BASIN WITH MULTIPLE SEDIMENT SOURCES: TECTONIC EVOLUTION, STRATIGRAPHIC RECORD AND RESERVOIR POTENTIAL OF THE BUNGURAN TROUGH, SOUTH CHINA SEA

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ABSTRACT

The Bunguran Trough is an intra-continental pull-apart basin located in the deepwater domain of the Rajang/West Luconia Delta province, offshore Sarawak. The area evolved as a tectonically-induced sag basin, where the two major lineaments, the Baram Line and the Red River Fault, appear to coalesce to form a major releasing fault bend. Its oldest stratigraphy was formed by shelf clastic deposits of the Late Oligocene Cycle I, Gabus Formation of the Natuna Basin, now buried to a depth of more than 7,000m. The Neogene clastics deposited above are of neritic and bathyal characters. The Early Miocene Cycles II/III, Arang Formation equivalent, consist of shallow marine to slope deposits, and are overlain by base-of-slope to very distal muddy sediments equivalent to Cycle IV and younger Terumbu and Muda formations. All sedimentary units, apart from the youngest Holocene section were subjected to deformation by a variety of tectonic drivers at distinct intervals.

Investigation of the Late Oligocene to present-day palaeogeographic evolution of the Natuna and offshore Sarawak regions, in conjunction with a study of the Plio-Pleistocene deformation history and the corresponding sedimentation rates in the Bunguran Trough reveal the following sediment source patterns:

- *The Natuna contributed medium to mostly fine-grained feldspatic and quartz-rich turbidite deposits.*
- *Fine sand and silt-rich deposits reached the Bunguran Trough from the fringes of the Rajang (or West Luconia) Delta. The advancing delta front generated turbidite currents running dominantly north to northeast. These clastics can be characterised as mud-rich, with channelised, and highly sinuous geometries accompanied with lobate turbidite deposits having higher sand potential.*
- *A minor amount of sediment might have been derived from localised sources in the Dangerous Grounds/North Luconia and Central Luconia Platform areas to the north and east, respectively.*

From Oligocene to Early Miocene times, sediments were probably sourced from the Natuna Arch/Terumbu Platform areas, but during the Neogene sediment supply shifted to the Rajang Delta in the south. In the Pliocene the Natuna area became important again, as demonstrated by mineralogy and recently acquired 2D/3D seismic data. In addition, the semi-quantitative analysis of the sedimentation rates showed that the rates were low before 3Ma, increasing in the Late Pliocene, and peaking in the Pleistocene. Physical compaction is thought to have played a key role in this trend, in addition to the increased sediment supply from the Natuna Arch.

This sequence stratigraphic and sediment compositional study suggests that the Late Miocene to Pleistocene (post-Mid Miocene Unconformity) intervals of the Bunguran Trough consist of predominantly deepwater slope to basinal deposits including turbidites, mass transport deposits, gravity flows and hemipelagic mudstones. Recent exploration well results suggest that sediment provenance from the Natuna Arch provided siltier material with some calcareous content, while the Rajang Delta provided very fine-grained material with very little sand. The quality and distribution of reservoir sand remain the main exploration risk in the Bunguran Trough, largely due to the fine-grained argillaceous nature of the predominant Rajang Delta source.

Key words: *Bunguran Trough, Natuna Arch, sedimentation, South China Sea, stratigraphy, tectonics*

INTRODUCTION

The South China Sea corresponds to a former area of Cenozoic crustal extension that is flanked by the Asian continent (Vietnam, China), the Philippines, and the Sundaland continent (Java, Borneo, and Peninsular Malaysia). The area saw periods of compression, manifested in strike-slip (and occasional thrust) movements along major lineaments (Jong et al., 2014 & 2015a; Kessler and Jong, 2016). Underlying the sedimentary fills of variable thicknesses, the basement is formed predominantly of strong to moderately-attenuated continental crust (Cullen et al., 2010; Madon et al., 2013; Jong et al., 2014).

Tectonic processes spanning the entire Tertiary affected the Bunguran Trough, and have been recently summarised by Jong et al. (2014 & 2015a) and Kessler and Jong (2016). With its deepwater sedimentation it represents distal equivalent of Rajang Delta and is dominated by the Bunguran Fold-Thrust Belt (Harun Alrashid et al., 2015; Jong et al., 2014 & 2015a; Kessler and Jong, 2016).

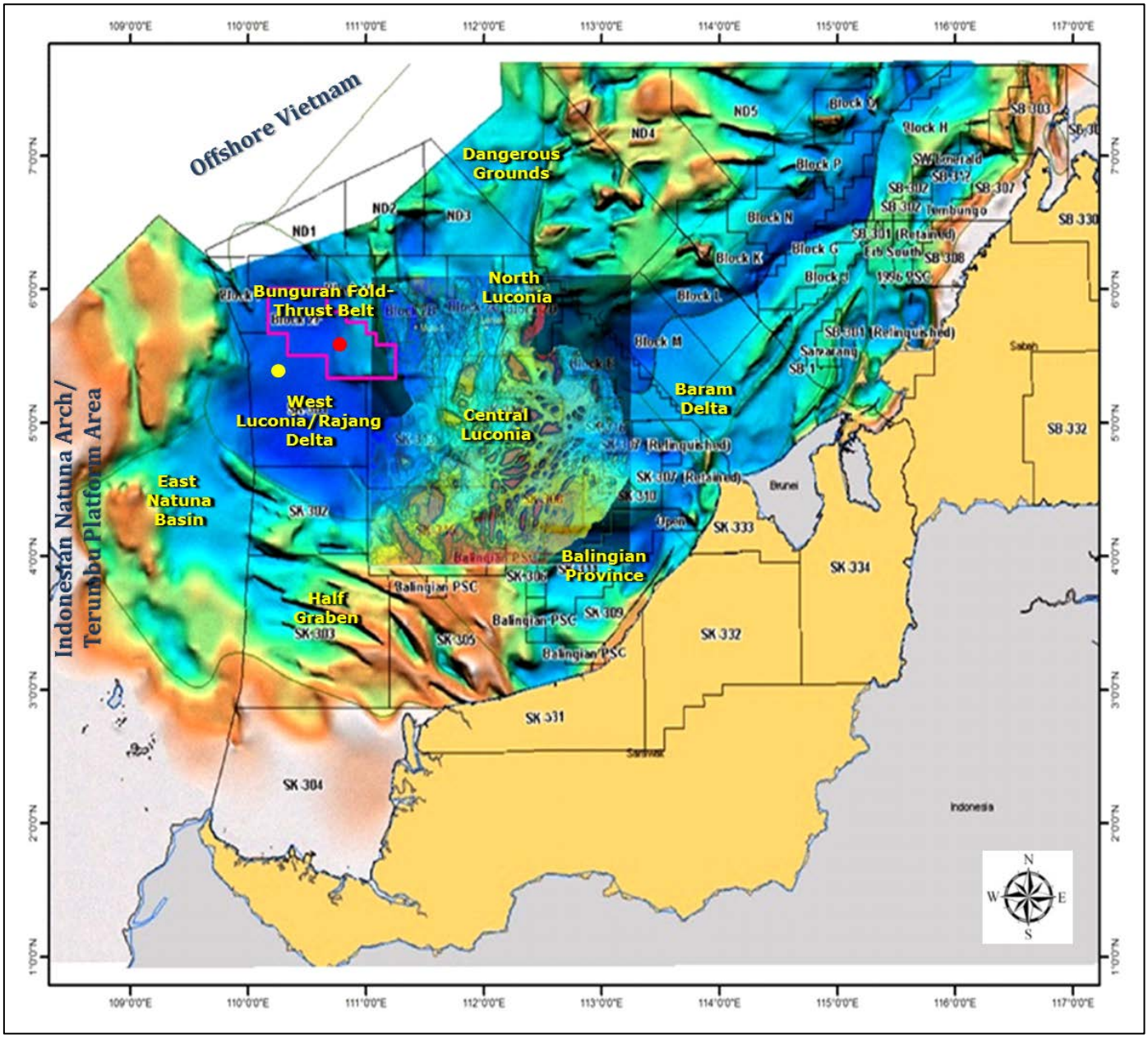


***Figure 1**: Location of Bunguran Trough, a low gravity anomaly in the Rajang / West Luconia Delta province with adjacent structural domains of NW Borneo. The trough is filled with Miocene to Quaternary deepwater Rajang Delta-derived sediments, augmented with a secondary source from the Natuna Arch/Terumbu Platform area, as shown by recently acquired and processed 2D/3D seismic data. The purple polygon area represents deepwater exploration Block 2F (DW2F) previously operated by JX Nippon and the red and yellow dots indicate the approximate location of exploration wells Jelawat-1ST1 (Noor Farinda Salim et al., 2015) and Jemuduk-1ST1 (Harun Alrashid et al., 2015), respectively. Modified after Jong et al. (2014).*

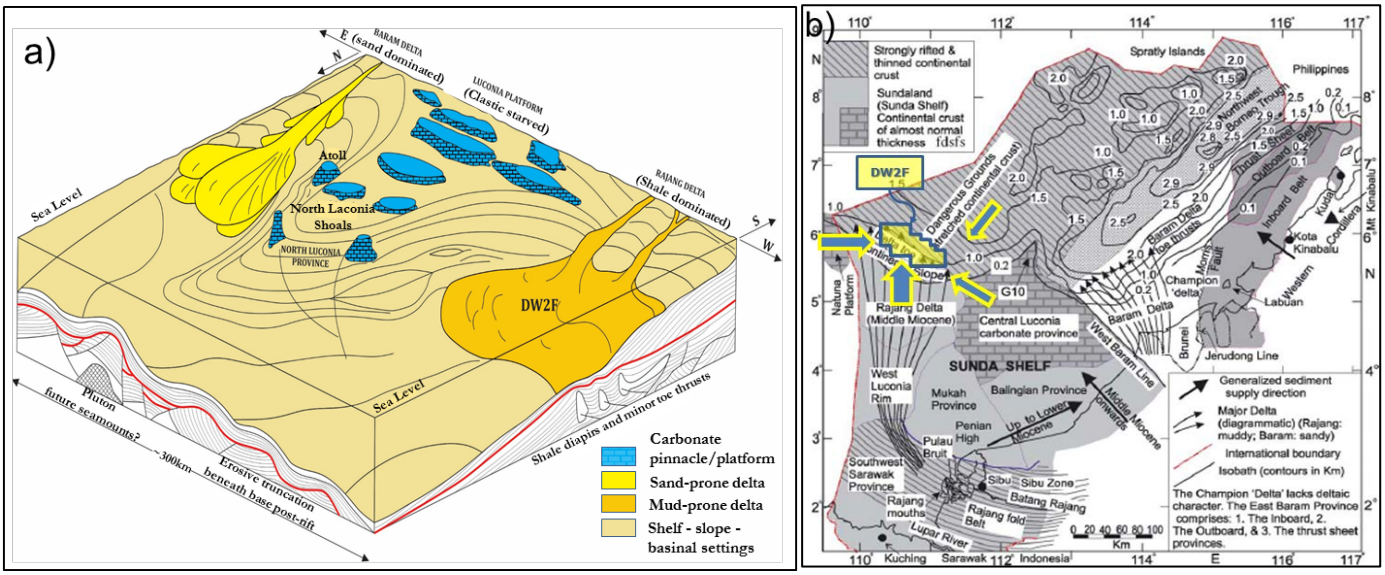


Figure 2: *a) A schematic sedimentary model for offshore Sarawak. b) The muddy Rajang Delta has extended over the continental passive-rifted margin as far north as the Dangerous Grounds and is the main source of deepwater sedimentation for the Bunguran Trough. Annotated arrows show potential secondary sedimentary sources from the regions of Natuna, Central Luconia and North Luconia/Dangerous Grounds (modified after Hutchison, 2004).*

The study area is located a few hundred kilometres offshore of Sarawak in the centre of the South China Sea and can be described as a roughly triangular crustal depression. It is wedged between the Natuna Arch/Terumbu Platform in the west and the Central Luconia Platform to the east. Both of the latter areas were the sites of Miocene to Pliocene platform and pinnacle reef development, as was the Dangerous Grounds/North Luconia massif to the northeast (Figure 1).

Sediments in the Bunguran Fold-Thrust Belt are predominantly of Late Miocene through Pleistocene age, and consist of mainly slope to distal facies of the Rajang Delta system (Figure 2) (Hutchison, 1989 & 2005; Kessler and Jong, 2014; Jong et al., 2015b). This section is separated by the Mid Miocene Unconformity (MMU) from the syn-rift, possibly coastal, shallow marine to slope clastic facies of Oligocene to Early Miocene age, inferred to have been sourced from the Natuna Arch (Figure 3). We conclude that sedimentary input originated from the Natuna Arch both in the early history of the basin, and again later during the Neogene. Figure 4 shows a regional geological section, interpreted based on seismic data across the shallow water Rajang Delta passing into the deepwater area of the Bunguran Fold-Thrust Belt.

In this paper, we first investigate the pulses of tectonic activity affecting the study area that could have resulted in increased basin subsidence, manifested in an unusually thick Neogene sedimentary sequence within the trough. The regional palaeogeography, stratigraphy and gross depositional environment evolution from Late Oligocene to Neogene times in the vicinity of the Bunguran Trough as well as in the greater offshore Sarawak Basin, have been compiled based on previous studies, including unpublished operator reports. The main objective of the paper is to establish the possible sedimentary provenance, reservoir potential and clastic depositional history of the Bunguran Trough.

REGIONAL TECTONIC DRIVERS

The unusually thick Neogene sedimentary sequence found in the Bunguran Trough depocentre cannot be explained by sedimentary processes alone, but requires enhanced subsidence and pulses of tectonic activity. With a current water depth in the order of 1,000m, and a Tertiary sequence at least 7,000-8,000m (Jong and Barker, 2015; Jong et al., 2015b), it is obvious that subsidence has continuously outpaced sediment supply, ensuring that the sedimentary environment has remained essentially slope to deep marine in nature. Tectonic processes have led to a thinning of crust beneath the Bunguran Trough, but the early subsidence history remains poorly understood due to the limitation of the current seismic data set.

At least four regional tectonic drivers are thought to have affected the Bunguran Trough area since the Oligocene. They are described below:

- **Extrusion and oroclinal bending**. The effect of the collision of the Indian and Asian plates on the South China Sea is still controversial. Tapponier et al. (1982) carried out a simple experiment, which gave rise to the idea that the collision of the Indian Plate with Asia not only led to the rise of the Himalayas and to a massive mushroom-like extrusion of the Tibetan Plateau, but also to major regional faulting, such as the Red River Fault system. Hutchison (1994) proposed that the extrusion tectonics not only resulted in faulting, but also in oroclinal bending of southern Sundaland (Figure 5), which was accomplished

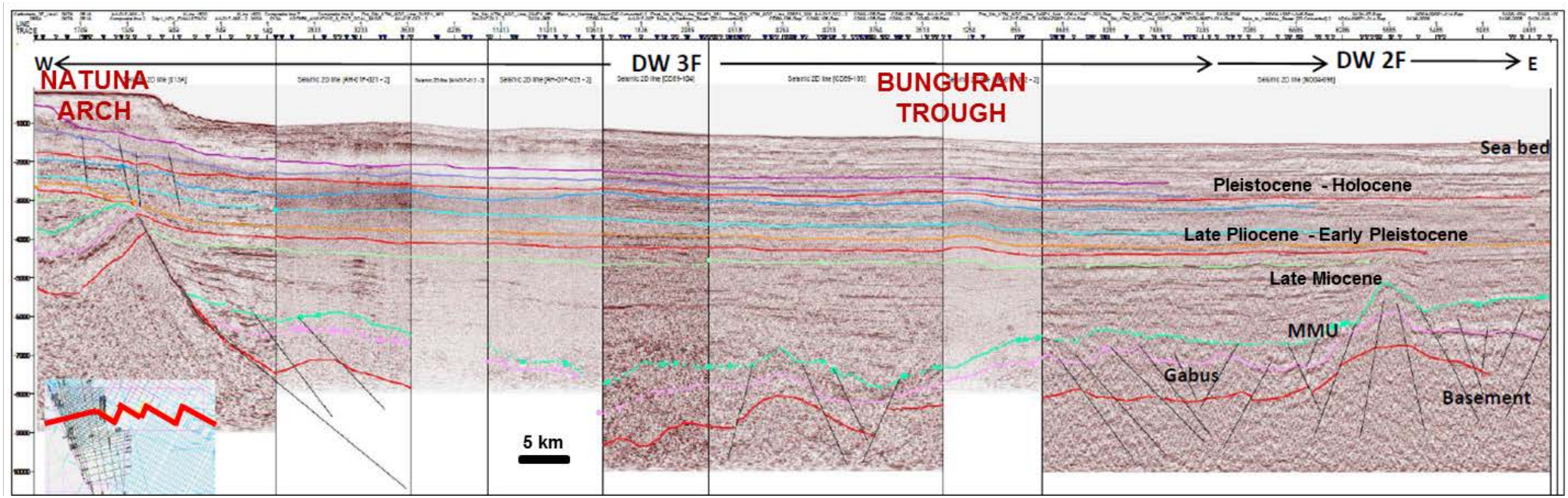


Figure 3: *A regional west-east oriented composite seismic line with key sedimentary sections, the Mid Miocene Unconformity (MMU) separates the syn-rift Gabus/Arang formations from the post-rift Neogene sedimentation.*

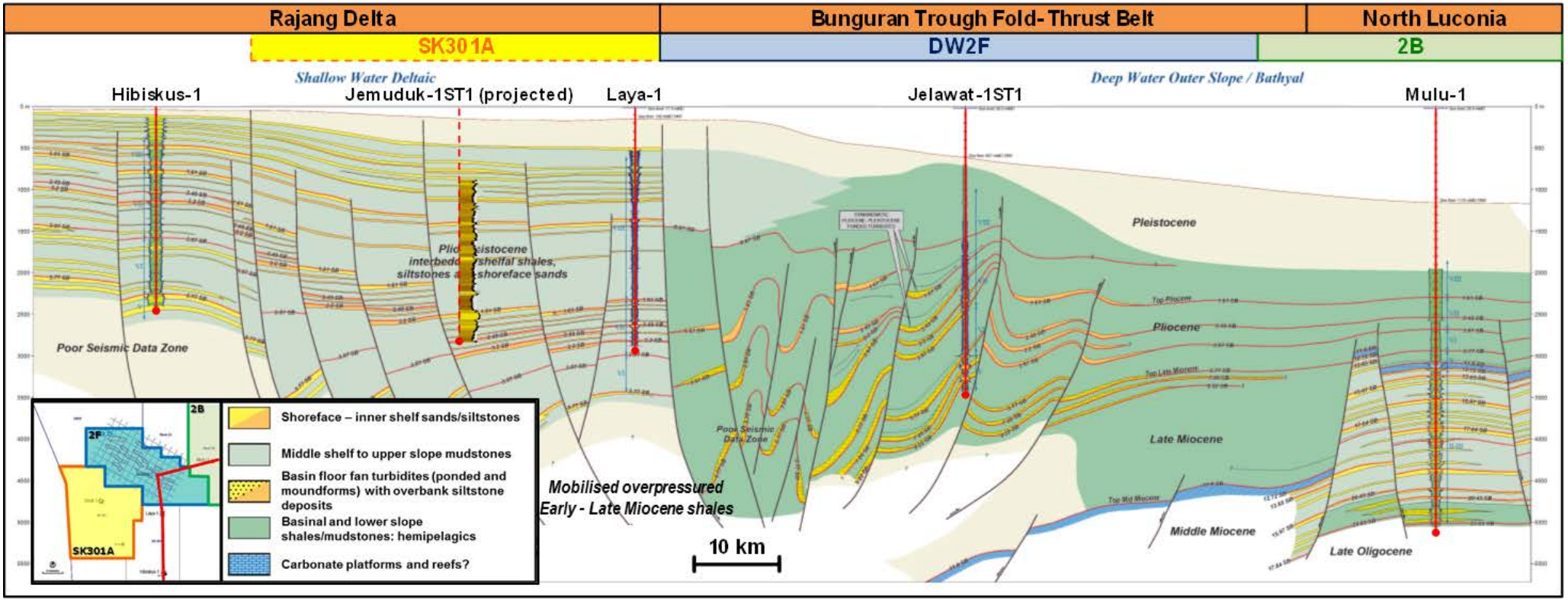


Figure 4: *Regional geological section of the Rajang Delta and deepwater Bunguran Fold-Thrust Belt. The inboard wells (Hibiskus-1, Jemuduk-1ST1 and Laya-1) tested mainly the Pliocene-Pleistocene shelfal to shoreface facies, while the outboard well Jelawat-1ST1 tested the Upper Miocene and Pliocene condensed bathyal to outer neritic facies. Mulu-1 targeted pre-MMU Cycles II/III overlaid by muddy turbidites. Apart from Jemuduk-1ST1, all wells found mostly poor developed sands. From Harun Alrashid et al. (2015), modified after Jong et al. (2014).*

