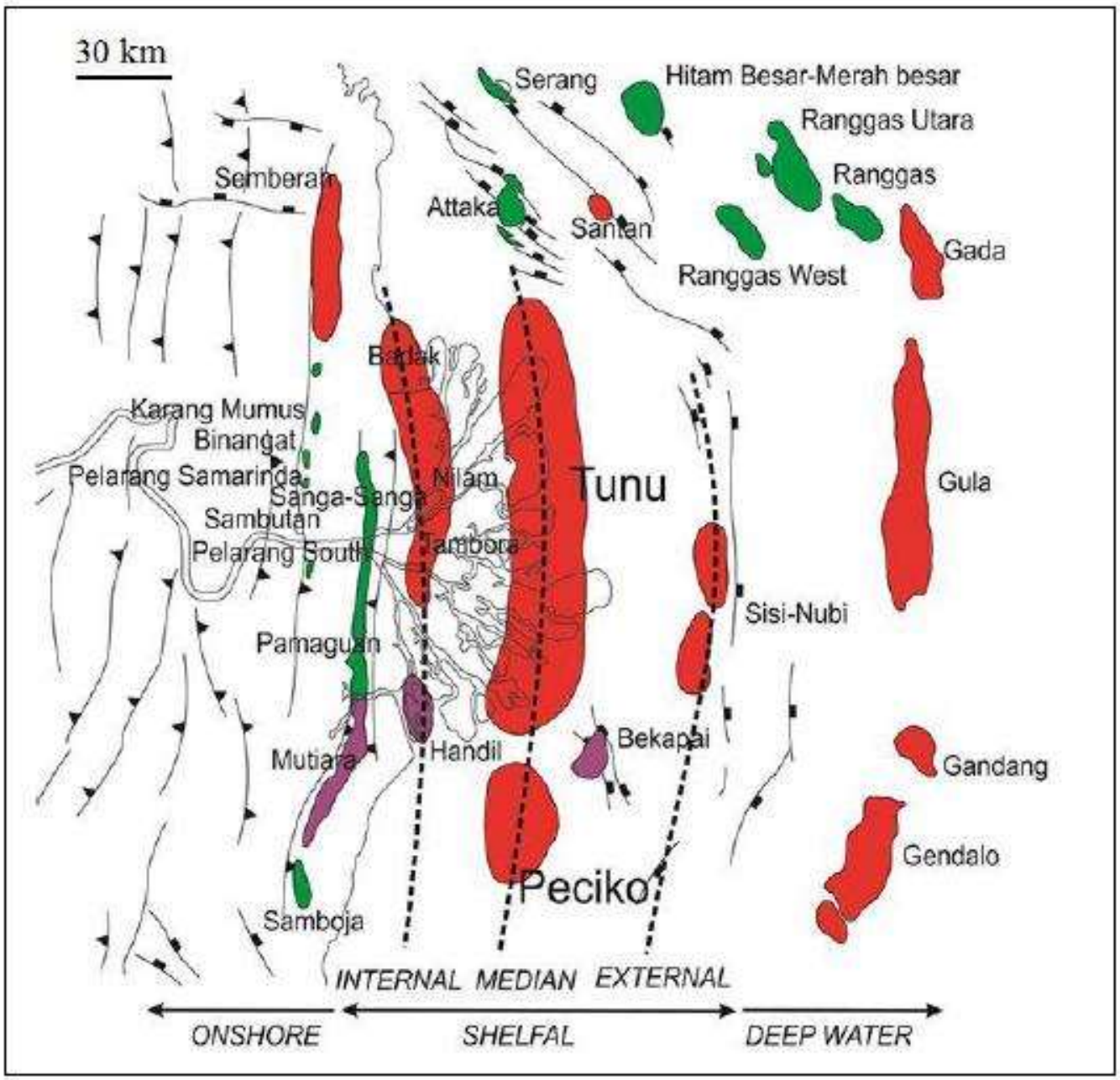


Figure 2. *Major anticlinal ridges in Lower Kutai Basin with an inferred hydrocarbon accumulation area, green and purple: oil red: gas (after Ramdhan and Goulty, 2010)*

the Anticlinorium ridge since Middle Miocene, which created successive delta progradation towards the east (Allen and Chambers, 1998).

For a decade, the structural development in the Kutai Basin has been receiving detailed reviews by many researchers, which has resulted in many published hypotheses (Satyana et. al. 1999), including amongst others vertical diapirism (Biantoro et al., 1992) gravitational gliding due to the eastward basin compensational subsidence and Kuching vertical uplift (to the west) (Ott, 1987, and McClay et al., 2000). Other tectonic movements were: inversion by regional wrenching (Biantoro et al.,1992), detachment folds over inverted structures (Chambers and Daley, 1995) and inverted delta growth-fault system (Ferguson and McClay, 1997).

Recent studies including ours have believed that the Northeast-Southwest oriented faults are the major fault that was constructed by the inverted delta growth fault system. This fault system becomes a major compartmentalizer, which separated the Samarinda Anticlinorium into

several parallel anticlinal or synclinal blocks (Figure 2).

Stratigraphically, the hydrocarbon-prolific sandstone units are belonging to Mentawir-Gelingsih Formation, a member of the Balikpapan Group. It consists of predominantly quartz sandstone, conglomerate, silty claystone and shale with intercalations of thin limestone and coal. The maximum thickness of the sediment to the east of the basin is 14 km, whereas the average thickness in the tertiary paleo-delta elsewhere is approximately 9 km. (Rose and Hartono, 1978, Allen and Chamber, 1998).

The oldest sediment was deposited on during the Middle Eocene, starting with an extensional rift phase associated with the initial spreading in the Makassar Strait. Deposition of the The deltaic sequence started in Early Miocene, continuously prograding toward the East with an average thickness of 3.5 km.

DATA AND METHODS

A detailed sedimentological section along roughly three kilometers transect was measured through several road cuts and coal mine sites. The depositional dip from cross laminated layers was recorded wherever possible for each section. The trace fossils, which are noticeable in Palaran, Semberah and Sangasanga outcrop were photographed to aid detailed identification and quantification. These locations of the measured stratigraphy and samples collected are saved in GPS in sub-meter accuracy and wherever possible were correlated to their subsurface equivalent layers by using either seismic data or published biostratigraphy markers (Marshall et. Al., 2015, Rösler et al., 2015 and Santodomingo et. al., 2015).

Integrated biostratigraphic data (foraminifera, nanno-plankton and palynology) from cutting, cores and sidewall cores were used to synthesize the regional marker. In delta-plain and upper delta front environments, the presence of the calcareous fossils demonstrates marine invasion and they are flooding surface indicators. There are several key fossils for environmental indicators such as: *Trochammina sp., Miliammina sp., the pollen of Z. ramonae, Florschuetzia sp., Cassuarina sp., Cephalomapa* and *Sapotaceae* for delta plain environment and *Dinoflagellate* for delta front environment (BATM Trisakti, 2013).

The 3D drone photogrammetry, photography and photomosaic of the outcrops were taken to capture and identify the size and geometry of the depositional elements. Core data were acquired from two wells and recovered some 30 metres of mixed sandstone, siltstone and shale sediments. The 3D CT scan of the core slabs was also acquired to see the internal character of cores. Standard wireline logs data are were used for correlation and formation micro-imager (FMI) was then used to identify sedimentary structures and the presence of the bioturbation in subsurface. These entire measurements and vast amount of information were integrated into the geological model.

