

# Exploration history and petroleum systems of the onshore Baram Delta, northern Sarawak, Malaysia

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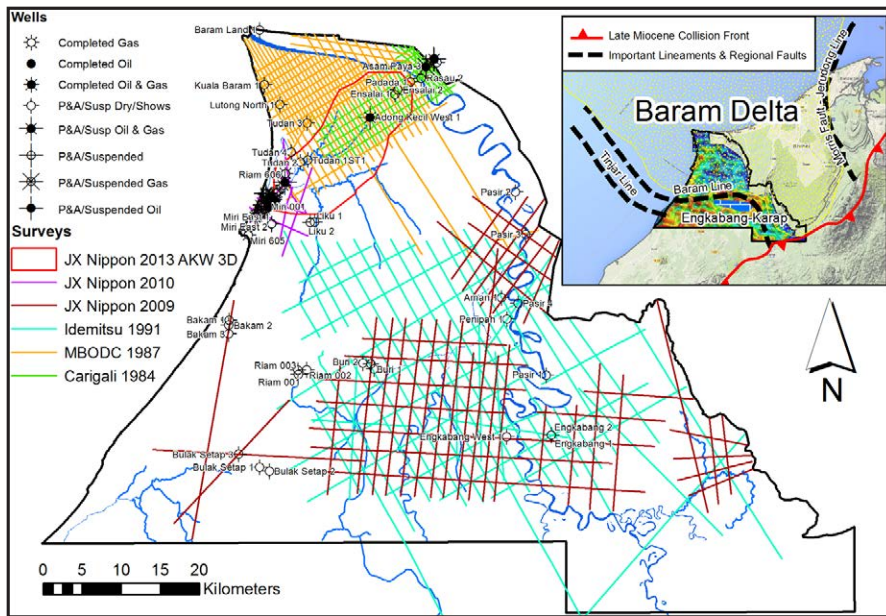
**Abstract:** The onshore portion of Baram Delta petroleum province in northern Sarawak is largely covered by the Block SK333 exploration permit, most recently operated by JX Nippon. It contains a complete sedimentary succession ranging in age from Mid Eocene to Holocene. A sequence-stratigraphic investigation of the area, based on 2009 2D seismic, integrated with recent biostratigraphic analyses conducted in 2010-2011, suggests that the sedimentary section has been affected by three major episodes of deformation which are: (1) Late Cretaceous to Eocene (79.5-36Ma) block faulting, (2) Late Oligocene to Mid Miocene (30-20.5Ma) wrench movement and related folding, followed by (3) Mid Pliocene to Holocene (4.0-0Ma) uplift and compressional folding. These tectonic episodes have resulted in a subdivision of the Block SK333 area into two major anticlinal trends: the Engkabang-Karap Anticline in the south, and separated by the large Badas Syncline, the northern Miri-Asam Paya Anticline. This configuration resulted in two distinct petroleum systems and respective hydrocarbon zones: (i) A southern overmature gas system sourced probably from deeply buried and carbonaceous Eo-Oligocene basinal shales containing reworked terrestrial organic matter, which charged wrench induced traps such as at the Engkabang-Karap Anticline that were later overprinted by compressional folding. The surface expression of this petroleum system is manifested by an active mud volcano on the western Engkabang-Karap Anticline axis, which emits thermogenic C<sub>1</sub> gas. Burial history modelling indicates that an earlier oil charge probably occurred during deep Oligocene burial, preceding basin reversal during the Pliocene-Holocene inversion episode, with the wrench-induced anticlinal closure which subsequently has been charged by late gas. (ii) A block-wide oil and gas system sourced from peak mature Mid-Late Miocene carbonaceous shales and coals in the synclines, charging inversion and compressional fold structures along the northern Miri-Asam Paya anticlinal trend, and also the Miocene section at the Engkabang-Karap Anticline. Expulsion and charge to traps commenced during the Late Miocene and is continuing to the present-day. Although the exploration results of the southern Eo-Oligocene carbonate play have been disappointing to date, the onshore Baram Delta still contains a number of attractive, both untested and partially tested plays that are yet to be fully explored. Lowstand delta and turbidite plays, a highstand delta shoreface play in the Miri-Asam Paya anticlinal area and a moundform stratigraphic play in the southern limb of the Badas Syncline are among the untested play identified in the study area.

**Keywords:** onshore Baram Delta, northern Sarawak, petroleum systems, sequence stratigraphy, SK333

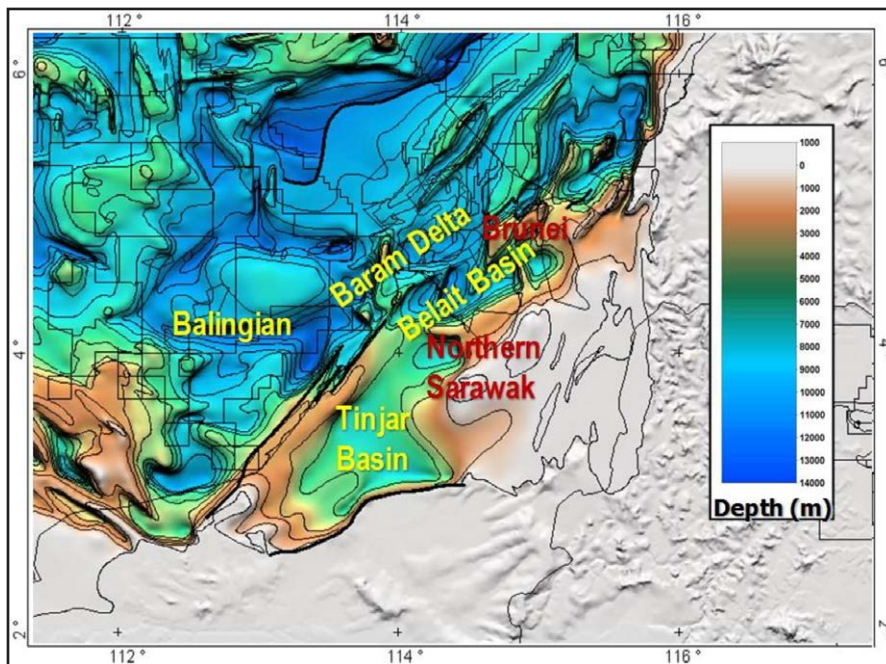
## INTRODUCTION

The Baram Delta, an area of some 7000 km<sup>2</sup>, is a roughly triangular-shaped feature with its apex located in onshore northern Sarawak and extended to include neighbouring Brunei in the northeast (Tan *et al.*, 1999; Figure 1). Approximately 85% of the basin is located offshore, mostly in shallow water of less than 50 m depth. The sedimentary fill, believed to be entirely Tertiary-aged, ranges in thickness from 3000 m in the inboard area to an estimated 10000 m offshore. Towards the southeast, the basin is confined by a thrust front of metamorphic Rajang Group deposits. Regional interpretation of the basin architecture based on gravity and seismic data suggests that two northeast-southwest ridges are dividing the deeper Palaeogene sedimentary section into the Balingian, Tinjar, Belait and Baram Delta basins (Figure 2), resulting into likely different hydrocarbon charge and migration mechanisms in the various parts of the Baram Delta.

In the late 1880's and similar to the other oil regions of the world, oil seeps provided the first motivation for oil exploration in northern Sarawak. In Brunei, exploration started in 1899 with the first recorded well drilled close to Brunei town, now known as Bandar Seri Begawan (Sandal, 1996). The onshore Baram Delta is the birthplace of the Malaysian oil and gas industry with the 1910 discovery of the first commercial oil field, the Miri Field. Encouraged by the significant discovery, enthusiasm was high across the border in Brunei and six companies were involved in the oil search including Royal Dutch Shell, which started operations in 1913 after discovering the Miri Field. By 1918, all other companies had pulled out except Royal Dutch Shell, which continued to search and found some accumulations of oil and gas in Labi, Belait in 1924. However, the find was too small to be commercialised. In 1925, the search for oil shifted to the Seria-Belait coastal strip and it was in 1929 that, the first giant commercial oil



**Figure 1:** Location map of Block SK333 in northern Sarawak and existing well and seismic database (with ~3000-line km of 2D). Inset map shows the outline of Baram Delta as defined by Tan *et al.* (1999) in the stippled area with bounding lineaments of Tinjar-Baram lines defining the western boundary and the Morris Fault-Jerudong Line forming the eastern boundary. Overlaid on the topography map is the gravity data acquired by JX Nippon (Jong *et al.*, 2016) with Engkabang-Karap Anticline highlighted as positive anomalies.



**Figure 2:** Interpreted depth to economic basement basin architecture of onshore Sarawak/Brunei and nearby offshore areas based on seismic and gravity data.

find in Brunei was made at the Seria Field by the British Malayan Petroleum Company, owned by Royal Dutch Shell, which was the forerunner to the present Brunei Shell Petroleum Company Sdn Bhd (BSP) (Sandal, 1996). For a long time, the onshore Miri and Seria oil fields were the only producing fields despite more than 65 exploration wells were drilled between 1914 and 1960. With the lack of further onshore exploration success and the breakthrough that came in the 1960's when technological advances such as shallow water 2D seismic acquisition made offshore exploration feasible, the exploration focus has since been shifted to offshore Baram Delta (Tan *et al.*, 1999).

This paper provides a brief review on the exploration history of the study area in the Malaysian territory with an emphasis on the exploration activities and data acquisition after the relinquishment of the Miri Field by Sarawak

Oilfields Limited, a subsidiary of Royal Dutch Shell in 1981. The chronology of the earlier exploration history and key events that led to the discovery of the Miri Field have been well documented by Sandal (1996), Tan *et al.* (1999), and also more recently by Sorkhabi (2010) and Wannier *et al.* (2011). In addition, Shell published internally a number of geological field guides and excursion reports. Kessler & Jong (2014) provided a potential explanation for the formation of the Canada Hills including an update of the structural interpretation of the Miri Field. The main objective of this paper is focussed on the petroleum geology and hydrocarbon habitats of the onshore Baram Delta in Block SK333. The evaluations are largely based on recently acquired 2D regional and reprocessed seismic lines (Jong *et al.*, 2013; 2015). It is noted that the subject has been partially addressed by Jong *et al.* (2016) in their

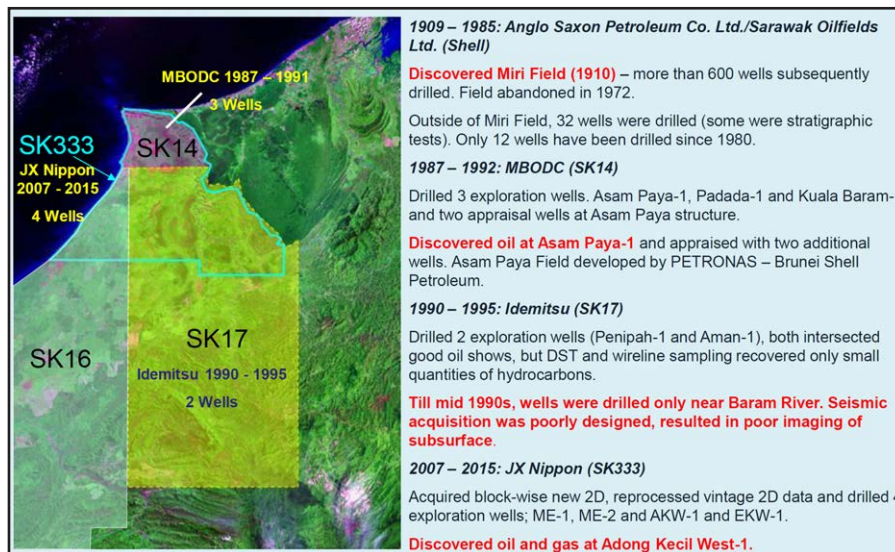
discussion of the structural development, deposition model and petroleum system of the Palaeogene carbonate of the Engkabang-Karap Anticline.

### EXPLORATION HISTORY

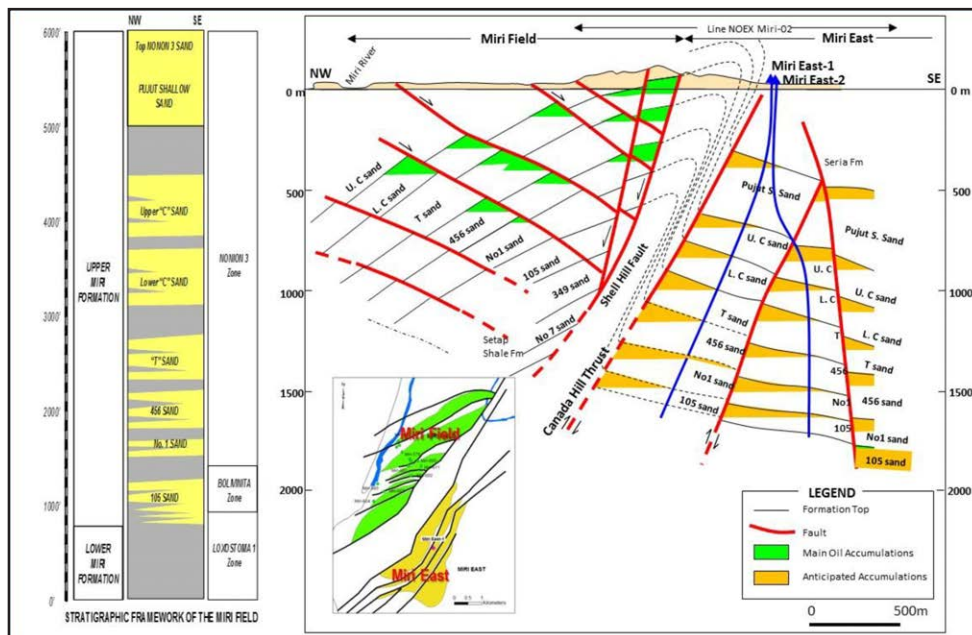
The area covered by Block SK333 has been licensed several times (Figure 3). It was initially granted to the Anglo-Saxon Petroleum Company Limited (later Sarawak Oilfields Limited, both part of the Royal Dutch Shell). The initial exploration of the area during this period led to the discovery and development of the Miri Field in 1910 (Figure 4), and the drilling of several prospects in the area. The Miri Field reached its peak annual production of 5.548 million barrels of oil in 1929. From 1931 onwards, the annual production significantly dwindled as a result of rapid pressure loss, as too many production wells (> 600!) had been drilled by then. After producing approximately 80 million barrels of oil the Miri Field was abandoned on 20<sup>th</sup> October 1972 in

spite of various enhancement efforts, and this was followed by the whole concession relinquishment in 1981 (Wannier *et al.*, 2011). After this Shell ceased to carry out onshore exploration. During Shell's 72 years of active concession period, outside of the Miri Field, 32 exploration and appraisal wells were drilled onshore. However, apart from Miri No.1, none of the wells encountered any economical hydrocarbon accumulation (Tan *et al.*, 1999). Nonetheless, it was noted that Well No. 604 hit a deeper, overpressured gas-/condensate-bearing zone of some 120 m thickness within the Setap Shale at a depth of 1783 – 1905 m. The reservoir was described as discontinuous lenses of fine sand, and possibly of turbidite origin (Kessler & Jong, 2014).

In 1984, PETRONAS Carigali Sdn. Bhd. (PCSB) carried out a 2D seismic survey, but no further exploration activity was carried out (JX Nippon, 2015). In 1987, Malaysian Baram Oil Development Company (MBODC), as an operator, together with PCSB, as a partner, were



**Figure 3:** Onshore Baram Delta exploration history and permit assignment since Shell relinquished the area in 1981. Former onshore Block SK14 and Block SK17 were operated by Malaysian Baram Oil Development Company (MBODC) and Idemitsu Oil Exploration (East Malaysia) Co. Ltd., respectively. Block SK333 was only recently relinquished by JX Nippon Oil & Gas Exploration (Onshore Sarawak) Limited in 2015. JX Nippon drilled 4 exploration wells with a sub-commercial oil and gas discovery made by well Adong Kecil West-1.



**Figure 4:** Schematic Miri Field - Miri East structural cross section. Stratigraphic framework of the Miri Field is shown on the left with estimated formation tops of Miri East interpreted from Miri Field data based on seismic interpretation. Main oil accumulations in the Miri Field are inferred from MBODC report (after JX Nippon, 2012b). Post-drilling, no hydrocarbon accumulation was encountered in Miri East-1 and -2, which were drilled downdip of the fault blocks. The wells confirmed the presence of migrated hydrocarbons based on weak oil shows from the T, 456 and 105 Sands but failed possibly due to fault seal failure.

awarded a Production Sharing Contract (PSC) for Block SK14 (Figure 3). In 1987 they conducted a 738-line km 2D seismic survey and in 1991 drilled three exploratory wells; Kuala Baram-1 in 1988, Asam Paya-1 in 1989 and Padada-1 in 1991.

Kuala Baram-1 tested Late Miocene highstand and transpressive system tract shoreface sands and was plugged and abandoned due to operational limitations. Minor gas kicks and weak oil shows were recorded. It is noted that the east-west closure of the Kuala Baram structure was difficult to resolve; hence, one of the potential reasons for the failure may be lack of an effective trap. Padada-1 was drilled to test a 3-way dip footwall closure. It had minor oil shows but failed, possibly due to cross fault seal failure. The drilling of Asam Paya-1 was triggered by the oil discovery by Rasau-2 in Brunei. Similar to Rasau-2, Asam Paya-1 targeted Late Miocene sands of the South Rasau structure - a fault bounded northeast trending anticline that straddles the Sarawak-Brunei border. The well discovered oil and gas accumulations in the Middle to Lower Cycle V coastal sandstone reservoir facies, which led to drilling of 2 appraisal wells, Asam Paya-2 and Asam Paya-3 in 1989 and 1990, respectively. Asam Paya-3 was not successful and is possibly located in a separate fault compartment. The block was relinquished in 1993 without the development of Asam Paya Field (Tan *et al.*, 1999). Presently, the field is on production under a unitization agreement between PETRONAS and BSP (Jong *et al.*, 2015).

