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Depositional Environment of Deep-Water Fan Facies: A Case Study of the Middle Miocene Interval at the Kutei and North Makassar Basins

Lingkungan Pengendapan Fasies Kipas Laut Dalam: Sebuah Studi Kasus pada Lapisan Miosen Tengah di Cekungan Kutei dan Makassar Utara

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Abstract-Massive exploration effort in the study area was conducted in 1996-2014 when deep-water drilling campaign found significant oil and gas discoveries but yet to optimally reach the middle Miocene deep-water sandstone reservoirs. Outcrops, well bores and 2D-seismic data had been incorporated in this study. Datum age from several taxon indicators have been utilized to correlate and unify various markers across the study area into four key biostratigraphy markers: M40, M45, M50, and M65. These four markers are at that point tied to the 2D seismic data in the act of the main horizons in conducting the seismic stratigraphy analysis over the study area not reached by wells. Identifying candidate of sub-regional sequence boundaries onshore and offshore that correspond with relative sea-level drops are the main result of this study. These results were integrated to generate the deep-water fan facies of the middle Miocene's gross depositional environment (GDE) maps, which generally show prograding succession easterly in the various shelf-breaks shifting laterally. The angle of slope and the horizontal length of the shelf-to-slope breaks significantly change from the Middle to Late Miocene until Recent time.

Keywords: GDE, deep-water fan, Middle Miocene, Kutei, North Makassar.

Abstrak-*Upaya intensif terhadap eksplorasi pemboran laut dalam di daerah penelitian yang dilakukan pada tahun 1996-2014 telah mencatatkan beberapa temuan cadangan minyak dan gas yang signifikan, walaupun belum secara optimal menembus reservoir batupasir fasies laut dalam berumur Miosen Tengah. Data yang digunakan meliputi singkapan batuan, sumur, dan seismik 2D. Umur datum beberapa indikator takson telah digunakan untuk menghubungkan sekaligus menyatukan marker yang bervariasi di seluruh wilayah studi menjadi empat marker biostratigrafi utama: M40, M45, M50, dan M65. Keempat marker ini kemudian diikat pada data seismik 2D sebagai horison interpretasi utama di dalam melakukan analisis seismik stratigrafi ke seluruh area studi yang tidak dijangkau oleh sumur pemboran. Identifikasi fitur-fitur seismik berupa kandidat batas-batas sekuen yang berhubungan dengan penurunan muka air laut relatif pada skala sub-regional di area daratan hingga lepas pantai merupakan hasil penelitian ini. Hasil penelitian ini diintegrasikan guna membuat peta lingkungan pengendapan (gross depositional environment/GDE) fasies kipas laut dalam pada lapisan batuan berumur Miosen Tengah, yang secara umum menunjukkan suksesi progradasi ke arah timur yang pergeseran lateral tepian paparannya bervariasi. Sudut kemiringan lereng, serta panjang horisontal dari batas paparan ke lereng bawah berubah secara signifikan dari umur Miosen Tengah ke Miosen Akhir hingga Resen.*

Katakunci: *GDE, kipas laut dalam, Miosen Tengah, Kutei, Makassar Utara.*

INTRODUCTION

Up to 8.0 km thick Kutei Basin (after Hall & Nichols, 2002; in Witts *et al.*, 2015) is one of the most prolific hydrocarbon basins in Indonesia (Figure 1) with ca.14 billion barrel of oil equivalent (bboe) discovered reserves to date. The study area partly covers the onshore-to-transitional area towards the offshore side of the Kutei Basin. The current oil and gas production come from the two major plays: Middle to Late Miocene deltaic play, and Late Miocene to Pliocene deep-water play.

SX deep-water drilling technology had pioneered a back-to-back drilling campaign to discover hydrocarbons in the latest Middle Miocene to Pliocene deep-water slope to basin-floor fan sandstones along the modern-day deep-water slope in 1996-2005 (Unocal Indonesia Exploration and Drilling Team, 2016). The second drilling campaign in 2009-2014 continued the discoveries in the Late Miocene to Pliocene deep-water sandstones. Multi bboe discovered reserves recorded the Gehem field with >400 feet net pay in the Middle Miocene deep-water fan sandstone (Unocal *press release*, 2003; and Unocal Indonesia Exploration and Drilling Team, 2016) that may potentially become the emerging deep-water play in the Kutei and North Makassar Basins.

An overall prograding-deltaic system easterly towards the younger-age intervals during the Miocene to Recent would settle the Middle Miocene play deeper thus have limited offshore well-bore penetration. Outcrops, well bores and 2D-seismic data had mainly been utilized in this study to compile key sequence biostratigraphy markers and identify candidates of key sequence boundaries correspond with relative sea-level fall. The final objective of this study is to generate gross depositional environment (GDE) maps of the Middle Miocene deep-water facies, in comparison with the younger-age proven plays.

Geologic Setting

Tectonically, the study area is bounded by the Sangkulirang Fault, Samarinda Anticlinorium, Adang Fault, and Majene Folded-thrust Belts (Figure 1), and is situated on the continental crust accreted to Sundaland during the Cretaceous to Cenozoic, and side-by-side with the other continental blocks derived from Gondwanaland in the Late Triassic to Late Jurassic (Metcalf, 2011 and 2013; Hall and Sevastjanova, 2012). Based on the Cenozoic structures, there are at least four main tectono-stratigraphic events in the Kutei Basin:

1) Middle Eocene NE-SW (Bachtiar *et al.*, 2013) rift-associated terrestrial succession in the lower Kutei to marine deposits in the upper Kutei Basin. This event was formed as the result of partial subduction along the edges of Sundaland due to the initiation of Australian continental movement northerly ca. 45 Ma. (Hall, 2013). A NW-SE morphologic trend of basement architecture was observed in the deep-water Kutei Basin, called North Makassar Basin (Nur'aini *et al.*, 2005; Hall *et al.* 2009 *in* Pubellier, 2013).
2) Late Eocene to Oligocene sag-related deep-to-shallow marine fine-grained materials deposited in a large embayment paleogeography (Morley and Morley, 2013; *in* Hall, 2013). This sub-regional sag was potentially associated with the ~35° counter-clock wised (CCW) Borneo rotation (Advokaat *et al.*, 2018). As the subsidence gradually ceased by Late Oligocene, back-stepping reefal carbonates developed over the syn-depositional highs along the southern and northern edges of the Kutei Basin (van de Weerd *et al.*, 1987; *in* Saller and Vijaya, 2002).