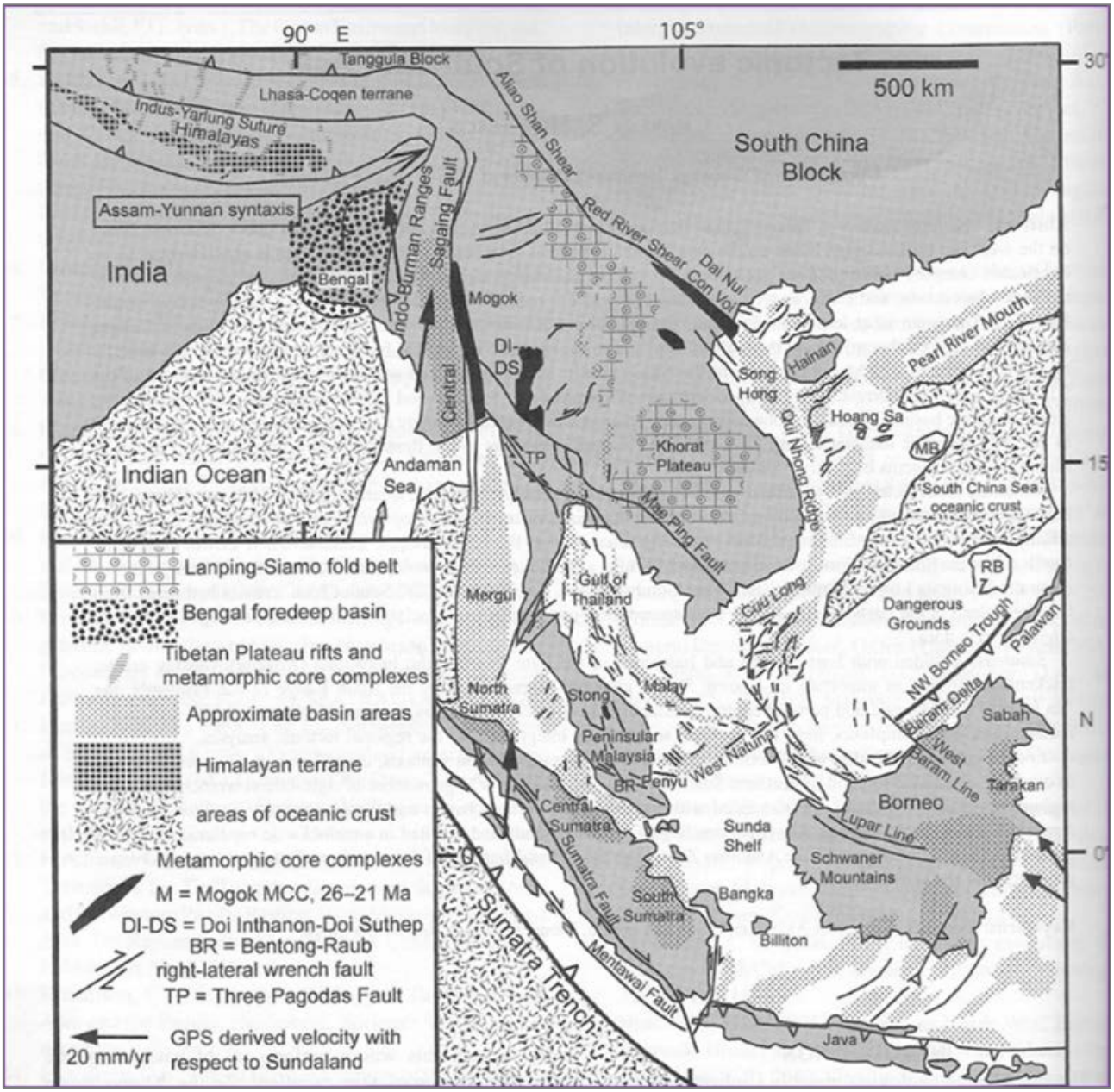


Figure 5: *Regional location map illustrating the Cenozoic structural setting of Southeast Asia. Modified after Searle and Morley (2011) as shown in Hutchison (2014).*

by anticlockwise rotation and right-lateral wrench faulting. During this process the outer zones of the orocline, including the Bunguran Trough, experienced transtentional tectonics leading to the formation of a releasing fault bend and pull-apart basin. Subsidence commenced at the end of the Oligocene, accelerated throughout the Early Miocene and continued periodically into the late Middle Miocene (Hutchison, 2004; Jong et al., 2014; Kessler and Jong, 2016).

- **Spreading in the centre of the South China Sea leading to a thinning of continental crust and large scale strike-slip movements within the basement fabric.** Starting during the Late Oligocene to the earliest Miocene, seafloor spreading lead to a triangular-shaped insertion of oceanic crust into the eastern Sundaland continental crust (Barckhausen and Roeser, 2004; Figure 6). As the gap in the continental crust opened, greater Borneo migrated in a southwest direction and underwent clockwise rotation. This resulted in basement shear reactivating detachment lineaments. Further to the north, in the Gulf of Thailand, there are also indications for a strong and persistent tectonic deformation episode, while seismic data from the Penyu and Malay basins (Tenggol Arch) show an intensely sheared basement, with pulses peaking near the boundary of the Late Oligocene and Early Miocene (Figure 7). Most movements appear to be dextral in nature. It is believed that the strike-slip movements seen in the Malay and Penyu basins and in parts of Natuna Basin are related to the Oligocene extension further east, but more work will be required to confirm this. Questions remain on how much shear, thinning and faulting the Bunguran Trough basement might have undergone as, unfortunately, the quality of seismic at this depth precludes an answer. We also believe that some of the observed South China Sea lineaments can be correlated

with sheared, "mobile" basement belts such as the Lupar Line, Three Pagoda Fault and Red River Fault, while others, such as the Baram Line, appear to form a boundary between strongly and moderately stretched continental crust (Kessler, 2010; Kessler and Jong, 2016).

- **Effect of the subduction along the Philippine margin.** Hall (2013) proposed that a subduction roll-back was active during Middle and Late Miocene in the Sulu Arc between Sabah and the Philippines and drove extension in northern Borneo and Palawan, accompanied by elevation of mountains, crustal melting, and deformation offshore. There were two important extensional episodes. The first at about 16Ma is marked by the Deep Regional Unconformity (DRU), whereas the second at about 10Ma produced the Shallow Regional Unconformity. Both episodes caused exhumation of deep crust, probably along low angle detachments. In a regional review of the complex interaction between basin subsidence and regional compressional events of the South China Sea, Kessler and Jong (2016) noted the

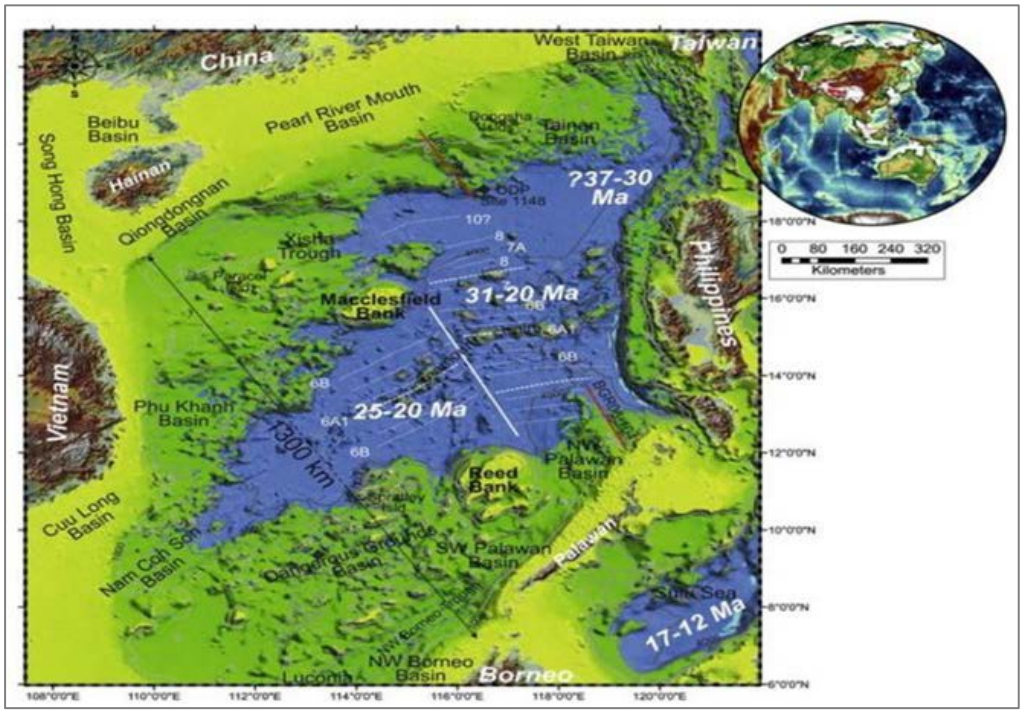


Figure 6: *Oligocene and Early Miocene oceanic crust (blue), as well as the stretched eastern Sundaland continental crust (green) dominate the central part of the South China Sea (from Barckhausen and Roeser, 2004).*

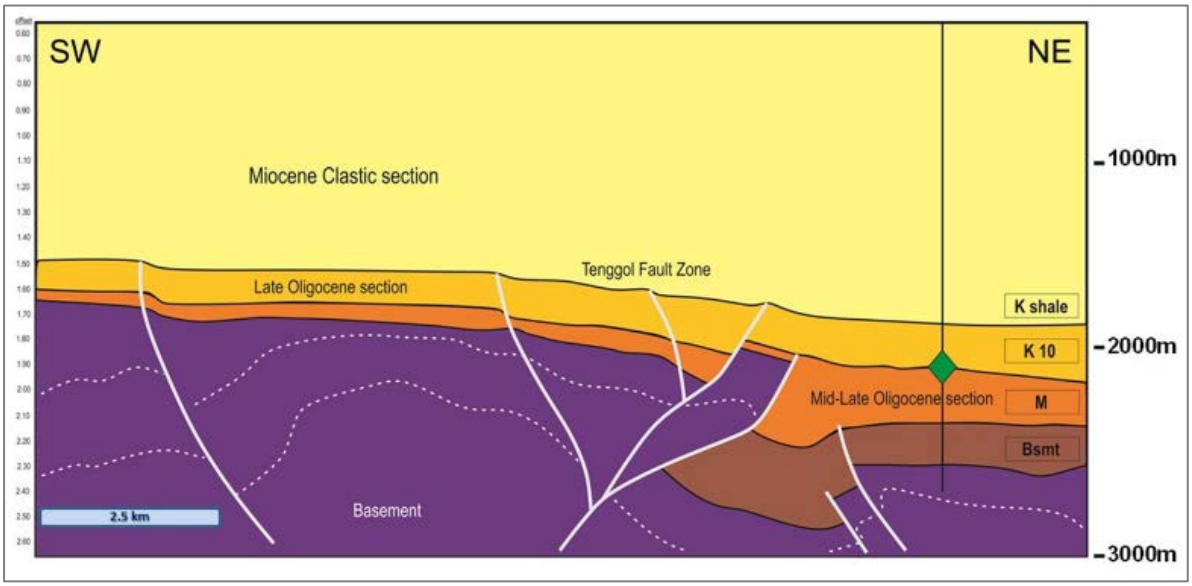


Figure 7: *A SW-NE geological section through the Tenggol Fault Zone, near to the Malaysia/Indonesia border, separating the Tenggol Arch (left) from the Malay Basin (right). The Malay Basin is characterized by a number of prominent lineaments and faults; during the Late Oligocene, older rift faults such as the Tenggol were reactivated in strike-slip mode, with the occasional occurrence of overthrusting (from Maga et al., 2015).*

positive age correlation of the DRU and MMU, both diachronous in nature with the latter being more established and has been mapped extensively in the region including the Bunguran Trough area. However, evidence to support the subduction process has triggered compression as far west as the Bunguran Trough will require further research, but compressional pulses identified by Jong et al. (2015a) have contributed to the formation of the Bunguran Fold-Thrust Belt along with gravitational collapses.

- **The collision of Asia/Sundaland with the Australian (Sahul) Plate.** According to Hall (2011), the Sula Spur promontory collided at 23Ma with the Sundaland margin. From 15Ma onwards, subduction roll-back into the Banda ocean plate, accompanied by extension and collision of the Banda Arc with the southern margin of the embayment took place. This collision may have contributed to the uplift of Borneo, to formation of the Rajang-Crocker mountain belt, and to a pulse of sand supply into the NW Borneo Foredeep and the Bunguran Trough (Kessler and Jong, 2015). There is no clear evidence that this collision has triggered compression in the Bunguran Trough, but we believe that transtension along the underlying releasing bend had a direct impact on its subsidence history.

Pull-apart basins are characterised by high subsidence rates early in the history of the basin (e.g. Molčan, 2013), and may remain high or even increase later, especially when driven by elevated sediment influx (e.g. Petrunin, 2007). We compare the pull-apart history of the Bunguran Trough with an analogue later in the paper, noting that research on the tectonic and structural evolution of the trough is in progress and, we hope, will be presented in a future publication.

REGIONAL STRATIGRAPHY, PALAEOGEOGRAPHIC EVOLUTION AND ENVIRONMENTS OF DEPOSITION

Understanding the relationship between the Natuna Basin area and its deepwater equivalent is crucial to establishing the initial sedimentation history of the Bunguran Trough. Although they are separated by the Baram Line/Red River Fault system (Jong et al., 2014), the Natuna Arch is the only area where older Tertiary sediments and the underlying basement fabrics can be studied.

Figure 8 summarises the stratigraphic and tectonic evolution of the two areas (and the nearby Nam Con Son Basin). Seismic mapping suggests that the syn-rift pre-MMU stratigraphic succession in the Bunguran Trough is a continuation of the pre-carbonate formations in East Natuna (Gabus and Arang), while the post-MMU sections correlate with the post-rift deepwater clastics of the North and West Luconia provinces.

In Figure 9 the stratigraphy of the Natuna Basin is compared to the Malay/Penyu basins to the west and the Nam Con Son to the north, where the sedimentary record is divided in four stratigraphic cycles or stages:

- An Eocene-Oligocene syn-rift sequence;
- A transitional and post-rift sequence (with variable timing in different basins);
- An inverted post-rift sequence (with variable timing in different basins);
- A Late Miocene and younger basin-fill sequence. Interestingly, the Bunguran Trough sediments also appear to show an imprint of inversion deep into the Pleistocene, as discussed later in this paper.

Based on regional well data, we propose that the oldest stratigraphy in the Bunguran Trough comprises progradational shelf clastics equivalent to the pre-MMU Late Oligocene to Early Miocene Cycles I-III Gabus and Arang formations of the Natuna area (Figure 8). These units are now buried beneath more than 7,000m in the basin depocentre and their presence remains unconfirmed. They are believed to overlie a crystalline granitic basement (Figure 3). The Gabus and Arang formations in the Natuna Basin contain reservoir quality sandstones of coastal plain, deltaic, and shallow marine origin with associated coals and argillaceous mudstones that source oil and gas discoveries. Associated mudstones, most extensively deposited during marine transgressions provide seals.

Post-MMU clastics are of neritic and bathyal origin. The Late Miocene Cycle V Terumbu Formation equivalent comprises some 3,000m of slope and base-of-slope deposits in the Bunguran Trough. During the Middle to Late Miocene, the Luconia and Natuna platform highs became sites of extensive carbonate deposition, with the development of numerous reef buildups. The latter form important gas reservoirs (e.g. Natuna and Jintan gas fields) and are overlain by a marine shale section. However, from the Middle Miocene time onwards low areas such as the Bunguran Trough were continuously filled with distal and fine-grained muddy sediments of the equivalent Muda Formation (Cycles VI to VIII, Figures 8 and 10). Sedimentation has continued at such a rate that the Holocene, dominated by large scale mass transport deposits and gravity flows of a fine-grained nature, is many hundreds of metres thick. Collins et al. (1996), however, commented that the Natuna Arch acted as a continental high throughout the Neogene, providing surrounding basins with clastic and carbonate sediments. A comparison between the stratigraphy and sedimentary facies of the high and low lying areas is shown in Figure 10.

The palaeogeographic evolution of the Sarawak continental margin since the Oligocene has been

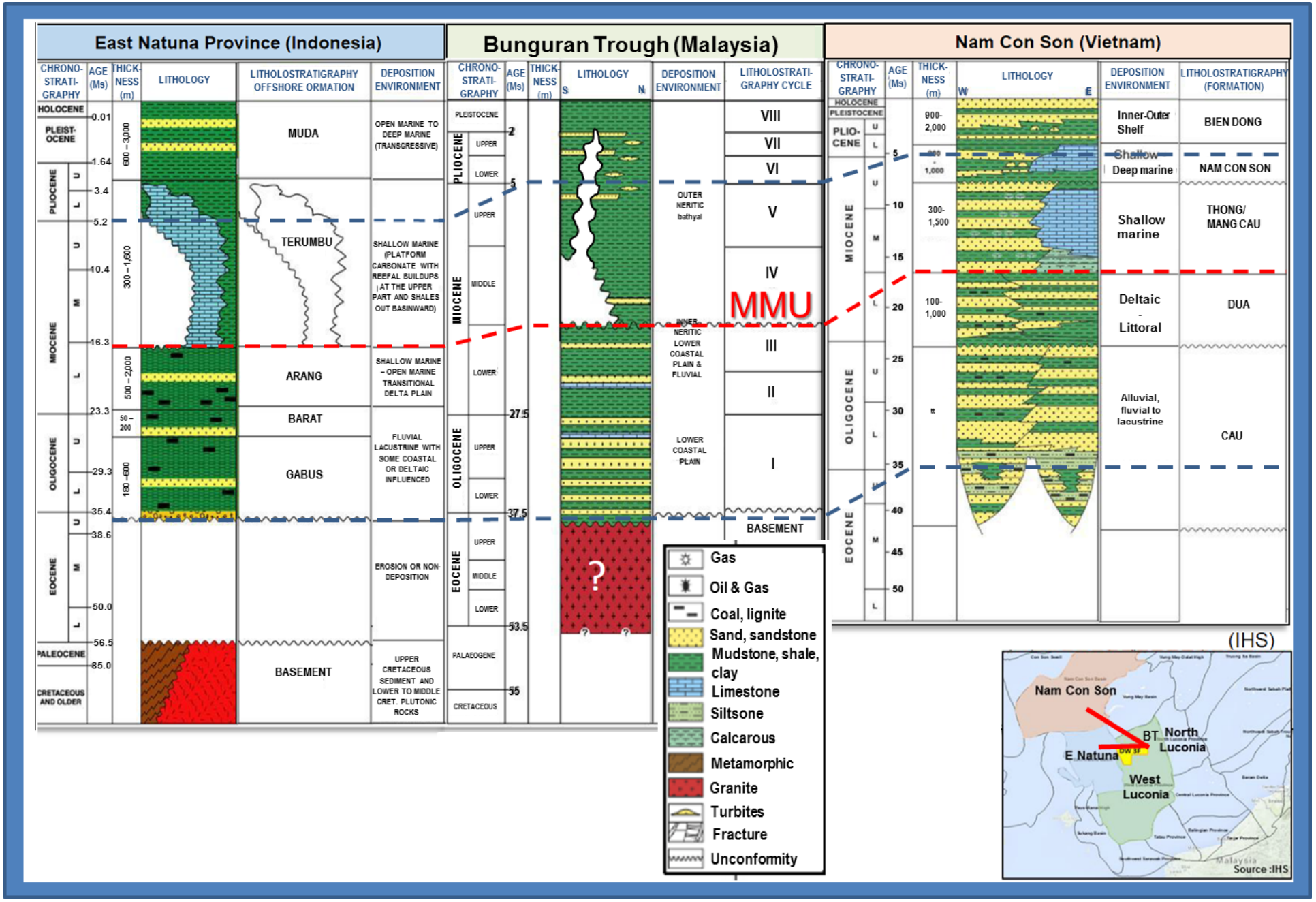


Figure 8: *IHS-derived general stratigraphic correlation and nomenclature used in the central and western South China Sea basins.*