Block SK17 (Figure 3) was awarded to Idemitsu Oil Exploration (East Malaysia) Co. Ltd. (Idemitsu) in 1991. The exploration phase kicked-off with the acquisition and processing of 1018-line km of 2D seismic data in 1991 and was followed by the drilling of 2 exploration wells, namely Aman-1 and Penipah-1. Aman-1 was drilled in 1993 to test the Mid to Late Miocene sediments in a 3-way dip closure on the Pasir Nose located on the southern limb of the Badas Syncline. The well was plugged and abandoned with both oil and gas shows across the targeted reservoir section. Penipah-1, drilled in the same year targeted the equivalent reservoir in a downthrown 3-way dip closure of the same structure. Oil shows ranging from poor to good quality were recorded in ditch cuttings, sidewall cores and conventional cores. Both oil and gas were recovered to surface during wireline logging operations. The block, however, was then relinquished in 1995 as both discoveries were deemed uneconomical at the time.

In 2007, after a long hiatus in exploration activities, JX Nippon Oil & Gas Exploration Onshore Sarawak Limited (JX Nippon), as an operator with PCSB as a partner signed a PSC for the onshore Sarawak Block SK333. During the first 3 years of the exploration period, extensive data acquisition and seismic processing projects were undertaken; including the reprocessing of 1730-line km of 2D seismic line, acquisition and processing of 850-line km of new 2D seismic lines, block-wide high-resolution gravity and magnetic surveys and a prospect-focussed surface geochemical survey. Four wildcat exploration wells were drilled namely Miri East-1,

Miri East-2, Adong Kecil West-1/ST1/ST2 and Engkabang West-1 (JX Nippon, 2015).

The Miri East-1 wildcat exploration well was drilled in 2011 with the objective to test the foot-wall equivalent of the Late Miocene reservoir units of the Miri Field (Figure 4). Good reservoir development was observed in the section above the Lower C Sand, but no reservoir facies were observed beneath the T Sand section. Post-well re-calibration of the time-to-depth relationship with the newly acquired data revealed that the initially interpreted faults and seismic horizons are much gentler in their dips, and thus the deviation of Miri East-1 well was towards the down dip of the fault block. No hydrocarbon accumulation was encountered, but the well confirmed the presence of migrated hydrocarbons based on weak oil shows from the T, 456 and 105 Sands, and also based on the gradual increase of gas levels with heavier n-alkane components below the C Sand, which resulted in a major gas kick at the 105 Sand. From the same surface locality of Miri East-1, Miri East-2 was drilled targeting a similar play. However, it resulted in a similar outcome as Miri East-1 (JX Nippon, 2012a and b; Figure 4).

The third exploration well, Adong Kecil West-1/ST1/ST2, drilled in 2012, tested the Late Miocene deltaic sandstone reservoirs of the most up-dip hanging-wall fault block on the Miri-Asam Paya anticlinal trend. 23 years after the last discovery of onshore economical oil at Asam Paya, the Adong Kecil West-1/ST1/ST2 exploration well encountered a 510 m hydrocarbon column (gross thickness) within the Lower Cycle V sandstone reservoirs confirmed by 2 drill stem tests (JX Nippon, 2013).

Engkabang West-1 was the fourth and last exploration well drilled by JX Nippon in 2013/14. It was aimed to test a different play type - the Eo-Oligocene carbonate bank play. The well penetrated 3 distinct target zones: (1) thickly developed silty claystone with thin intercalations of sandstone and limestone layers, correlated with the transition zone above the massive carbonate section in Engkabang-1, (2) a massive and very tightly-cemented carbonate that was correlated biostratigraphically to the massive carbonate observed in Engkabang-1, and (3) a calcareous shale zone below the massive carbonate similarly encountered in Engkabang-1. The well's total depth was called shallower than expected due to operational constraint, and consequently, the inferred deeper and older carbonate section remained untested. Although gas shows were recorded from fractures within the carbonate section, a drill stem test confirmed tight reservoir and no hydrocarbon flow (JX Nippon, 2014; Jong *et al.*, 2016).

In summary, many of the old wells (pre-1980's) drilled based on geological mapping, seep detection, gravity surveys (1900-1940) and sparse low-fold seismic (1940-1980) appear to be off-structure, when compared with the currently available and mostly adequate high-fold 2D coverage. The seismic data varies both in coverage and quality across the area (Figure 1). The north is covered by a regularly-spaced 1987 (geophone and bay cable) 2D grid on both sides of

the Baram River. The main shooting direction is northwest-southeast, parallel to the strike of the Baram River. The line spacing is about 1 km. These lines are linked by a few strike lines, shot in southwest-northeast direction. A coarse grid of 2D exists over tracts of the Lambir Hills. Line spacing is in the order of 5-7 km. A regular grid with *ca.* 1.5 to 2 km spacing, acquired by Idemitsu in 1991, is available in the southern plain area (Marudi-Engkabang), and is infilled by some 850-line km with a similar grid space acquired by JX Nippon in 2009. In 2010, a few 2D test lines were also shot over the Miri Field to further delineate the structure's fault compartments. The results were mixed, but the data were later used to infer a possible wrench-related structuration with pop-up feature associated with the formation of the Canada Hills (Kessler & Jong, 2014).

In order to further enhance reservoir characterization and to address concern on fault connectivity over the Adong Kecil cluster, following the Adong Kecil West oil and gas discovery, a first onshore 3D seismic survey in Malaysia was conducted. It covers an area approximately 181.98 km<sup>2</sup> across the Miri-Asam Paya anticlinal structure (Figure 1). Despite the enhanced imaging of the subsurface *via* the 3D seismic survey and potential for the Adong Kecil

West development, JX Nippon officially relinquished Block SK333 in early 2015 in the light of falling crude oil prices and hence a reduced economic outlook for the project.

Table 1 summarises the key exploration well results drilled in Block SK333.

**REGIONAL SETTING, DEPOSITIONAL HISTORY AND DEFORMATION SUMMARY**

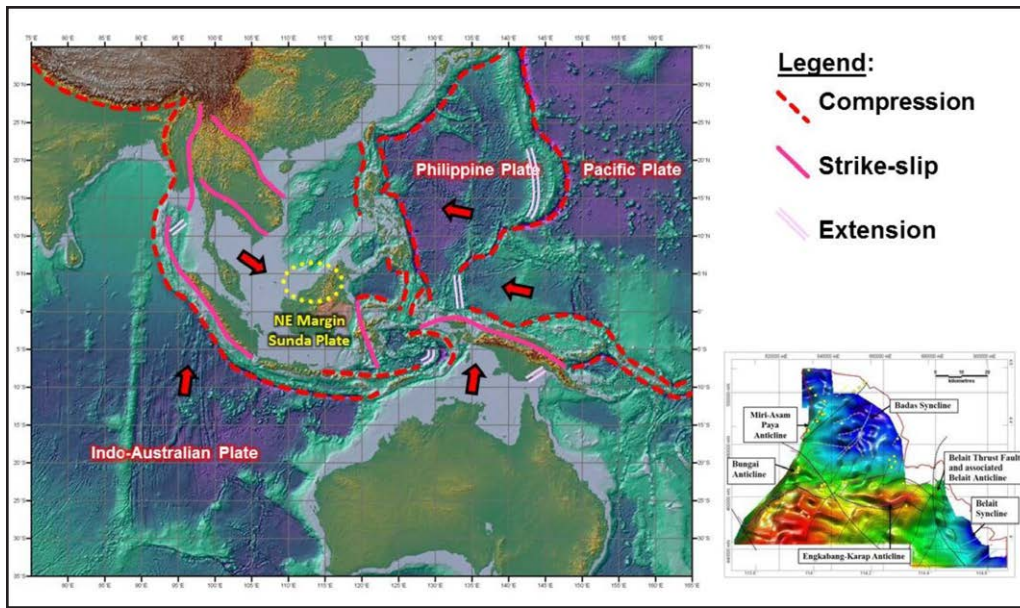
The Cenozoic evolution of the NW Borneo margin records a diverse array of tectonic events including subduction, block faulting, compression and large-scale continental strike-slip faulting occurring in spatially and temporally complex relations. An understanding of the northern Borneo plate tectonic evolution is therefore critical to better understand the observed styles of structural development in the onshore Sarawak area. These onshore structures play a vital role in providing migration pathways and traps for the subsequent migration and preservation of hydrocarbon accumulations.

The Baram Delta is situated on the north-eastern margin of Sundaland, which is strongly influenced by three major dynamic plate tectonic vectors (Figure 5): (1) northward subduction of the Indo-Australian Plate, (2) westward

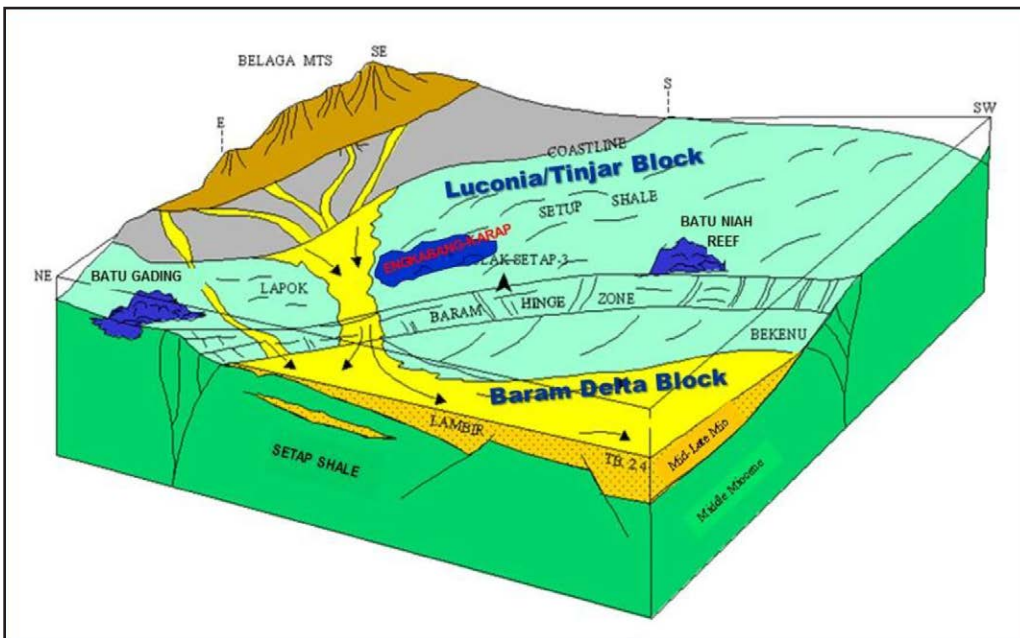
**Table 1:** Summary of key exploration well results in Block SK333. The exploration drilling efforts, from the Miri Field discovery in 1910 until the drilling of well North Lutong-1 in 1965, were carried out in a complex structural setting without modern technology such as 3D seismic and were hence based on poor seismic resolution. See Figure 1 for well locations.

Well	Year	TD (m)	Target (Cycle)	Reservoir (Cycle)	Seal	Migration	Trap	Results
Miri-1	1910	?		V			3WHW	Discovered Miri Oilfield (80 MMbbls)
Buri-1	1922	893		III?			4W?	Surface mapping/seeps. Recovered oil from shallow reservoirs. Gas blowout at 900m.
Buri-2	1923	192		III?			4W?	Surface mapping/seeps. Recovered oil in Cycle III?
Buri-3	1924	889		III?			4W?	Surface mapping/seeps. Recovered small quantities of oil.
Riam-1	1927	946		III?			4W?	Surface mapping/seeps. Free oil in sandstone to 179m. Dry gas to 563m.
Rasau-1	1929/31	?		V			3WFW	Gravity survey only. Oil shows.
Riam-2	1930	507		III?			4W?	Surface mapping/seeps. Oil shows.
Tudan-1	1935	2114	V	V				Surface mapping/core holes. Gassy water recovered on JFT.
Tudan-2	1937	2034	V	V				Surface mapping/core holes. Minor oil shows.
Bulak Setup-3	1951	3546	I, II				4W?	Common gas shows in fault zones. Oil reported in BS-1 (1915).
Tudan-3	1953	2657	V	V				Poor seismic control. Free oil in mud at 2590m.
Pasir-1	1954	1482	strat	IV				Poor seismic control. Stratigraphic investigation. Weak oil shows.
Pasir-2	1954	2875	strat	IV - V				Poor seismic control. Stratigraphic investigation.
Pasir-3	1955	3049	strat	IV - V				Poor seismic control. Stratigraphic investigation. Weak oil shows.
Bakam-3	1958	2709	strat	IV			?	Surface mapping/seeps. Drill on gravity high?
Engkabang-1	1959	3374	III	I - III			4W	10m NOS 173 - 213m in Cycle III. Gas recovered on test from 3024m in Melinau Limestone.
Engkabang-2	1960	488	III	III			4W	Oil sands thinner than at Engkabang-1. DST oil at low flow rate.
Ensalai-1	1960	2831	V	V			3WFW	Drilled in closure but more than 100m down-dip of crest.
Baram Land-1	1965	3294	V	V - VI			?	Structure uncertain, poor seismic control.
North Lutong-1	1965	3406	V	V - VI			3WHW	No / weak TWT closure, limited seismic coverage.
Tudan-4	1979	1820	V	V			?	Pre-drill structural interpretation was incorrect.
Pasir-4	1980	2591	IV	IV - V			3WHW	Oil pay interpreted?
Kuala Baram-1	1989	914	V	V - VI			3WHW	Gas shows. Gas kick at TD (3000 psi overpressured).
Asam Paya-1	1989	2814	V	V			3WHW	Asam Paya oil discovery. 80m NOS, 45m NGS. Currently producing.
Asam Paya-2	1990	2051	V	V			3WFW	Appraisal well drilled in the downthrown fault block from Asam Paya-1. Limited gas pay.
Asam Paya-3	1991	2450	V	V			3WFW	Appraisal. Weak oil shows. Drill out of closure? Different fault compartment?
Padada-1	1991	2545	V	V			3WFW	Minor oil shows - cross fault seal?
Penipah-1	1993	2319	IV	IV - V			3WHW	Redrill of Pasir structure. Good oil shows, oil / gas recovered on RFT. Leaky trap?
Aman-1	1993	2709	IV	IV - V			3WHW	Good oil shows. Leaky trap?
Miri East-1	2011	1923	V	V			3WFW	Footwall trap. Oil shows with major gas kick at 105 Sand. Poor reservoir in lower part of the objective interval.
Miri East-2	2011	1600	V	V			3WFW	Footwall trap. Weak gas shows with poor reservoir development.
Adong Kecil West 1/ST1/ST2	2012	3170	V	V			3WHW	Adong Kecil West oil and gas discovery. 510m gross thickness of HC-bearing column interpreted.
Engkabang West-1	2013/14	4090	I - III	I - III			4W	Shallow oil and deep gas shows. Tight carbonate reservoir encountered.

■ = present ■ = uncertain ■ = absent 3WFW = 3 way dip footwall, 3WHW = 3 way hanging wall, 4W = 4 way closure



**Figure 5:** SE Asia present-day plate tectonic setting. The Baram Delta lies on the NE margin of Sundaland at the juxtaposition of three major tectonic plate vectors with northward subduction of Indo-Australia Plate, westward subducting Pacific/Philippines plates and the south-easterly extruding Sunda Plate (including Indochina). After Teas, 2005. Inset map shows key tectonic elements on gravity anomaly map of Block SK333.



**Figure 6:** Schematic block diagram of northern Sarawak with a regional perspective of Late Miocene/Pliocene times. Luconia/Tinjar Block constitutes the foot-wall, the Baram Delta the hanging-wall NW of the Baram Hinge Zone defined by the Baram Line. Given the folding of areas such as the Badas Syncline, Lambir Hills, Miri etc., northern Sarawak serves as an example of relief-inversion (after Kessler, 2009; Jong *et al.*, 2016).

subduction of the Philippine Sea Plate along with the trailing subduction of the Pacific Plate, and (3) south-easterly extrusion of Mesozoic continental blocks of the southern Sunda Plate as a wedge between the Indo-Australian and Philippine Sea plates.

The delta is separated from the relatively stable Mesozoic Sundaland Craton by the northwest-southeast trending Baram (or West Baram) and Tinjar lines, which are palaeo-transform faults, but are presently zones of large-scale steeply NE-dipping normal faults (Cullen, 2014). The eastern part of the delta is separated by the Morris Fault-Jerudong Line (see Figure 1 inset for location), a palaeo submarine continental slope commonly referred to as a ‘sinistral wrench fault zone’ by Hutchison (1994) from the old and highly deformed Inboard Belt of offshore NW Sabah.

A summary for the geological setting of the study area is provided by Kessler (2009) and Jong *et al.* (2016),

which encompasses the Baram Delta Block and the adjacent foot-wall terrain of the Luconia/Tinjar Block (Figure 6). While the hanging-wall Baram Delta Block was rapidly subsiding during clastic sedimentation, the Luconia/Tinjar Block had a lower subsidence rate. Being only moderately folded, this latter terrain is characterized by a number of synclines with minor overthrusting (see Figure 5 inset). The Baram Line acted as a tectonic discontinuity linking the relatively stable Luconia/Tinjar Block to the mobile and siliciclastic-dominated Baram Delta Block. A simplified chrono-stratigraphic summary for northern Sarawak and adjacent Brunei covering the study area is provided by Kessler & Jong (2016) and is shown in Figure 7.