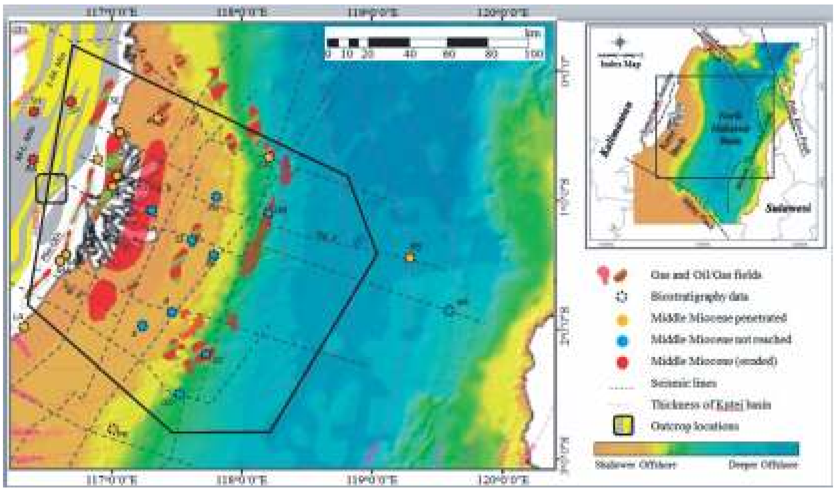


Figure 1. Outline of the study area (black polygon) along with the present-day major structural element (see the index map), surface geology map (modified from Supriatna *et al.*, 1995), hydrocarbon fields, well penetration symbols, 2D seismic lines (some are shown in the other figures; see the numbers), sedimentary thickness, and water depth.

3) Early Miocene uplift and erosion along with the initiation of huge clastics progradation had resulted in the proto Mahakam deltaic succession to the east. This contractional event is interpreted due to an additional of ~10^{o} CCW Borneo rotation (Advokaat *et al.*, 2018). The prograded deltaic systems reached its highest sedimentation rate in Middle Miocene, known Middle Miocene Unconformity (MMU) or VIM 58-62 (Morley *et al.*, 2016). The peaks of high-sedimentation rate are suggested to correspond with emplacements and uplifts in the hinterland. This combination had deliver huge clastic sediments into the paleo deep-water slope from the Middle Miocene to Pliocene with the main phases of uplift at 14, 11, 8.5 and 3 Ma. (Morley, 2014). These huge sedimentary masses had initiated the gravitational flow to form the toe-thrust fold belt in the distal part of the system (McClay *et al.*, 2000).

4) Pliocene compressional event had risen West Sulawesi highlands to expose and erode the Mamasa granitoid (Fraser *et al.*, 2003) then transported it into the deep-water North Makassar basin until the Recent time (Puspita *et al.*, 2005). At the same time, N-S trend Samarinda anticlinorium had been formed (Moss *et al.*, 1997) and partially prevented the sediment from the highlands to pass it through, hence the Kutei Lake formed. Significant volume of sediment was still able to flow following the proto Mahakam river system (Allen, 1996; *in* Wilson and Moss, 1999) towards the Kutei and North Makassar basins easterly.

Methods

Sequence Stratigraphy: Concept and Practice

Several taxon indicators that have datum age have been used as a tool in correlating and combining key biostratigraphic markers across the study area. Internal data from Pertamina and published sources are very beneficial to better understand the chronology of both lateral and vertical facies change variation. Sequence biostratigraphic application provided further detailed and definitive application to the deformation-related cyclicity of sedimentation rates of the circum-Borneo basins (Morley, 2014 and Morley *et al.*, 2016).

Evaluating tectonics and sedimentary processes of the Middle Miocene onshore and offshore Kutei Basin are essential to explain how prograded delta was able to transfer enormous clastic sediments towards the deep-water setting. Basic concept of sequence stratigraphy is applied as it discusses rocks relationships in a chronostratigraphic framework of repetitive, genetically-related strata bounded by either erosional surfaces, hiatus, or correlative conformable stratas (van Wagoner *et al.*, 1988). Three parasequence sets are 1) progradation, 2) retrogradation, and 3) aggradation, demonstrate unique seismic features that are able to suggest the rate of deposition relative to the rate of accommodation space (Figures 2 and 3).

Depositional system tracts of lowstand (LST), transgressive (TST), and highstand (HST) are determined in later stage based on the parasequence-set stacking patterns characterized by the geometry and the associated facies of each system tracts. The lowstand in a basin with shelf break like the offshore Kutei Basin, is considered the most important system tract in this research. It may provide type-1 sequence boundary or forced regression (Posamentier, 2004) that enable canyon formation and incised-valley erosion to deliver fan-shaped like clastic deposits further onto the slope fan and basin floor during relative sea-level fall.

In addition to the influence of relative sea-level fall, Shanmugam (2013, 2015, and 2017) had introduced another concept called gravity driven down-slope process along the shelf margins down to the deep-water environments. This concept declared the most reasonable mechanism that is able to transport the gravel to coarse into the deep-water slope and basin floor have mainly been related to mass-transport deposits triggered by gravitational process to become slide, slump, and debris flow.

Data (Constraint and Benefit)

Due to limited well penetration in the Middle Miocene deep-water play, the 2D seismic data is considered key important tool in this study. The usage of seismic data (Malecek *et al.*, 1993; Butterworth *et al.*, 2001; Saller *et al.*, 2008; Yoga *et al.*, 2009; Pratama-Laya *et al.*, 2014) is very helpful to define termination features such as incision, clinoforms, and geomorphology of the shelf, slope, and basin floor (Figures 2 and 3).

The outcrops around Samarinda (Cibaj, 2013, Renema *et al.*, 2015; Marshall *et al.*, 2015), well-logs patterns, cuttings, and core data from the onshore/offshore wells (Cibaj *et al.*, 2014 and 2015), and key biostratigraphy markers (Kadar, 1998; Cibaj, 2009; Morley *et al.*, 2011 and 2016; and Morley, 2014) had been integrated to define key sequence boundaries, parasequence sets with their associated facies.