OUTCROPS OBSERVATION, RESULTS AND INTERPRETATION

The outcrop observation, visual characterization of core and well correlation show similarities and are comparable in lateral variability, succession, inferred geometry and scale. These characters can be considered to be unique to the proto-Mahakam delta and cannot be found elsewhere in the other deltaic systems. Generally, the stratigraphic succession could be subdivided into three main characters. The following are some key examples referred to their type locations (Figure 3).

Stadion Utama Palaran

The Stadion Utama Palaran is located on the southern side of the modern Mahakam river (Samarinda Seberang area). The 250 m. dip-parallel outcrop is exposed on both sides of the main access towards the Stadion Utama Palaran. The outcrop displays several repetitions of what is inferred as coarsening-up parasequences and present a clear observation of the facies changes from the fluvial dominated upper delta plain to the strongly tidal influenced lower delta plain and delta front (Figure 4a and 4b). This outcrop provides an excellent opportunity to learn about the ideal deltaic succession without any noticeable external controls on the depositional architecture, including morphology, biogenic and oceanographic aspects in the lower distributary and delta front area. This outcrop is slightly older than the Serravallian age (13.82-11.62 Ma) based on the limestone dating at the top of the sequence (Rösler et al., 2015; Santodomingo et al., 2015).

The deltaic succession in the lower part shows a sharp-based contact typical of the erosional boundary (rip up clast, lag deposit); followed by channel filled deposit comprising of coarse to medium grained sandstone with trough cross-bedding that gradually changes into high angle to low angle planar cross-bedding (Figure 4b). This change suggests decrease of bedload capacity; and possibly indicates flow deceleration as the channel abandonment phase began. Bioturbation (*Skolithos* and *Ophiomorpa*) intensifies upwards and the top of channel is capped by a more tidally influenced deposit. A thin and sulphuric coal deposit is present with locally intercalated thin lenticular

oyster bed; interpreted as a peat beach deposit. Significantly, this deposit marked a local transgressive event specific to this paleo-drainage area (Figure 4c).

The coarsening and thickening-upward sequence with various magnitude of tidal and probable wave control is present, typical of the progradational delta front deposit, depending on the local environment during the sedimentation (Figure 4d). This last sequence is interpreted as occurring in the highstand sea level periods. This entire succession is repeated for at least two semi-full cycles within the entire total length of Stadion Utama Outcrop.

Simpang Makroman

The Simpang Makroman outcrop is located in the exit way of the Lana Harita mining site in Simpang Makroman and exposed for more than 40 meters along strike and can be divided into two facies units. The lower unit consists of alternating thin siltstone and sandstone with well-preserved flaser and wavy structures, which gradually changes into interbedded sandstone in organic mudstone (Figure 5). This unit is intensively bioturbated with dominant burrows by *Ophiomorpha, Skolithos, Phycosiphon* and some *Diplocraterion*. In the middle part, the unit is scoured and cross-cut by 1.2 m. thick medium to very fine sandstone.

The sandstone shows wedge bed geometry, finning upward succession and seems to be devoid from bioturbation except in several spots where *Ophiomorpha* is observed. A calcareous, fine to medium bioclastic and fossiliferous sandstone is found in the middle of the channel. This clastic carbonate is possibly occurring in the distal reach of the reef encrusting area, thus suggesting a clear seawater environment with minimum bedload reaching the sea. The channel is fining-upward with visible current ripples and climbing ripples in the upper part of the channel.

Based on the ichnofacies and the physical proximity to the marine environment and also the increase of marine influence upwards, this channel

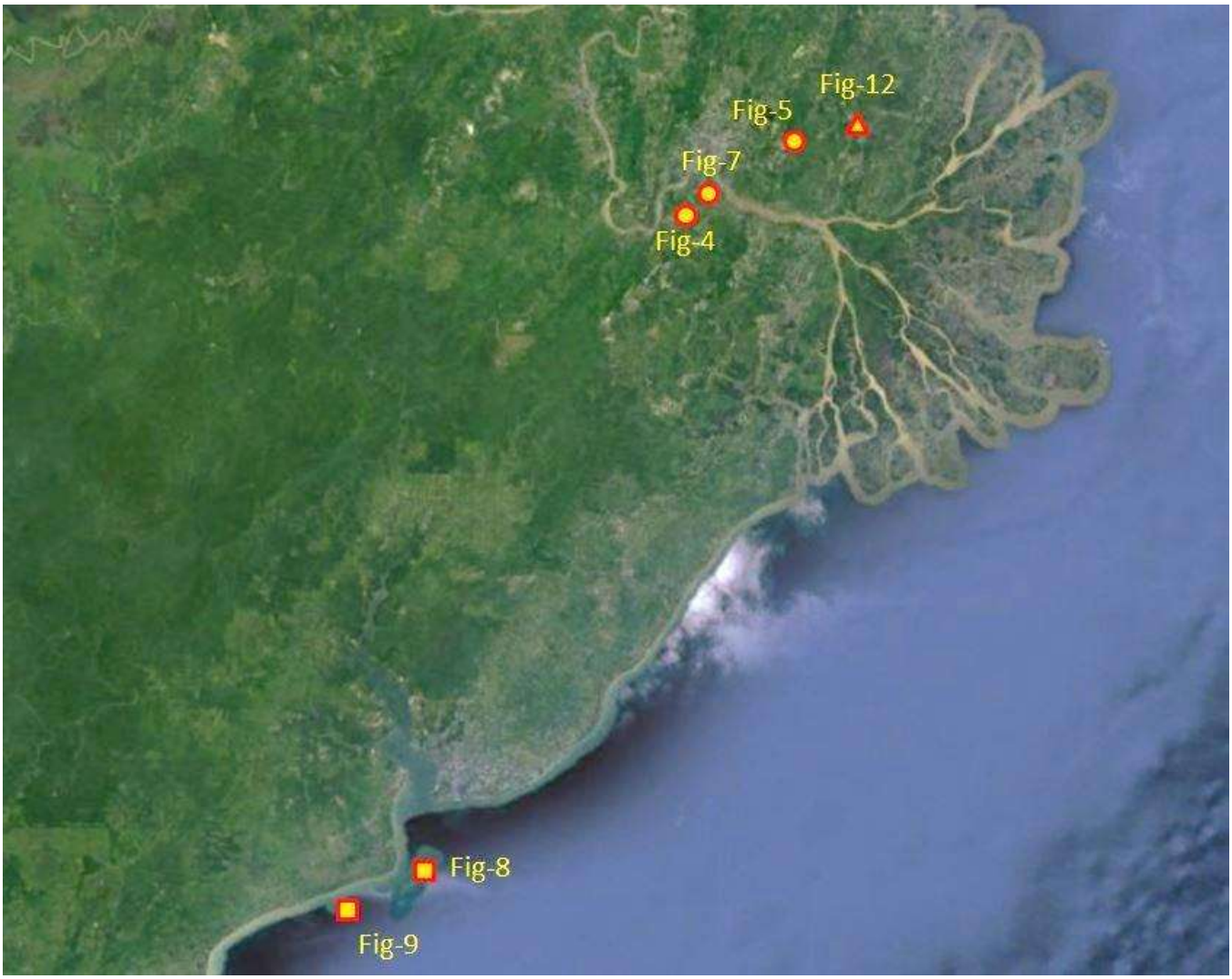


Figure 3. *Index map shows the location of objects discussed in this study (square = modern deposits, circle = outcrops and triangle = subsurface data (map created from Google Earth)*

was interpreted as back-filled tidal channel deposited during the early transgression. In North Kutai Lama (NKL), oil is produced from this type of sandstone (C groups) with a typical serrated and spiky log character, Pertamina EP nicknamed as "*Hidung Petruk*" log (Figure 6). The uppermost - succession of the outcrop was cut by thick sandy deposit which consist of medium to fine grained sandstone with trough cross lamination to planar cross lamination. This sandy interval has a sharp basal contact suggesting that the tidal sequence is eroded and partly cannibalized by the upper shoreface succession.