Many oil and gas wells have been drilled into the delta’s sedimentary sequence, but most reached total depths within the Neogene section. For this reason, there are hardly any well data available for the deeper Early Miocene

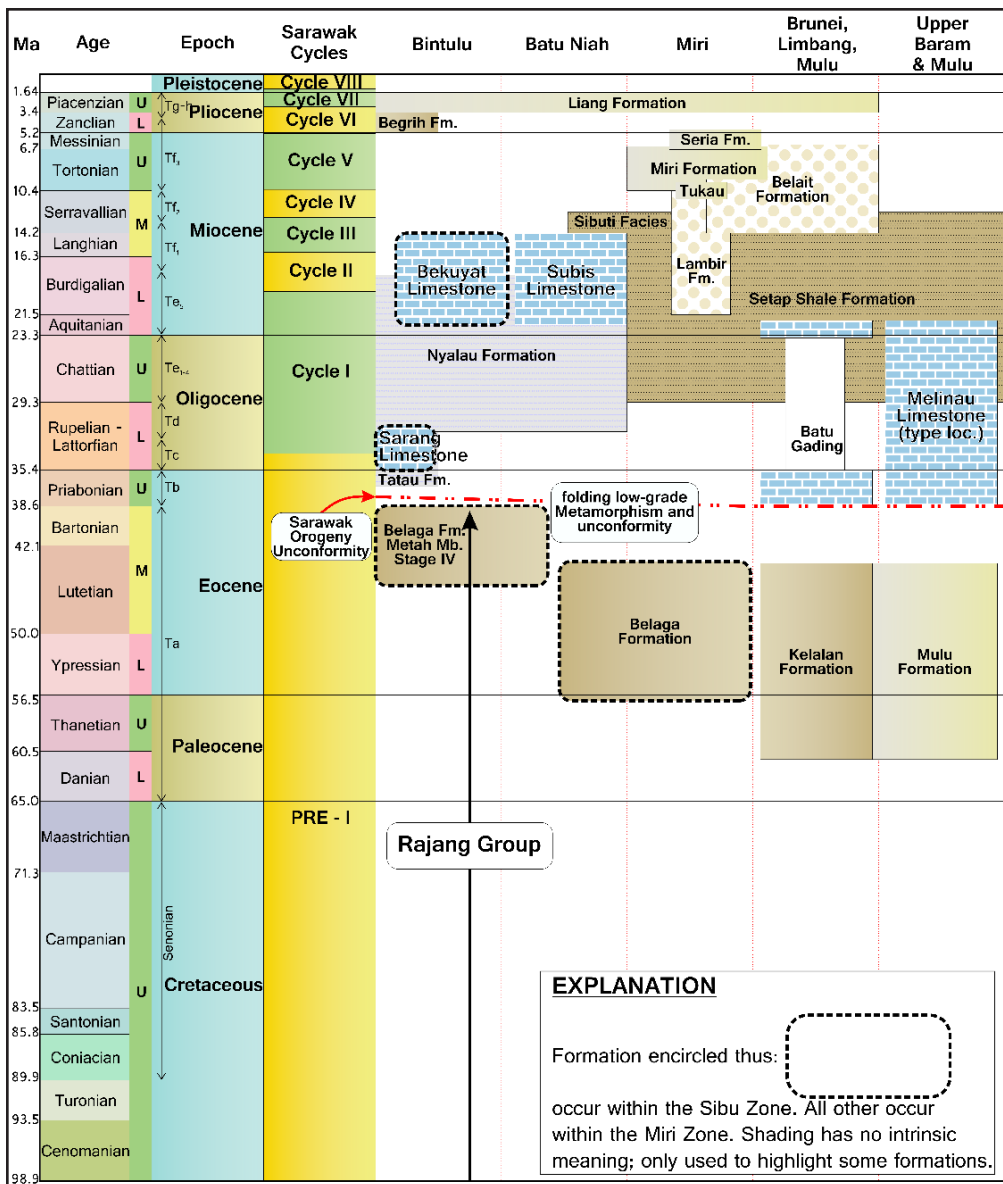


Figure 7: Chronostratigraphic table of the major formations of the Miri Zone covering northern Sarawak and adjacent Brunei area. The Upper Cretaceous to Upper Eocene Rajang Group (flysch) forms the Sibiu Zone and potentially underlies the Miri Zone. The Sarawak Orogeny caused low-grade metamorphism and strong folding characterized by steep dips of the Rajang Group. The overlying formations (molasse) are much less deformed, and unmetamorphosed, except in localized shear zones. After Kessler & Jong (2016) and modified after Hutchison (2005, Figure 22).

and Palaeogene basin fill. The older sedimentary sections crop out in one location in northern Sarawak, namely in Limbang (Kessler & Jong, 2016 and this volume). This outcrop, together with a couple of deep well penetrations in Engkabang-Karap area located on the southern fringe of the onshore Baram Delta suggest that there are potentially no Rajang Group turbidite sequences present beneath the delta, but might have been thrust over the Sarawak Foreland Basin (Jong *et al.*, 2016; Kessler & Jong, 2016 and this volume).

A tentative description of sedimentary sequences and tectonic events characterising the study area is presented below.

During the Late Eocene, the onshore Sarawak area was covered by a bathyal basin with the development of transgressive carbonate banks and shoals along its northern shore (Kessler & Jong, 2016 and this volume). A period of wrench-folding occurred along the Baram Line resulting in the Engkabang-Karap Anticline and associated structuration.

During the Mid Miocene, well-defined major unconformities exist caused by simultaneous tectonic deformation episodes in the Borneo surrounding areas. This resulted in major phases of uplift and erosion and hiatuses of sedimentation in the uplifted areas (Leong, 1999; Madon, 1999; Kessler & Jong, 2015a). One of the Mid Miocene unconformities is covered by the Setap Shale. This formation is a deep marine, prominent sequence of dark clays and shales with minor intercalations of siltstones and sandstones (Kessler & Jong, 2015b). Rapid deposition of the Setap Shale and hence limited dewatering during compaction resulted in its ductile and overpressured characteristics. The shale's ductility was later responsible for the present deformation of the overlying sediments. A release of pressure and liquids from the Setap Shale can still be observed today in mud volcanoes around the Miri and Engkabang-Karap areas (Hutchison, 2005; Kessler *et al.*, 2011; Jong *et al.*, 2016). The calcareous and relatively fossil-rich upper part of the Setap Shale due to marls and thin limestone layers

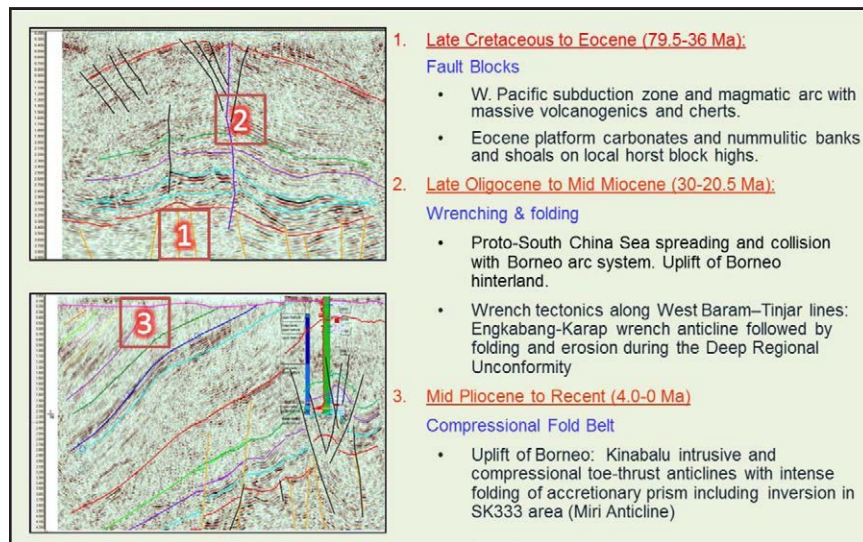
is distinguished as the Sibuti Formation by Wannier *et al.* (2011) and Khor *et al.* (2014). By Late Miocene, the onshore northern Sarawak area is characterised by shelf deltaic progradation and aggradation systems, as well as turbiditic sedimentation in slope to basin floor settings. The large Miri listric growth faults started to develop creating the future foot-wall of the Miri-Asam Paya Anticline.

From Pliocene to Pleistocene, deltaic progradation continued with re-deposition of sediments supplied from the uplifted and eroded Borneo hinterland forming the sand-rich Baram Delta system with the deposition of the Lambir, Tunku, Miri and Liang formations. The Lambir Formation is described as an alternation of shallow marine sandstones with limited calcareous shales (Kessler & Jong, 2015b). The Miri Formation, the prolific zone of the Miri Field (Figure 4), is a succession of deltaic, well consolidated, mostly fine grained sands with moderate porosity (Tan *et*

*al.*, 1999). The Tunku Formation (laterally equivalent to the Miri Formation), is however poorly consolidated with alternating soft clays and finely dispersed lignitic material. The Lambir, Tunku and Miri formations are overlain by Pliocene, marine transgressive successions of sands and clays with minor lignite contributions referred to as the Liang Formation (Wannier *et al.*, 2011). During this time, the onshore northern Sarawak area was an area of highstand deltaic progradation with turbidite deposition in the present-day offshore area. Major deformation episodes that occurred during the Pliocene resulted in the present-day distinct truncation of the folded strata.

The succession of the major tectonic episodes (Table 2) resulted in the observed deformation structural styles in the northern Sarawak region (Figure 8):

1. Late Cretaceous to Eocene (79.5-36Ma). Block faulting of the crystalline basement of a metamorphic complex



**Figure 8:** Observed structuration styles in Block SK333 as a consequence of three major tectonic episodes: (1) Late Cretaceous to Eocene (79.5-36 Ma) block faulting, (2) Late Oligocene to Mid Miocene (30-20.5 Ma) wrenching and folding and, (3) Mid Pliocene to Holocene (4.0-0 Ma) compressional tectonism.

**Table 2:** NW Borneo - summary of key chrono-stratigraphic events (compiled from various sources including Hall, 2002; Teas, 2005; Balaguru & Hall, 2009; Cullen, 2010; Balaguru & Lukie, 2012). The highlighted red events are potentially associated with and impacting on the two younger observed tectonic episodes: Late Oligocene to Mid Miocene (30-20.5 Ma) wrenching and folding and, Mid Pliocene to Holocene (4.0-0 Ma) compressional tectonism experienced in Block SK333.

KEY EPOCH	Gradstein <i>et al.</i> (2004)/Haq <i>et al.</i> (1988)	TECTONO-STRATIGRAPHIC EVENT
Base Pliocene	5.73 / 5.5Ma SB	Major Australia – Indonesia arc collision compressional folding: 4.0 Ma. Continuing turbidites related to Shallow Regional Unconformity (SRU) erosion.
Base Late Miocene	11.3 / 10.5Ma SB	Major global eustatic lowstand of sea level (Andaman Sea opening). Early folding, inversion, uplift of Borneo and major deltaic/turbidite debouchment. Waning Deep Regional Unconformity (DRU) erosion.
Intra-Early Miocene	21.0 / 21.0Ma SB	Commencement of SCS microcontinent collision with Borneo arc system & Australoid convergence: continuing hemipelagics and clastic offlaps. Start of DRU erosion.
Base Oligocene	33.9 / 36.0Ma SB	Sundaland Indochina extrusion and SCS microcontinent drift towards Borneo; inversion tectonics mostly along transfer fault zones; continued thermal sag in Makassar Basins: hemipelagics in basinal areas.
Top Middle Eocene	41.0 / 42.5Ma SB	Celebes breakup & sea floor spreading, preceded by late syn-rift transgressive clastics: block faulting.
Top Early Eocene	50.5 / 49.5Ma SB	Celebes Sea rift onset? Initiation of North and South Makassar Basins syn-rift and crustal thinning? Beveled fault blocks and onset of immediate post-rift transgressive marine carbonates.



(Leong, 1999), which became faulted and truncated by erosion as a result of the tectonic break-up of Celebes Sea. The erosional surface was later non-conformably overlain by marine sediments and the development of an Eo-Oligocene carbonate platform with nummulitic shoals in the Engkabang-Karap area.

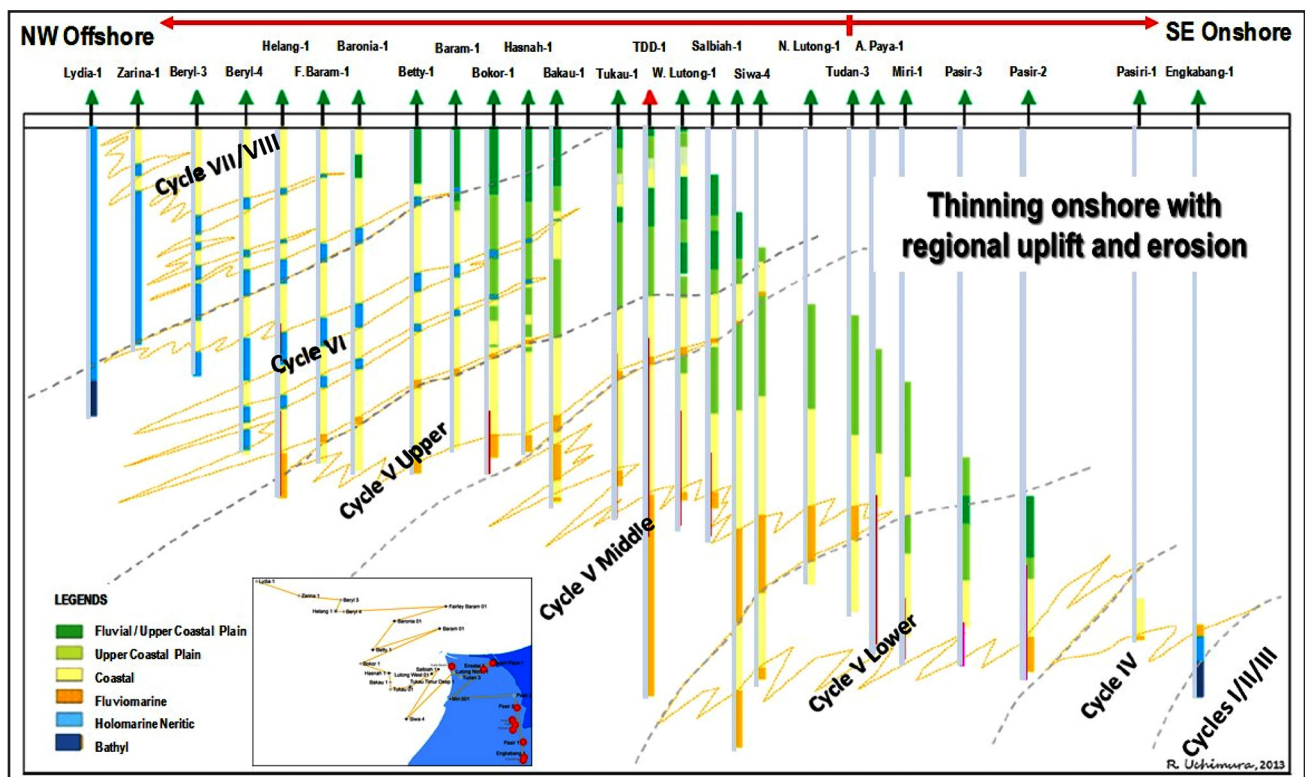
2. Late Oligocene to Mid Miocene (30-20.5Ma). Wrench faulting and inversion tectonics, possibly related to the cumulative effects of the spreading of the proto-South China Sea, subduction along the Borneo Trench and the uplift of the Borneo hinterland. Wrenching along the Baram and Tinjar lines accommodated these effects, producing the wrench structuration over the Engkabang-Karap Anticline.
3. Mid Pliocene to Holocene (4.0-0Ma). Continuous compressional folding resulted in a distinct folding overprint over the onshore Sarawak area (Kessler & Jong, 2014; 2015a; 2016). This compression event led to the inversion of listric foot-wall sedimentation in the northern Miri area.

### SEISMIC FACIES INTERPRETATION AND MAPPING OF DEPOSITIONAL ENVIRONMENTS

In 2010-2011, JX Nippon conducted a detailed sequence stratigraphic study covering Block SK333, with the objective of establishing a stratigraphic correlation framework

in support of sequence stratigraphic and depositional models covering the Paleogene to Neogene successions of the onshore Baram Delta. The palaeo-geographic and environments of deposition (EODs) maps generated are used for predicting the potential source, reservoir and seal distributions and to help identify and rank drillable leads and prospects. The study was based on block-wide remote sensing interpretation of a high resolution gravity and magnetic dataset to firstly identify regional structural trends. A total of approximately 3000-line km of 2D seismic data were interpreted (Figure 1), and more importantly, 10 key wells were selected for high resolution biostratigraphic analysis (CoreLab, 2010) in order to establish a more reliable well-based sequence and lithofacies interpretation. These dataset forms the main input for this integrated palaeo-environmental and sequence stratigraphic study.

The 10 key wells mentioned include Kuala Baram-1, Ensalai-1, Asam Paya-1, Pasir-3, Pasir-2, Aman-1, Pasir-4, Penipah-1, Pasir-1 and Engkabang-2, all of which are geographically located along the Baram River, and proved invaluable for a well to seismic correlation exercise. Figure 9 shows a regional onshore-offshore correlation of sedimentary facies across the Baram Delta, where a continuous Miocene to Holocene sedimentary succession could be studied. The products of the high resolution biostratigraphic analyses such as the interpreted EOD maps



**Figure 9:** Regional onshore-offshore correlation of sedimentary facies across the Baram Delta. The lithological succession shows a mega progradational, upward coarsening sequence with several occurrences of shaly intervals reflecting several pulses of marine flooding events as bottomsets of local para-sequences. Well tops were stratigraphically repositioned (after JX Nippon, 2015). Inset map shows the locations of selected wells (in red), geographically located along the Baram River for biostratigraphic analyses (CoreLab, 2010), where a continuous Miocene sedimentary succession could be studied and established. Overall 18 sequence boundaries (SB) with key maximum flooding surfaces (MFS) were identified based on biofacies and well lithofacies interpretation, and in good agreement with seismic data.