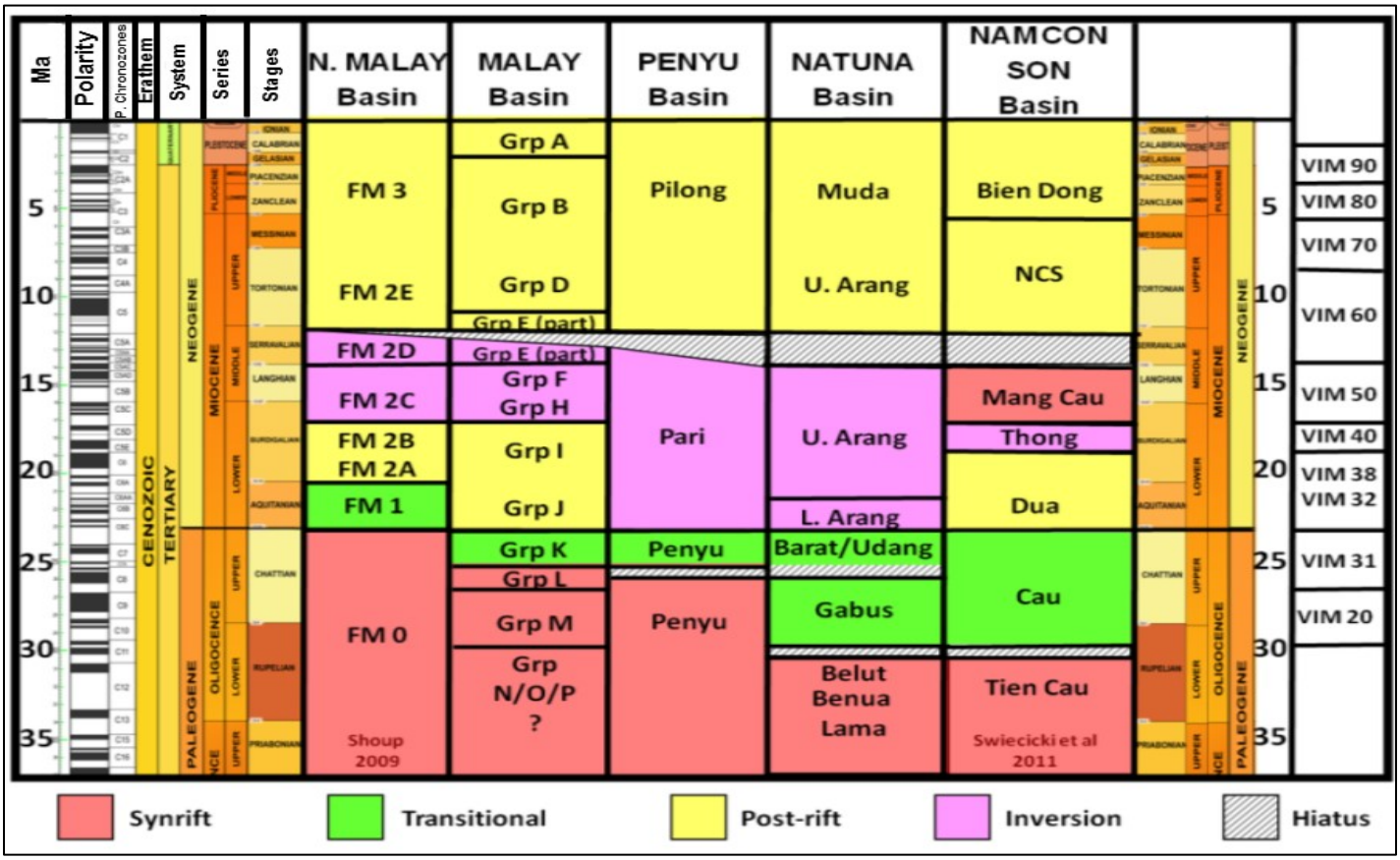


Figure 9: *Stratigraphic correlation summary for the Malay-Penyu-Natuna and Nam Con Son basins. The implied diachronism of the inversion events cannot be confirmed at this point (from Shoup et al., 2012).*

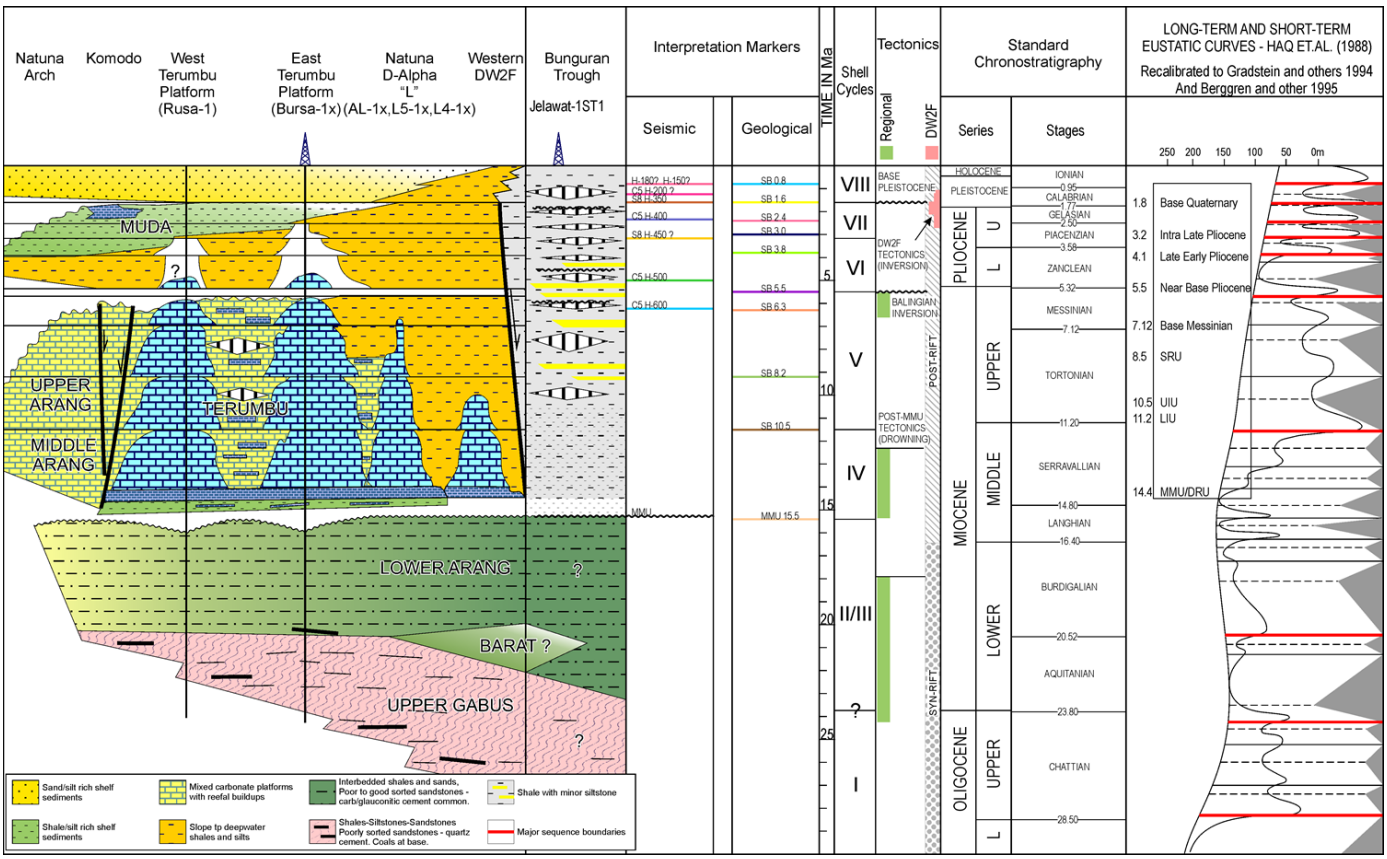


Figure 10: *Sedimentary facies of Bunguran Trough and neighbouring Terumbu Platform showing pre-MMU clastic sedimentation and post-MMU carbonate buildups (modified after original compilation by HESS, 2008).*

documented by Madon (1999) and by Ho and Jong (2000; Figure 11).

Sediment supply from the south of the Bunguran Trough was noted from Miocene to Pliocene times. Focussing more on the specific intervals of Cycles V to VI, study by Dr. Peter Barber (*pers. comm.*), indicates progressive progradation and migration of the proto-Rajang Delta front through time, resulting in a sediment source direction that changes from southeast in the Late Miocene to southwest in the Early Pliocene and Pleistocene (Figure 12). Figure 13 summarises the paleo-shelf break trajectories of the shelf edge migration from Miocene to Quaternary times.

Litho-Stratigraphy

Although given the paucity of well penetrations the stratigraphy of the Bunguran Trough is less well-understood than the adjacent Natuna and Central Luconia regions, its relative distance from continental shorelines logically results in a mud-dominated environment, with limited amounts of sand. Delivery systems may have changed in direction over time, but in the absence of 3D seismic data, fairway mapping cannot be conducted across the shelf. The following section describes the lithologies of the Bunguran Trough (Figure 14):

- **Cycle I, Oligocene - Pre-MMU Gabus Formation equivalent:** This unit is a reservoir target in areas of less subsidence within the offshore and has been positively tested in North Luconia wells, where good reservoir parameters have been recorded. However, at a depth of greater than 7,000m this unit is non-prospective in the Bunguran Trough, although extrapolation from Indonesian well data suggests that paralic facies may be present (Figure 15). Additional feeders from the now submerged areas of the Dangerous Grounds, North Luconia and Central Luconia areas could have existed but these are also speculative.

- **Cycles II-III, Early to Middle Miocene – Pre-MMU Arang Formation equivalent:** No significant feeder systems from the Natuna Arch have been recognised and a clay-prone facies is expected in the Bunguran Trough. Reservoir potential is discounted for this interval (Figure 16), but it becomes more prospective in proximal settings such as at the shelf margin and in shallow marine depositional settings where fluvial-deltaic sediments including coal seams were deposited, and where it forms a secondary target to the carbonate buildups of the Terumbu Platform.

- **Cycles IV-V, Late Miocene - Terumbu Formation equivalent:** Jelawat-1ST1 tested Upper Cycle V in the Bunguran Trough. Minor sand intervals, deposited in channel-levee settings (Noor Farinda Salim et al., 2015) were encountered, but they were so fine-grained and tight that a pressure could not be taken. On the Natuna Arch and Central Luconia Platform, this interval is dominated by gas-bearing reef buildups. From the latest 2D seismic spanning the Natuna Arch/Terumbu Platform, and Bunguran Trough, there is evidence that small carbonate buildups might have formed across the area during Cycle IV (Figure 17). The environment of deposition is neritic to bathyal in the Bunguran Trough and sandy beds may occur in base-of-slope channel deposits. Ditch cuttings from Jelawat-1ST1 analysed for grain size and inorganic geochemistry/mineralogy suggest that more quartz sand may be present in the Miocene, although poorly sorted and of very fine grain size. These observations with other findings will be discussed in more detail later in the paper.

- **Cycles VI-VII, Pliocene - Muda Formation equivalent:** The base-of-slope to basin floor depositional environment of the Pliocene is basically the same as that of the Miocene; except that the sediments were channeled increasingly into elongated depocentres parallel to growing thrust-cored anticlines of the Bunguran Fold-Thrust Belt. Accordingly, syn-kinematic Pliocene sediments that cover the crests of the nascent Miocene anticlines are likely to be represented by condensed sections or unconformities rather than by turbidite channel sands.

- **Cycle VIII, Pleistocene - Muda Formation equivalent:** The Pliocene sediments are interpreted to become increasingly less confined due to the diachronous “switching-off” of active anticline development within the basin. Material was again reaching the area from the west and southwest and there are indications of turbidites and gravity driven mass flow deposits on the seismic. Serrated Gamma-Ray signatures in the Pleistocene of Jelawat-1ST1 well are indicative for thin beds, whose thickness may be below the detection limit, or an amalgamated response.

- **Post Cycle VIII - Holocene:** The Holocene of the Bunguran Trough is formed of neritic-bathyal soft clay sediments. The seismic shows frequent “wipe-out” zones due to percolating gasses and the seabed surface is covered by pockmarks and mud-volcanoes. Within this unit large scale (kilometre scale) mass transport complexes/deposits, debrites and turbidites can be identified from the seismic data. This level exhibits a large scale reworking of both the shelf and slope areas.

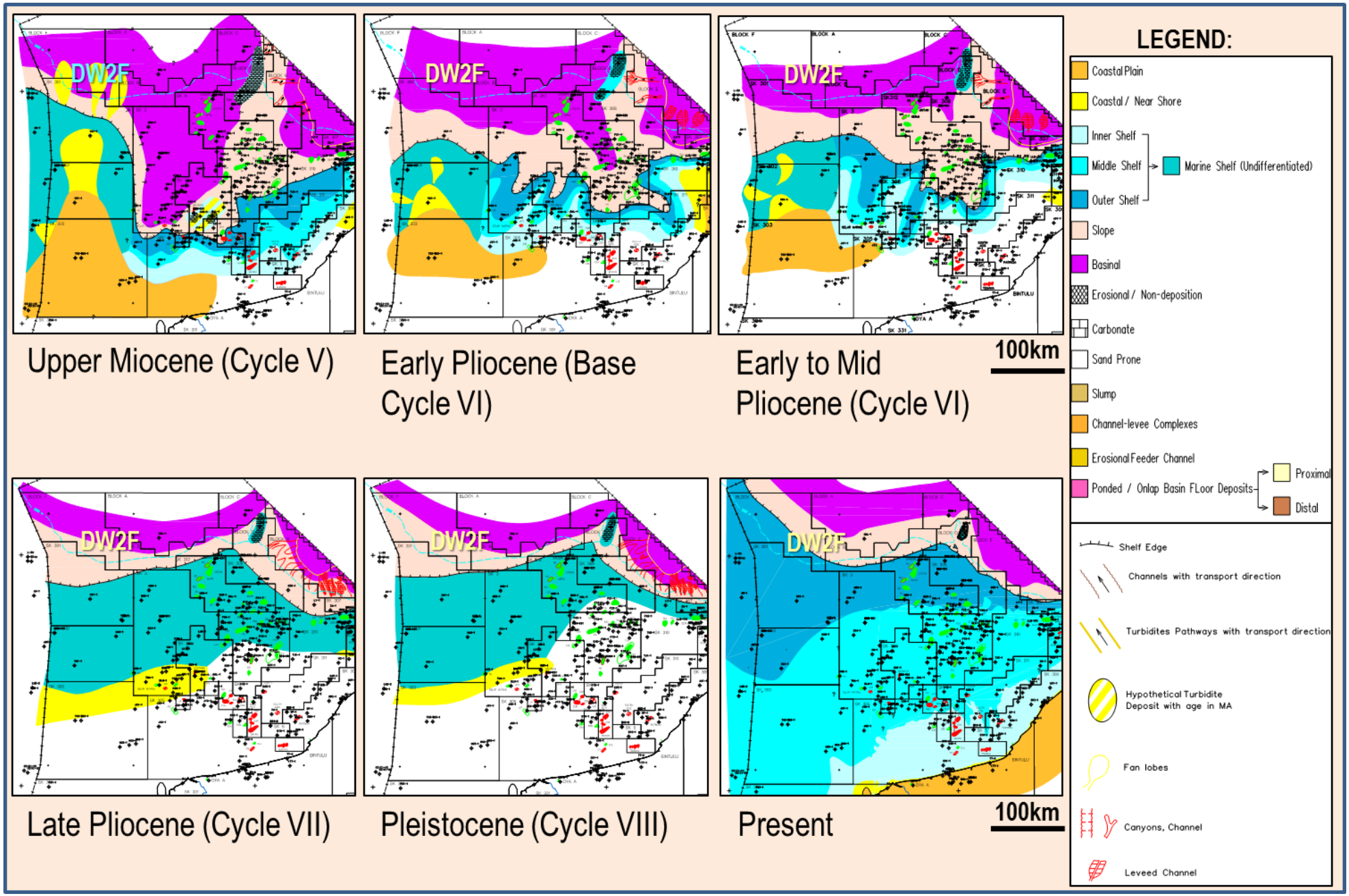


Figure 11: *Palaeogeographic evolution of the Sarawak continental margin since the Late Miocene. Sediment supply from the south to the slope to basinal setting of Bunguran Trough (DW2F) is noted from Miocene to Pliocene time onwards (modified after Ho and Jong, 2000).*

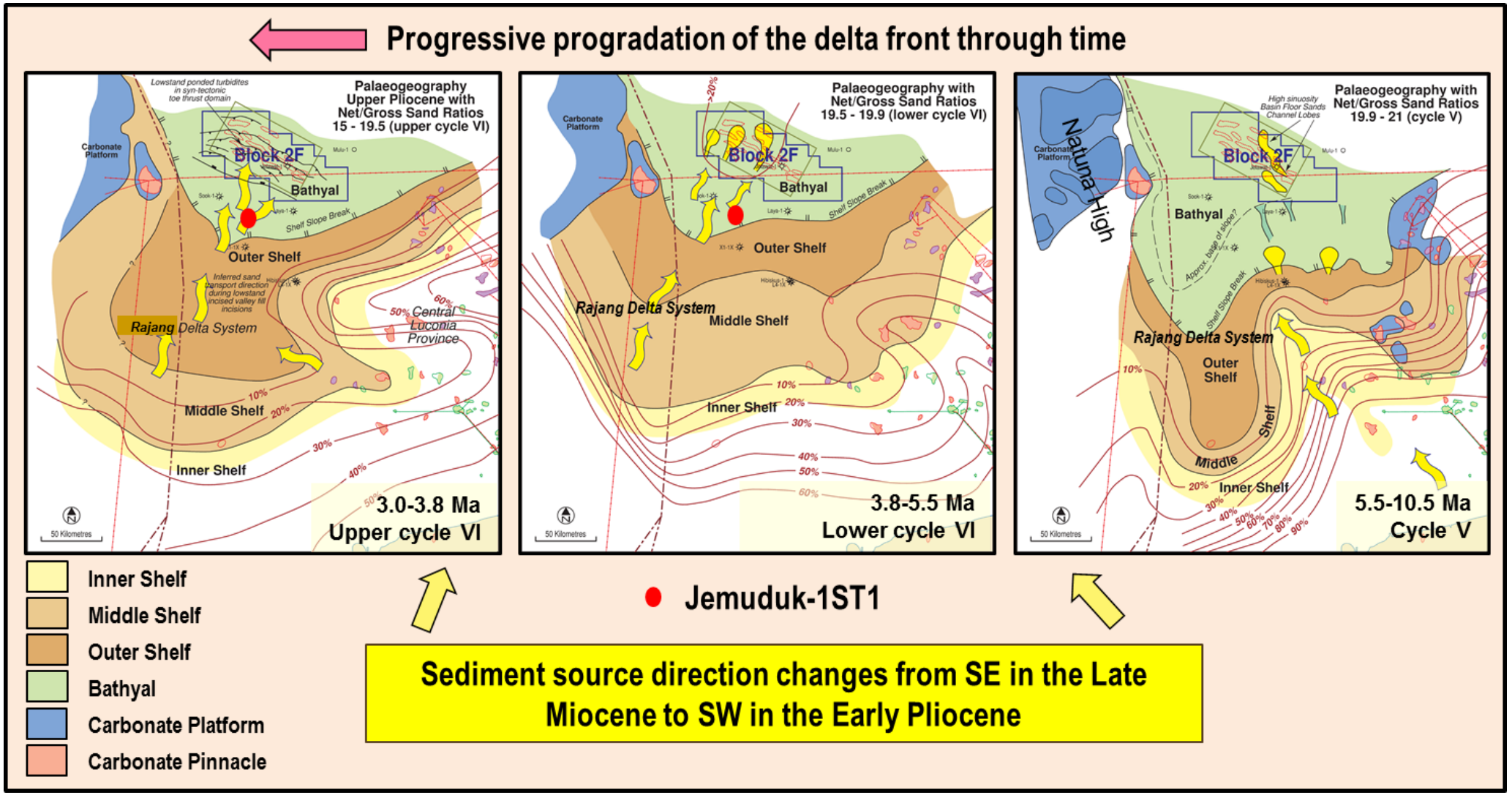


Figure 12: *Progressive progradation and migration of proto-Rajang Delta front through time from Cycle V to Cycle VI, contours indicate net/gross sand ratios (figures courtesy of Dr. Peter Barber).*