Figure 4. *(a) aerial view of the outcrop at stadion Utama Palaran stadium shows a repetition of the deltaic parasequences (b) The vertical succession is showing a succession that interpreted as lowstand fluvial channel-fill into the transgressive and highstand shallow marine deposit. (c) The coquina bed in the thin coal layer indicates a transgressive delta front deposit. (d) The oscillation wave ripple sediment on in the upper interval shows a gradual change from a litoral littoral environment into a shallower marine. deposit. Coordinates: 512349.03 m E, 9935280.49 m S, (see Figure 3 for the outcrop location).*

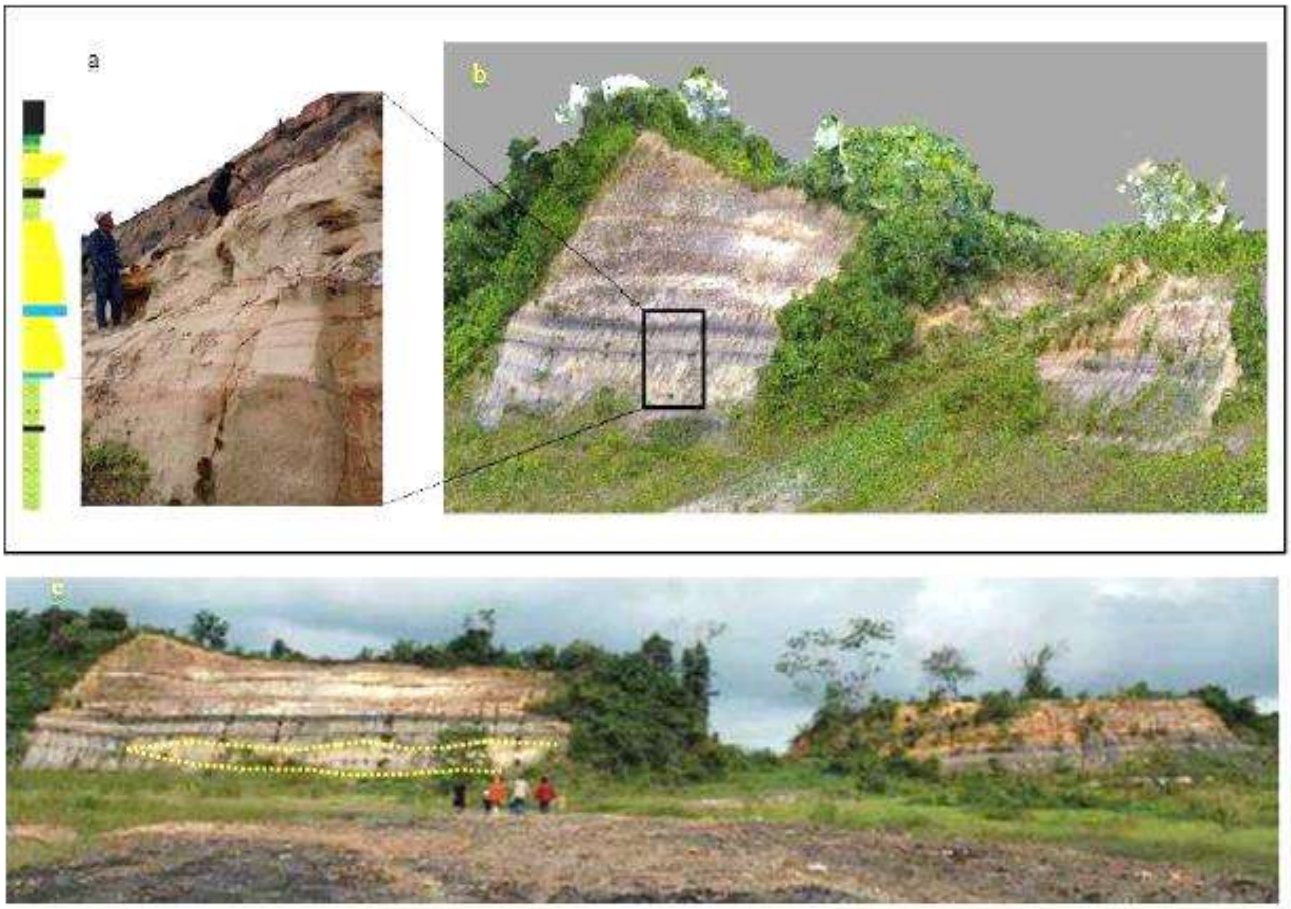


Figure 5. *(a) The succession of tidal channel in Simpang Makroman outcrop shows an intercalated thin limestone in the bottom part of the channel. This limestone occurrence suggests the retrogradation of the carbonate during subsequent fine sand deposition suggesting of backfill type. sedimentation. (b) Aerial drone view showing an (inset: of the measured stratigraphic section (c) the cross section view of the exposure shows the geometry of the channel (yellow dotted line). Coordinates: 518422 m E, 9943987 m S, (see Figure 3 for the outcrop location).*

Mahkota Dua Bridge

The Mahkota dua bridge outcrop exposes 70 m. along strike that shows a transverse section of the typical lower delta plain to delta front sequence interpreted as mixed sand and mud tidal flat crosscut by a distributary channel (Figure 7). The lower section is intensively burrowed by *Ophiomorpha*. The typical tidal characters such as alternations of flaser, wavy and lenticular sedimentary structures are present as a carbonaceous material in the sand and shale laminae. At the base of the sand, armored mud balls are also locally present, possibly as a product of reciprocal transport of eroded masses of clay in the intervening wave and tidal zone. The sand is interpreted as tidal channel sand.

The coal deposits found in the upper part of the sand are sulphuric and high in clay - Content (high impurity) which suggest an estuarine coal origin. The upper part is distributary channel fill, with coarse sand to pebble grain sized material. The presence of a paleosol (ancient soil deposit rich in oxide) and rootlets at the base of the channel suggest that the tidal flat has been exposed sub-aerially before being cannibalized by the channel. In the upper part, the facies gradually changes into a non-deltaic sequence marked by fine to medium grained sandstone with 0.4-0.7 m. thick with erosional bases and clear oscillation ripple and hummocky cross stratification on the top. Both upper and lower shoreface are present in the outcrop. This characteristic shows rapid subsidence between the deltaic and shallow marine cycles.