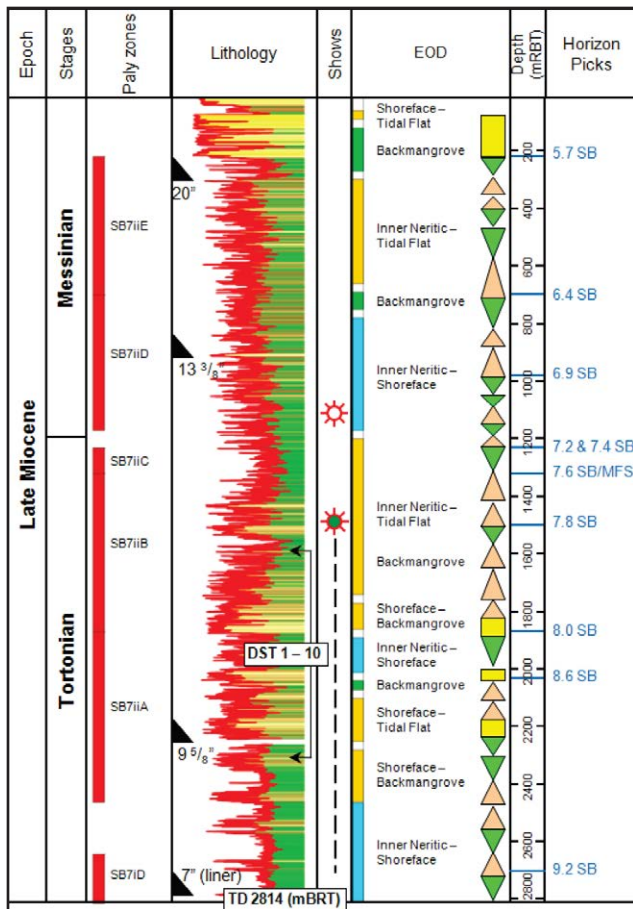


Figure 10: An example of integrated well lithology.

and the identified sequence boundaries (SB) represent the critical geological controls of the study. Hence updating of the geological data base was carried out, especially the well to seismic ties and correlation to seismic of the various EOD's and lithofacies types. This is an important exercise for understanding seismic facies responses. Subsequently, integrated well lithofacies logs (lithologs) with interpreted well sequence boundaries, maximum flooding surfaces (MFS) and EODs were generated for each of the studied wells (Figure 10). The well SBs and EOD annotations were carefully correlated with seismic picks and stratal geometries as shown in the example of the well to seismic ties at wells Penipah-1 and Pasir-4 (Figure 11). The results suggest an excellent correlation of litholog calibration to seismic data that show a pronounced monoclin dip to the northeast in this particular example.

Based on the well lithofacies and sequence stratigraphic results, a chrono-stratigraphic chart was constructed for the Block SK333 area (Figure 12). Most SBs interpreted in this project are third to fourth order (1-3 and 0.1-1 Ma, respectively), largely related to global-eustatic events. Local tectonic events are responsible for disturbances to the Haq *et al.* (1987) coastal on lap curve. High-frequency cycles (0.01 to 0.1 Ma) seem to be too narrow to be resolved on our chrono-stratigraphic chart (Figure 12), but may still be recognised on litholog profiles as coarsening and fining upward cycles.

In this study, three generic depositional models for Block SK333 were developed based on analogue studies: (1) steep carbonate bank and shoal model for the southern part of the study area (Figure 13), (2) delta plain to shoreface model

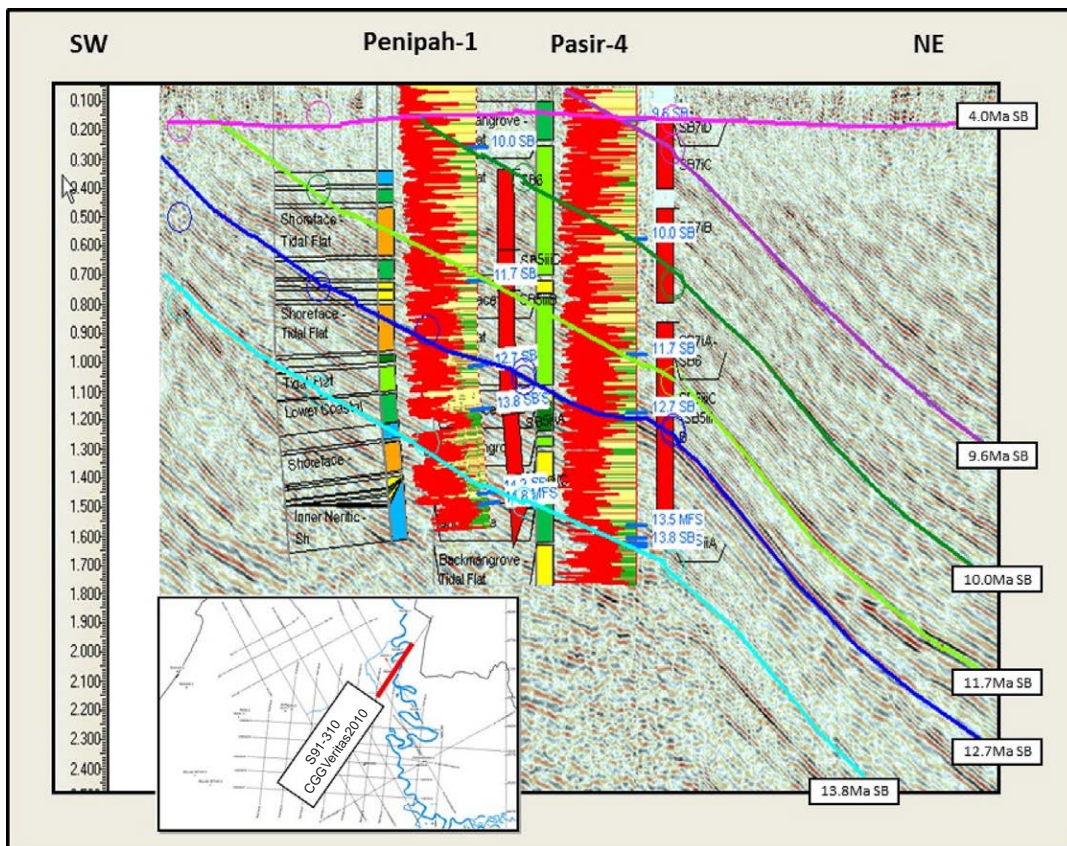


Figure 11: An example of well to seismic tie illustrating lithofacies well log calibration to seismic data. Note the excellent correlation of picks and pronounced monoclin dip to the northeast. See Figure 10 for lithofacies legends (after Jong *et al.*, 2013; 2015).

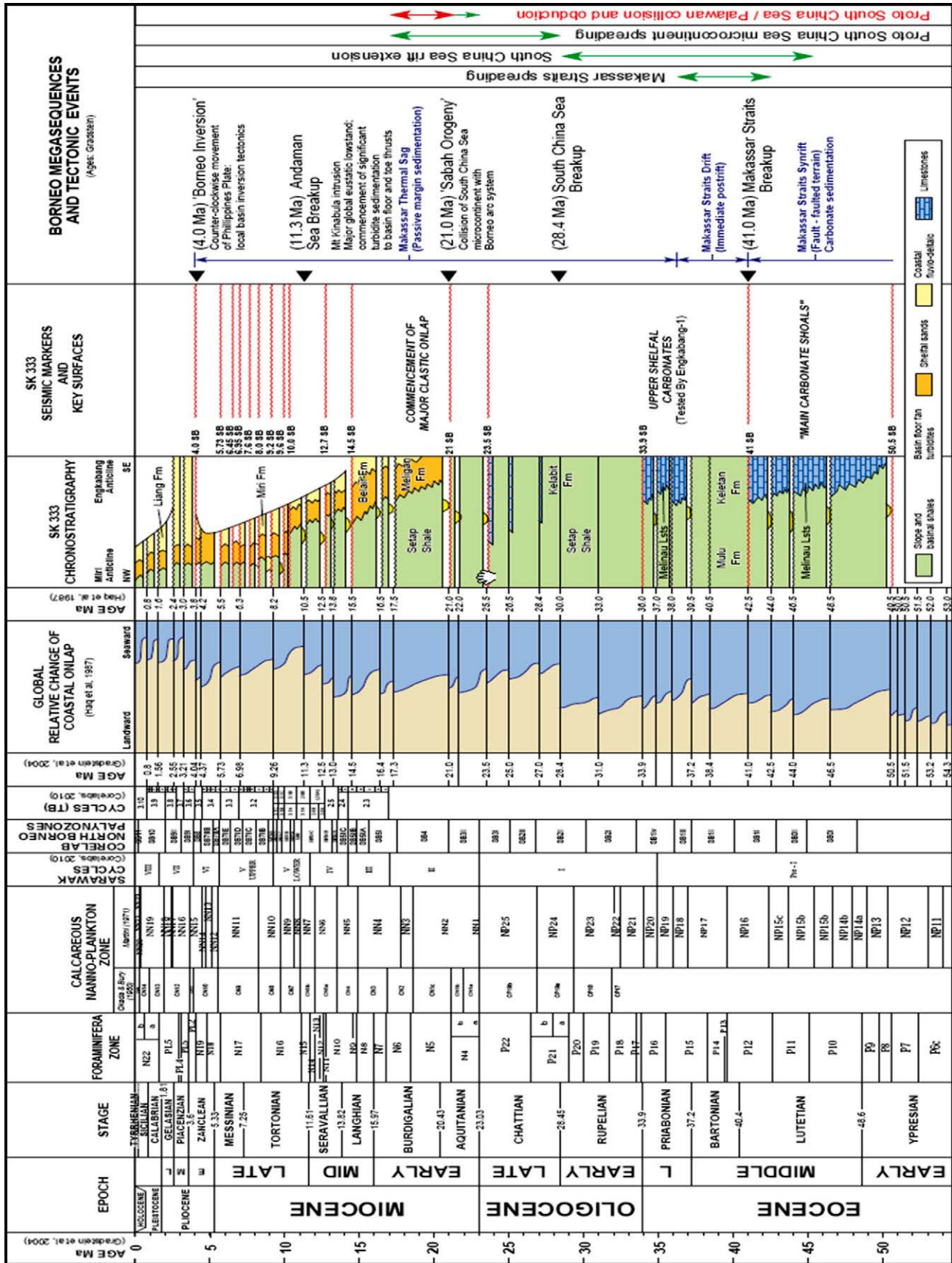
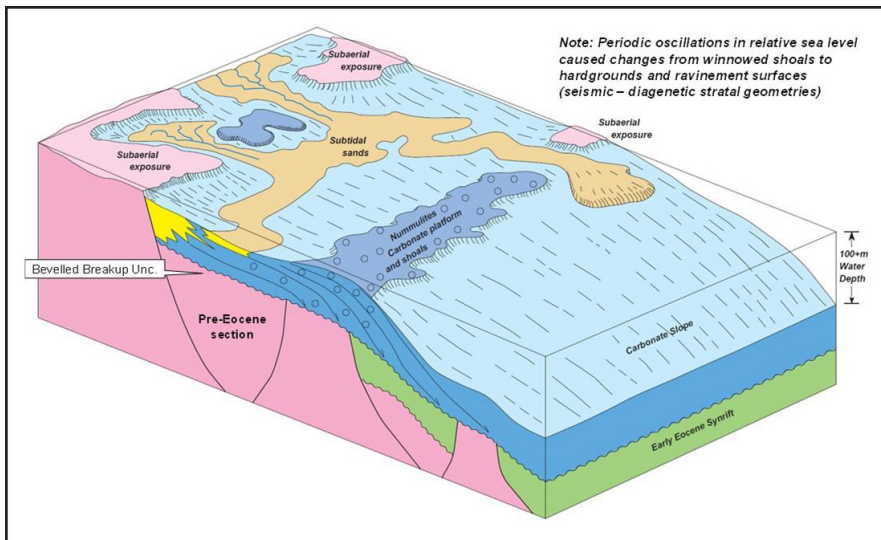
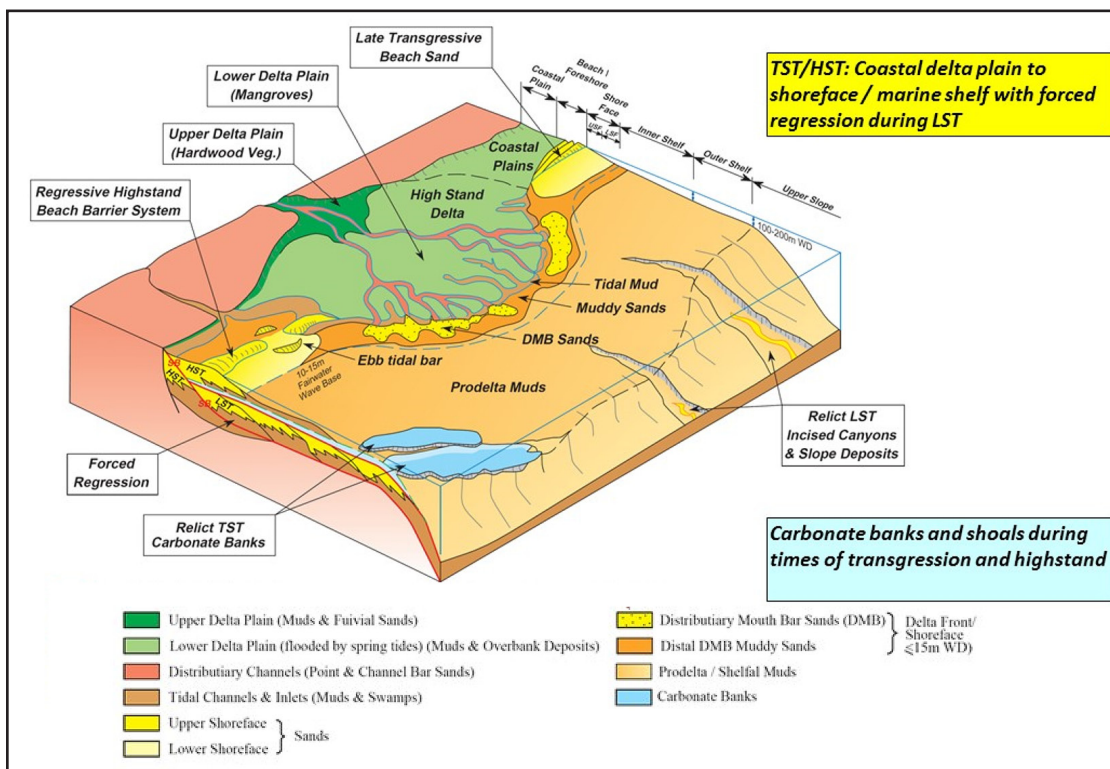


Figure 12: Chrono-stratigraphic chart for Block SK333. Global relative change of coastal onlap after Haq et al. (1987) with comparison ages from Gradstein et al. (2004).



**Figure 13:** Eocene prograding carbonate reservoir model adapted for the southern Engkabang-Karap Anticline carbonate based on the model of Ypresian nummulitic steep carbonate ramp model of northern Tunisia (picture courtesy of Dr. Peter Barber).



**Figure 14:** Schematic delta to shoreface facies and environmental setting adapted for SK333 block-wide evaluation (picture courtesy of Dr. Peter Barber).

applicable for the entirety of the study area (Figure 14), and (3) turbidite model for the northern part of the study area (Figure 15). The Ypresian nummulitic steep carbonate shoal model of northern Tunisia (Vennin *et al.*, 2013) serves as an analogue for the carbonate interval (Melinau Formation-equivalent) encountered at depth in Engkabang West-1 well (JX Nippon, 2014). Coastal delta plain to shoreface models were used to address the prograding Palaeogene to Neogene successions of the onshore Baram Delta, including forced regression and carbonate bank and shoal growth during the transgressive and highstand periods (Catuneanu, 2002). For the palaeo-deepwater environment of the northern part of Block SK333, a lowstand turbidite model was adopted.

Three regional composite seismic sections striking across the study area from southeast to northwest were utilised to create seismic sequence stratigraphic profiles. An example is shown in Figure 16. The interpretation of seismic facies matches fairly well with the interpreted biostratigraphic data. The recognition of shelf breaks for each interpreted horizon is critical for the understanding of facies distribution: topsets updip of the shelf break are shoreface to delta plain facies, and bottomsets downdip of the shelf break are dominantly turbidites to basinal shale facies. From the seismic sequence stratigraphic sections, five main potential plays have been identified (Figure 16): (1) Eocene carbonate banks and shoals affected by

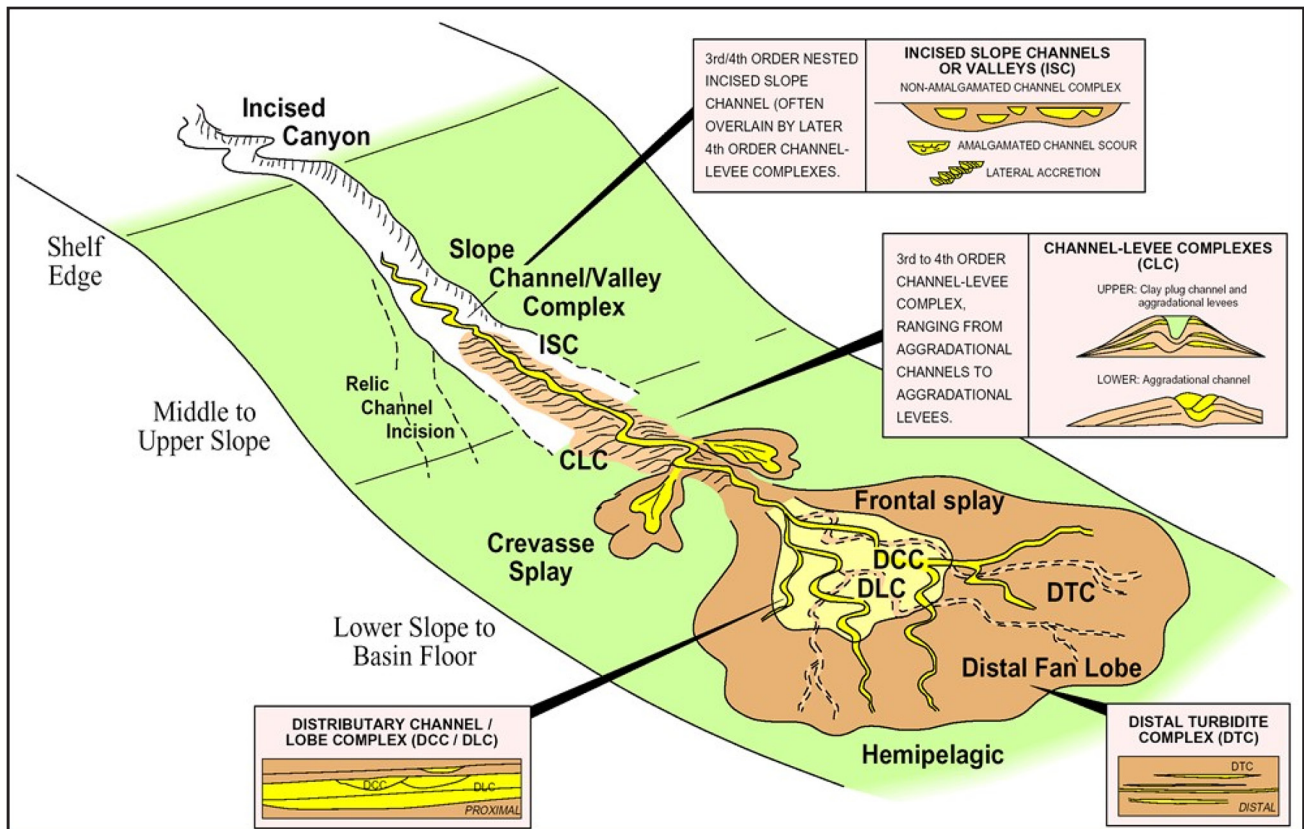


Figure 15: Turbidite model adapted for the analysis of northern Block SK333 area (picture courtesy of Dr. Peter Barber).

wrench inversion structuration with anticlinal closure in the Engkabang-Karap area, (2) Mid Miocene turbidites affected by inversion deformation with potential anticlinal closure in Engkabang-Karap area, (3) Late Miocene to Pliocene highstand shoreface sands with structural and, potentially, stratigraphic traps in Miri-Asam Paya Anticline area, (4) Late Miocene to Pliocene lowstand delta sands with stratigraphic traps in Miri-Asam Paya Anticline area, and (5) Late Miocene lowstand turbidites with structural and stratigraphic trapping in Miri-Asam Paya anticline area. These play types with seismic examples will be discussed in more detail in the play summary section.