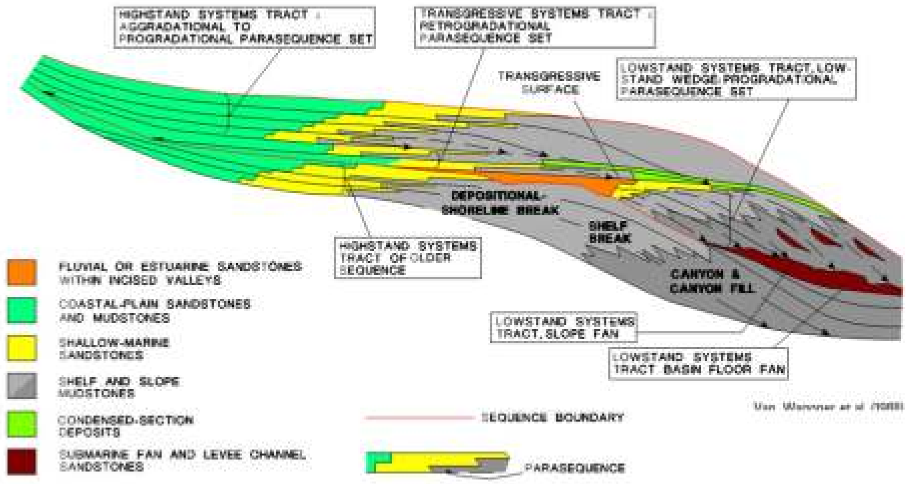
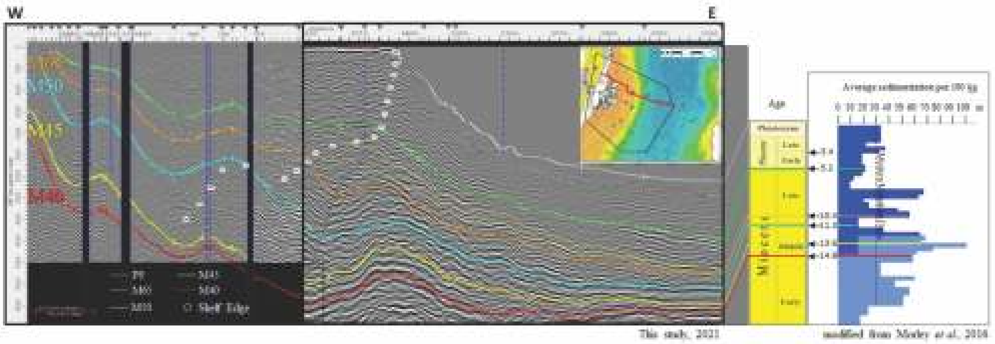


Figure 2. A scheme of parasequence-depositional sets explaining the megasequences of highstand system tract (HST), lowstand system tract (LST), and transgressive system tract (TST); van Wagoner *et al.*, 1988.



source:modified from Morley et al., (2016)

Figure 3. A key composite 2D-seismic line with four "M" markers (this study, 2021) showing the Miocene's prograding shelf edges, in relation to the average sedimentation rates with stratigraphic age column on the right-hand side .

RESULT OF THE STUDY

Various Middle to Late Miocene's biostratigraphy markers across the study area that usually presented in different names, have finally been compiled into four regional markers; M40, M45, M50, and M65. Since this study refers to the "KR" markers, a biostratigraphy scheme introduced by Morley *et al.* (2006) the well known top Middle Miocene's absolute age of 10.2 Ma was modified to 11.4 Ma. With this, many offshore wells penetrated the Middle Miocene were in fact still in the earliest Late Miocene.

This chapter will assign key evidences of sequence boundary candidates that are associated with relative sea-level fall in two main geographic locations of the study area; onshore and offshore.

Onshore to Modern Delta Areas

The north-western part of study area lies from the onshore to transition zones of the modern Mahakam fan-shaped delta where most of the Middle Miocene section, the focused interval of this study is well exposed at the westernmost part along the north-northeast to south-southwest (NNE-SSW) Samarinda Anticline (Figure 1). And at the same time the Middle Miocene deltaic sandstones are the main hydrocarbon-producing reservoirs in the major fields; Nilam, Badak, Semberah, and Mutiara as an overall regressive succession from the latest Langhian (N9) to top Serravallian (N12-N13).

The regional well-to-seismic correlation onshore in this study was initiated at the Badak Nilam-Lampake fields as there are widely covered by 3D seismic and key deep stratigraphic wells with biostratigraphy data. The deepest penetration at the Nilam and Lampake fields is down to the overpressured zone of J (M40-M45). After detailing the seismic-to-well logs correlation, the key regional flooding events with an average thickness of 60 feet shale were carefully tied to the 3D seismic data, and correlated wider to the other onshore and offshore fields using the available 2D seismic (Figure 3).

Sequence Biostratigraphy

Correlation between sub-regional onshore ILX and M markers is as follow: C_ILX (M65); E_ILX (M50); I.2_ILX (M45), and K_ILX (M40); Figures 4 and 5. Most of the ILX markers are thick shale, while the J and K are mainly defined using the 2D seismic data due to limited well penetrations. The biostratigraphy correlation onshore Kutei Basin had utilized the planktonic foraminifera biochronozones along the Miocene until Recent (Malecek and Lunt, 1996), and palynology assemblages in the Early Miocene (Carter and Morley, 1995). Unfortunately, this study is unable to utilize the inconclusive palynology study of the Middle-Late Miocene at the Nilam and Mutiara wells (VICO Indonesia, 1996). The biostratigraphy evaluation of the Samboja and Lamaru wells at Wain Sub-basin represents the upper part of the Middle Miocene (Unit-6; Kadar, 1998). This area had been partially eroded and outcropped around the surface locations of the Samboja well. The overall strata suggest a regressive succession that show gradually changes from the marginal marine to inner shelf towards the younger section.