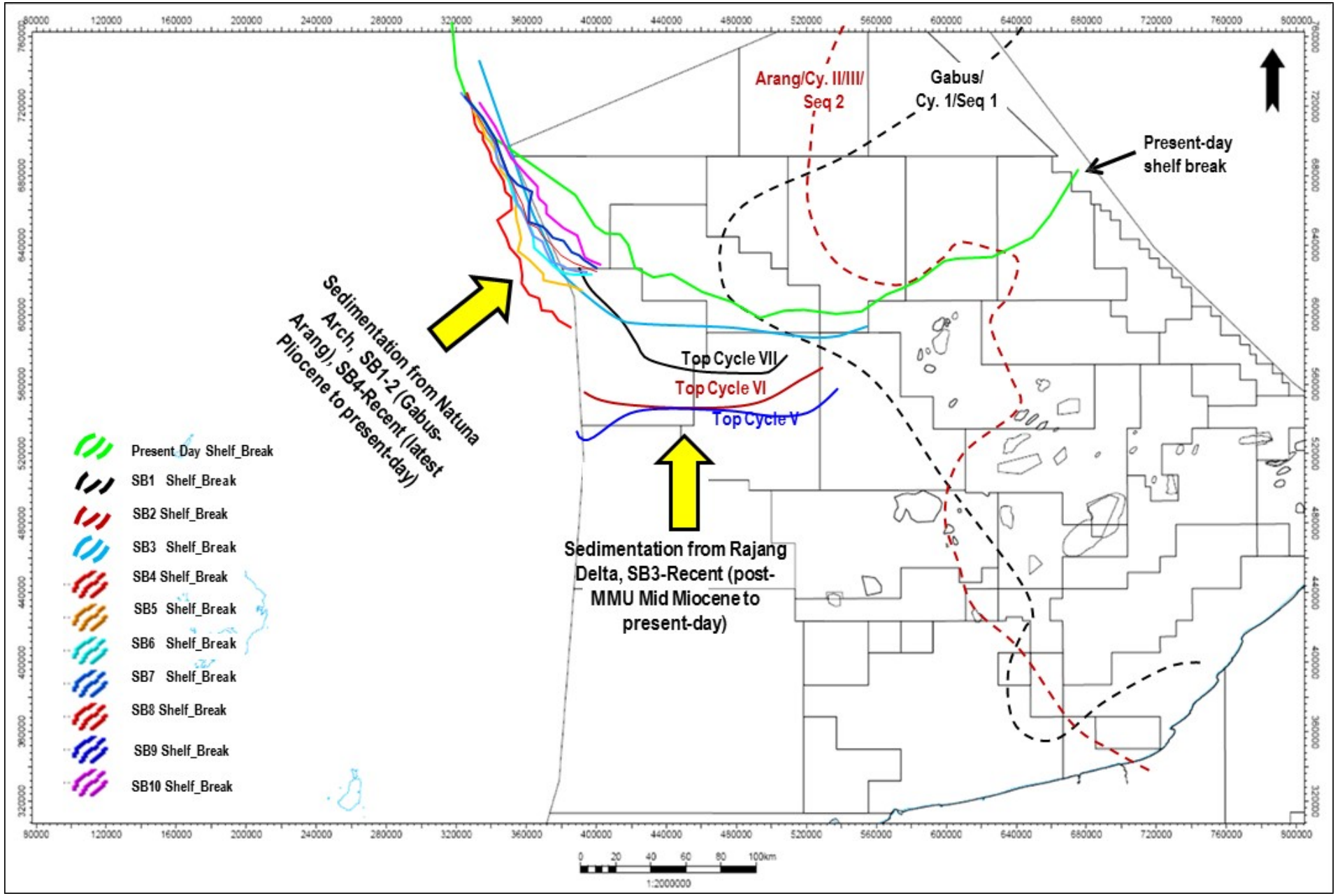


Figure 13: *Miocene to Quaternary paleo-shelf break progradation, identified from seismic data. Shelf breaks for Cycles V-VII to present-day are based on Kessler and Jong (2014), shelf breaks of the Tertiary sequence boundaries (SB1 to SB10) are from PETRONAS Carigali (2014). The pre-MMU Gabus and Arang clastic shelf breaks (equivalent to the Nyalau Formation in the Balingian Province) in offshore Sarawak are speculative.*

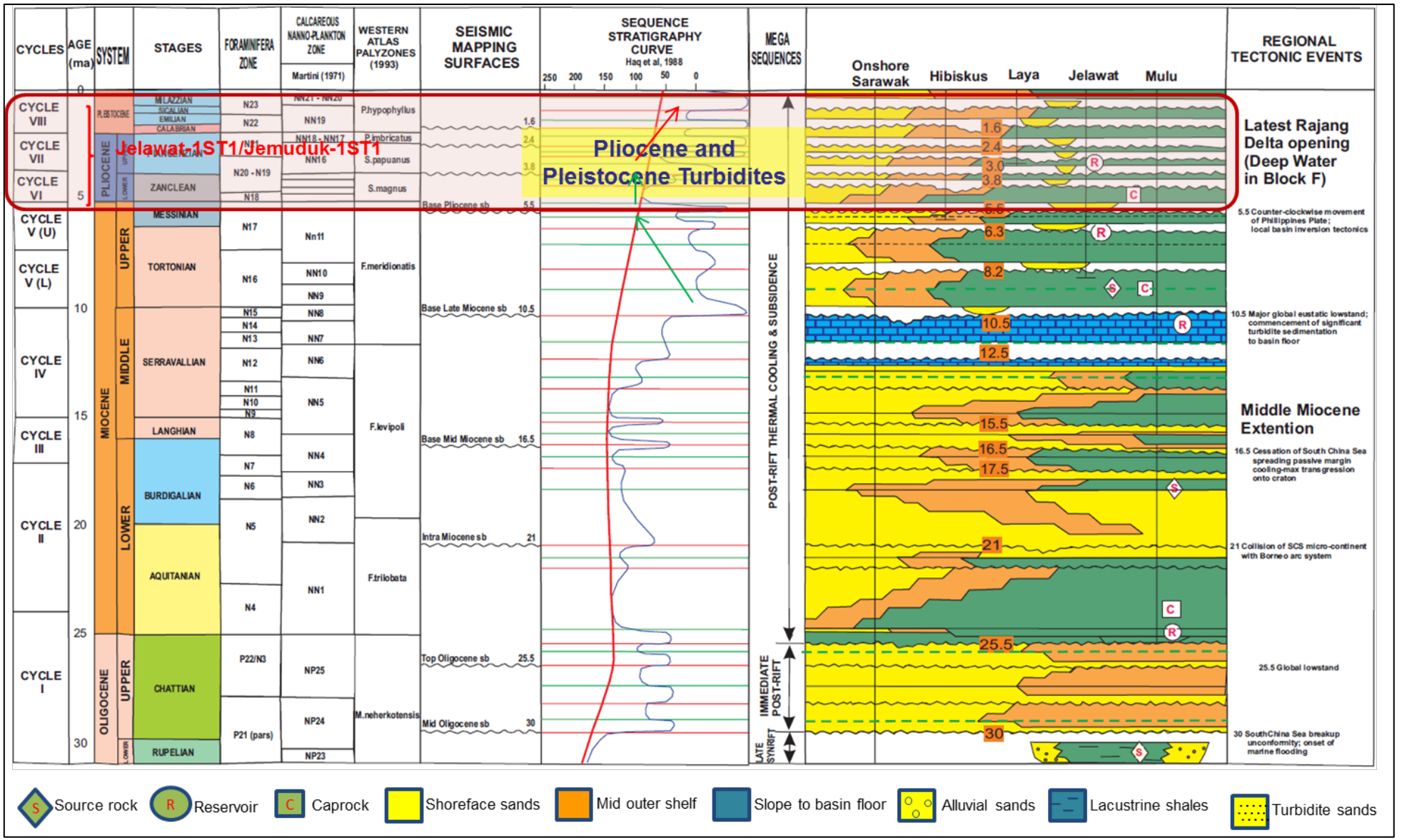


Figure 14: *Localised chrono-stratigraphy of the Sarawak Basin of which the Bunguran Trough forms a sub-basin. The Cycle nomenclature coined by Shell is used to identify the main chrono-stratigraphic units (from Jong et al., 2014).*

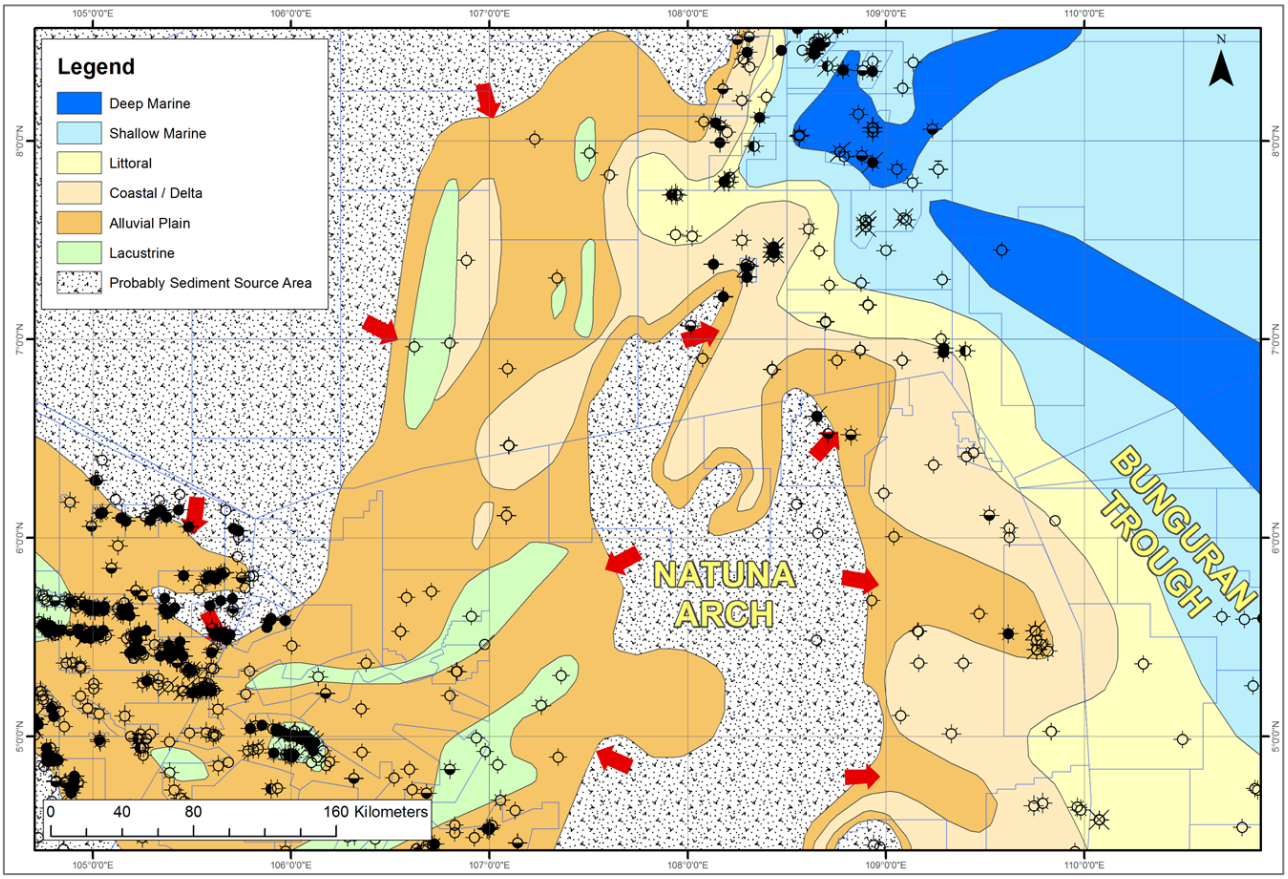


Figure 15: *Upper Oligocene (Gabus Formation, Cycle I) schematic palaeography of the Natuna Basin and surrounds indicating area of erosion and sediment transportation direction (red arrows), modified after Robertson (2004).*

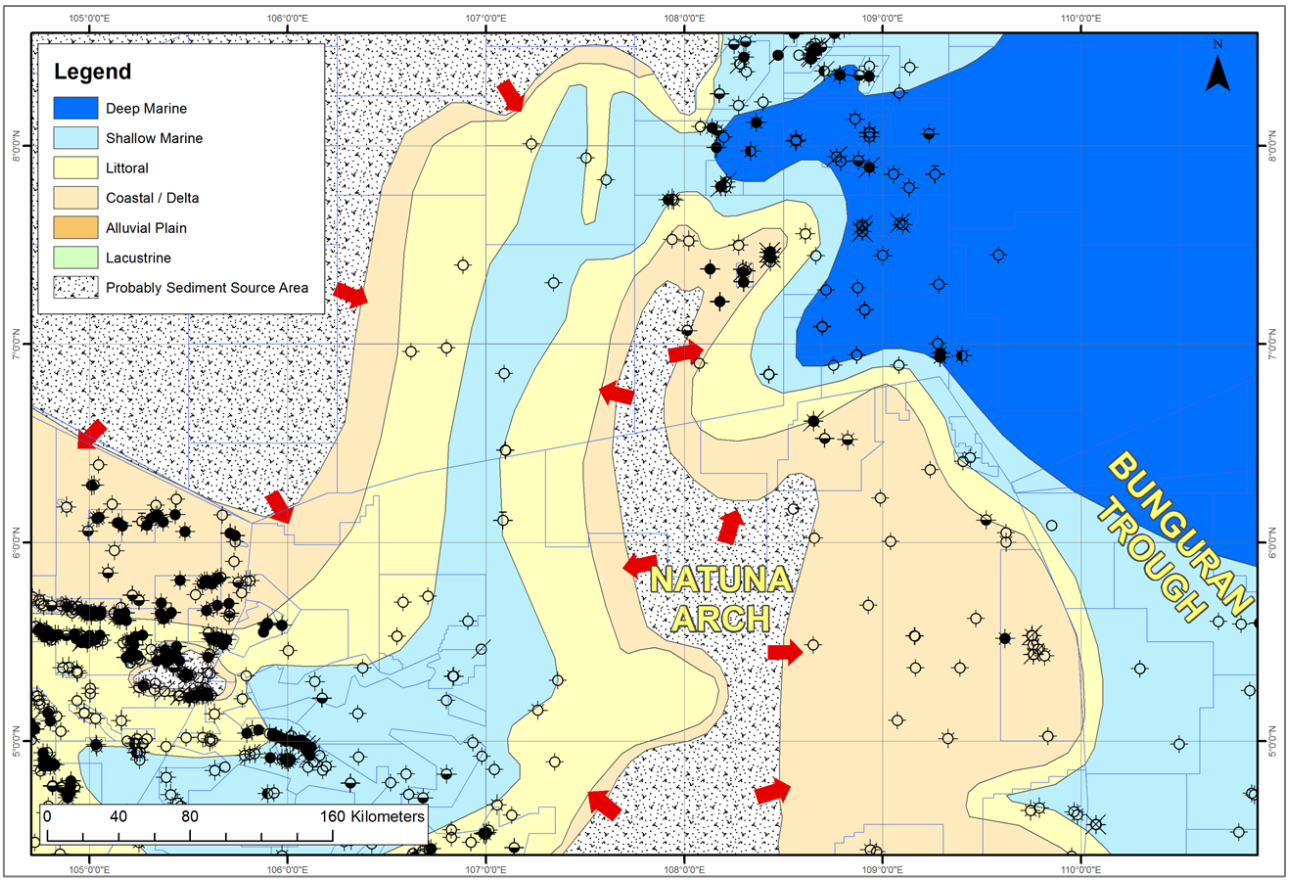


Figure 16: *Lower Miocene (Arang Formation, Cycles II/III) schematic palaeography of the Natuna Basin and surrounds indicating area of erosion and sediment transportation direction (red arrows), modified after Robertson (2004).*

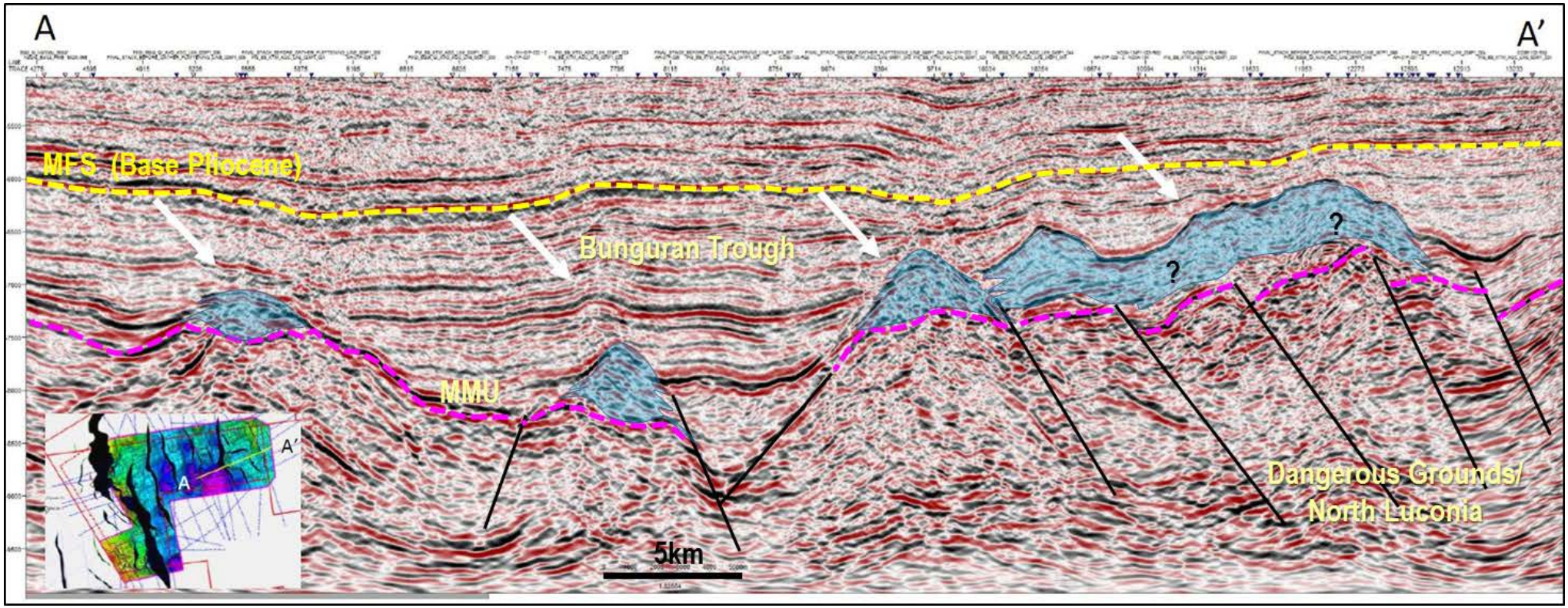


Figure 17: *Indications for isolated carbonate buildups (white arrows) seen below the pre-MMU section of the Bunguran Trough sedimentary sequence. Some sedimentary inputs in the Bunguran Trough depocentre to the south could have been derived from the pre-MMU basement high of the Dangerous Grounds and North Luconia.*

SEQUENCE STRATIGRAPHIC INTERPRETATION

Figure 18 shows a simplified model (without growth faults), which applies the principles of sequence stratigraphy to the overall Sarawak offshore foreland basin and highlights the two main depositional settings of the shallow marine Rajang Delta and the deeper neritic to bathyal settings of the Bunguran Trough.

Study of the area (Figure 19; Jong et al., 2014) suggests that the main exploration targets are likely to be gravity deposits, such as low density turbiditic flows (Cycle VIII) linked to periods of structural growth. Diachronous structural growth controls accommodation space creation and thus deposition. By carrying out a sequence stratigraphic analysis based on bio-stratigraphical control and litho-stratigraphy we have identified a set of tectono- and chrono-stratigraphic units (Figure 14). These provide a predictive tool that allows us to interpret the distribution of potential reservoirs, seals and source rocks (Figure 20).

Late Miocene (Upper Cycle V)
At the Jelawat-1ST1 location, the Upper Miocene (Cycle V) is dominated by two very fine low density channelised turbidite sandstones, interpreted based on their typical Gamma-Ray boxcar signature (Figure 20). The environment of deposition is likely basin floor in a distal setting. Stratigraphic principles predict that levee-channel complexes should dominate at base-of-slope and mid slope, while further up the slope delta toe and shallow marine sediments containing the transgressive MFS (maximum flooding surface) with associated basal transgressive sands should lie distally of highstand prograding delta deposits. Lowstand sequence boundary unconformities (SB) on the shelf could result in erosion and re-deposition of deltaic deposits into the base-of-slope/basin floor. However, the limited 3D seismic coverage precludes a source to sink, shelf to basin floor connection from being mapped.

Early Pliocene (Lower Cycle VI)
This sequence is dominated by a 3rd order TST (transgressive systems tract) and HST, which results in major a aggradational stacking pattern of 4th order cycles (Figure 21). This long lived sea-level high results in the formation of condensed mud-dominated sections in the bathyal zone throughout the Early Pliocene with limited turbidite reservoir potential.