### Southern area

Focusing on the Eo-Oligocene Engkabang-Karap carbonate bank and shoal play in the southern part of Block SK333, the study reveals carbonate development initiated atop the sequence boundary (angular unconformity) of the pre-rift faulted sequence (50.5 Ma SB) (Figures 16 and 17). Several distinct seismic facies packages with their respective stratal geometries and amplitude characteristics are present between the 50.5 to 23.8 Ma SBs. Stratum 1 to 2, characterised by opaque, moderately continuous amplitudes, is interpreted as biohermal banks or shoals. Stratum 2 to 4, characterised by continuous moderate amplitude reflectors with shingled to oblique clinofolds, is interpreted as a prograding transgressive and highstand system tract carbonate shoal. Stratum 4 to 5 represents highly continuous, high amplitude parallel reflectors interpreted as weathered

vadose zone above the highstand system tract carbonate shoal, and stratum 5 to 6 is characterised by continuous moderate amplitudes, interpreted as a combination of pelagic carbonates and basinal shales (Figure 17).

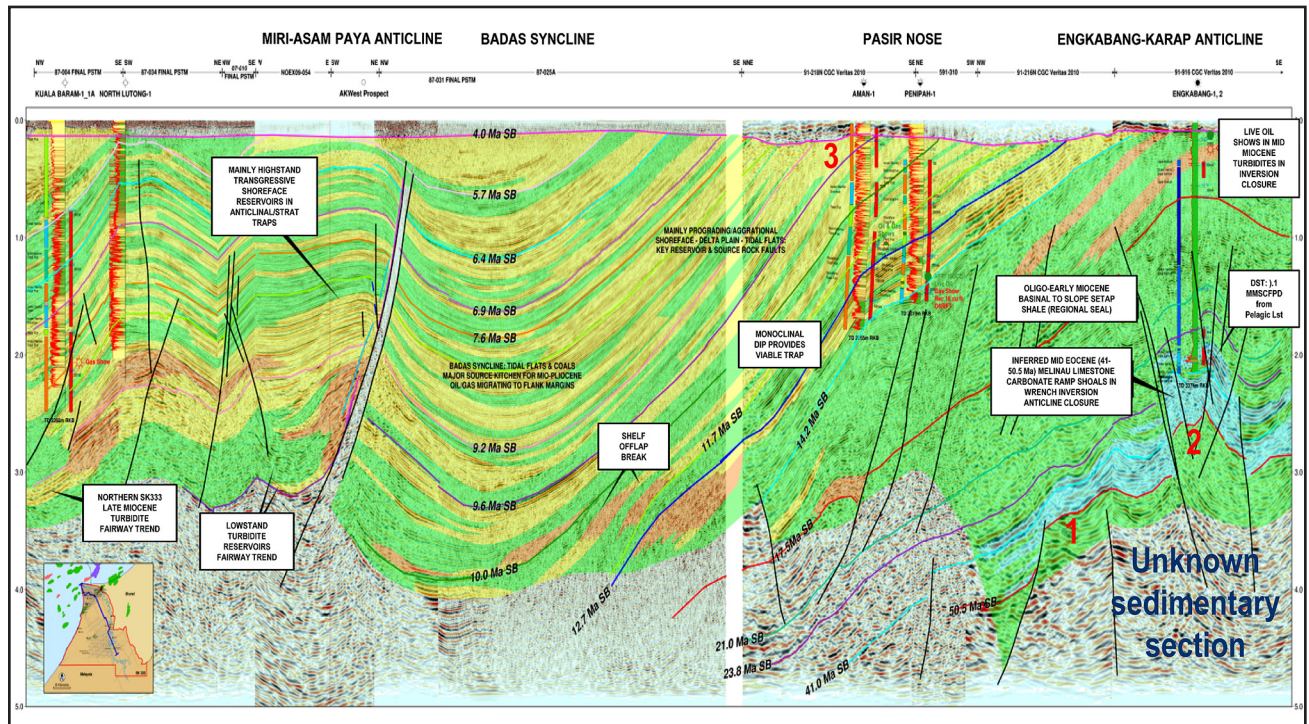
From the stratal geometries of the Mid to Late Eocene section, an active development of a transgressive and highstand system tract carbonate shoal is interpreted. This carbonate shoal is interbedded with hard grounds believed to have been formed during lowstand system tract erosional periods. This carbonate growth possesses an overall geometry of a progradational and aggradational shoal morphology with thinning at both of its inboard and outboard wedges. The absence of high relief bioherms or classic onlap facies suggests a lack of framework builders. This was later proven from the well results of Engkabang West-1 (JX Nippon, 2014). Such characteristics are also evident in the local outcrops of Batu Gading and Gunung Mulu (Melinau Formation-equivalent) (Kessler & Jong, 2016 and this volume). The Eocene carbonate section of Gunung Mulu is made up of large shoal of nummulites, as coral framework builders are not prevalent until Late Oligocene (Wilson & Rosen, 1998; Wilson, 2008). Above interpretation is also based upon the analogue Ypresian steep nummulitic carbonate shoal model in the El Garia Formation of northern Tunisia – an oil producing reservoir and the second largest oil field in Tunisia (Anz & Ellouz, 1985).

An alternative explanation for the observed variations in the carbonate facies evolution from the Late Eocene to Middle Miocene in northern Sarawak is suggested by Kessler

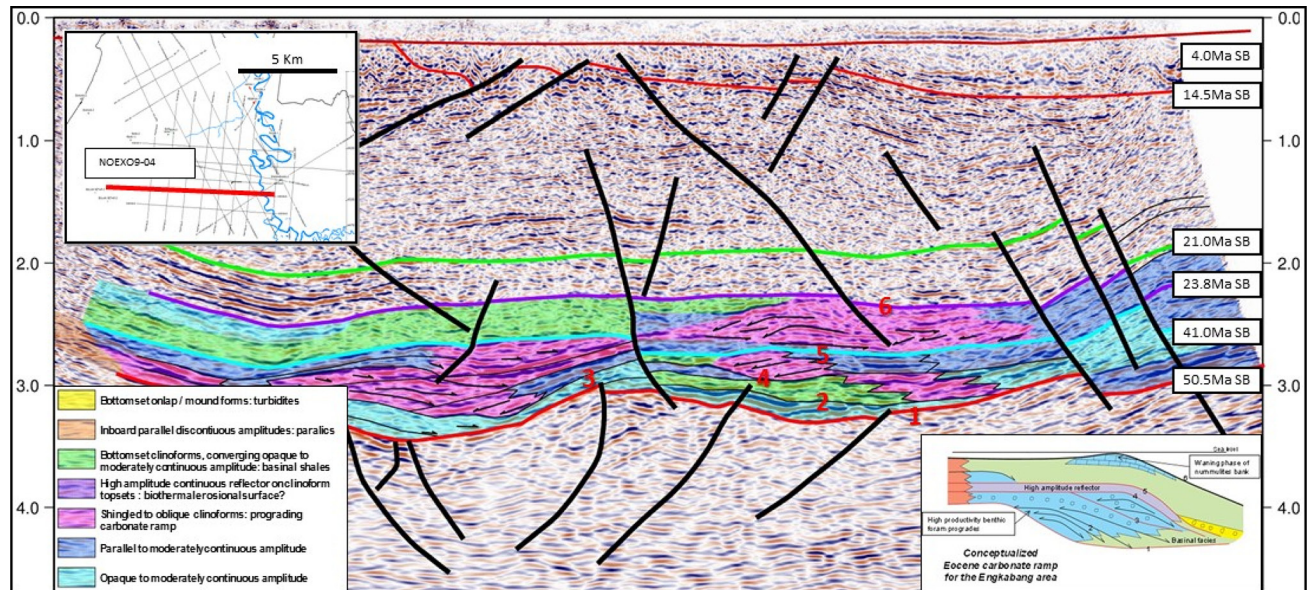
& Jong (this volume). According to Kessler & Jong the older Late Eocene-Oligocene carbonate platform has developed during a deepening upwards cycle, whereas the younger Early-Middle Miocene platform represents a shallowing upwards sequence. Consequently, the authors propose that the sequence comprising two carbonate platforms and

clastic intervals as one mega-cycle caused by successive drowning, with a maximum water depth in the Oligocene. Subsequently it was followed by a gradual uplift of the area culminating in renewed carbonate deposition.

The facies map (Figure 18b) illustrates the first stage of a carbonate bank and shoal development in a northward



**Figure 16:** Interpreted composite seismic sequence stratigraphic profile striking across the study area in the southeast-northwest direction highlighting the identified play types at Engkabang-Karap area in the south to Miri-Asam Paya anticlinal areas to the north. Annotated are key SBs established based on well to seismic integration. The red numbers 1, 2 and 3 represent the three major deformation episodes described in Figure 8. Colour code for depositional facies: light blue = carbonate, light green = slope to basin shale, light yellow = sandy shoreface facies, light brown = turbidite fairway trends downdip of shelf breaks (after Jong *et al.*, 2013; 2015).



**Figure 17:** Interpreted seismic facies of Engkabang-Karap carbonate play along Strike Line NOEX09-04. This strike section very clearly demonstrates at least 3 prograding clinoform ramp cycles (stratum 2-3, 3-4 and 5-6). Distinct geometries can be identified ranging from opaque to high amplitude continuous representing inferred ramp and biohermal shoals with erosional cycles of interbedded hardgrounds related to lowstand system tract erosional episodes (after Jong *et al.*, 2013; 2015).

progradation along an east-west trending facies belt of likely benthic foraminiferal banks locally incised by tidal channels (stratum 1 to 3). An erosion episode followed and later a drowning phase of the area causing the retreat of the carbonate bank to the eastern part of the area (stratum 4 to 5). Post 41.0 Ma SB, subsequent carbonate bank development was restricted to high relief localities and was later smothered by abundant clastic influx. Based on the biostratigraphic analysis of Engkabang West-1 ditch cuttings, the carbonate palaeo-environment is interpreted as a middle to outer neritic, deep marine depositional environment (JX Nippon, 2014; Kessler & Jong, this volume).

### Northern area

The northern part of Block SK333 refers to the area northwards from the southern limb of the Badas Syncline. In the sequence stratigraphic profiles (Figure 16), the shelf breaks show a general north-westerly migration during 50.5 to 5.7 Ma SBs. The geometric profile of the Early Miocene to Pliocene section is predominantly progradational with the exception of two aggradational episodes during 10.0 to 9.6 Ma SBs and 7.6 to 6.4 Ma SBs, and one retrogradational episode from 9.2 to 8.0 Ma SBs (Figure 18a).

Environment of deposition maps were generated for the Mid Eocene - Early Pliocene, 4.0 – 50.5 Ma SBs (Figure 18). The Mid to Late Miocene interval (41 to 50.5 Ma SBs; Figure 18b) represents an interplay of several composite progradational and aggradational carbonate banks and shoals, resulting in series of east-west trending belts ranging from paralic to carbonate shoal to basinal facies. The second composite interval covers 21.0 to 41.0 Ma SBs (Figure 18c), where the 33.7 Ma SB shelf break is within the Engkabang-Karap Anticline area. Main reservoir facies are expected to be shelfal to upper slope facies with potential basinward turbidites, while pro-delta and basinal shales (containing reworked terrestrial algal matter) could be the main source rock.

During the interval 21.0 to 14.2 Ma SBs (Burdigalian to base Langhian age; Figure 18d), the shelf break was within the northern limb of the Engkabang-Karap Anticline and the southern limb of the Badas Syncline. The main reservoirs are expected to be shelfal to shelfal facies with potential turbidites downdip. The basinal shales, with potentially reworked terrestrial matter, are again expected to form the source rock of the area. From 14.2 to 10.0 Ma SBs (base Langhian to base Tortonian age; Figures 18e and 18f), the shelf breaks prograded north-westward to lie within the southern limb and central part of the Badas Syncline. From 14.5 Ma SB onwards, these younger sections subcrop towards the south and southeast of the study area due to compressional tectonic deformation that occurred from Mid Pliocene to Holocene times. The main reservoir facies are expected to be shelfal, tidal and turbidite facies with tidal and delta plain peats rich in coaly organic matter as the potential source rock facies. From 10.0 to 9.2 Ma SBs (base to middle Tortonian age, Figures 18g and 18h), the shelf break was located within the northern limb

of the Badas Syncline and the Miri-Asam Paya Anticline. During this time, most of the northern area is covered by a southwest-northeast trending swath of tidal flats, shoreface and shelfal facies. The main reservoir facies seems to be a likely turbidite facies beneath the Miri-Asam Paya Anticline, which later continued to be deposited in the northern flank of the anticline. The shoreface facies is also one of the primary reservoirs representing the Miri Field producing zone. Again, the tidal and delta plain peats represent the probable source rock for the area.

The shelf break continued to further prograde north-westward to the present-day offshore area from 9.2 to 4.0 Ma SBs (middle Tortonian to Zanclean; Figures 18i to 18n). The shelf break at 8.0 Ma SB was located approximately at the present-day coastline (Figures 18i and 18j). During this time interval, the northern area remained covered by tidal flats, shoreface and shelfal facies with the main reservoir being shoreface facies and the peats of tidal and delta plains as the potential source rock facies for the area (Figures 18i to 18n).

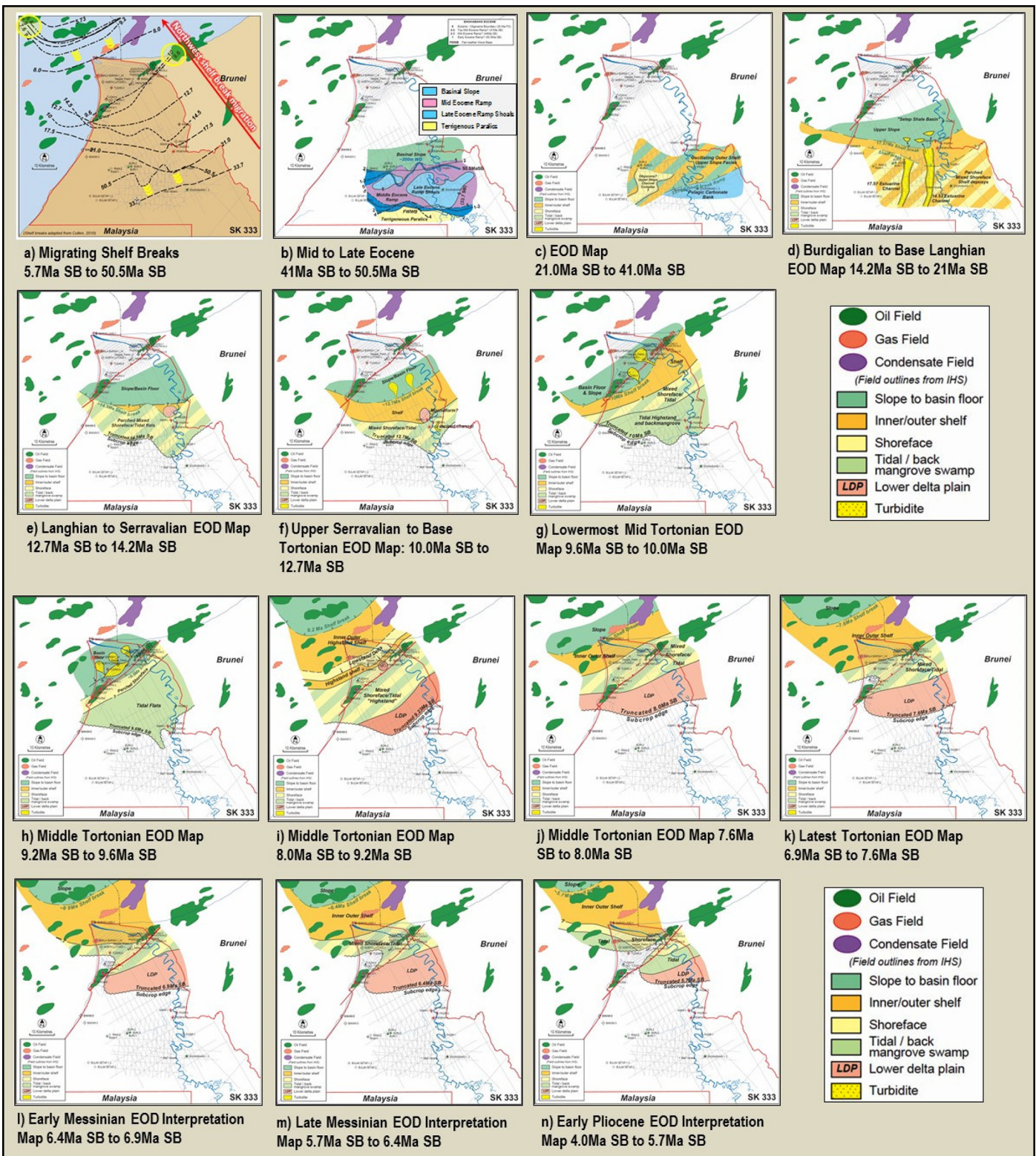
### SUMMARY OF PETROLEUM SYSTEMS

The integrated well and seismic sequence stratigraphic investigation has narrowed down the prospective key structural and reservoir development in Block SK333 to two zones: (1) Eo-Oligocene carbonate in the Engkabang-Karap Anticline with possibly reduced porosity and permeability due to its deep burial depth prior to uplift deformation associated with later inversion tectonism, and (2) Late Miocene to Pliocene clastics deposited along strike of the Miri-Asam Paya Anticline with viable porosity and permeability properties (Figure 19).