4-*km* thick outcrops are located at the Samarinda Anticlinorium around the Samarinda City show a general progradation of the offshore slope deposits to fluvio-deltaic packages that has range from the uppermost part of Early Miocene (<18 Ma) to the lower part of Late Miocene (11.05 Ma). It comprises mainly the Middle Miocene sediments bounded by two reefal carbonates that coincides with rapid sea-level rises: the earliest Middle Miocene (15.3 Ma) Batuputih reef; and the earliest Late Miocene (11.6 Ma) Stadion reef (Renema *et al.*, 2015; Marshall *et al.*, 2015). Despite of limited sample recovery of the nannofossil, planktonic foraminifera, and other calcareous microfossils, these outcrops evaluation provided refinement of the Middle Miocene age defined in the previous biostratigraphy studies of Moss and Chambers (1999), Wilson (2005), and Cibaj (2009). To fill in the gap in age-resolution due to the rarity of fossil assemblages aforementioned, larger benthic foraminifera (LBF) have been utilized as the basis for the "Letter Classification" (Renema, 2007; *in* Renema *et al.*, 2015); as displayed in Figure 5.

Incisions during Relative Sea-level Fall

According to the integrated core, well logs, and 3D seismic data at the Nilam field, two Incised Valley Fill (IVF) sandstones in the Middle Miocene interval were recognized; the G053B and I0420. More IVF candidates that proportionally associated with low or high gamma-ray (GR) coals (Figure 7), and thin limestone had been observed at the other major fields as tabulated in the Figure 4. The geometry of G053B IVF feature demonstrates 3 km wide and 45 m thick well developed amalgamated channel sandstones. This IVF system requires a fall in relative base sea level of more than 50 meters in providing a topographic low due to lowstand incision that associated with sedimentary bypass to the deep-water setting at this sequence boundary (Butterworth *et al.*, 2001).

The geometry of the older IVF feature; I4200 sandstone consists of two separate channels, the south and the north. Based on 3D seismic attribute map the southern one has 1-2 km wide, and 35 m thick amalgamated blocky channel sandstones. While the northern channel has ~1 km wide, and 30.5 m thick amalgamated channel sandstones penetrated at Nilam north well. Both channel systems had eroded the underlying HST coals and mouth-bar shale and sandstone packages. One of the deepest Nilam well located between the northern and southern IVF channels, homogenously penetrated the HST interfluve section.

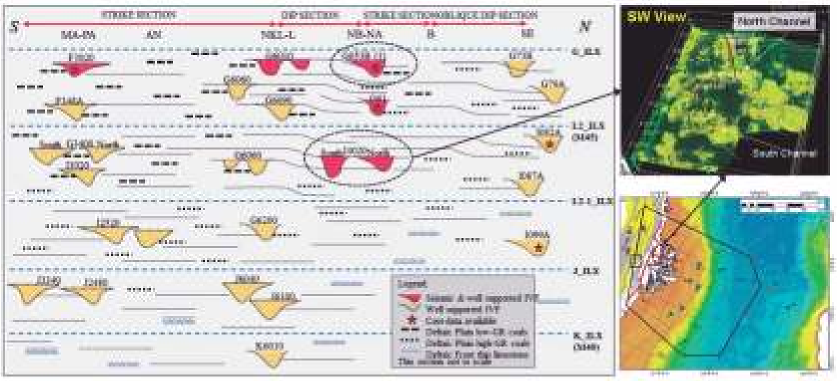


Figure 4. Proven and candidate Incised Valley Fill (IVF) of very thick amalgamated channel sandstones that may correspond with the LST sequence boundaries in the onshore fields. The G053B IVF (Butterworth *et al.*, 2001), and the I4200 IVF in this study have been observed from seismic and wells.

Recognition of these IVF features onshore representing the proximal part of the Kutei Basin will aid paleogeography definition of the depositional fairway towards the deep-water settings. These incision features may reflect the presence of sequence boundaries during periods of relative sea-level fall that potentially exposed the paleo shelf as sedimentary bypassed zone.

Clinoforms and Sedimentation Rates

Onshore and offshore composite lines of 2D and 3D seismic tied to the key wells cover the proximal to distal parts of the study area. The clinoforms seen in the 2D and 3D seismic data at the northern part of study area clearly show the progradation parasequence sets from the J (M40) to E (M50). This is a bit more distal than the equivalent age outcrops at Samarinda between the Batuputih (M40) and Stadion (M50) reefs.

The highest sedimentation rate of the Kutei and outboard Sabah Basins were indicated in the Middle to Late Miocene as the result of Sabah uplift and erosion (Hutchinson, 2005; *in* Morley *et al.*, 2016). This major prograding event was also well defined by a sequence biostratigraphic marker, called MMU (Middle Miocene Unconformity). Further detailed evaluation of sequence biostratigraphy on 11 (of >50 total wells) onshore wells tied to seismic had been compiled to observe the sedimentation rates, and age equivalent offshore Kutei (Morley *et al*, 2006 in Morley, 2014; Figures 3 and 5).

Despite the data point is only from a few onshore wells, increasing in the sedimentation rates began at the latest Early Miocene (after 17 Ma). The rate as an average twice that of the Quaternary Mahakam towards the Middle Miocene interval (Morley, 2014). The sedimentation rates were fluctuated and reduced within the Middle Miocene thermal maximum along with high global sea levels causing the deposition of carbonates along the distal shelf of Batuputih limestone, which is in this study correlated to the M40 marker. This low rate was followed by extremely high rate of clastic influx through the latest Middle Miocene indicated by the thick fluvio deltaic succession that is well exposed in the Samarinda area (Marshall et al, 2013 *in* Morley, 2014; Marshall *et al*, 2015).

Offshore Area: Shallow to Deep Water

Three quarters of the study area lies offshore shallow to the deep-water north Makassar Strait. The western part offshore is bounded by the Peciko, Tunu, and Attaka fields. The central part offshore is defined by Dian Ragat and Sisi Nubi trends that situated near to the present-day shelf margin. The deep-water fields lie along the outer rim of present-day slope (Figure 1).

Sequence Biostratigraphy

Following up the Indonesia's largest deep-water exploration program to date in the north Makassar Strait in 1996 to 2005, further detailed evaluation had successfully improved the basin wide biostratigraphic zonation by developing reliable index fossils, incorporating palynology into the re-evaluation, and more importantly tying to the seismic and wells. This effort had calibrated eleven regional chronostratigraphic seismic horizons; called “KR” markers.