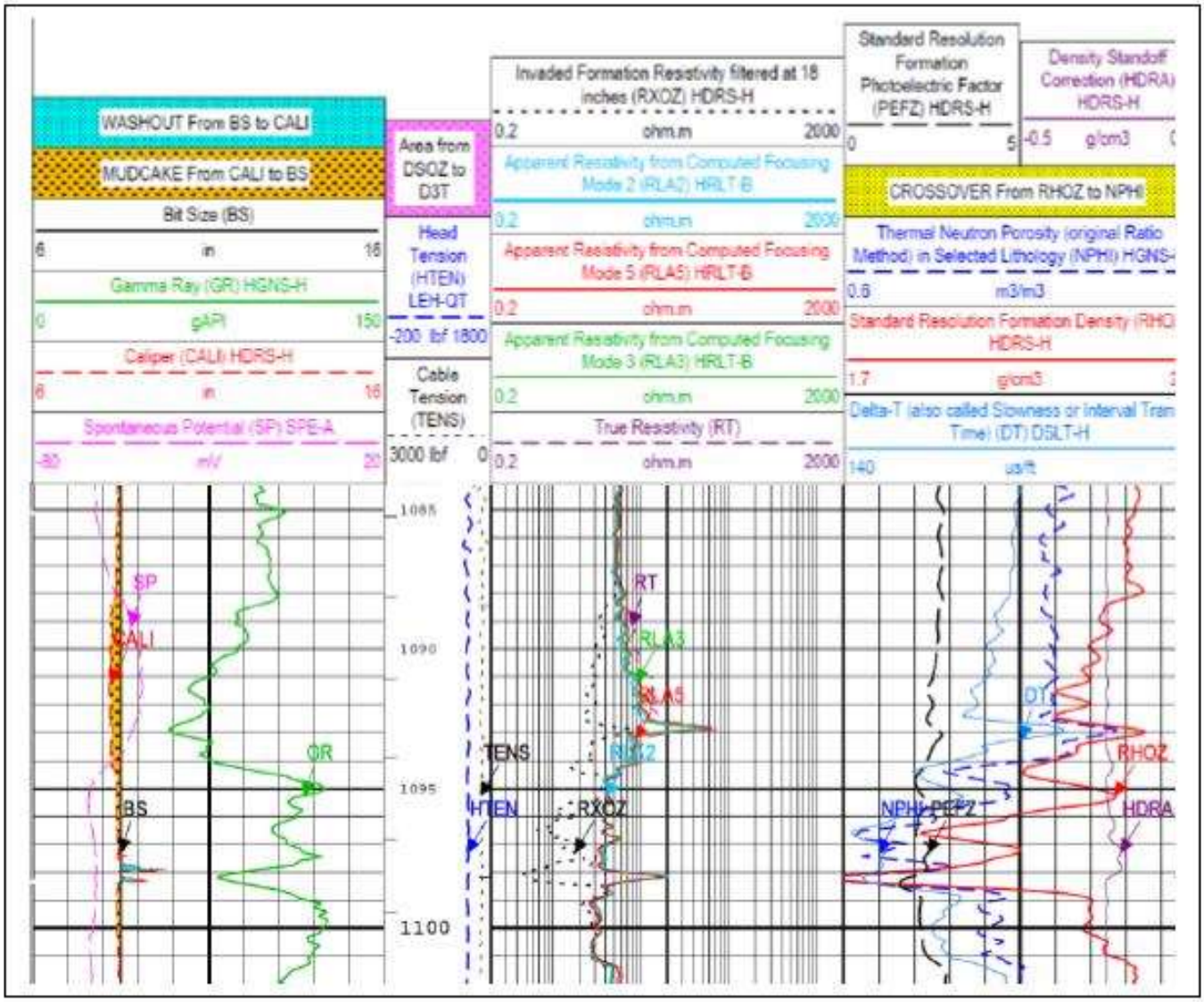


Figure 6. *Type log of the backfilled tidal channel, the spiky character in the bottom part of the channel is a thin limestone layer. These log characteristics are often qualitatively and quantitatively overlooked and are considered as a non-attractive interval, although actually* produce a fair *amount of the hydrocarbons.*

Modern Deposit Analog

Three sand lobes deposits clustered in the southern isthmus of the Balikpapan Bay are possible analogs for the abandoned lobe and backfilled channel deposits. Several small rivers and streams have delivered sediment that extends 6 km from the river mouth. The sand bodies are elongated toward the east, 600 – 1000 m wide and 1000-1500 m long with an average thickness of 40-60 cm. for individual packages. The sand is fine to medium grained, with coarsening up pattern; sprinkled with coral thallus in the upper zone. The lobe front is gently inclined (1-20 slope) and becoming a patchy substratum of symbiotic coral colonies consisting of many species such as *Acropora sp, Isopora sp, Meandrina sp, and Turbinaria sp*; all are living within 3-8 m sea water depth (Figure 8).

This colony is a micro-environment that is unique and, considering its close proximity to the active river system, can only be found in Balikpapan Bay. This coral symbiotic growth is possible due to the partial barrier created by the sand lobe bodies that restrict the hypopycnal flow toward open marine. Mud suspension accumulated on the landward direction becoming a clay plug that is sometimes effective in isolating the channel from the lobes (Figure 9 and 10).

Based on the sonar profiling, the channels in the lobe upstream are possibly still active and retrograde, creating backfilled channel systems. During the intervening periods, the sub-aerially exposed area of the lobes seems to be strongly reworked by the mix of tidal and wave forces. Ling-

uoid to crescentic-shaped current ripples are common and occur both in landward and seaward slopes. This deposit is considered as analogous to the Simpang Makroman outcrop and to the-subsurface mid Miocene reservoir sand (C-03 sand group) although the modern deposut complexes are expected to be several factors smaller.



Figure 7. *a) The Mahkota dua bridge outcrop shows a parallel strike exposure of the delta front to lower delta plain sequence which is rapidly subsiding by the shallow marine deposit. b) The hummocky cross stratification suggests a storm beds at the lower shoreface environment appear on the top of the succession. c) Armored mud balls at the base of the sand are interpreted as a product of intervening between wave and tidal force.* d) The intensive *Ophiomorpha* burrow at the lower sand unit suggest the depositional in a tidal environment. Coordinates: 516590.58 m E, 9940196.88 m S, see Figure 3 for the outcrop location.