For the majority of Late Miocene to Pliocene clastics within the central part of the Badas Syncline, poor reservoir characteristics are anticipated due to likely considerable compaction, which itself has a low chance for hydrocarbon entrapment but provides an effective source kitchen area for hydrocarbon generation (Figure 19). The three tectonic phases of structural deformations have resulted in the above anticlinal trends with two different petroleum systems (Jong *et al.*, 2013; 2015). While trapping is not considered a critical risk for the onshore Baram Delta with the presence of inversion anticlines and fault-bounded foot-wall and hanging-wall traps, the inherited risks of other petroleum system elements are higher. The associated risks and uncertainties of these elements are summarised below.

### Source rock model and hydrocarbon generation

The southern gas system is the older petroleum system believed to be sourced from the deeply buried and present-day overmature Eo-Oligocene basinal shales. They are likely age-equivalent to the Belaga and Tatau formations (Figure 7). However, the source rock potential of these shaly formations remain uncertain. For example, the younger Oligo-Early Miocene, slope to basinal Setap Shale was found to contain generally poor source rock. Source rock studies carried out on both outcrop and subsurface samples



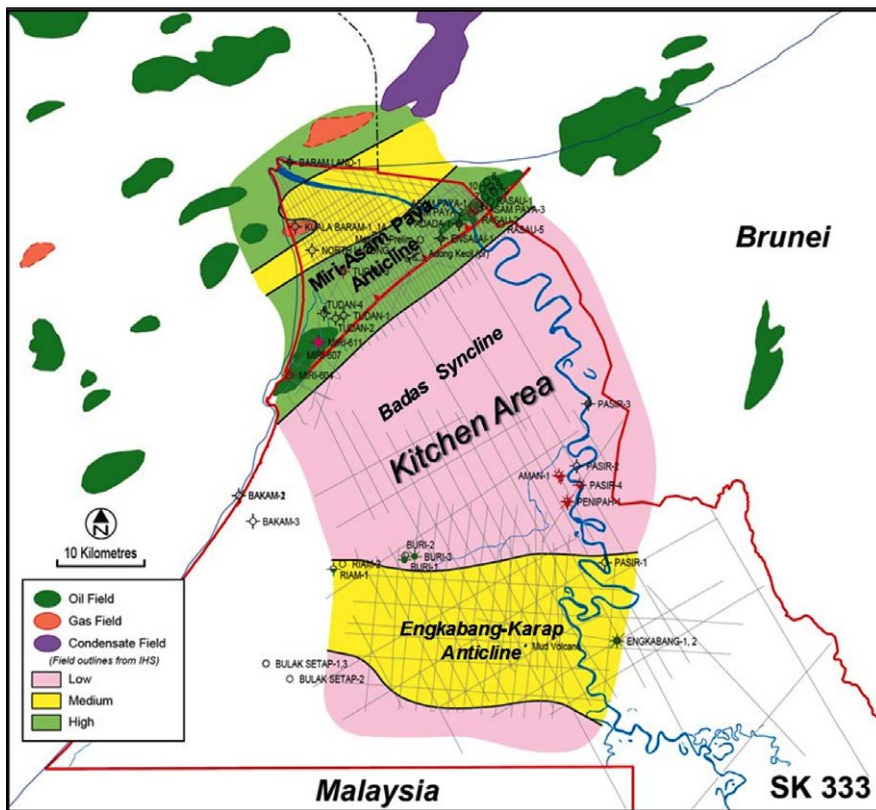
**Figure 18:** Interpretation of environments of deposition (EOD) from the onshore Baram Delta from 50.5 - 4.0 Ma based on an integrated approach of well lithofacies and seismic sequence stratigraphic study (modified after Jong *et al.*, 2013; 2015).

show that the shales possess fair organic carbon richness and poor hydrocarbon generating potential (Ismail & Abu Hassan, 1999). The Setap Shale samples contain Type III organic matter with potential to generate predominantly gas, and their biomarker assemblages are characterised by features that suggest the source rocks were derived from

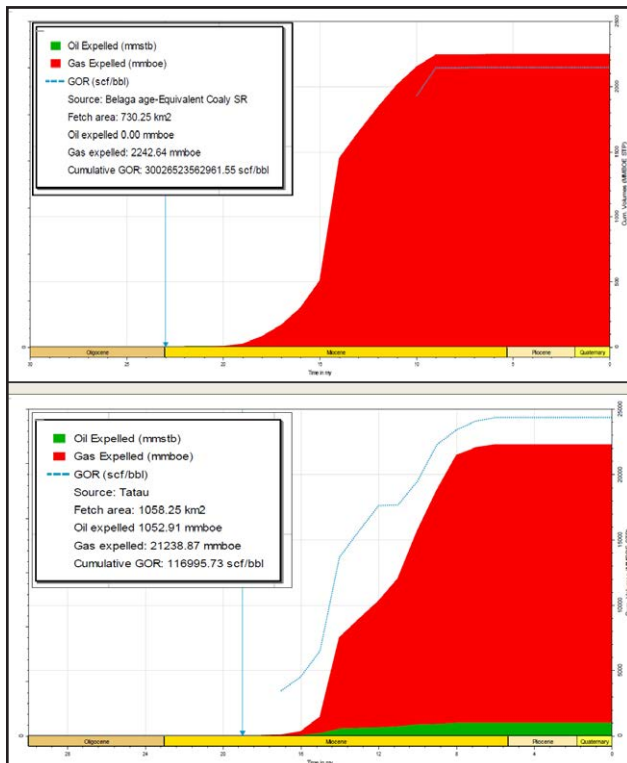
terrestrial organic matter input and higher land plant resins (Ismail & Abu Hassan, 1999).

Oil charge, however is believed possible with the re-deposition of delta source material containing organic matter that consists of oil-prone resins, plant leaves and coal fragments that were subsequently transported into the





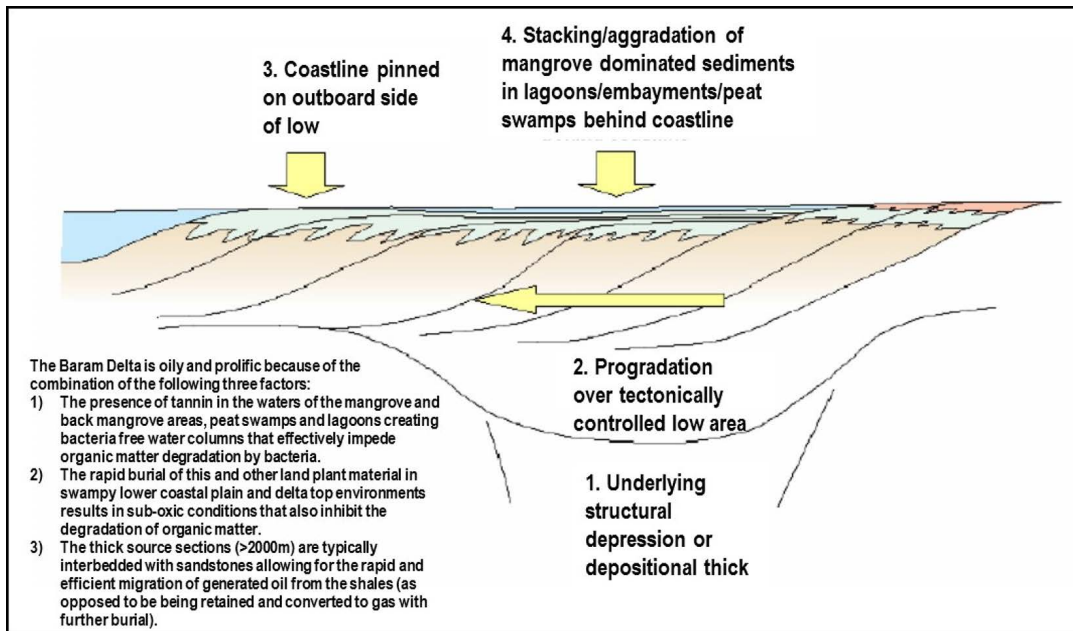
**Figure 19:** Block SK333 reservoir presence and effectiveness map. The Badas Syncline has poor reservoir characteristics with low effectiveness anticipated due to its likely considerable compaction, but provide an effective source kitchen area of mature Cycle V carbonaceous shales and coals for hydrocarbon generation and migration to the Miri-Asam Paya Anticline.



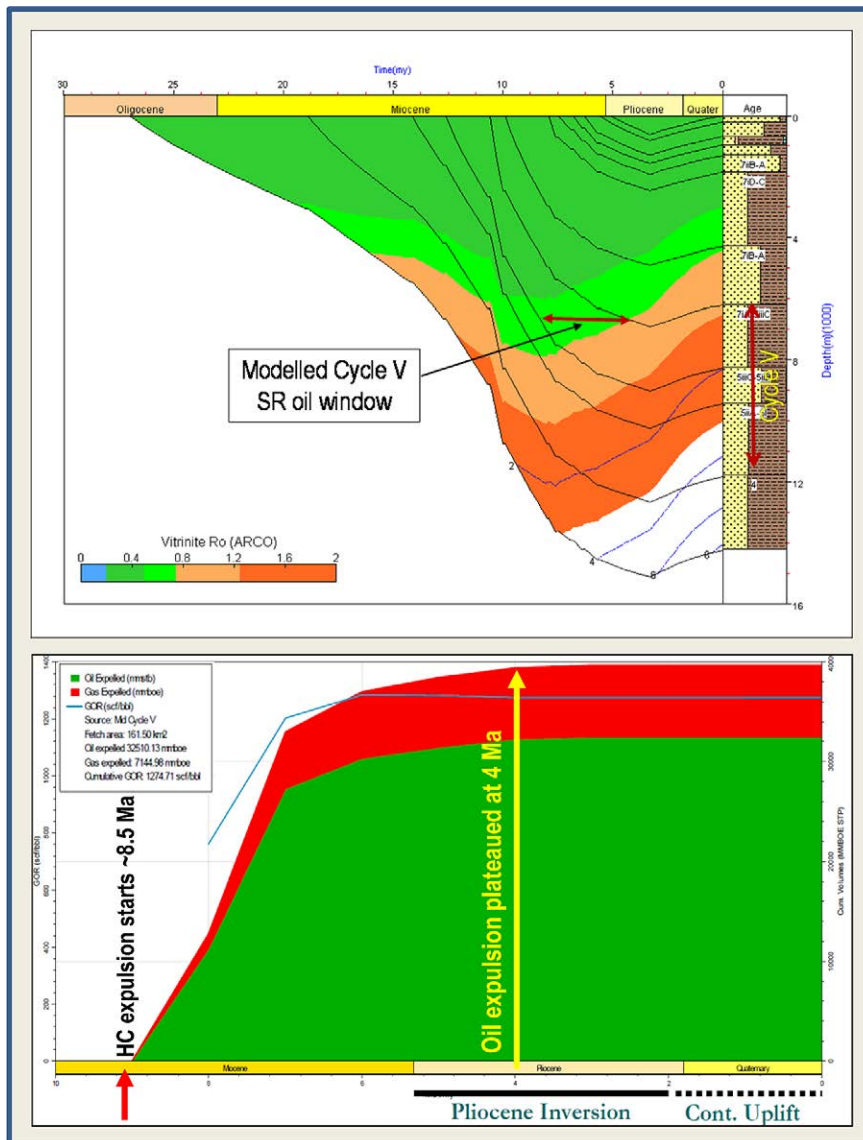
**Figure 20:** Southern SK333 hydrocarbon generation history. Top - modelled Belaga-age-equivalent source rock (~35.5 Ma) starts expelling hydrocarbon around 20 My ago, peaked and ceased expulsion at around 9 Ma preceding the Late Miocene-Holocene uplift. Bottom - modelled Tatau-equivalent source rock (~28.5 Ma) suggests expulsion began ~ 19 My ago with gas and associated oil, peaked and ceased expulsion at around 7 Ma preceding the Late Miocene-Holocene uplift.

deepwater basin by turbidity currents (Dunham *et al.*, 2003; Longley, 2005). According to Dunham *et al.* (2003) and Saller *et al.* (2006), the organic matter is not disseminated within the turbidite; rather, the kerogen becomes concentrated into laminae that can reach up to 15% TOC. This method of deposition is in marked contrast to typical marine source rocks, which become enriched in organic matter during periods of exceptionally low terrigenous clastic influx, as during times of condensed sequence deposition. In contrast, terrestrial oil-prone kerogen becomes concentrated in the deepwater during times of high clastic-influx from the shelf. However, it is noted that this model has so far been proven only in the Miocene section of the Kutei (e.g., Peters *et al.*, 2000; Dunham *et al.*, 2003; Saller *et al.*, 2006) and Sabah (e.g., Algar, 2012; Jong *et al.*, 2014) basins.

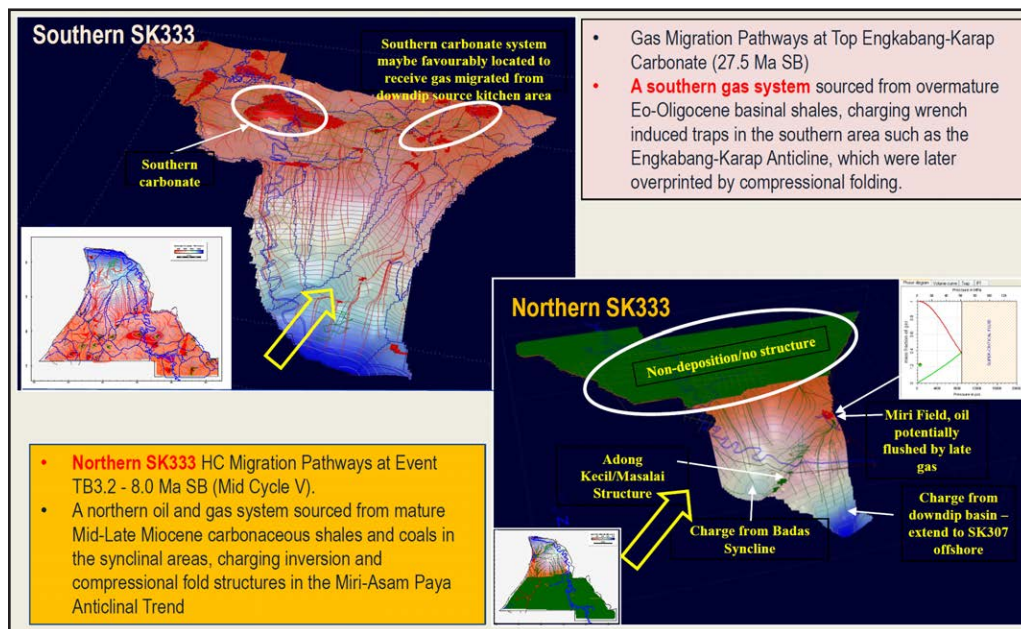
During the Early Miocene, this petroleum system was believed to have charged the Late Oligocene to Mid Miocene wrench-induced traps of the southern Engkabang-Karap Anticline (Figure 20). They were later influenced by Mid Pliocene to Holocene folding. This still active petroleum system is leaking at the present-day surface by an active mud volcano in Karap, atop the western part of the Engkabang-Karap Anticline. It releases mostly un-burnable gas (Kessler *et al.*, 2011; Jong *et al.*, 2016), however another seep on the nearby Bakong River releases C<sub>1</sub> gas. Burial history modelling of the Tatau-equivalent source rock with Organofacies D/E of Pepper & Corvi (1995), equivalent to the Type III terrestrial organic matters of paralic/lagoonal shales and coals behind the shoreline suggests that an earlier oil charge probably occurred during deep Oligocene-Miocene burial, preceding basin reversal



**Figure 21:** Schematic summary of the 'delta top ponding' model for the accumulation and preservation of organic matter (after Longley, 2005).



**Figure 22:** Northern SK333 hydrocarbon generation history. Top – burial history modelling at Asam Paya-1 with the modelled Cycle V source rock interval entering oil window at around 9 Ma. Bottom - the modelled Cycle V source rock (10.7 Ma) suggests oil expulsion begins ~ 9 My ago and plateaued at around 4 Ma with continued uplift.



**Figure 23:** Charge modelling for Block SK333 indicating the chance for dominantly gas sourced from now overmature Eo-Oligocene basalinal shales with reworked terrestrial matter in Southern SK333 (top left), and a Northern SK333 oil and gas system sourced from mature Mid-Late Miocene carbonaceous shales and bituminous coals (Organofacies D/E) in the synclinal area of the Badas Syncline (bottom right).

during the Pliocene-Holocene inversion episode (Figure 20). The wrench-induced anticlinal closure was subsequently charged by late stage gas.

The northern, younger and more extensive oil and gas petroleum system is sourced from Mid to Late Miocene tidal and delta plain peat deposits, carbonaceous shales and coals at depth in the Badas Syncline. According to Longley (2005), the Baram Delta contains prolific shelf production area characterised by structural grains orthogonal to the depositional dip resulting in a mechanism that control deposition and enrichment of source intervals called 'delta top ponding' (Figure 21). In this model, the presence of tannin in the waters of the mangrove and back mangrove areas, peat swamps and lagoons creating bacteria free water columns that effectively impede organic matter degradation by bacteria. The rapid burial of this land plant material in swampy lower coastal plain and delta top environments results in sub-oxic conditions that also inhibit the degradation and therefore better preservation of organic matter. In our fieldwork of the Miri Field outcrops, we observed source rock intervals containing oil-prone bituminous coals occurring as thin-bedded organic-rich layers beyond the resolution of conventional logging tools. These bituminous units are high in waxy organic and liptinitic contents for oil generation.