In the Middle Miocene, both “M” (this study, 2021) and KR markers (Morley *et al.*, 2006; Morley *et al.*, 2011) are correlated with their equivalent position as follow: (1) M65 to KR 100 (Intra NN9), (2) M50 to near top KR 110 (Base NN8 or top NN7), (3) M45 to KR 140 (Top NN5), and (4) M40 to KR 150 (Top N9) as shown in Table 1. These markers had been regionally tied to the seismic across the study area in order to generate isochron, isopach, and finally two gross depositional environment (GDE) maps. Fossil indicators of each top markers in this study are as follow: (1) Top M65 is a lowstand event associated with *Catinaster calyculus* (10.4 Ma); (2) Top M50 (top Middle Miocene 11.3 Ma) is the LO of *Discoaster deflandrei* and the FO of *Catinaster coalitus* condensed section; (3) Top M45 is a maximum flood that associated with the LO of *Sphenolithus heteromorphus* (13.6 Ma); (4) Top M40 is a maximum flood that correspond to the LO of *Praeorbulina glomerosa* (14.8 Ma) as noticed in Table 1.

According to the KR biostratigraphy scheme, only few offshore wells inside the study area; Attaka on the shelf and Gehem in the deep water that reached the top middle Miocene, which was defined in more detailed age of the Tortonian-1a to Serravalian-3b (Palynova, 2003; Morley, 2014).With minimal well penetrations, the chronostratigraphic chart of this study mainly relies on the seismic stratigraphic correlation (Figure 5).

Incision and Slump Scar Evidences

Shelf margin stability and shelf slope angle are the least aspects to enable slumping process (Edwards, 2000; and Mora *et al.*, 2001; both are *in* Yoga *et al.*, 2009). Steep slope with relative sea-level fall happened behind the shelf slope break imply less incisions over the shelf areas but may cause large slump scars on the delta front. Alternatively, a steep slope with sea-level fall beyond the shelf break provides deep erosions over the outer shelf so called by-passed zone (Mora *et al.*, 2001; *in* Yoga *et al.*, 2009).

Table 1. Summary of the "M" marker characters in this study that correspond datum age, foraminifera and nanno-plankton zonations, and taxon indicators (modified from Palynova, 2003 and Morley *et al.*, 2011)

Markers	Datum age (Ma)	Zone	Taxon indicators and marker character
M65 / KR100	10.43	Intra NN9	Base Catinaster calyculus: base within DH2 lowstand (1)
	10.9	Base NN9	Base Discoaster hamatus: within DH2 lowstand (1 and 2)
M50	11.29	Base NN8	Base Catinaster coalitus: condensed section (1)
	11.3	Top NN7	Top Discoaster deflandrei: intra DH1 lowstand (1)
Mi45 / KR140	13.59	Top NN5	Top and acmes of Sphenolithus heteromorphus: maximum flood (1 and 2)
Mi40 / KR150	14.8	N9	Top Praeorbulina silicana and Praeorbulina glomerosa: in maximum flood (1 and 2)