The aggradational stacking patterns indicate high sea-levels, and permitted the development of thick shallow marine deltaic bodies, which may form reservoirs on the shelf. Jemuduk-1ST1 encountered reservoir quality sands in a mud-rich delta, but the potential for sands to enter the Bunguran Trough via turbidity currents at later lowstands is limited.

Lower Late Pliocene (Upper - End Cycle VI)
Towards the end of the Early Pliocene, the global 3rd order curve of Haq et al. (1988) records a falling stage. In response to the reduced accommodation space, a series of 4th order cycles with an overall down- and out-stepping stacking pattern were developed in the Bunguran Trough area. The forced regression and midstand systems tract development results in a distal migration of facies belts as can be seen on Gamma-Ray channel-levee signatures, albeit in fine-grained argillaceous rocks. The magnitude of the lowstand resulted in significant erosion and down-cutting of the shelf HST and TST of previous systems tracts and the development of incised valleys. This provides the mechanism to transport delta-top sediments into the bathyal realm and deposit them as channel-levee deposits on the slope and in basin floor fans (Figure 22). The mixture of mud and sand provides the dynamics needed for long transport distances driven by an auto-suspension feedback system.

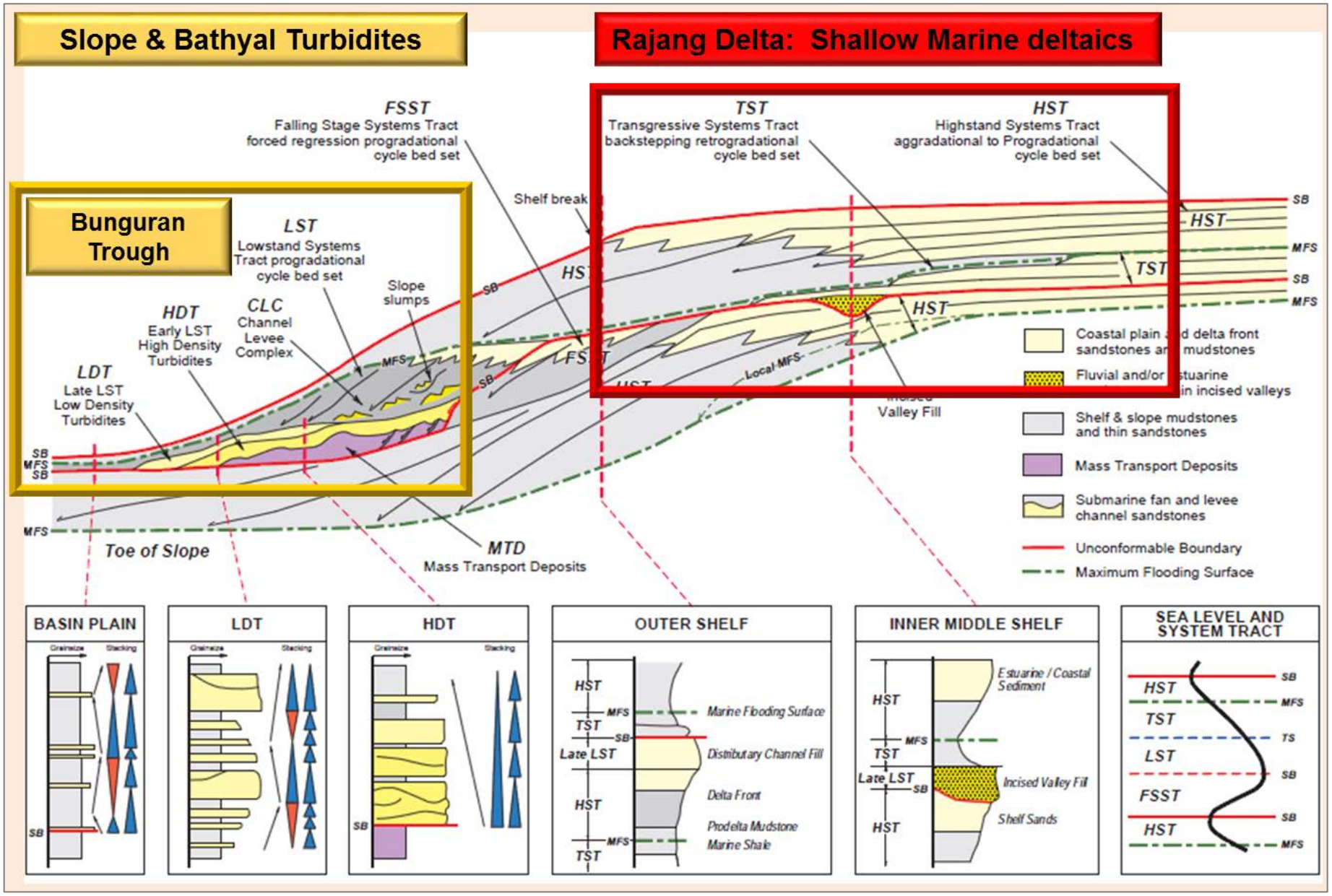


Figure 18: *Idealised sequence stratigraphic principles and system tract behaviours.*

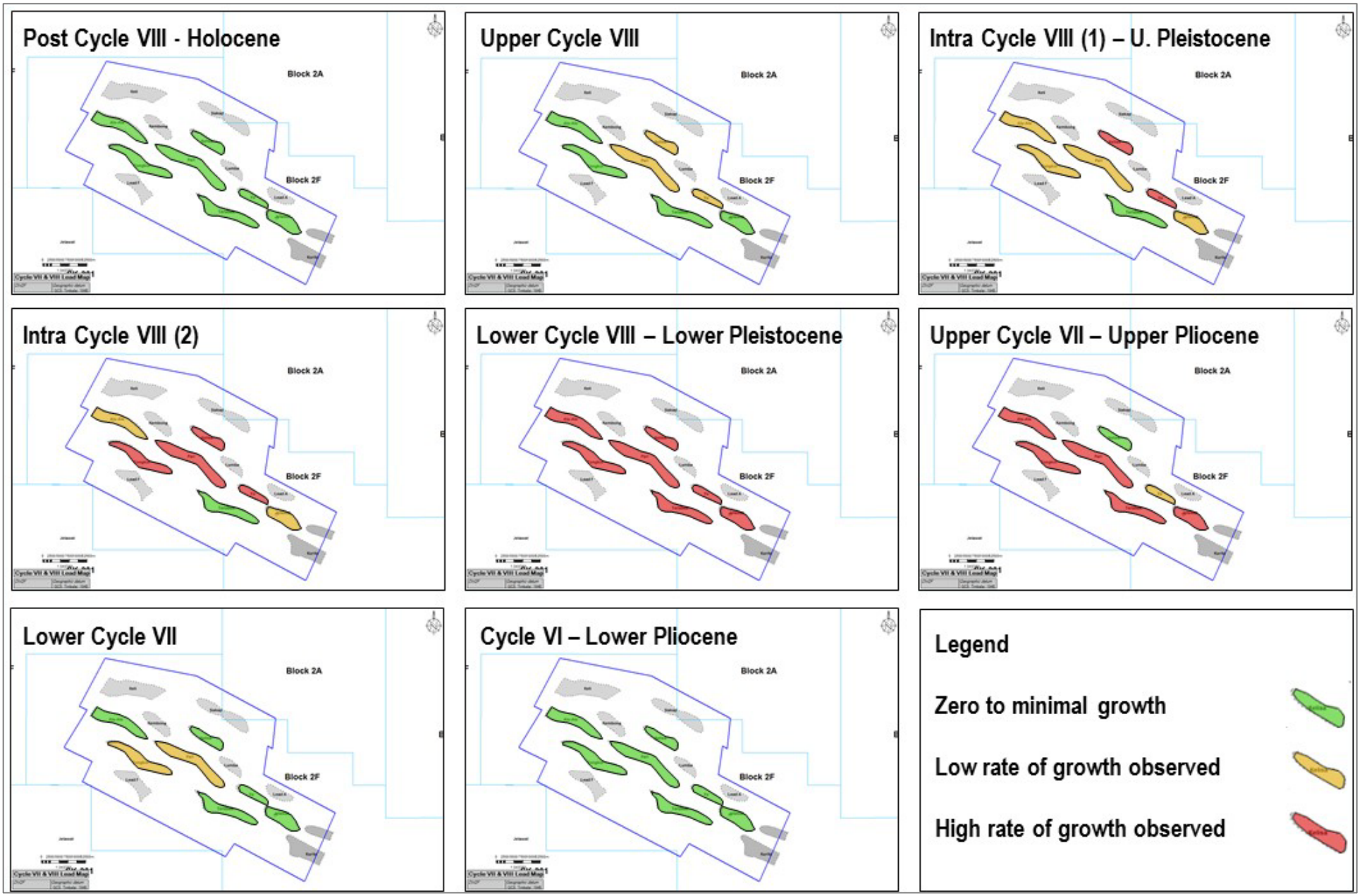


Figure 19: *Structural evolution of toe-thrust structures based on growth profiles, where it can be observed that post-Cycle VIII deformation activities slowed-down significantly (from Jong et al., 2014).*

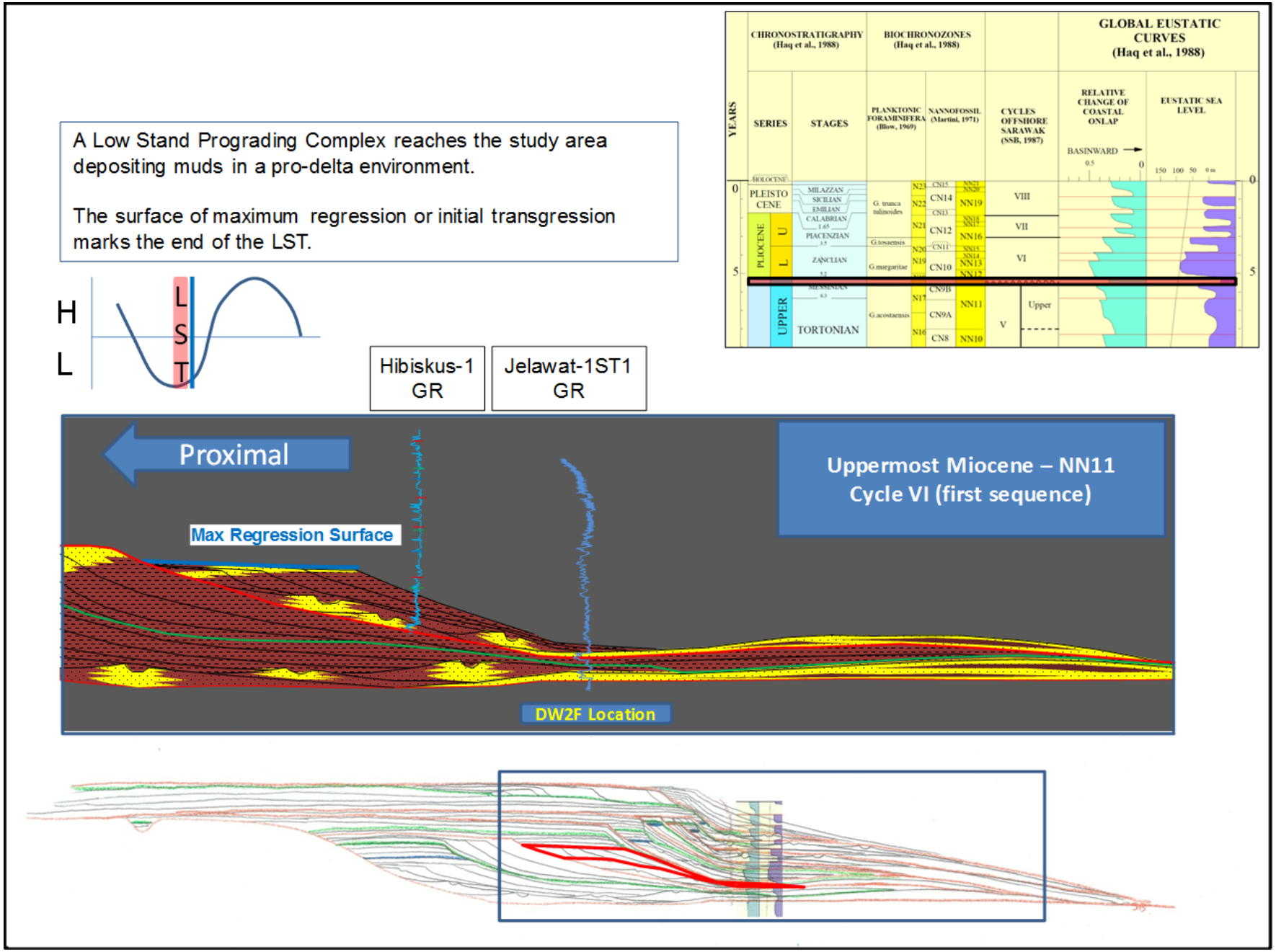


Figure 20: *Upper Miocene – Cycle V sequence stratigraphic setting (from Jong and Barker, 2015).*

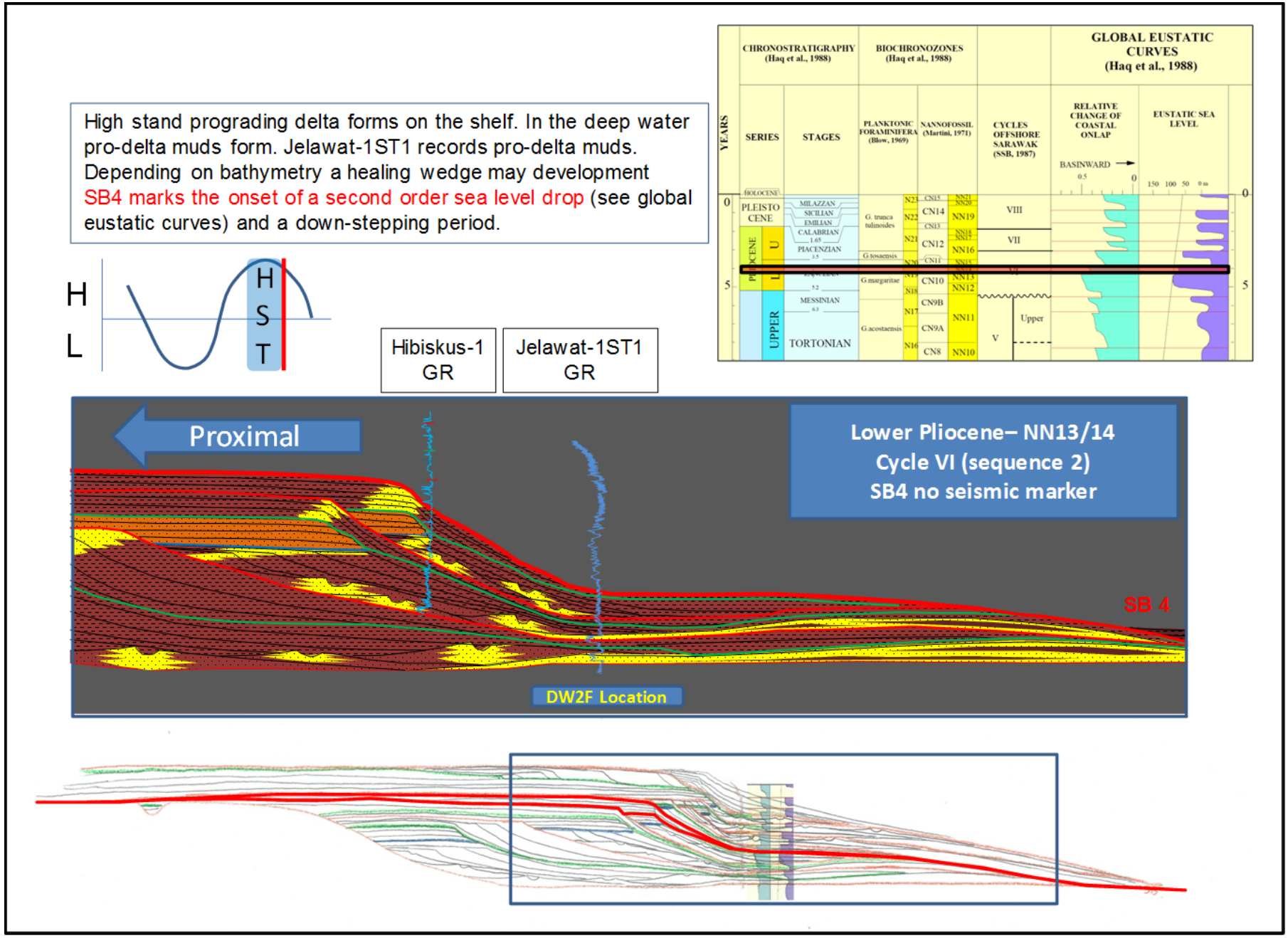


Figure 21: *Lower Pliocene – Cycle VI sequence stratigraphic setting (from Jong and Barker, 2015).*

Late Pliocene (Cycle VII)
The Late Pliocene is interpreted (Figure 23) to contain base-of-slope sediments consisting of distal channel-levee complexes, but is dominated by hemipelagic mudstones. Eustatic sea-level rise is shown by well-developed TST and HST sediments, which are predicted to cover the shelf. The large areal size of the shelf area inhibits focus of the sand fraction and this may explain why the majority of the wells in the Rajang shelf failed to find effective shallow marine reservoir sands. Jemuduk-1ST1 is an exception in this respect and shows that sands can be focused into channels during lowstand or in response to tectonics, i.e. into a growth fault.

Early - Middle Pleistocene (Cycle VIII)
Due to limited data at the Jelawat-1ST1 well and limited 3D seismic over the shallow marine shelf area, the Pleistocene is not included in the Jelawat-1ST1 sequence stratigraphic model (Figure 23). Based on the model we can predict that:

- Even on mud-rich Rajang Delta, fine sands were deposited in shallow marine conditions. These are not extensive bodies due to the mud-rich nature of the sediment source, but sand fraction focusing processes do exist, as proved by the Jemuduk-1ST1 well.
- Lowstand basin floor fans will dominate the bathyal zone. Incised valleys could act as paths for erosion and re-mobilisation of shallow marine sands. If such sand-focused areas are eroded, sandier basin floor fans may be present.
- Numerous lowstands could occur throughout the Pleistocene based on the global sea-level curve of Haq et al. (1988).
- Hemipelagic deposits of bathyal type will be deposited at TST and HST periods.

MIGRATION OF SEDIMENT PROVENANCE AND RESERVOIR POTENTIAL

All the Bunguran Trough reservoirs drilled so-far were deposited in a slope channel to basinal depositional environment (Figure 24). The channels developed in areas of low relief with limited amounts of accommodation space, and their characteristics are as follows:

- Slope channel deposits formed as a result of turbidite processes that sinuously propagated from point sources at the shelf margin towards the deep sea. Some channels may have been affected by counter-clockwise seabed (geostrophic) currents.
- Slope channel deposits were influenced by the changing relief of the slope. Rising anticlines led to deposition in the intra-anticline valleys rather than in crestal positions.
- Reservoirs are more (Plio-Pleistocene) or less (Miocene) unconsolidated, and sedimentation of the turbidite deposits occurred rapidly.
- Reservoirs comprise very fine-grained, more-or-less homogeneous sands with poorly rounded grains. Medium and coarse fractions are completely missing.
- Apart from quartz, the sands contain plagioclase feldspar, calcite and pyrite. The K-feldspar and plagioclase indicate primary granite and gneiss sources of the sediment rather than reworked sandstones. This means that not all turbidite deposits are likely to be derived from the Rajang Delta as is often argued, but that supply potentially came from the nearby Natuna Arch (Figure 25).
- Carbonate present in Miocene clastic sediments suggests that water depth, at least during the Miocene, was shallower than it is today (at least less than 800m, the approximate Calcite Compensation Depth, CCD). This is also supported by the evidence of small carbonates buildups in the pre MMU section within the Bunguran Trough itself (Figure 17).