The Late Miocene to Holocene hydrocarbon expulsion and migration charged the inversion and fold structures along the Miri-Asam Paya Anticline area (Figure 22). The Mid Miocene section at the Engkabang-Karap Anticline, where oil shows were encountered by Engkabang-1 and Engkabang West-1 wells (JX Nippon, 2014), was likely charged by the same petroleum system. Figure 23 summarises the outcomes of charge modelling study conducted in Block SK333.

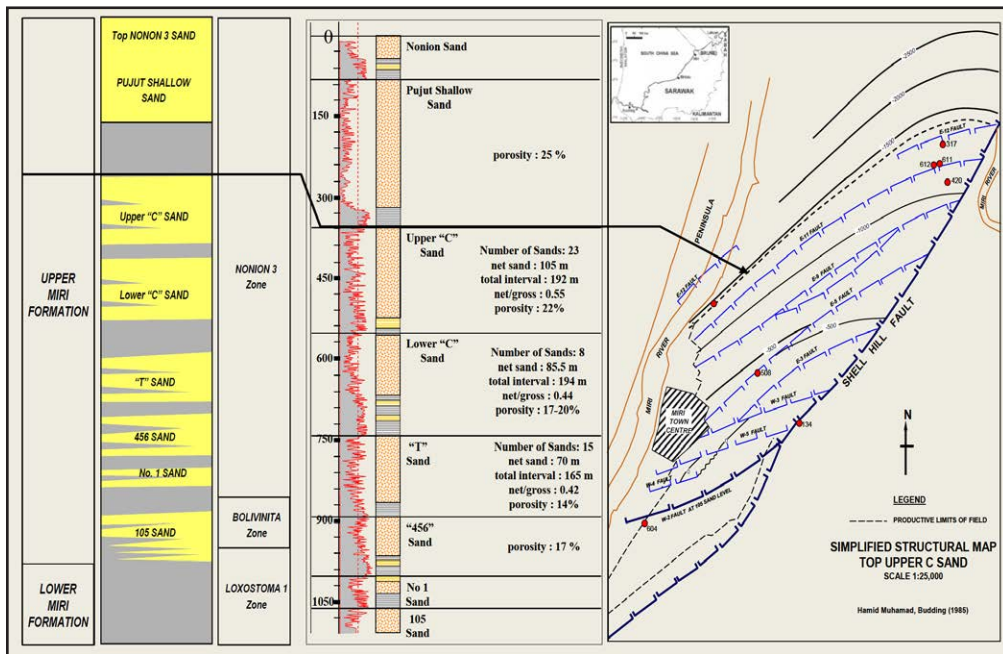
### Reservoir quality and effectiveness

In southern SK333, uncertainty in the initial Engkabang-1 (Shell, 1960) well test quality and the potential for a large in-place resource led to the drilling of Engkabang

West-1 in 2013-2014 on the western culmination of the Engkabang-Karap Anticline by JX Nippon (JX Nippon, 2014; Jong *et al.*, 2016). The well discovered non-economic gas due to tightly-cemented carbonate reservoirs. In the study of the Engkabang-Karap carbonates by Jong *et al.* (2016), the authors concluded that relatively deep burial of carbonates has led to partial dissolution of grains and formation of stylolites. Mobilized carbonate (calcite) likely filled fractures and prevented major fracture porosity systems. Observation from a time-equivalent section of Late Eocene/Oligocene carbonate rock exposed in the Batu Gading outcrops shows the matrix rock there is very tightly cemented and dissected by major and minor fault and fracture systems, which display calcite re-mineralisation implying that there is little or no fracture permeability retained. Current circumstantial evidences from the study point to porosity/permeability occluding diagenetic processes could be more prevalent in affecting carbonate reservoir quality, hence a medium chance is assigned for the reservoir presence and effectiveness for the Engkabang-Karap Anticline (Figure 19).

The primary reservoir targets in northern SK333 are the highly porous and permeable, generally medium to fine grained deltaic shoreface sands. The Upper Cycle V containing a number of thick sandy units is the most fruitful interval in terms of the hydrocarbon discovery in and around northern SK333. Although the seismic events are monotonously dominated with flat events, the well data shows upward coarsening sequence with alternation of thick shallow marine shales and deltaic shaly sandstones.

The rocks exposed around the Miri city, Sarawak, which belongs to the Upper Miocene Miri Formation, are the uplifted part of the subsurface, oil-bearing sedimentary strata of the Miri Field (Figure 24) and possibly also for the offshore fields (Teoh & Abd. Rahman, 2009). Liechti *et al.* (1960) described the formation as a predominantly shallow marine arenaceous succession, based on observations of outcrops of the Miri Anticline (Figure 25) and examination



**Figure 24:** Type log and properties of the reservoir units in the Upper Miri Formation, Miri Field. The simplified structural map of Top Upper C Sand is shown on the right (modified after Tan *et al.*, 1999).

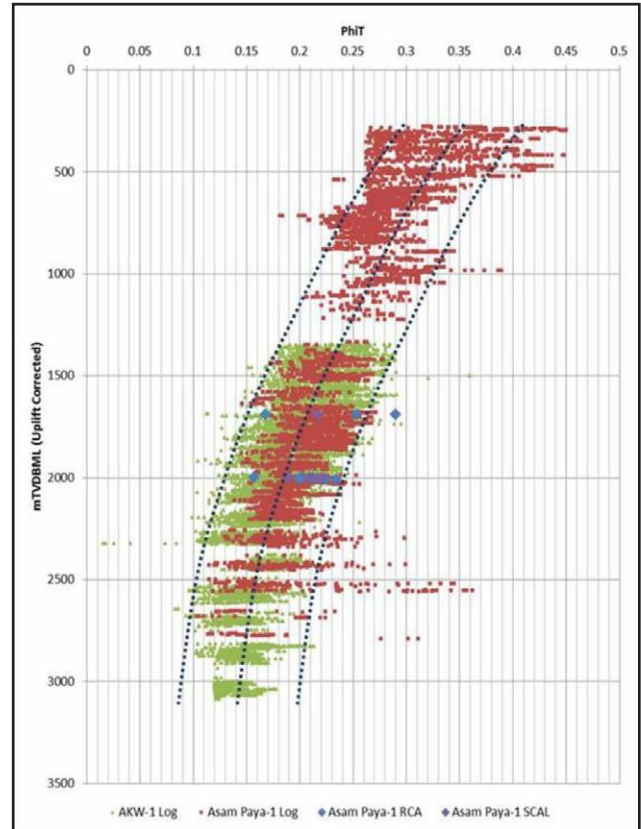


**Figure 25:** An outcrop of Upper Miocene Miri Formation showing cross bedding in the deltaic sandstone (after Sorkhabi, 2010).

of subsurface material from the Miri and the Seria fields. The basal contact with the underlying Setap Shale Formation is a gradual transition from an arenaceous succession downward into a predominantly argillaceous succession. The maximum total thickness of Miri Formation estimated in the Seria Field in Brunei is over 6000 feet (1830 m). Overall, the general porosity-depth relationship indicates good reservoir preservation with an average of 15% total porosity down to a depth of 3500 m below surface along the Miri-Asam Paya anticlinal trend (Figure 26).

### Sealing capability

A top seal is expected to be present over the entire study area in the form of either the regional Late Oligocene-Early Miocene Setap Shale, particularly for the southern carbonate play or more locally by the fourth to fifth order shaly maximum flooding surfaces forming intra-formational seals. Sometime a sub-regional 'master-seal' often provides



**Figure 26:** Total porosity versus depth plot from Adong Kecil West-1 and Asam Paya-1.

the top seal to larger structures and 'stacks' of reservoir-seal pairs (Figure 27). In the Adong Kecil West structure, oil and gas intervals were discovered in multiple stack reservoirs. Each reservoir has independent pressure system as the reservoirs are being separated by thick and massive intra-formational shale. Top seal effectiveness in the study area is generally excellent, except where wrench faulting

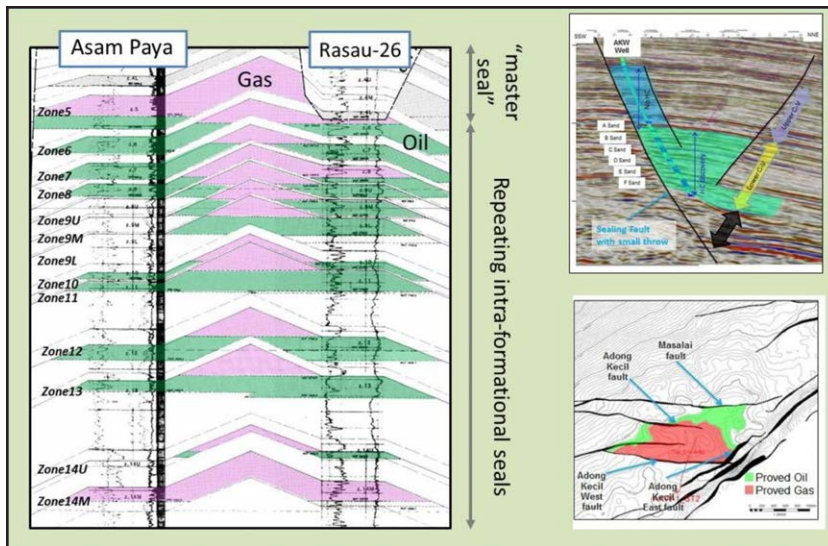


Figure 27: Hydrocarbon distributions in the Asam Paya-Rasau structure within multiple stack reservoir-seal pairs (left). The Adong Kecil structure with sealing Adong Kecil West and Adong Kecil East faults (right). After JX Nippon (2015).

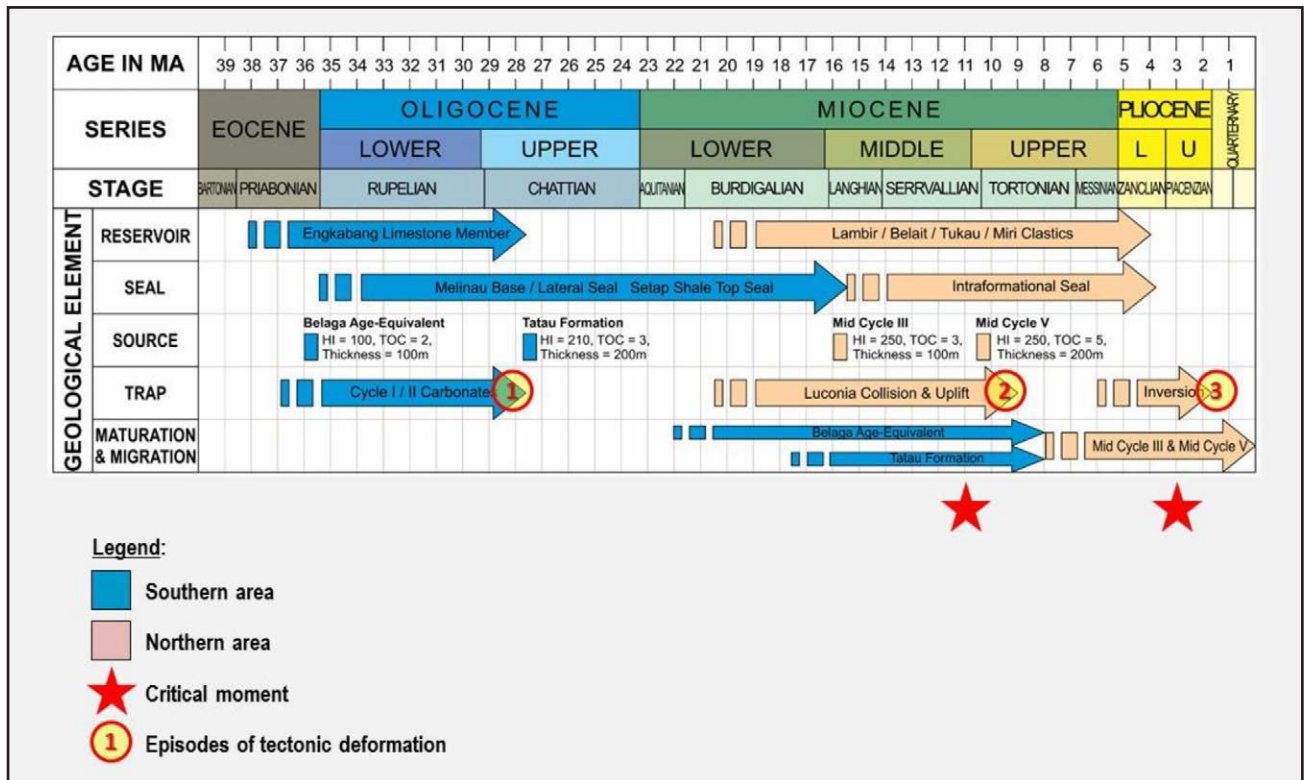


Figure 28: Block SK333 petroleum system summary chart. The chart shows the occurrences of both the older southern overmature gas system and the younger northern oil and gas system. The three major tectonic episodes of deformation that resulted in trap formation and the critical moments of both petroleum systems are also annotated on the chart.

potentially causing seal failures. Lateral seal failure can be a risk for stratigraphic traps, however cross fault sealing capacity has been demonstrated in a number of discoveries such as the Miri, Seria and Adong Kecil West (Figure 27) fields with excellent shale gouge ratios in an overall shaly system. Limited seal effectiveness is also expected within the northern and southern limbs of the Badas Syncline due to their monoclonal dips that may cause leakage for the hydrocarbons.

In summary, two major zones of optimum play fairway development are separated by the Badas Syncline: (1) Miri-

Asam Paya Anticline with prolific hydrocarbon charge likely from the Late Miocene coals and peats complimented by excellent Mid Miocene to Early Pliocene shoreface-shelfal reservoir sands with an upside of deeper turbidite sand, and (2) Engkabang-Karap Anticline with a higher risk-reward potential than the Miri-Asam Paya trend due to its high maximum depths of burial (5-6 km?) of the objective Eo-Oligocene carbonate reservoir and consequent tight reservoir characteristics. There is a confirmed oil migration fairway from the Badas Syncline to shallower Mid Miocene turbidite reservoirs (Figure 16). The turbidites are poorly imaged

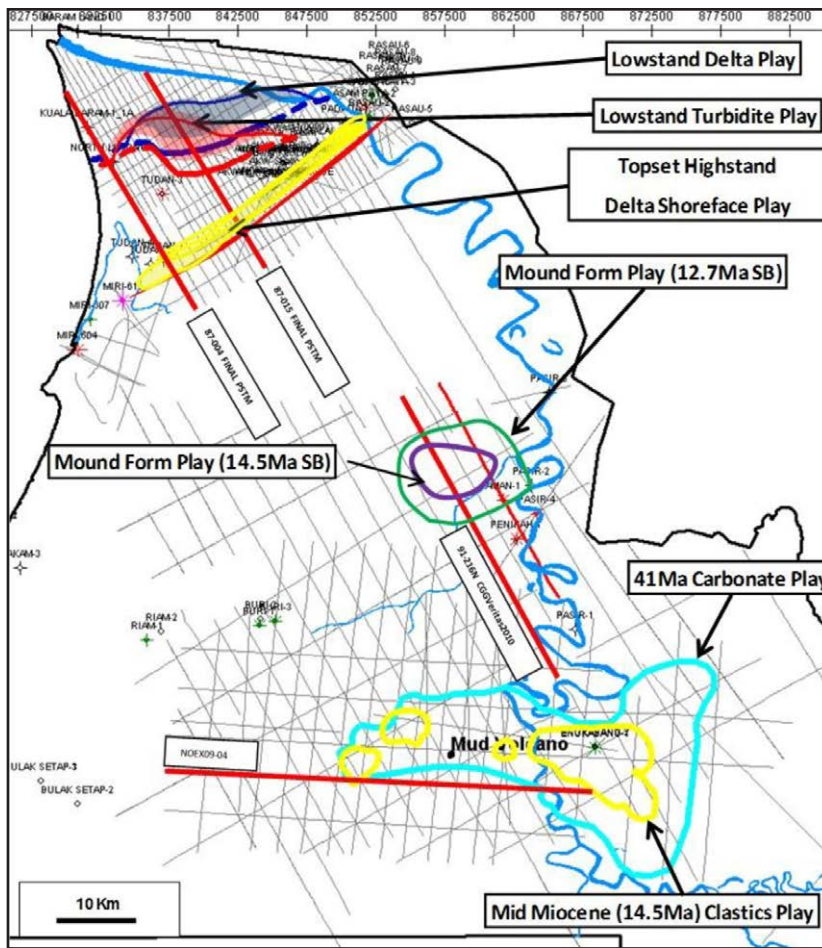


Figure 29: Block SK333 summary of play concepts (after Jong *et al.*, 2013; 2015).