(1) Palynova, 2003; unpublished
(2) Morley *et al.*, 2011

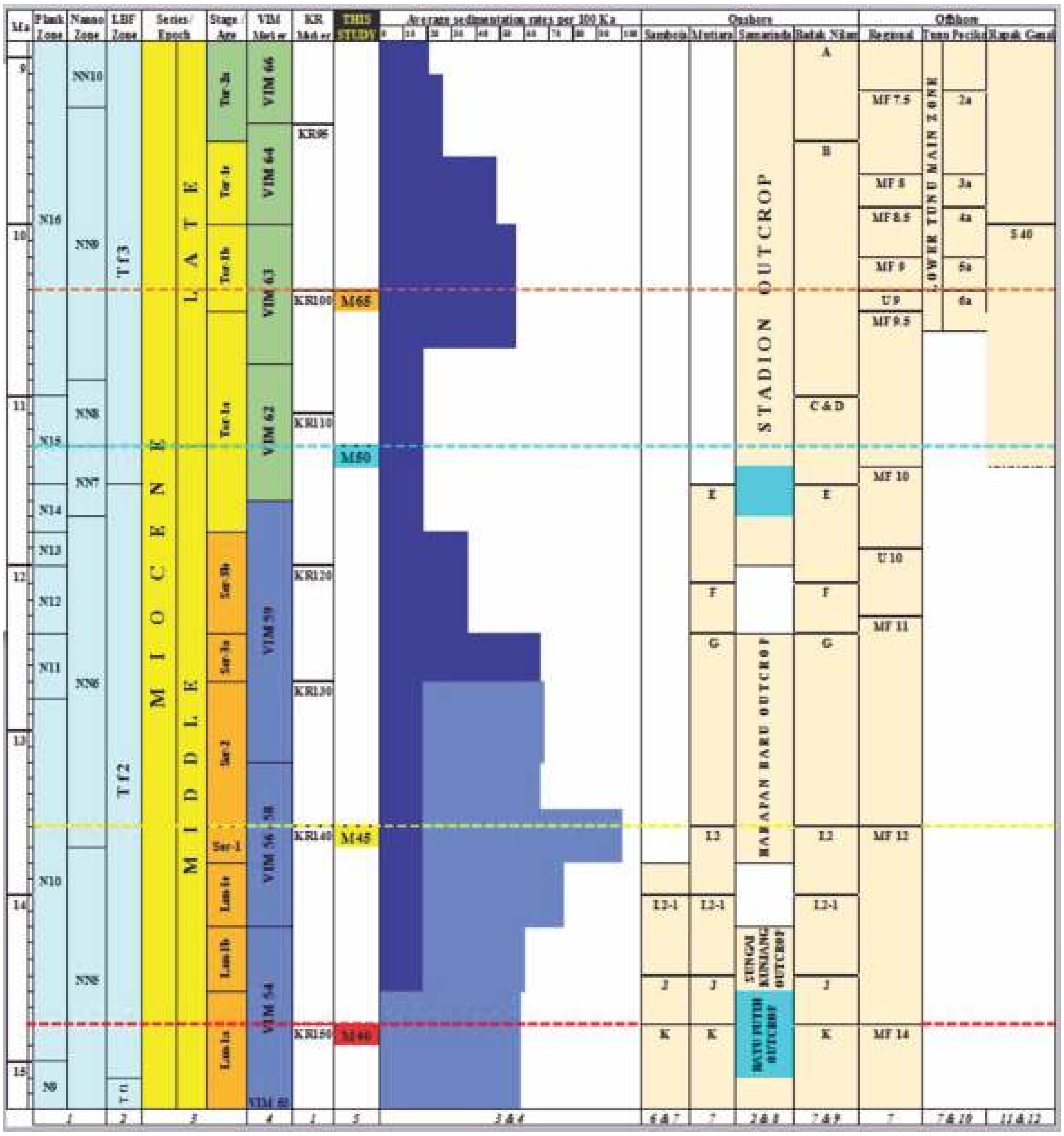


Figure 5. Compilation of the "M" marker of this study with the regional markers from various authors across the study area. References are in numerical order at the base of Figure 1. Morley *et al.* (2006), 2. Renema *et al.* (2015), 3. Morley (2014), 4. Morley *et al.* (2016), 5. This study (2021), 6. Kadar (1998), 7. PEP, PHSS, PHM, PHKT (modified after Wiweko, 2000), 8. Marshall *et al.* (2015), 9. Butterworth *et al.* (2001), 10. Cibaj *et al.* (2014), 11. Guritno *et al.* (2003), 12. Unocal Indonesia (2003).

Dozens of slump scar features were indicated trending parallely to the anticline of Tunu field and mapped using 3D seismic data that tied to the Tunu's wells. The scars exist in the latest Middle Miocene to earliest Late Miocene stratigraphic units, which has an age equivalent with the M65 marker (Figure 6). Rapid sedimentation and/or fault reactivation might trigger slope instability along the shelf margin that initiated slump scars. The uppermost part of the slump scars corresponds to the lowest eustatic level coincides with high sedimentation rate accumulated under compacted sedimentary sections along the shelf margin. Consequently, it became unstable and collapsed to trigger larger scale slump scars in landward direction. One of the scar in the Tunu field has a dimension of ~3500 m wide at dip direction with ~200 m thick (Yoga *et al.*, 2009), while as a comparison slump scar associated with a N-S canyon near the shelf edge of the deep-water north Sumatra Basin has dimension of 300 to 600 m wide at strike direction, and up to 300 m thick (Hakim *et al.,* 2019).

The other LST related evidences are well observed in sedimentological description over the Late Miocene's Upper Fresh Water Sands conventional core data at the Nubi field (Cibaj *et al.,* 2015). It suggested an up to 20 m thick fluvial system's coarse grained and cross-bedded sandstones that incised through the marine shales. It has commonly been described in sequence stratigraphy as forced regression process. This fluvial system was overlain by the following transgressive marine shale. Logs also suggested a lot more potential forced regressive channel sandstones along the Upper to Middle Fresh Water Sands at the Sisi and Nubi fields.

<u>Clinofroms and Sedimentation Rates</u>

Composite lines of 2D and 3D seismic data in Figure 3 clearly show series of clinoforms in the northern and southern parts of study area. The clinoforms are associated with progradation parasequence sets from the offshore markers KR 150 and MF14 (M40) to KR 100 and MF9.5 (M65), up to the top Late Miocene of KR 50 and MF3 (P0). These clinoforms are laterally equivalent in age with the ones seen in the seismic lines onshore.

An observation of sequence biostratigraphy on 28 (of >50 total wells) tied to the seismic data were used to calculate the sedimentation rates offshore Kutei (Morley *et al.*, 2006 *in* Morley, 2014); Figures 3 and 5. Since most of the offshore wells mainly reached total depth at the earliest Late Miocene with few of them reaching the latest Middle Miocene, they were able to indicate high sedimentation rates of clastic inputs during the latest Middle Miocene to the earliest Late Miocene (12 to 10 Ma) of the KR 120 to KR 100 intervals. This is consecutively followed by significant reduced in sedimentation rate of up to about the 8.5 Ma. Another high sedimentation rates during 8.5 to 7.2 Ma with an average twice that of the Quaternary Mahakam, spanning the KR 80 to KR 70 interval, where most of the hydrocarbons found so far in the deep water Kutei Basin (Morley *et al.,* 2006 *in* Morley, 2014).

Regional Chronostratigraphy

A play cartoon is made based on the composite 2D seismic lines running west-northwest to east-southeast (WNW-ESE) in the northern part of the study area is selected to build simplified dip line chronostratigraphic chart of the focused study interval; Middle Miocene. The chart starts with the Samarinda Anticlinorium at the western end, and crosses the Lampake, Nilam, Tunu, and deep-water fields, and continues until the eastern end of the study area.

Structurally, the western end of the play cartoon suggests south-southwest to north-northeast (SSW-NNE) trend of the tight and high relief inverted folded thrust belt systems that changes easterly with lower relief but wider folds until the present day deep-water slope, and gets into much lower to no relief basin floor province in the easternmost part of the study area (Figure 6; upper picture).

Stratigraphically, the chart clearly demonstrates an overall progradation succession with maximum to non-erosive, as well as partial eroded sections of the present day outcrop and the IVF symbols from west to east. The well penetration into the Middle Miocene gets less into the offshore area easterly and makes the chronostratigraphy chart mainly relies on the seismic stratigraphic correlation (Figure 6; lower picture).

Gross Depositional Environment (GDE) Maps

There are three GDE maps in this study signifying the Middle Miocene of M45 and M50, as well as the earliest Late Miocene of M65. In addition to the seismic stratigraphic features identification along with well data, the following key supporting data are found very useful to generate simplified GDE maps, *i.e.,* (1) combined isopach maps of the low gamma-ray (GR) insitu coals and high GR transported coals are utilized to define the relative position between the deltaic plain with the delta front. Thinner isopach of the insitu coals intersect along an interpreted line with thicker transported coals easterly toward marine direction; (2) net to gross (NTG) of the sandstone ratio map is beneficial to indicate the relative lateral avulsions of the active delta within each marker intervals; (3) isopach maps between the “M” markers suggest the paleogeography interpretation given the limitation of well penetration and seismic image quality toward the offshore region. The thicker areas correspond with the sedimentary trends along the delta to marine shelf, and settled the depositional pods of potential sandstone reservoirs into the deep-water slope and basin floor. Thin isopach in the eastern part of the study area represents the condensed section of the deep-water settings (Figure 7).