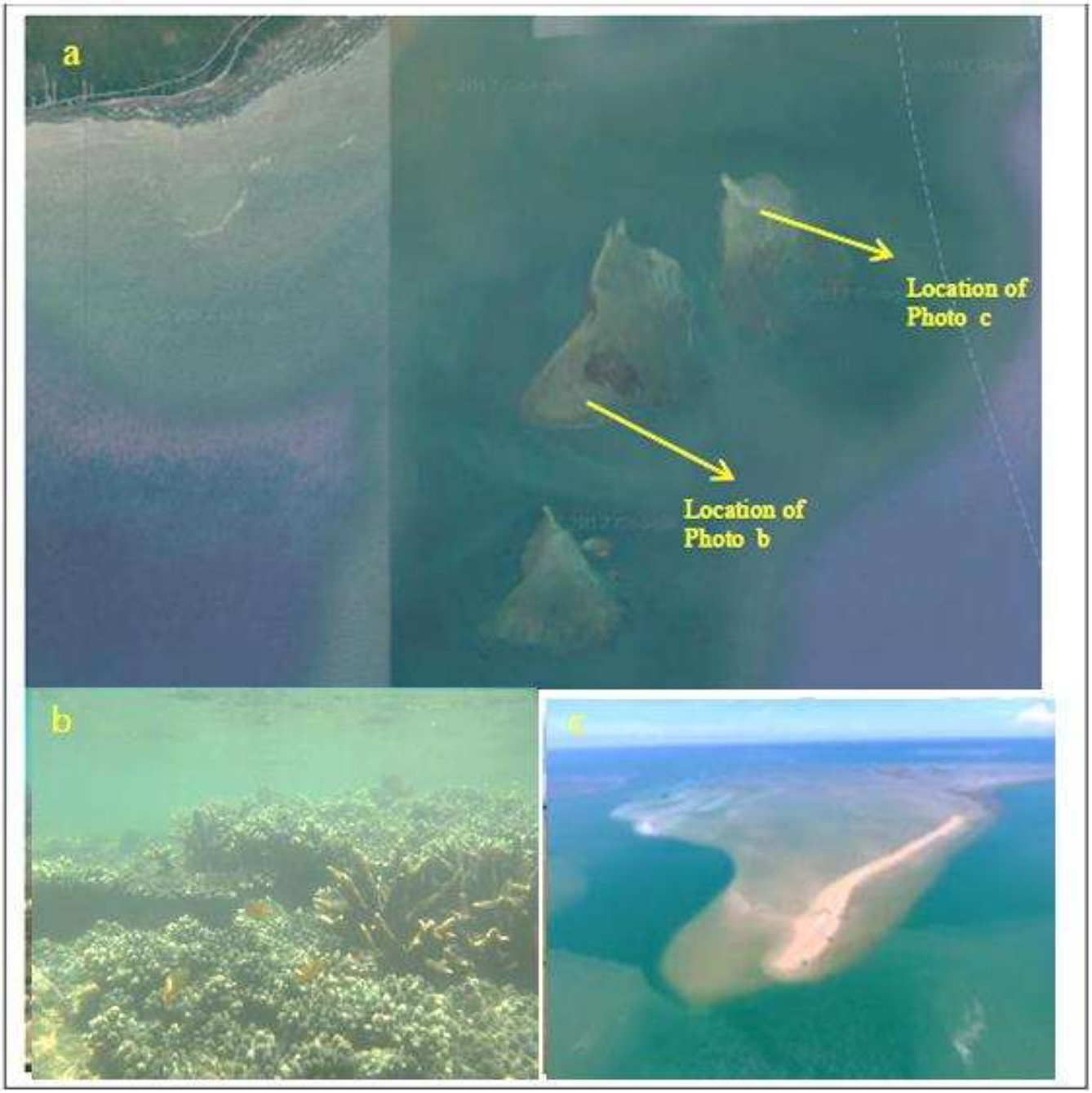


Figure 8. *a) A cluster of sand lobes in the southern isthmus of Balikpapan Bay (Google Earth image). The minimum distance to the present river mouth is 6 kilometers suggesting a significant sea level rise during the depositional period, b) a coral colony on the lobes front, and c) the sub-aerially exposure area of the sand lobes during the low tide consist of fine to medium grained sand with scattered coral thallus. Coordinates: 475337.13 m E, 9846559.47 m S, see Figure 3 for the location.*

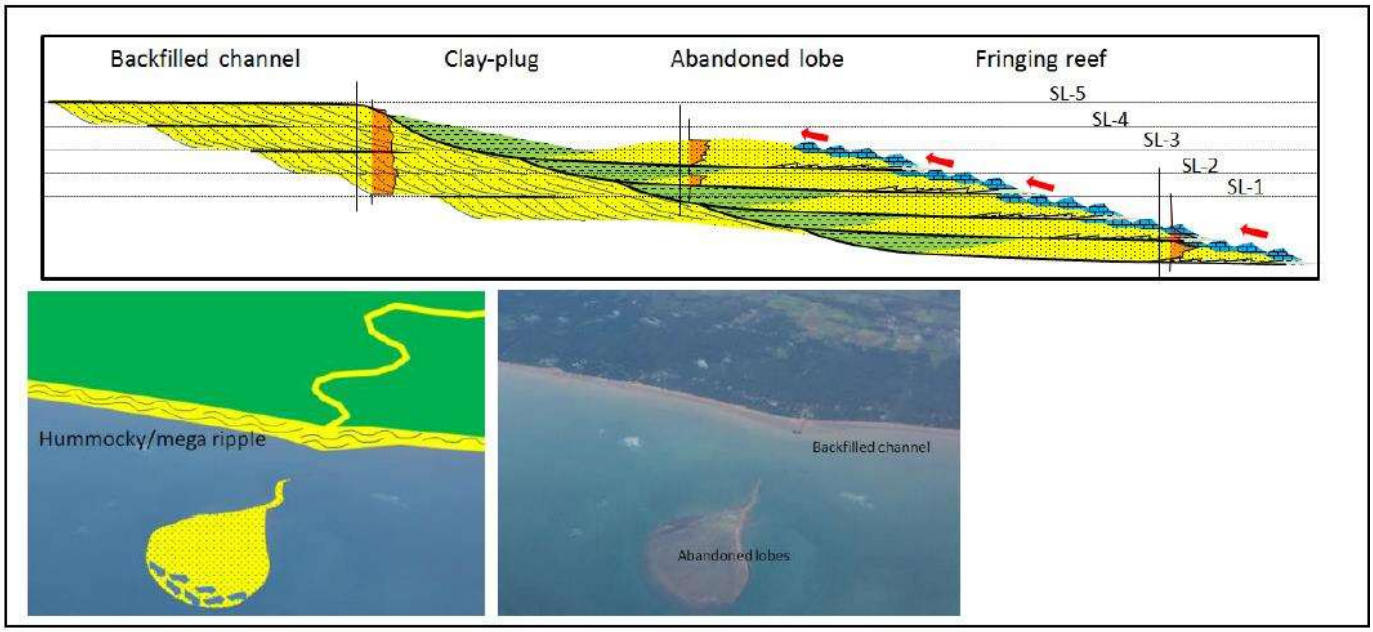


Figure 9. *Idealized cartoon section of the abandoned lobes and backfilled channel deposit based on the modern analogue in the Balikpapan Bay. SL = Sea Level. Coordinates: 465976.40 m E, 9844878.07 m S, see Figure 3 for the location*



Figure 10*. The simplify cartoon of evolution of the abandoned lobes in the Balikpapan Bay, left: the river was normally flow and deliver terrigenous sediment (yellow) during the low sea level period. Middle: during the high sea level period the sand lobes deposition was terminated. The relief of the sand mound creates the barrier thus enable coral growth on the lee side of the slope. In the landward direction, the river is start to backfill toward upstream. Right: the coastal longshore current reworked the coral thallus into a barrier ridge with a North-South elongation.*

Subsurface Data Analog

The similar facies characteristics of the backfilled channel and abandoned lobe deposits were also found in well logs correlation in the eastern flank of the North Kutai Lama (NKL) structure. The well correlation shows a variation from the thick and blocky characters on the west to the thinner coarsening up or finning up sandstones in the east (Figure 11 and 12). Prior to this analog study, we have assumed that the sand bodies are not connected due to their dissimilar log characters. However, the well test, oil production and pressure monitoring data shows that these sand bodies are at least partially connected. The thick and blocky succession in the west represents distributary or backfilled channels whereas the thin sandstones represent either abandoned lobes or tidal channels to seaward. The backfilled channel sandstone is often characterized by low resistivity phenomenon (e.g. below 10 ohm-m); this is possibly due to the intensive burrowing that introduced mud into the sand body. These burrows in the high energy channel-filled sandstones are common and observed in outcrop, such as in Stadion Utama Palaran (see Figure 4) and probably has a similar genesis to the low resistivity channel sandstone reservoirs in the Attaka Field (Trevena et al. 2003).

Well correlation also demonstrates that lateral facies variation strongly influenced the quality of the reservoir sand. Special core analysis (SCAL) shows that the presence of carbonaceous material decreases reservoir permeability, thus although the sand porosity is generally increasing toward the east, the reservoir permeability tends to be decreasing, probably due to the presence of the tidal origin shale laminae and carbonaceous material (e.g. leaves and wood fragments) (Figure 13). This sandstone group age is constrained by biostratigraphic marker *Ammonia elphidium* suggests the deposition of ancient proto-Mahakam delta system began during middle Miocene age.