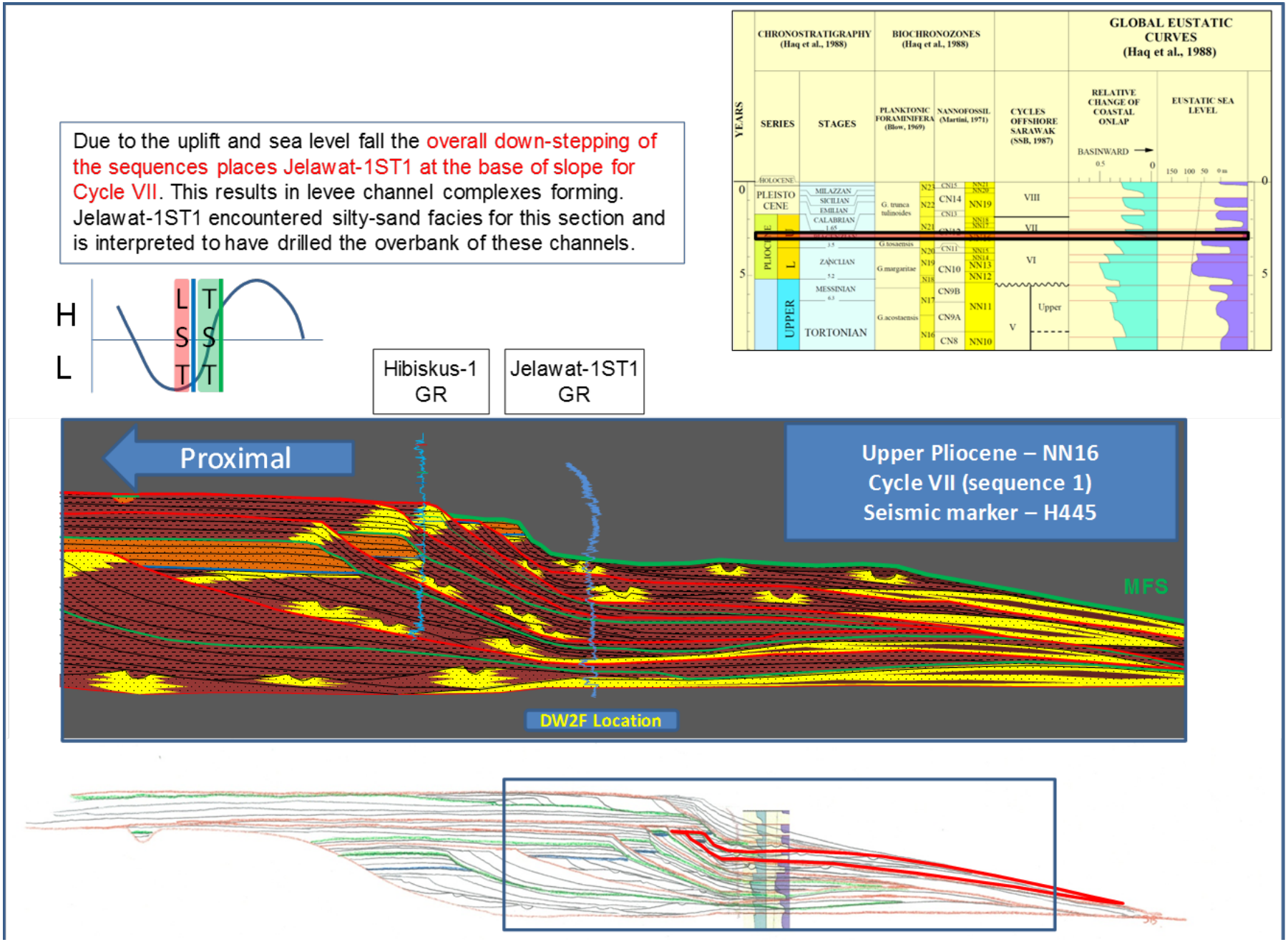


Figure 22: *Lower Upper Pliocene – Cycle VII sequence stratigraphic setting (from Jong and Barker, 2015).*

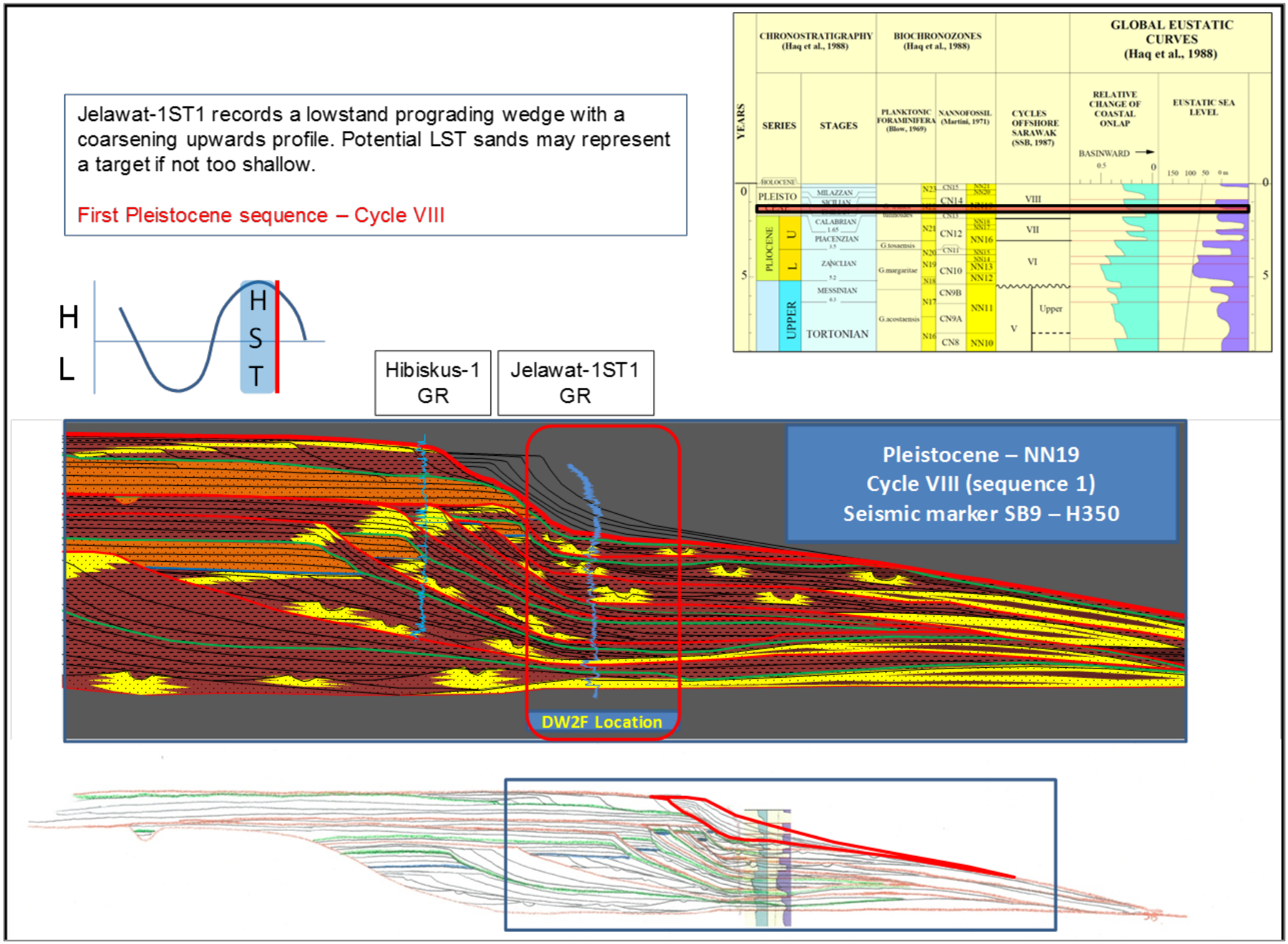


Figure 23: *Upper Pliocene and Pleistocene – Cycles VII and VIII sequence stratigraphic setting (from Jong and Barker, 2015).*

- All reservoir units contain significant amounts of clay; this may result from long distance transport (Rajang Delta component, Natuna Arch) coupled with the mud-rich nature of the turbidite system (Figure 24).
- It is uncertain however, whether the clay is part of the sand matrix, or is organised in layers; possibly many of the drilled reservoirs comprise thin-beds (but this is unconfirmed by logs).

The palaeogeographic evolution of the Bunguran Trough area from the Oligocene onwards is poorly known thanks to the lack of well data (Madon, 1999). Nonetheless, several authors have attempted depositional environment studies in offshore Sarawak and Indonesia (Figures 11-12 and 15-16), and proposed sediment supply provenances for various time intervals as summarised below:

- During the Late Oligocene, sand is likely to have originated from the Natuna Arch, upon which exposed highs lay between basins with the syn-rift Gabus and Lower Arang formations, as illustrated in Figures 15 and 16.
- From the Miocene to Quaternary (Figures 11-12), and with the Sunda shelf starting to submerge, sediment transport and provenance source changed and the majority of the sediment supply came from the mud-rich proto-Rajang Delta. A secondary source of sediment supply from the Natuna Arch has also been demonstrated.

The geoseismic section shown in Figure 25 covers approximately 130km and illustrates the structural form of the Bunguran Trough from west to east. This transect begins on the East Natuna/Terumbu Platform and extends across the shelf break, down the slope and into the Bunguran Trough. It shows significant differences when compared to the south to north regional geoseismic section shown in Figure 4. Firstly, the Terumbu Platform is dominated by reef carbonates with many hundreds of metres of relief overlain by Plio-Pleistocene deposits that are thinner when compared with the Rajang Delta. Also no large growth fault system is present in this shallow water section (Figure 25), a markedly different structural geometry to that observed in the Rajang Delta domain (Figure 4). The section also shows a shallower basement well-defined on seismic. Lack of subsidence on the Terumbu Platform is the reason carbonate buildups have dominated this area throughout the Neogene period. Figure 25 shows a prograding package in the post-MMU intervals, which supports the direction of sediment transport from East Natuna/Terumbu Platform into the Bunguran Trough depocentre (Figure 26).

The Bunguran Trough resides in a slope setting throughout the Neogene to the north and east of the margin fault systems. The steep slope facilitated transportation of sediments from the Natuna Arch and contributed to the accumulation of thick Plio-Pleistocene deposits in the Bunguran Trough.

Sedimentary input from the Dangerous Grounds/North Luconia and Central Luconia Platform remain speculative but in view of their high relief compared to the subsiding Bunguran Trough, it would not be surprising if some sedimentary inputs into the Bunguran Trough have originated from these regions (Figures 17 and 27).

Regional geological studies carried out by JX Nippon have shown that the Bunguran Trough resided in a neritic to bathyal setting dominated by marine gravity flow processes and open marine hemipelagic deposition throughout the Neogene (Figures 11-12).

Based on seismic attribute extractions, inversion and spectral decomposition displays, clear evidence exists for gravity flows which, it was hoped, would be of reservoir quality. Large scale gravity flow fairways were seen throughout the Upper Miocene to Quaternary on the available seismic dataset. In a limited area of the Bunguran Trough covered by 3D seismic, base-of-slope depositional environments such as channels/levees can be observed within the Miocene, while the Pliocene is characterised by well-imaged structurally confined turbidites. Unconfined gravity flow deposits and mass transport deposits are present in the Pleistocene and Holocene. Figure 28 shows the influence of structural kinematics on sedimentary fairways, whereby Cycles V/VI sequences are mainly unconfined and pre-kinematic, while post Early Cycle VIII structural growth shows a decline to a post-kinematic phase.

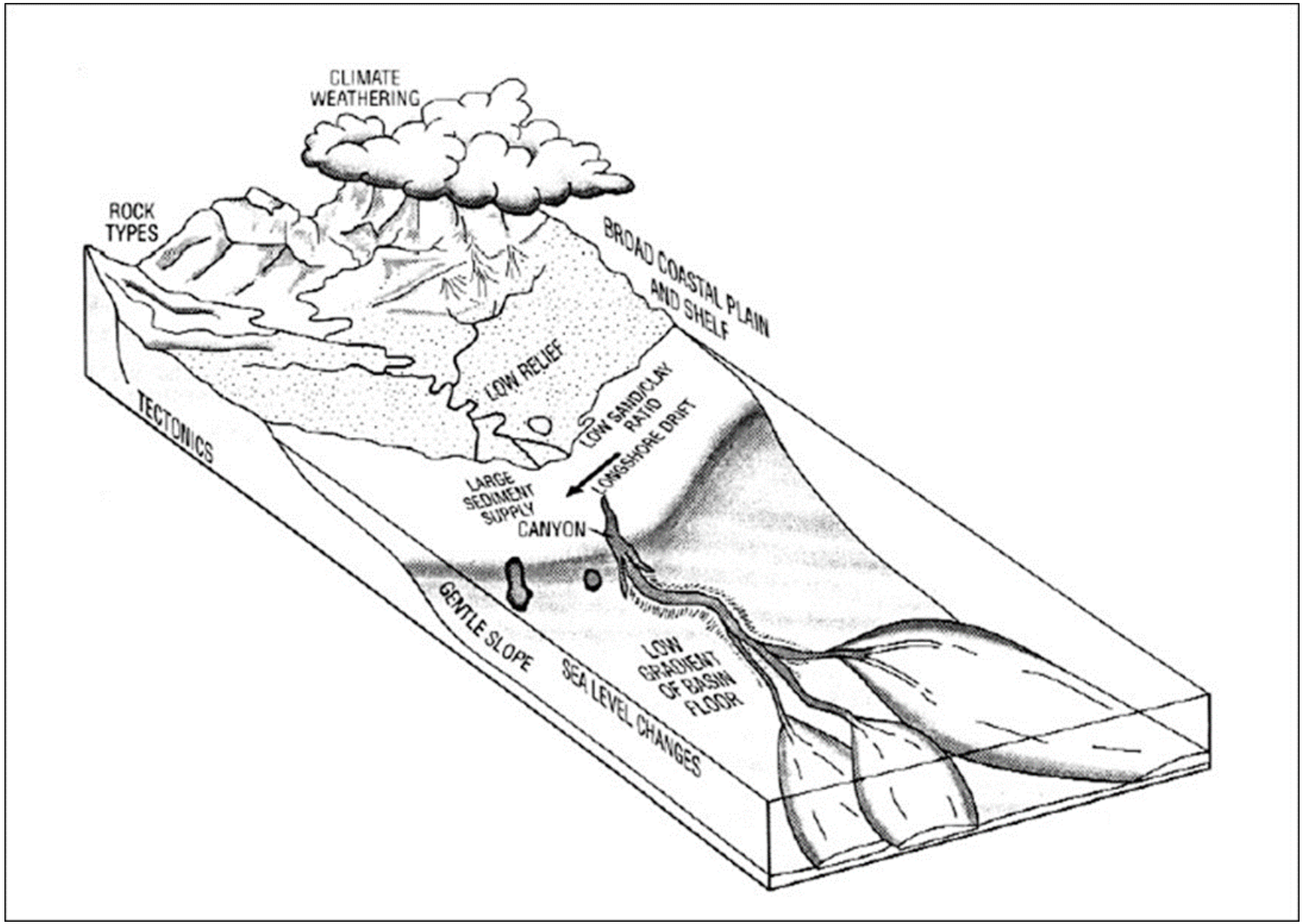


Figure 24: *Depositional model for fine-grained, mud-rich turbidite system (from Bouma, 2000). Note a gentle shelf to slope transition is interpreted since no shelf to slope break can be defined on regional 2D/3D data.*

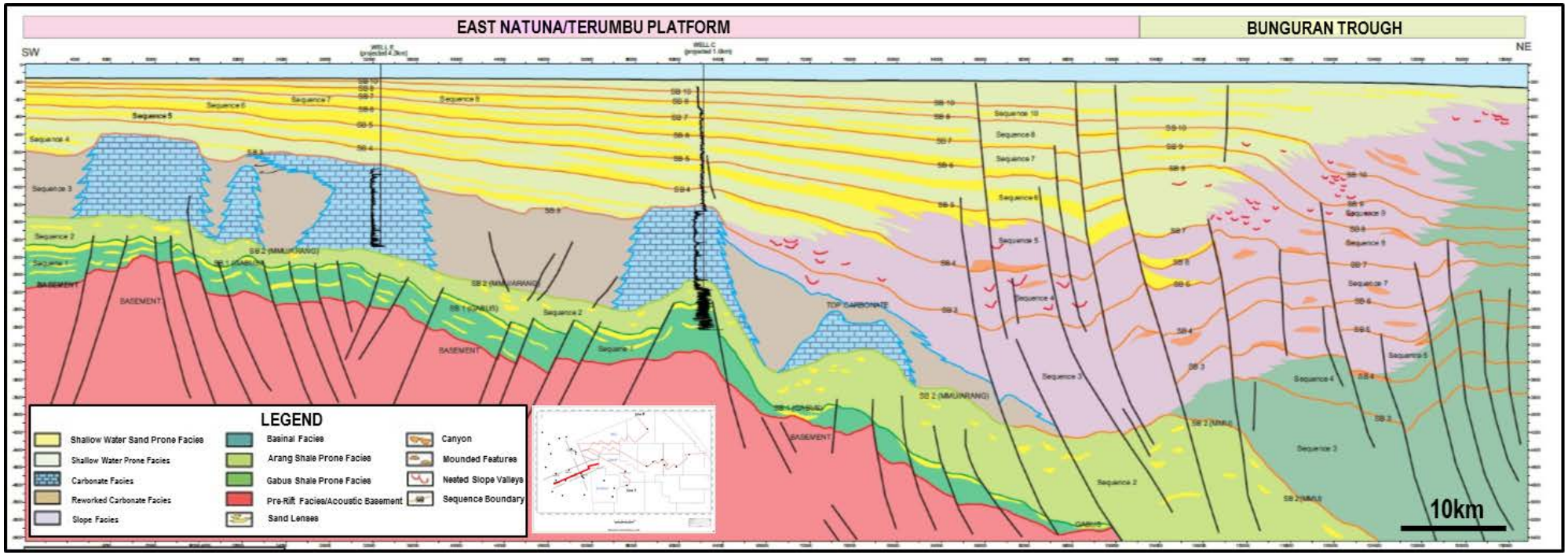


Figure 25: *W-E geoseismic composite line section covering East Natuna/ Terumbu Platform and Bunguran Trough showing identified sequence boundaries, faults and seismic facies (modified after PETRONAS Carigali, 2014).*

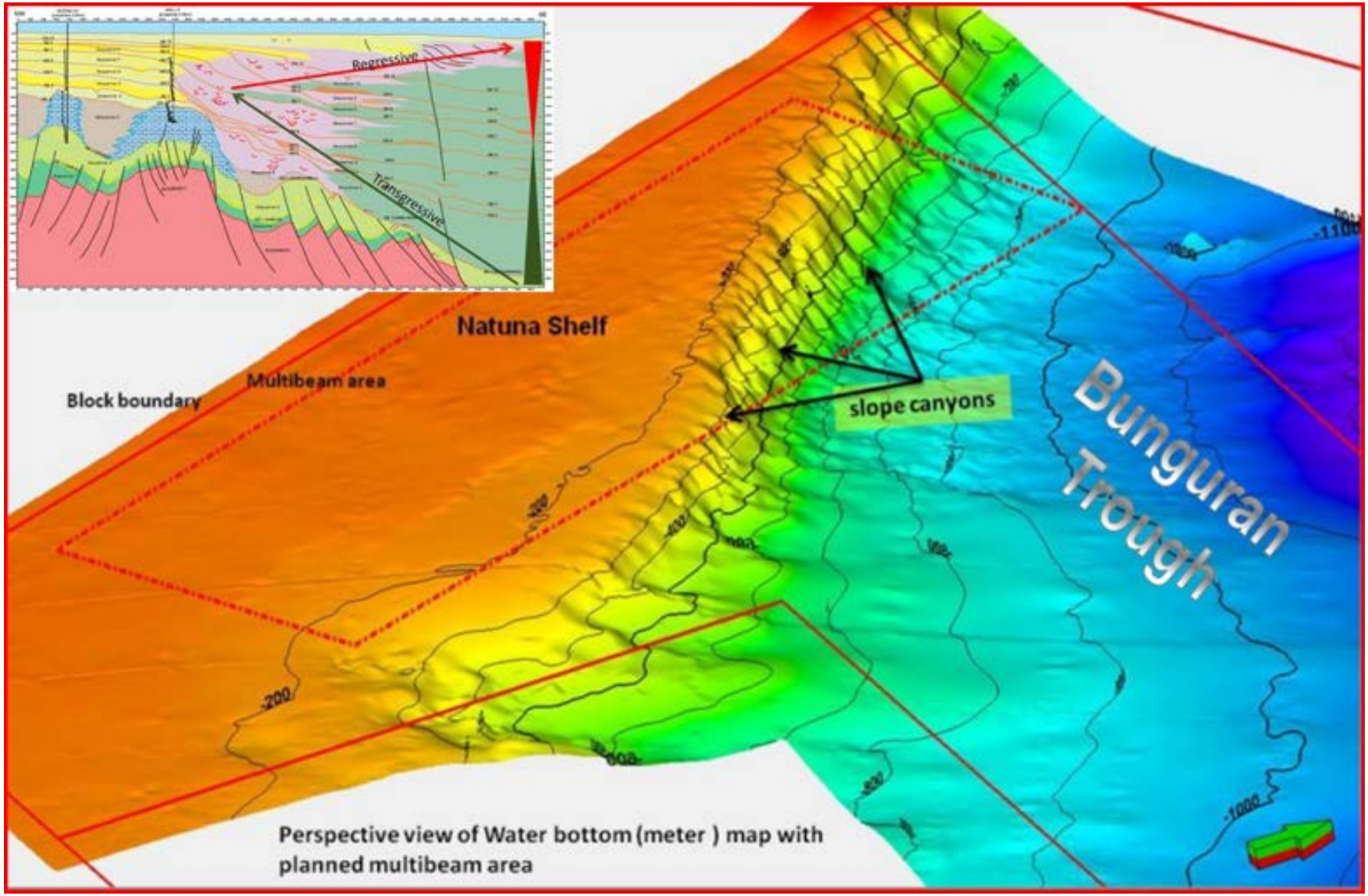


Figure 26: *Present-day seabed image of the Natuna shelf illustrating the presence of slope canyons to the direction of Bunguran Trough. Inset diagram shows significant progradation of the Late Miocene to Plio-Pleistocene clastic sequences from Natuna High transporting proximate sediment eastwards to deepwater Bunguran Trough area (from PETRONAS Carigali, 2014).*