Coal thickness and sandstone NTG maps are only generated onshore since the Middle Miocene interval is mainly penetrated by well bores. In contrast with the offshore region, seismic derived isopach map is the key supporting tool to define the lateral and vertical thickness variations with regards to the depositional trend observation during the generation of GDE maps.

DISCUSSION

The GDE maps demonstrate the Middle Miocene M45 and M50 deltaic progradation easterly towards the younger section (Figure 8). The most noticeable difference between the two GDE maps are at the central part where the shelf edge do not shift much, unlike the northern and southern ones. The geometry of basin-floor fans (dark-brown polygons) are intentionally drawn to filling in the thick isopach trends, avoiding and/or stopped then ponded along the western flank of the syn-depositional structure (paleo high), which is reflected by thin isopach (Figure 7). The dimensions of the fan are considered to be similar to the Pleistocene (20x20 sq.km) and Late Miocene's Gendalo (10x20 sq.km) fans (Saller *et al.*, 2008), with some of them are slightly larger of ca. 30x30 sq.km. The orange dashed lines illustrate the interpretative IVF and slump scars.

Several evidences of the relative sea-level fall that associated with forced regression process have been observed onshore and offshore based on the seismic and well data. They are the IVF sandstones that scoured the lower deltaic to delta front settings below and above the M45, slump scars along the latest Middle Miocene's shelf edge (M65), and the Late Miocene's up to 20 m thick cross-bedded fluvial sandstones that incised the underlying marine shales at Sisi and Nubi fields.

This study suggests another evidence of forced regression event in the Middle Miocene within the M40 to M65 markers. It is where significant progradation of the shelf break from the K/J_ILX (M40) to I.2_ILX (M45) markers have the distance of 13-km and 19-km. These are clearly defined in the depth sections of the seismic data in the northern (Tunu) and southern (Sapi-Peciko) areas, respectively; as displayed at two seismic sections in Figure 9. It happened when the sedimentation rate is likely to be higher than the accommodation space due to uplift and erosion at the proximal side. This huge event is able to incise part of the by-passed zone and delivering enormous clastic sediments into the paleo deep-water settings.

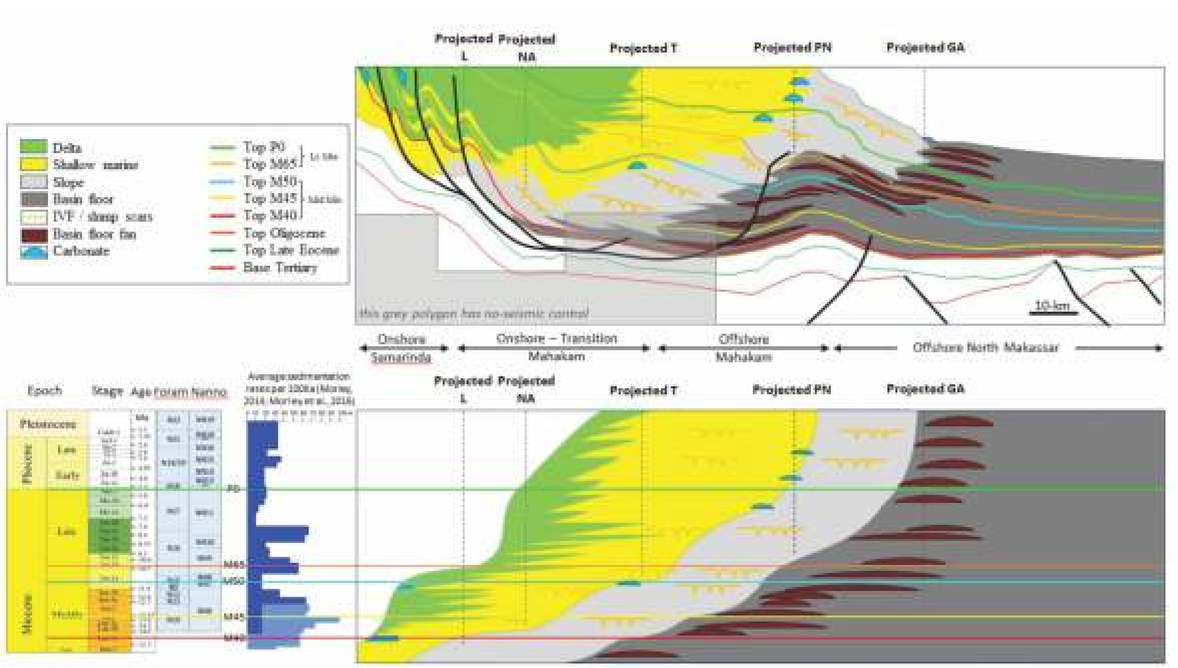


Figure 6. Play cartoon and regional chronostratigraphy of the study area derived from a key line in Figure 3.

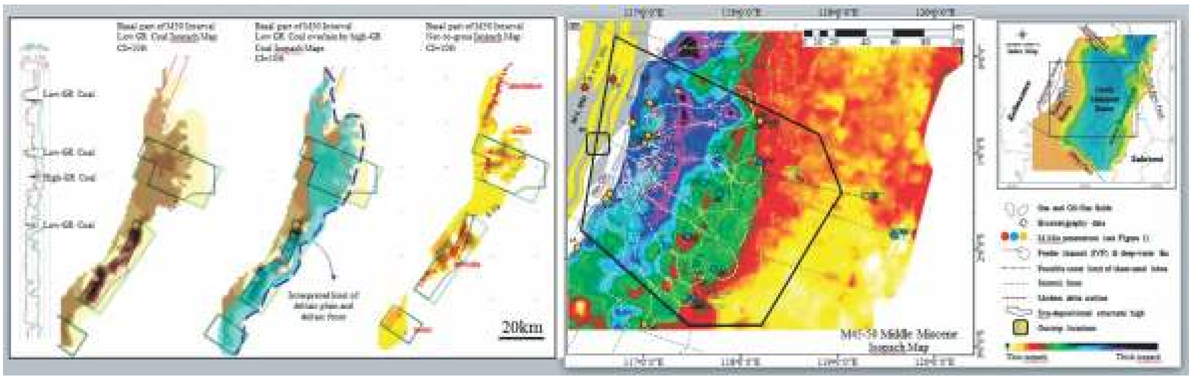


Figure 7. Low-and high-GR coals with net-to-gross sandstones ratio maps (Nugrahanto *et al.*, 2004); left map. The isopach map of M40-M45 illustrates the thickest (magenta) and thinnest (yellow); right map, with surface geology map (Supriatna *et al.*, 1995).