Reservoir Geometry

In general, three major reservoir geometries have been identified, including: (1) backfilled distributary, (2) channel-filled, abandoned lobes or (3) mouth bar and tidal channel-filled (correlation in Figure 11 and 12 and geological model in Figure 14). The backfilled distributary channel filled sand generally shows amalgamated, fining -upward or cylindrical shape sequences. Individual sand units from 8 to 15 m. thick channel fill sequences, bounded with the remarkable basalt conglomerate at the bottom. The sandstone is generally medium to coarse-grained and internally displays trough or planar cross-stratification in 30-45 cm. thick bed-sets. Planar cross stratification occurs in the upper part of the sand unit with lesser frequency. Paleo-current orientations determined from trough cross stratification are generally unidirectional and indicate a predominantly south-south east trend. In the upper part of the sand unit, the sequence shows a finning upward trend, with the medium to fine grained sandstone into mud dominated deposits. Strong tidal signals such as thin mud drape, flaser, wavy and lenticular laminae are present in the upper mud unit. Mudstone interbedding up to 50 cm thick is commonly silty to sandy and shows thin lamination, lenticular or wavy. The degree of the bioturbation intensifies upward. Paleocurrent orientation determined from trough cross-stratification is generally unidirectional and indicate a predominantly south-southeast trend.

The abandoned mouth-bar deposit is represented by thin to medium thick sand (45- 150 cm) and mostly shows gradational evolution rather than erosional appearance in the basal unit. The sandstone is very fine to medium in size, passes downward into structure-less clay and silt. The succession is showing an interbedded mudstone and sandstone; where the sandstone is increasing in thickness with a gradual change from mud dominated into sand dominated upward. The burrow is present anywhere and intensifies in the top 10 cm of the succession. Mud drape, ripple cross lamination and planar cross lamination are common and ubiquitous. In some abandoned bars carbonate streaks are also present as an intercalation in the sandstone bed-set. Comparison with modern deposits shows that this facies is laterally continuous for 2-4 kilometers and sometimes forms a coalesced bar complex.

The tidal channel appears as fining upward sequence with relatively thin to medium sand fill thickness (2-4 meters). Cross lamination, flaser, lenticular and wavy sedimentary structures are common. The lower boundary is usually marked by an erosional surface and locally, by spherical, armoured balls. Paleo-current orientations determined from trough cross stratification are generally multi-directional depending on the channel orientation and preserved tidal ebb and flood direction. Subsurface data shows that the thin carbonate streaks are is sometimes present as an intercalation in the near base or middle interval of the channel.

DISCUSSION

The Palaran, Makroman and Mahkota dua bridge outcrops seem to be suitable analogues for a transgressive channel model. The Sea level rise tends to create entrapment in the shelf area. The high sediment influx forced the sedimentation to coalesce backward creating retrograde channeling. Some rivers continuously flowed during the maximum high sea level periods, thus the deposits

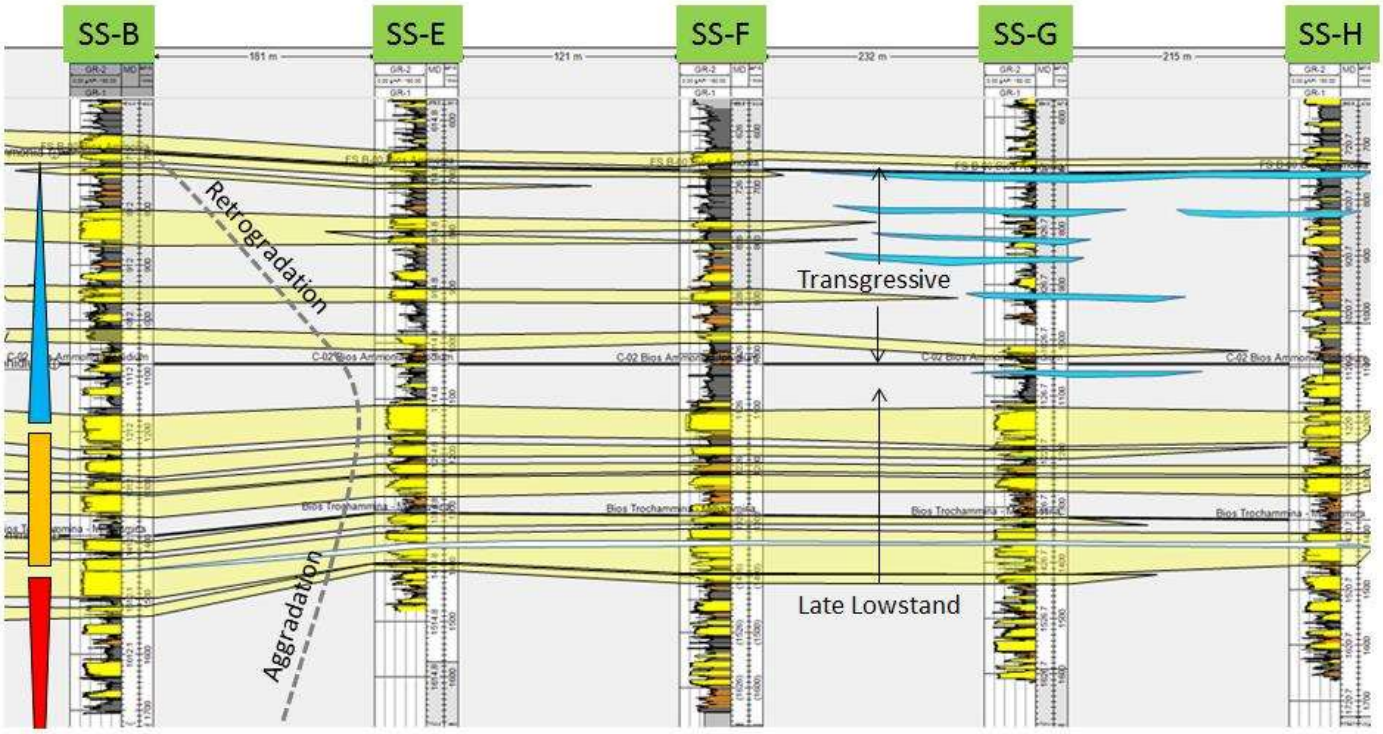


Figure 11. *4th order sequence stratigraphy correlation of wells focused on the A. elphidium marker, the bypassed oils are mostly found within the transgressive package interval (see Figure 14 for the position of wells).*