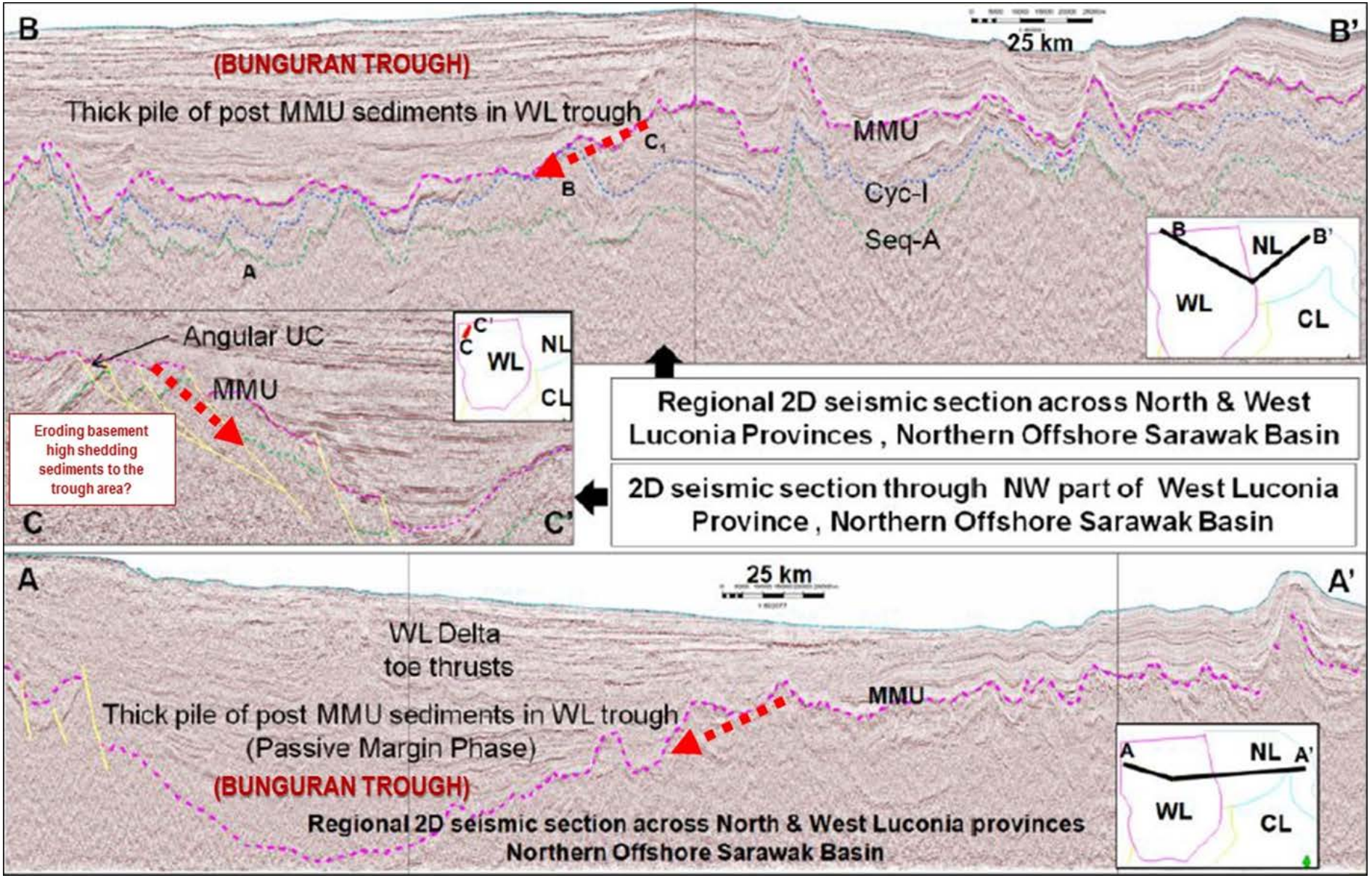


Figure 27: *Representative seismic profiles across northern offshore Sarawak suggest that the regional MMU may be diachronous. Post-MMU section is dominated by hemipelagics, interrupted by mass transport-dominated sequences. Some of the Bunguran Trough (WL Trough) sediments may be derived from the pre-MMU basement high. CL=Central Luconia, WL=West Luconia and NL=North Luconia (modified after Iyer et al., 2012).*

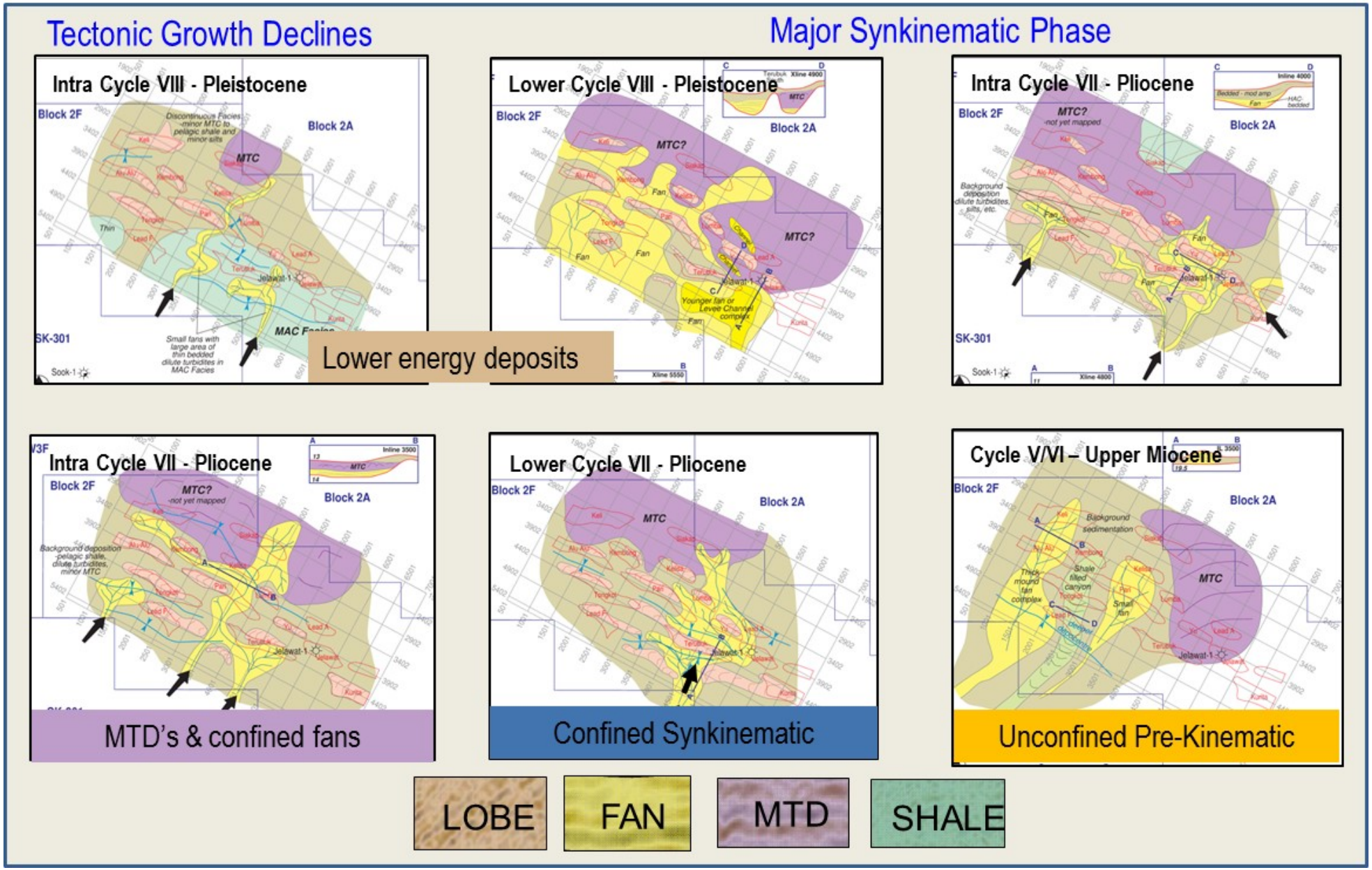


Figure 28: *Influence of kinematics on sedimentary fairways on gross depositional environment maps. Unconfined pre-kinematic fans become increasingly constrained with anticlinal growth. Significant influx of MTD's (mass transport deposits) before lower energy deposition towards the end of the syn-kinematic phase is common.*

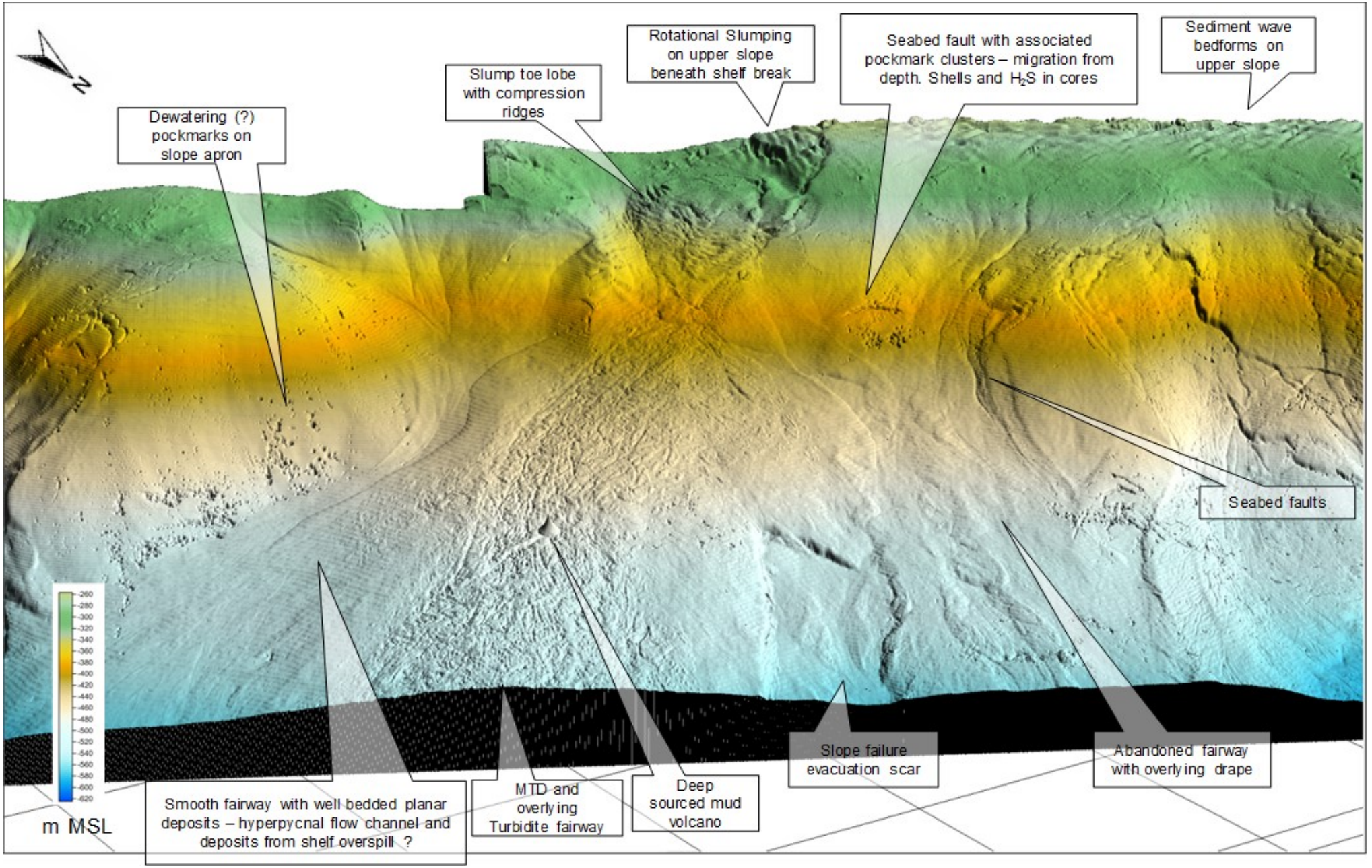


Figure 29: *Present-day seabed 3D Rendering looking SW with basic interpretation of sedimentological processes of slope to basin floor setting within the Bunguran Trough.*

Aspects of Reservoir Quality

A good analogue for the palaeo-depositional environment is represented by the present-day seabed, which provides a high resolution image (Figure 29, previous page) of various gravity flow processes (Figure 30).

Detailed petrophysical evaluation of Jelawat-1ST1 confirmed that the reservoir consists of very fine sand and silt combined with mud with average porosities of 11% to 13% and very low permeabilities (Figure 32a). This assessment is supported by MDT data, indicating mainly tight or supercharged rock. Throughout the well, there are indications for gas and condensate, which might have attenuated the seismic response. Estimated net thicknesses are between 3.7m and 20m (Figure 32b).

In the Bunguran Trough, locating well-developed sand fairways remains the key challenge for exploration success. Long transport distances result from the high mud/silt fraction of the Rajang Delta, and low density turbidites (Figure 30), rather than high density sand deposits such as those found in the offshore Sabah area can be expected. The latest well "T-1" encountered gravity flows as predicted, but as in Jelawat-1ST1 they were characterised by very fine-grained, argillaceous and chaotic sediments. The "T-1" well did encounter minor gas-bearing turbiditic deposits in the target interval as predicted by multi-attribute analysis, but these were very fine-grained and chaotic in sedimentary structure, and therefore of non-effective reservoir type.

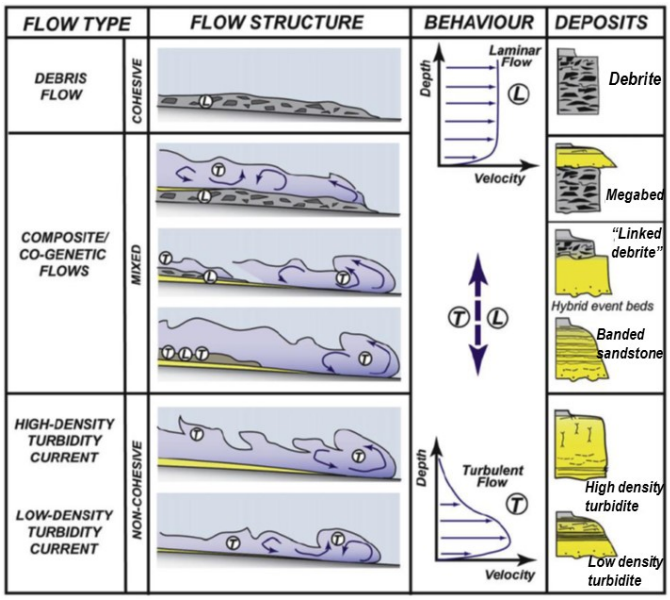


Figure 30: *Spectrum of gravity flows and associated deposits (from Haughton, 2003).*

The paucity of cores, side-wall cores and pressure analyses makes it difficult to assess the reservoir quality in the area of this study. The few reliable data points strongly suggest, however, that reservoir quality is marginal when compared with the Sabah, Natuna and Central Luconia areas, but could be adequate for gas/condensate. Based on study of the Cycle V sequence from various shelf well locations, there is a general decrease in net sand content towards the slope and basin in the direction of the Bunguran Trough (Figure 31).

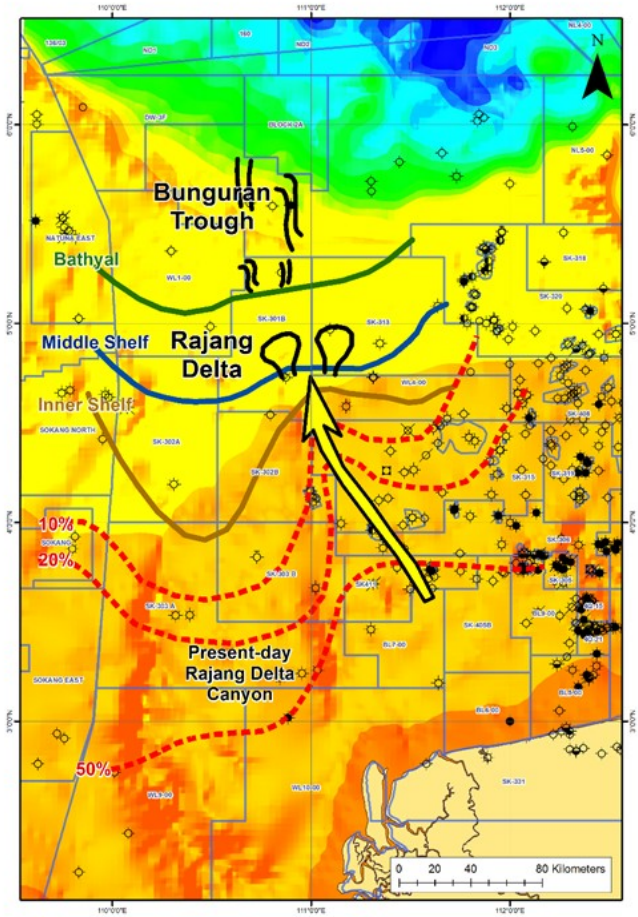


Figure 31: *From offshore Sarawak shelf wells the Late Miocene Cycle V sequence shows an overall decrease in net sand content (%) towards the slope and basinal settings expected in the Bunguran Trough. Contour intervals are overlain on top of present-day bathymetry map with a clear Rajang Delta canyon indicated to the south. Modified after Kessler and Jong (2014).*

In comparison to Jelawat-1ST1, Mulu-1 (Figure 33a, see well location in Figure 4) encountered an age-equivalent section with porosity up to 29% and permeability of about 1,500mD (Figure 33b). The net thickness assessed in Cycle VII sand is 24m, so better reservoir sand outboard of DW2F (as in Mulu-1) can be expected. The effort in the Bunguran Trough should therefore be focused on the identification and mapping of promising turbidite fairway systems, the hope being that sand-rich deposits with better quality reservoirs can be identified.