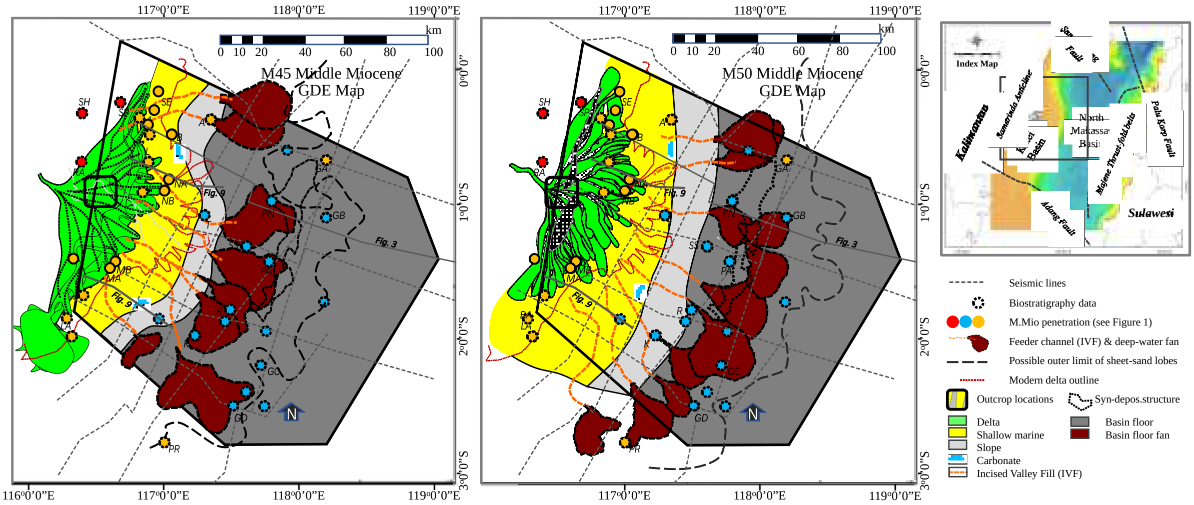


Figure 8. GDE maps of the middle Miocene M45 and M50 levels showing prograding delta (green) and shelf break (light grey) to the eastern direction.

Flattening the key seismic lines were conducted to simply restore the paleo shelf and slope breaks into their original positions although this method has limitation at some points. However, converting the seismic lines from time-to-depth would considerably accommodate the x and y scale difference. Variation of the seismic velocities with increasing depth may result in the inconsistencies on the vertical height of the slope break. Degree of syn-depositional folding deformations since the Early Miocene might shorten the original lateral distance of shelf to slope breaks without being preceded by a structural restoration work.

With the limitations aforementioned, Figure 9 illustrates a graph of slope angles and horizontal length from the shelf edge to the slope break at each markers. It is divided into the northern and southern areas, presented from the older to younger ages upwardly. The most obvious finding in this graph is a significant decrease in deep-water's slope angles (orange bars) of the shelf breaks in the Middle Miocene (M40 to M50) to Late Miocene until Recent (M65 to Recent) intervals, from 5-10 degree to <5 degree, respectively. However, the horizontal lengths of shelf to slope breaks oppositely increase from up to 12 km in the middle Miocene to a range of 25 km to 40 km in the Late Miocene to Recent time.

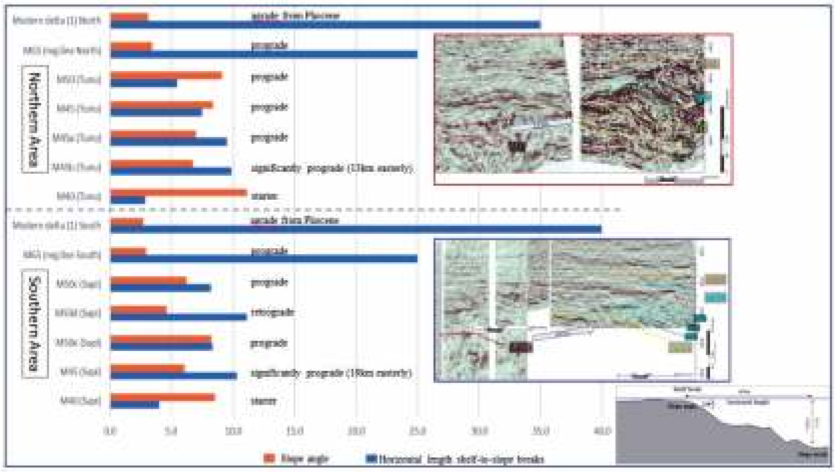


Figure 9. A bar graph of slope angles (orange) and horizontal length from the shelf edge to the slope break (dark blue) at each marker. Two flattened seismic lines represent the northern (red box) and southern (blue box) areas that show clinoform successions from west to east. The slope angle of the modern delta is measured from the water depth map in Roberts and Sydow (2003).

CONCLUSIONS

As we may all know the onshore region has very good data coverage in the Middle Miocene rock layers. However, it is less complete in the younger Miocene intervals as it has been partially or fully unroofed due to its relative position on the degree of Kutei Basin deformation. The offshore area on contrary have been very limited well penetrations at the Middle Miocene section by now hence the seismic data holds more important role, instead.

Key biostratigraphy markers utilized in this study: M40, M45, M50, M65 are to have greater focus in mapping the Middle Miocene's deep-water facies distribution in a gross depositional environment (GDE) maps offshore.

The most appropriate place for the Middle Miocene basin floor fan deposition is defined to follow the thick isopach areas, with their body geometries replicating the Pleistocene and Late Miocene's fans. The GDE maps of the studied interval defined an overall prograding succession easterly, where the central part is less shifted than the northern and southern parts. The Middle Miocene succession exhibits substantial changes from the Middle into the Late Miocene until Recent intervals; a decrease in the angle of the slopes and a longer length of the lateral distance between the shelf to slope breaks.

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