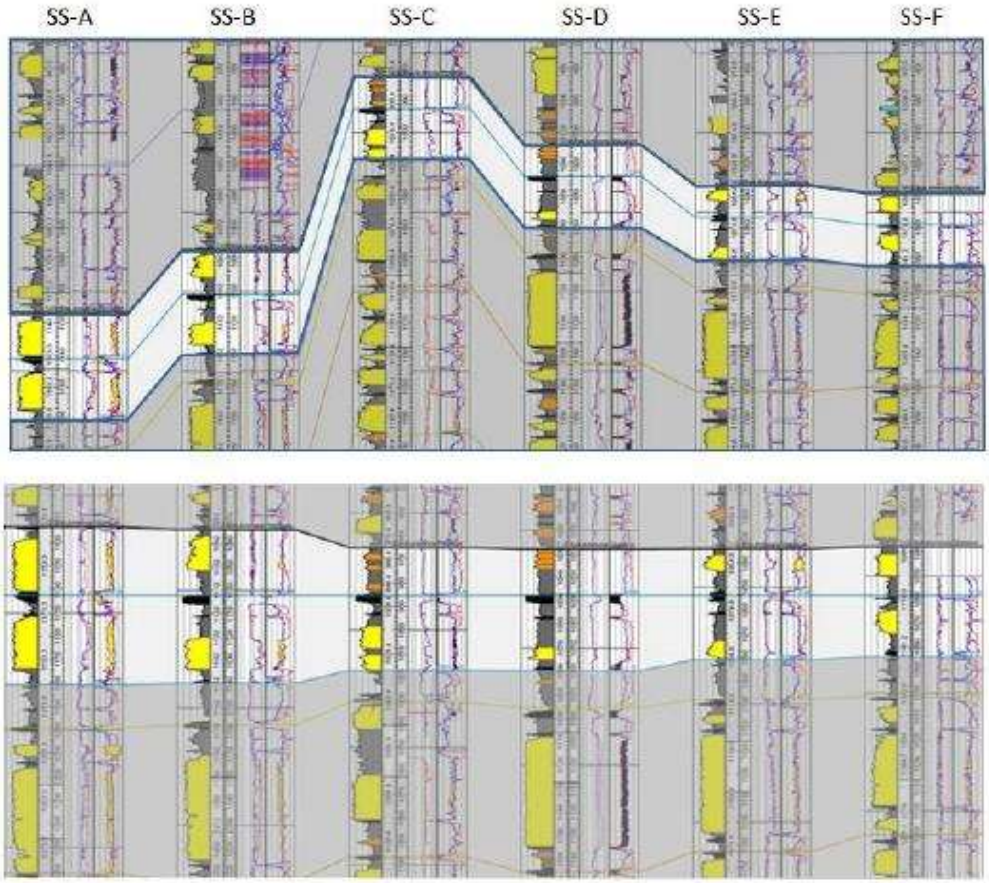


Figure 12. *West to East cross section through C-03 reservoir in structural (above) and flattened (below) view in the North Kutai Lama field. Noted the gradual change from blocky high resistivity logs character in the West to thinner bell shaped logs with low resistivity in the East. Logs shown are gamma ray, resistivity, density and neutron. Top marker is A. elphidium horizon. Position of wells are shown in Figure 14*

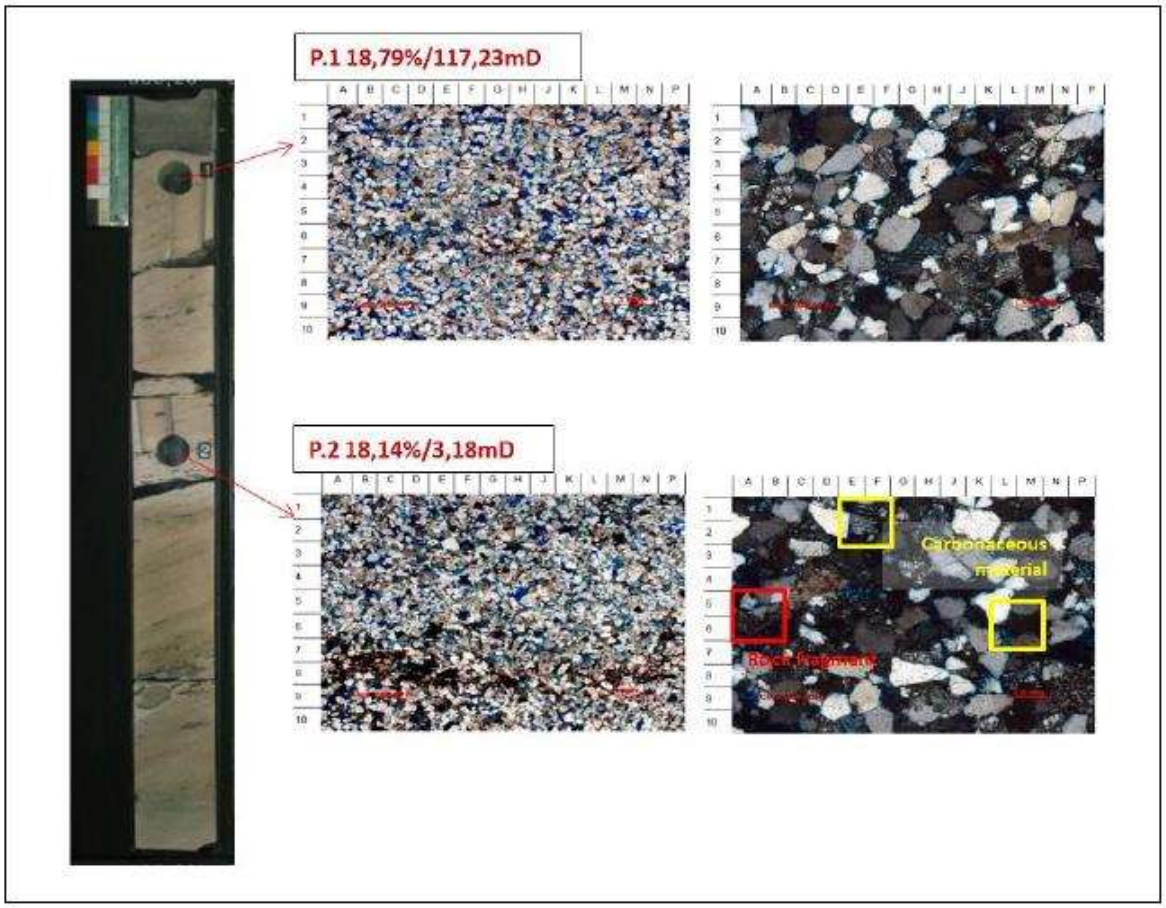


Figure 13. *Core plug from Southern Sangasanga well shows decrease in permeability due to the presence of carbonaceous material. Both core plugs have an almost similar porosity value.*

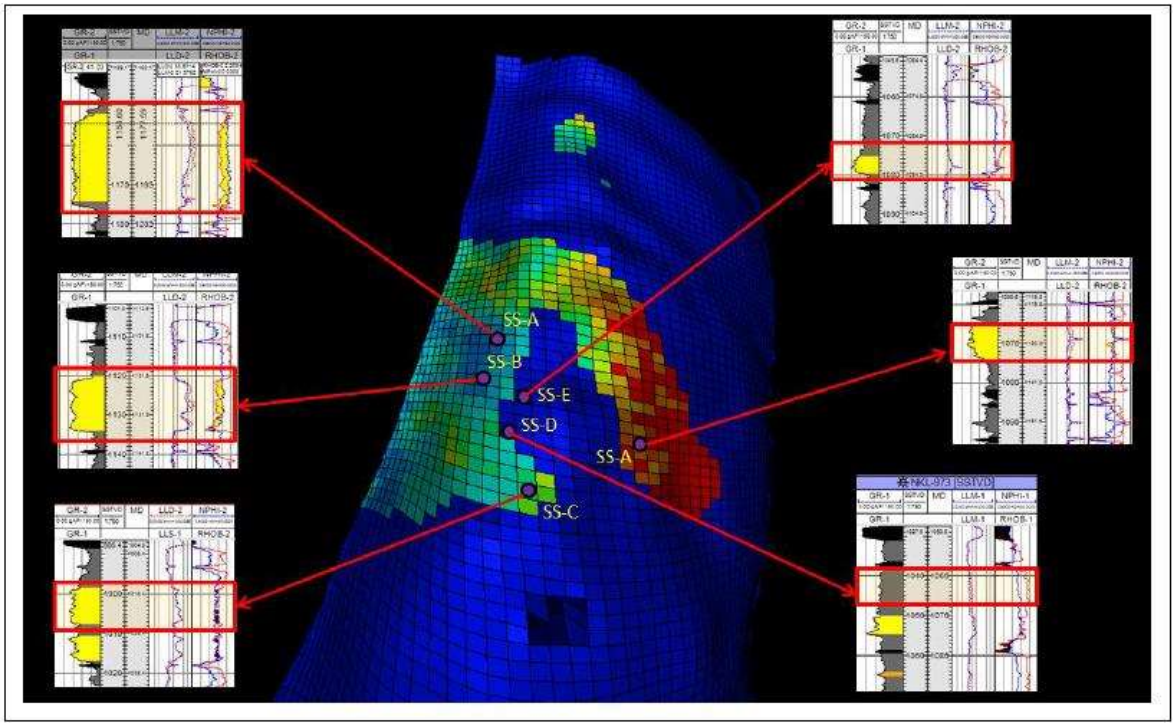


Figure 14. *The static model of C-03 sand with the lateral facies variation (see Figure 3 for the field location and Figures 11 and 12 for the wells cross section)*

are transported alongshore and in some cases re-deposited as shallow marine deposits such as upper to lower shoreface. The modern example of the backfill channel has been found in Balikpapan Bay. The example shows an active channel system which is shifted backward, meanwhile the distal area of the channel was inactive leaving seawater sufficiently clear to enable the growth of coral reefs.