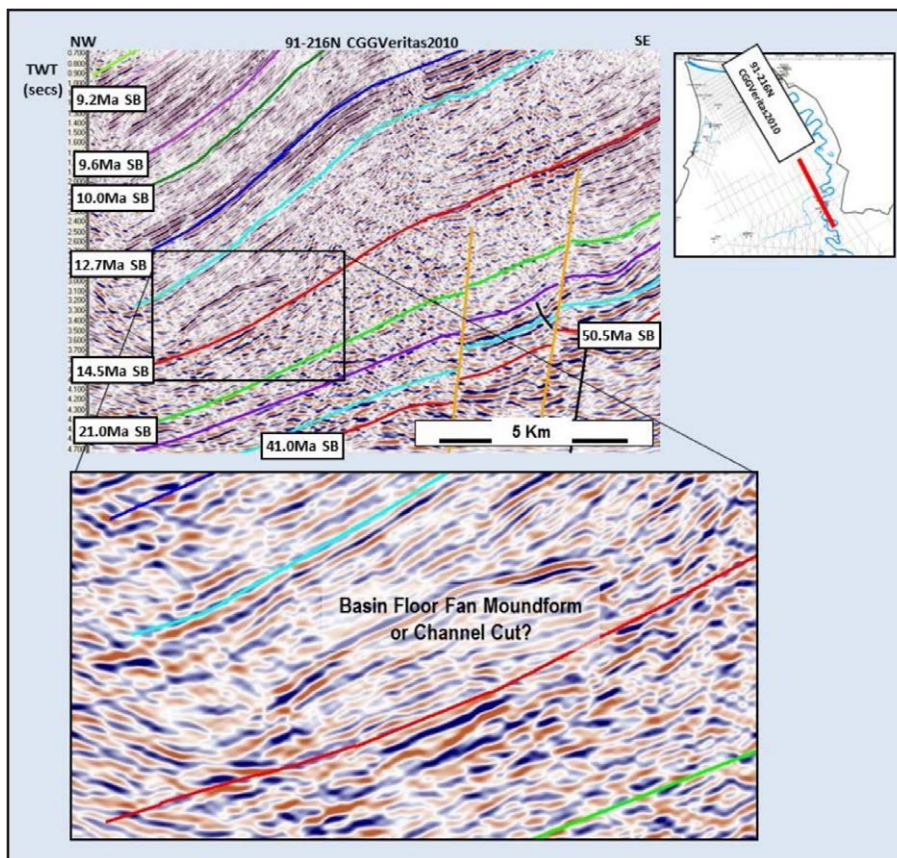
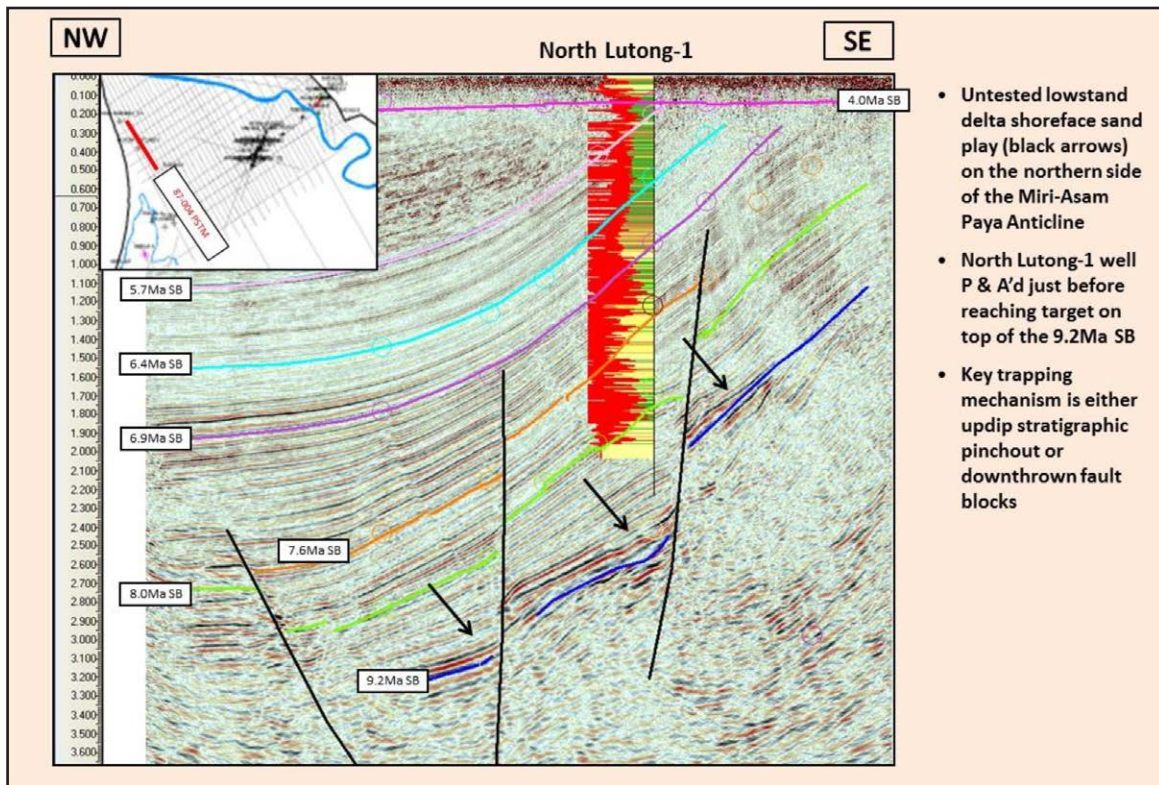
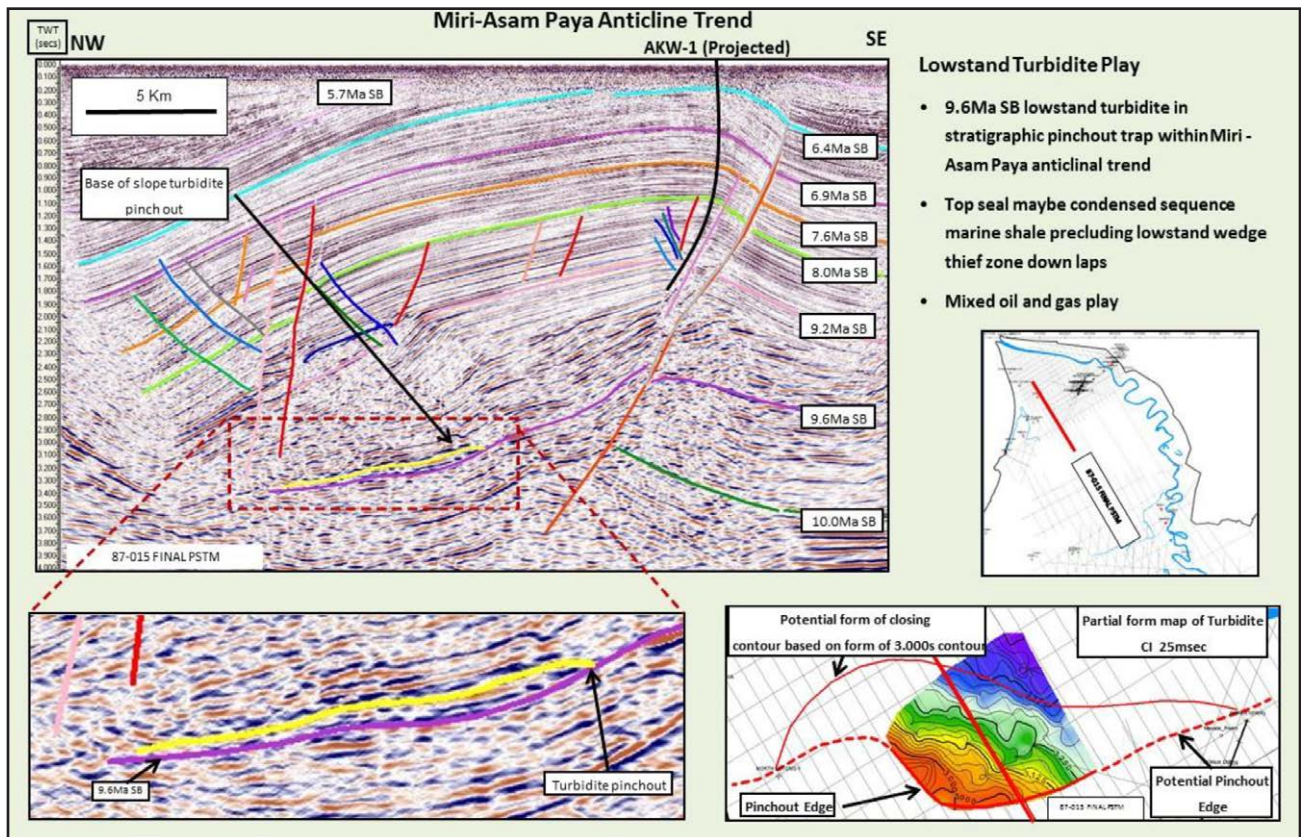


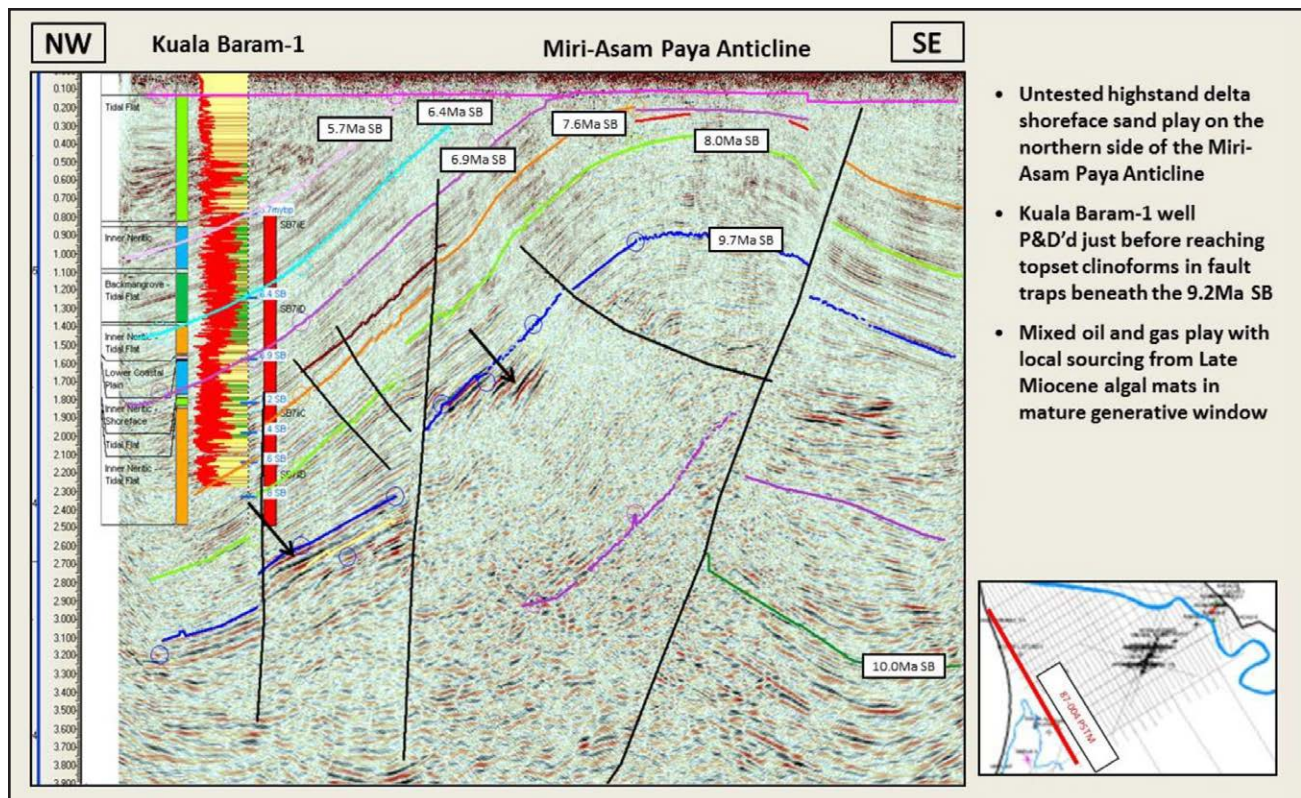
Figure 30: Badas Syncline southern flank stratigraphic mound, potentially an untested basin floor fan moundform (14.5 Ma SB).



**Figure 31:** Lowstand delta play, North Lutong-1 Area. This untested play (highlighted by the black arrows) was identified in the deeper section of North Lutong-1 well, which was plugged and abandoned before penetrating the interpreted seismic response due to operational constraints (after Jong *et al.*, 2013; 2015).



**Figure 32:** Another untested play of lowstand turbidite was observed in the deeper part of the Miri-Asam Paya Anticline simply overlying over the 9.6 Ma SB. The play, which also has the potential for both oil and gas trapping, is stratigraphically contained with the condensed sequence of marine shales potentially acting as the top seal (after Jong *et al.*, 2013; 2015)..



**Figure 33:** Highstand delta play, Kuala Baram-1 to Miri-Asam Paya Anticline. The partially tested play is characterized by the strong continuous seismic signal with distinct clinoform geometry between the 9.6 to 9.2 Ma SB on the northern flank of the Miri-Asam Paya Anticline (after Jong *et al.*, 2013; 2015).

on the existing seismic and may only be resolved by 3D seismic. These two petroleum systems from the onshore Baram Delta are well illustrated and summarized in the petroleum system summary chart (Figure 28).

### SUMMARY OF PLAY CONCEPTS AND EXPLORATION POTENTIAL

Block-wide, new and existing exploration plays that range from the Eo-Oligocene carbonates to the Late Miocene-Pliocene clastics were identified across three main areas: (1) Engkabang-Karap Anticline, (2) Southern limb of Badas Syncline, and (3) Miri-Asam Paya Anticline (Figures 16 and 29). These play concepts, as summarised below admittedly need further evaluation to mature them to individual prospect for resource ranking.

The shallower clastic Mid Miocene section in the Engkabang-Karap Anticline area may have potential as oil shows with low resistivity log responses were encountered in Engkabang-1 (Figure 16). An equivalent play was tested by the Engkabang-2 appraisal well (Shell, 1960). A drill stem test resulted in poor flow of both oil and water suggesting high water saturation. Located downdip, Engkabang West-1 encountered the Mid Miocene clastic play with oil shows at shallow depth. Based on the post Engkabang West-1 re-mapping exercise, the well is apparently located outside closure, while Engkabang-1 is at the oil-water contact. Both wells seem to have penetrated the residual/dead oil trapped in the palaeo-migration pathway and suggests the

possibility of attic oil in the shallower part of the structure (JX Nippon, 2014).

The monoclinical dip at the southern limb of Badas Syncline has the potential for stratigraphic pinchout traps (Figure 16). Moundforms of uncertain origin (basin floor fan?) lying above the 14.5 Ma SB have been recognised and the environment interpreted from seismic facies analysis suggests an outer shelf to upper slope depositional setting (Figures 29 and 30).

Across the Miri-Asam Paya anticlinal trend, a number of different play types were identified (Figure 29). The 4-way dip or fault closure dependent anticlinal play has been tested and proven by the discovery of the Miri Field, and also by the recent oil and gas discovery made at Adong Kecil West-1 in 2012 (JX Nippon, 2013). Nevertheless, the equivalent hydrocarbon-bearing reservoir intervals located on the foot-wall along the Miri-Rasau fault system remain untested (Jong *et al.*, 2015). In the northern flank of the Miri-Asam Paya Anticline, a lowstand delta play related to the 9.2 Ma SB forced regression of shoreface sand with stratigraphic pinchout configuration was identified. The top seal of this play is inferred to be provided by the marine shales of the MFS from the subsequent transgressive system tracts. This lowstand delta play was also identified by seismic below the technical TD of well North Lutong-1 (Figure 31). Hence, the play remains untested.

Another untested lowstand turbidite play was observed in the deeper part of the anticline overlying the 9.6 Ma SB.



The play, which has the potential to trap both oil and gas, is stratigraphically contained by a condensed sequence of marine shales acting as a potential top seal (Figure 32). A prominent yet only partially tested play is the highstand system tract shoreface play. This play is characterized by a strong continuous seismic signal with distinct clinoform geometry between the 9.6 to 9.2 Ma SBs on the northern flank of the Miri-Asam Paya Anticline where the shoreface sands were deposited at the edge of the shelf break. The play is also observed beneath well Kuala Baram-1. This well was plugged and abandoned above the identified play (Figure 33).

## CONCLUSIONS

After a hiatus of Sarawak onshore exploration activity since 1995, JX Nippon acquired and operated Block SK333 to revive the oil and gas exploration of the Baram Delta. Activities commenced in 2007 with extensive data acquisition followed by multi-disciplinary geological and geophysical studies in order to enhance the understanding of the hydrocarbon habitats and petroleum systems.

The 2D seismic data acquired in 2009 indicate significant structural deformations including block faulting, wrench and folding tectonism, local overthrusting and compressive folding, not recognised on older seismic or from geological surface mapping. The structural styles in Block SK333 observed on seismic are the results of three major tectonic episodes: (1) Late Cretaceous to Eocene (79.5-36 Ma) block faulting, (2) Late Oligocene to Mid Miocene (30-20.5 Ma) wrenching and folding and, (3) Mid Pliocene to Holocene (4.0-0 Ma) compressional tectonism.

The sequence stratigraphic study conducted in 2010 – 2011 found two distinct petroleum systems that had likely generated hydrocarbons and charged entrapments in the study area. The study also identified new untested plays in three major areas of the Miri-Asam Paya Anticline, the southern limb of the Badas Syncline and the Engkabang-Karap Anticline.

The highest ranking prospect was drilled by well Adong Kecil West-1/ST1/ST2 in 2012. This well discovered oil and gas. After the Adong Kecil Westwell results, JX Nippon acquired the first 3D onshore seismic in Malaysia covering the Miri-Asam Paya anticlinal trend. However, resources were considered sub-commercial and Block SK333 was therefore relinquished in 2015.

The southern area seemed to have experienced strong tectonic stresses caused by movements along the nearby and converging Baram Line and Belait Wrench system, as evidenced by active mud volcanism. Although the petroleum system for the Engkabang-Karap carbonate area is fairly well-established with potentially significant volume upside (Jong *et al.*, 2016), further de-risking of the carbonate play is required. Only a well-established fracture system or fracking would make the tight carbonates a decent reservoir with acceptable permeability. The confirmation of a fracture system will require high density 3D seismic coverage.

The onshore Baram Delta still contains a number of

both untested and partially tested plays yet to be fully explored. The lowstand delta play, the lowstand turbidite play, the topset highstand delta shoreface play in the Miri-Asam Paya Anticline area and the moundform stratigraphic play in the southern limb of the Badas Syncline are among the identified untested plays. The identified and assessed prospects and leads within the block suggests that the study area may contain a total undiscovered in-place resource of up to one billion barrel of oil equivalent (JX Nippon, 2015).

In addition to above, the Miri Field presents a significant near field exploration opportunity with deeper untested fault compartments. The gas-condensate with some 120 m of hydrocarbon column discovered by Miri No. 604 deserves further appraisal. A development plan for Adong Kecil West is still outstanding. In case of future improving crude oil prices, more enticing exploration terms and additional 3D seismic data, we foresee a new revival of oil and gas exploration activities in the onshore Baram Delta area.

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