The most important difference between the current model with the other classic fluvio-deltaic model (e.g. Mississippi, Ganga-Brahmaputra and Orinoco Delta) is the rapid cyclicity between terrigenous flux and marine input. The sequence found in outcrop shows a complete cycle of terrigenous or fluvial deposit; gradually changing to a tidal or estuarine one followed by marine deposits. The - succession is often very thin being only 25 and even in more extreme case is only 15 m. or less. Gradation non-from calcareous to calcareous shale is often observed but sometimes negligible due to the stronger terrigenous signal.

The insight from the comparable modern Mahakam delta system shows that with only 40 km long from head of facies to the shelf and 55 km wide, Mahakam could be considered as a "dwarf delta". This factor accounts for the fluvial, tidal and wave interactions in a spatially constrained net depositional area. The rapid and short distance river flow and channel avulsion also accounts for the variation in onshore sediment storage and marine sediment input. In the light of this new finding, the new modified depositional sequence based model should be applied to the reservoir development strategy.

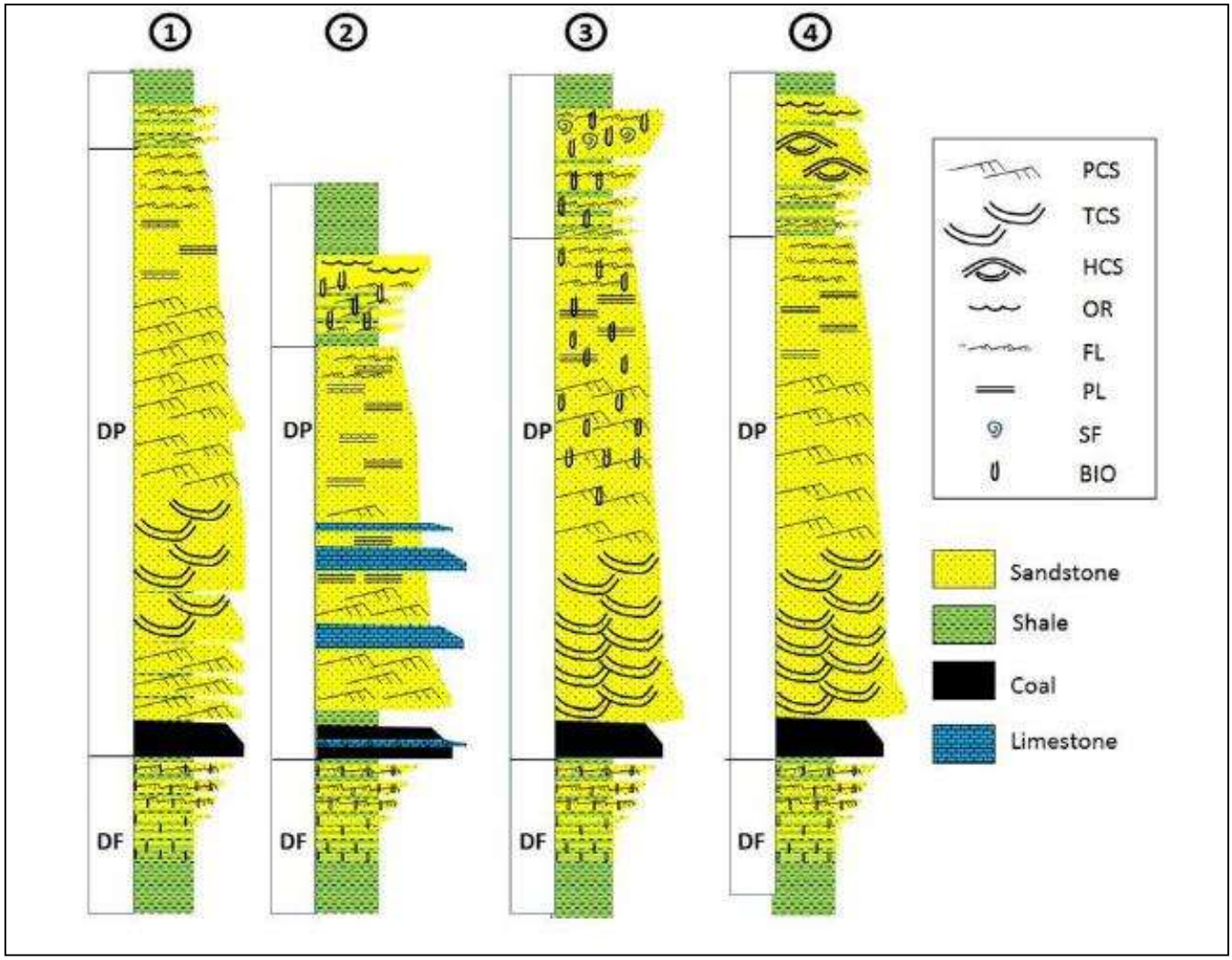


Figure 15. *Idealized depositional sequence of fluvial-deltaic cycle in Mahakam based on their response to the mixed tidal and wave influence. (1) normal (2) backfilled channel (3) drowned channel and (4) channel to shoreface rejuvenation. Abbreviations: PCS= planar cross stratification, TCS, trough cross stratification, HCS= hummocky cross stratification OS=oscillation ripple, FL= Flaser, SF= shell fragment, BIO= bioturbation. DP = Delta Plain, DF = Delta front.*

CONCLUSION

The fluvial to shelf sediment transport in the Mahakam delta is rapidly shifting between each distributary system, thus creating unique processes in terms of the systems tract succession. Our observations in outcrop and subsurface confirms that along-strike, the cycle between terrestrial and marine deposits (e.g. carbonate input) are highly divergent. Therefore, in this area, the sequence stratigraphic correlations should be carefully constrained by their corresponding paleo-drainage system.

Outcrops and modern deposits show evidence that deltaic channels sometimes do survive in extreme high sea level conditions. We propose three new genetic depositional sequences of transgressive channel due to their specific characters at the channel upper boundary, namely: i) drowned fluvial channel, ii) backfilled/keep-up channel and iii) channel to shoreface rejuvenation (Figure 15). These unique phenomena are likely caused by (a) low slope gradient of the delta plain area that creates a large tidal prism area that covers the entire delta systems, from delta front through the head of deltaic facies, (b) a relatively short (40-45 km.) fluvial to shelf sedimentation conduits combined with (c) relatively high precipitation and sedimentation fluxes. This new insight could be used for the re-assessment of the geological model.

The present study has enriched our knowledge on various type of transgressive or highstand sand deposits geometry which has been long concealed. This study contributes data and ideas to improve field production through identification of additional bypassed oil reserves.

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