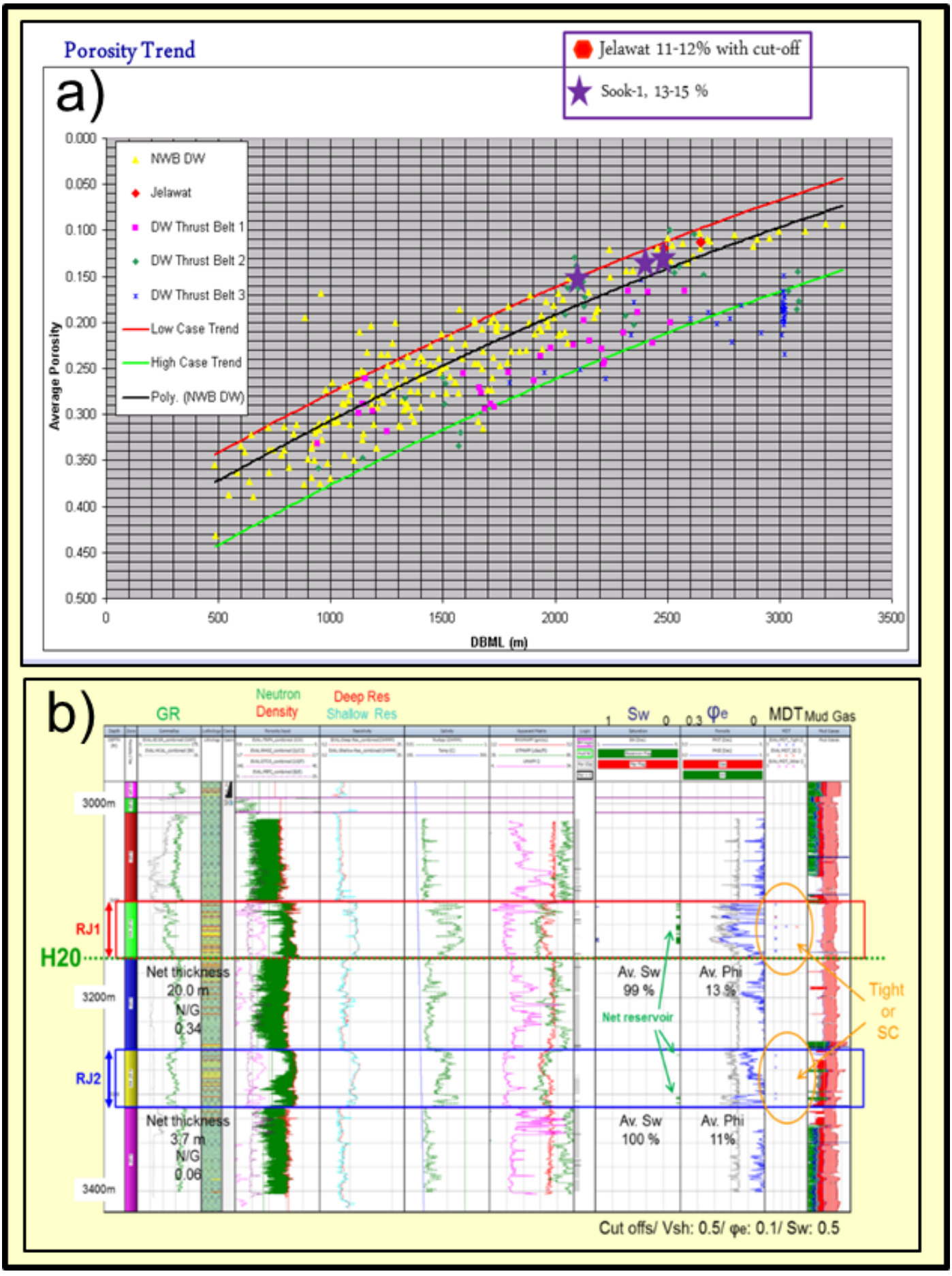


Figure 32: *a) Porosity-depth trend curve with porosities of Jelawat-1ST1 and neighbouring Sook-1 in comparison to Sabah well data. The remaining DW2F Miocene prospects generally lie at similar depths to the target interval. b) Petrophysical re-evaluation of Jelawat-1ST1 carried out by JX Nippon in the Miocene section. From Kessler and Jong (2014).*

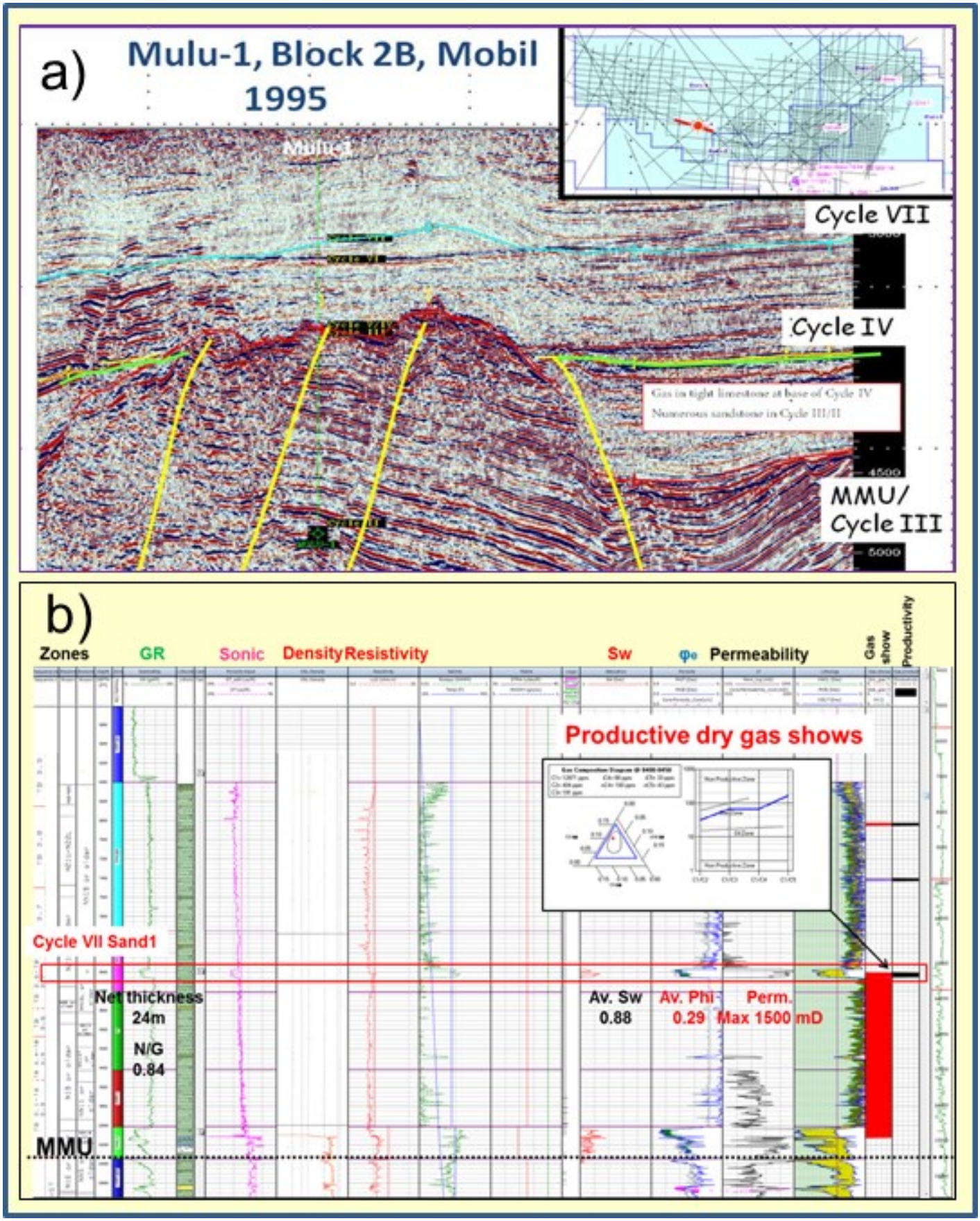


Figure 33: *a) Mulu-1 was drilled on the of the outer horst blocks of the North Luconia Platform. Porous Cycle III sediments are buried by about 2,000m of muddy turbidites in the Bunguran Trough. b) Petrophysical evaluation and reservoir properties of Mulu-1. From Kessler and Jong (2014).*

STRUCTURAL DEVELOPMENT AND ESTIMATION OF THE SEDIMENTATION RATE

From the seismic interpretation it is apparent that the Bunguran Trough, and in particular the Bunguran Fold-Thrust Belt, is complex with clear diachronous kinematic evolution across the basin. Because the depositional regimes are gravity flow driven and are controlled by structural highs that define the palaeo-bathymetry, a good understanding of the timing of the structural development is essential to the analysis of sedimentary fairways. Pre-kinematic structures are likely to contain unconfined fan systems and may form natural targets once folded, while syn-kinematic turbidite sand fairways tend to deflected around the growing structures. Seismic attribute mapping was employed to map depositional fairways, but without calibration the main risk is the presence of good quality reservoirs (Figure 28): If only argillaceous or very fine and poorly sorted sediments have entered the Bunguran Trough reservoir quality sands will be hard to locate. Only further exploration both *via* expensive 3D seismic and exploration drilling can reduce the risk.

Deformation History
In order to study the deformation history of Bunguran Fold-Thrust Belt structures we restored structures to their pre-deformation state. The Bunguran Trough is dominated by structures formed of tightly folded Pleistocene to Miocene sediments decoupled from the deeper basement above a postulated over-pressured marine shale decollement (Jong et al., 2014 & 2015a). These anticlines were examined by calculating the rate of shortening at different geological times to provide a proxy for the rate of growth.

The rate of shortening is calculated by measuring the full length of the folded horizon and comparing it with the present-day line length.

Line shortening (m) = Folded length (m) minus (-) Present-day cross-section length (m)

The rate of shortening can then be calculated based on the temporal data and is calculated:

Rate of shortening (m/Ma) = Line shortening (m) / Time period (Ma)

The present cross-sectional length was kept constant at 10,000m for all the structures examined. The rate of deformation in various structures is presented in Figures 19 and 28, with an example from the Jelawat structure shown in Figure 34. Overall, the following mega-sequences were identified.

- Pre-Kinematic: Late Miocene – Early Pliocene (Cycles V to VI);
- Syn-Kinematic: Late Pliocene (Cycle VII);
- Transitional-Kinematic: Early Pleistocene (Cycle VIII);
- Post-Kinematic: Late Pleistocene/Holocene (Late Cycle VIII to present).

Sedimentation Rate
Concurrently, maximum sedimentation rates in the Pliocene to Quaternary were analysed by measuring the true stratigraphic thickness of the sedimentary sequence for each time period:

Max sedimentation rate (m/Ka) =
True stratigraphic thickness (m) / Time period (Ka)

The maximum rate was reached by sampling in the frontal syncline of the growing structures where the accommodation space was greatest.

The calculated sedimentation rates, with an example from the Jelawat area, show a clear declining trend from very high sedimentation rates in the very recent <600Ka to low rates up to 3Ma (Figure 34). This trend can partly be attributed to compaction and may be partly apparent: The high rate of sedimentation for the most recent 600Ka of ~1.5m/Ka reduces over time to <0.5m/Ka along a power function trend. Lower Cycle VIII shows an increase in rate, corresponding to a period of high deformation and thus accommodation space creation in the frontal synclines where the measurements were made. The high rate opens up the possibility that a secondary source from the nearby Natuna Arch might have contributed to the sediment supply of the Bunguran Trough during this period.

DISCUSSION

Tectonic and Subsidence History
The Bunguran Trough is thought to comprise a pull-apart basin, characterised by strike-slip movements leading to the formation of deep asymmetrical half-grabens, and a graben fill that can often be correlated with the magnitude of strike-slip occurring in the crust beneath the graben. To examine whether or not the Bunguran Trough is a pull-apart basin, we compare the Bunguran Trough with a well-researched potential analogue, the Dead Sea graben as described by Petrunin (2007):

"The Dead Sea Basin (DSB) is located at the Dead Sea transform (DST) boundary, and divides the African and Arabian plates. The basin formed as a result of crustal extension in a domain where the DST has left-side overstepping and accommodation of 105km sinistral displacement along the DST has led to the formation of a 150km long and more then 8-10km deep pull-apart basin during last 17 million years. Previous generic modeling results (Petrunin and Sobolev, 2006) demonstrated that the thickness of the brittle layer and friction strength at major faults, as well as the magnitude of strike-slip displacement control the thickness of sediments and

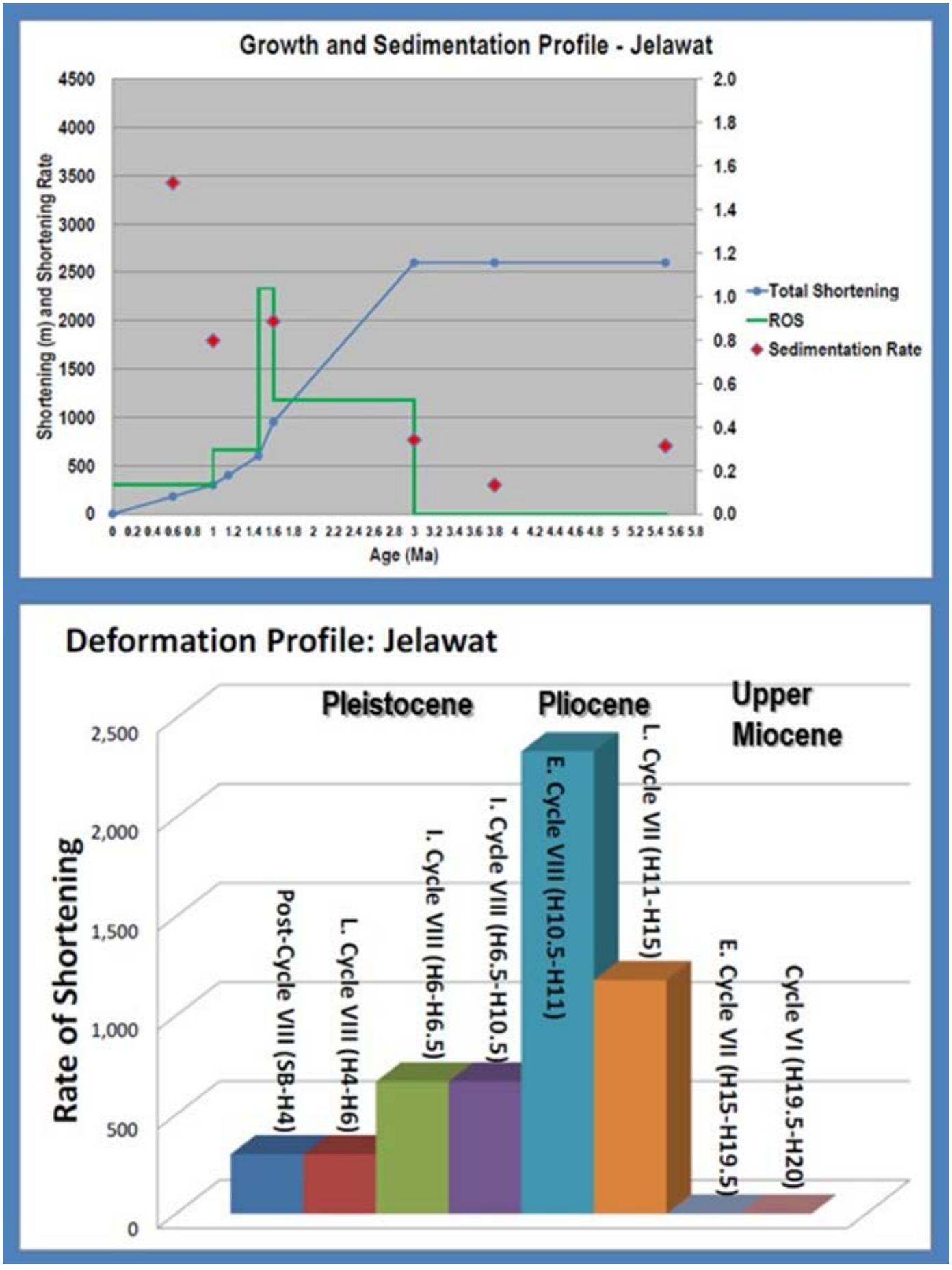


Figure 34: *a) Growth and sedimentation profile, and b) Deformation profile of Jelawat structure (from Jong et al., 2014).*

deformation pattern beneath the basin. However, the generic models predict decrease of the sedimentation rate in a pull-apart basin with time although there is an indication that the sedimentation rate in the Southern Dead Sea Basin remained high, or even increased during the last few million years resulting in the deepest Cenozoic sedimentary basin on the Earth. In present study we consider effect of lower crustal viscosity and rate of friction softening on sedimentation rate. The modeling shows that both those parameters significantly influence maximum thickness of sedimentary layer, shape of the basin and sedimentation rate. Under very fast softening rate (five times friction coefficient dropping at differential displacement of a few kilometers) all models with reasonable lower crustal viscosity generate maximal subsidence rate at the beginning of the basin formation and decreasing sedimentation rate (up to zero) at the late stage of evolution during the model time of 20 million years. Under the very slow softening rate (five times friction coefficient dropping at differential displacement of a few hundred kilometres) models with any reasonable crustal rheology show acceleration of sedimentation with time but the rates are too low to form 10 km deep basin during 20 million years. The models with medium softening rate (five times friction coefficient dropping at differential displacement of few tens of kilometres) and strong lower crust, generate near constant or even increasing sedimentation rate with time, as well as deep sedimentary basin which is generally consistent with evolution and structure of the DSB."

The Bunguran Trough, which resides over a potential releasing bend at the intersection of the Red River Fault and Baram Line, has a similar length and depth of sedimentary fill as the DSB. Although the majority of pull-apart basins are sediment starved due to their high subsidence history and a single source, the DSB the Bunguran Trough appear to share an increasing sedimentation rate with time up to the Late Pleistocene, as illustrated in Figure 35. In addition, the fact that the high subsidence rate recorded in the Bunguran Trough is matched by a high sedimentation rate strongly suggests that multiple sediment sources have been feeding the subsiding basin.

Sedimentation History and Reservoir Potential

The deepwater sediments of the Bunguran Trough are mud-prone. However, while the entire rock sequence, or even gross reservoir packages may be dominated by shale, this may not necessarily hold for individual sand and coarse silt beds. Whole rock bulk mineralogical composition analysis of ditch cuttings from Jelawat-1ST1 well intervals 2,330-3,421m (Upper Miocene to Lower Pliocene) suggests there may be more sand and silt in the Miocene, compared to what the mudlog indicates (Figure 36).

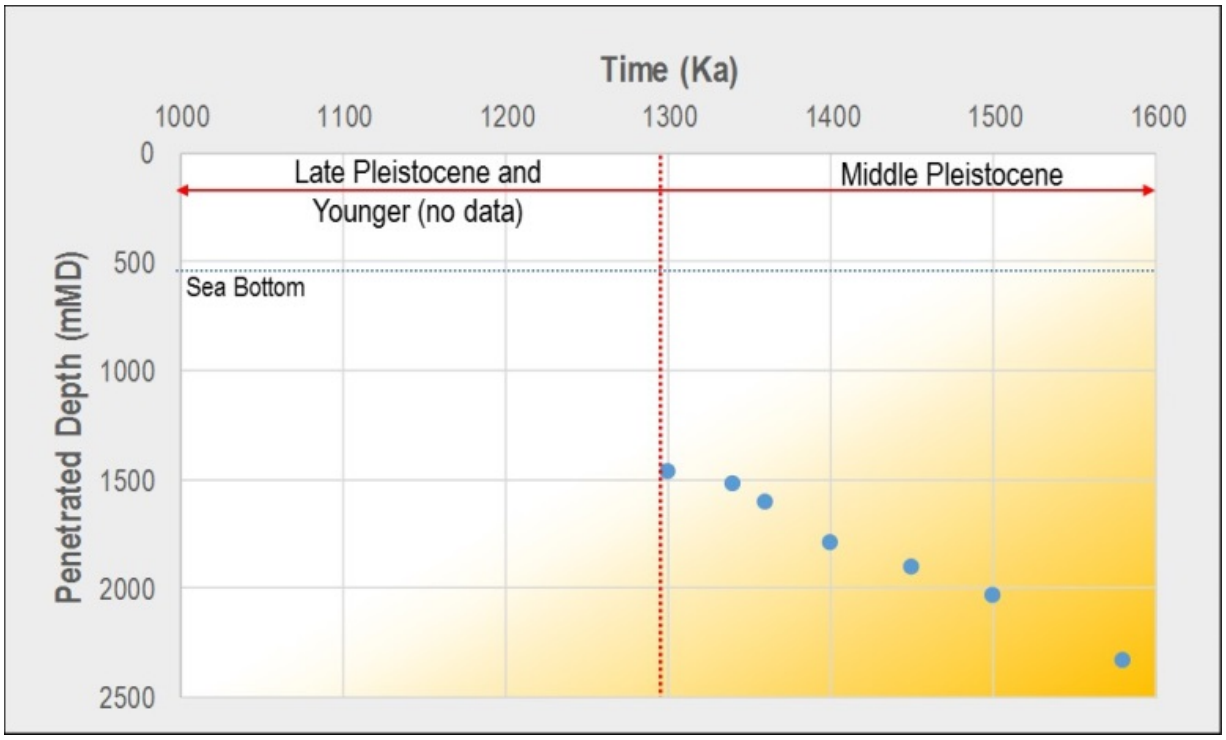


Figure 35: *Compacted sediment thickness versus timing of deposition based on detailed biostratigaphic interpretation of well data from "T-1" well. The plot suggests apart from a high subsidence rate that almost one kilometre of compacted sediment was accumulated in less than 300,000 years during the Middle Pleistocene, and that about 2km of sedimentation in the last 1,600Ka, was deposited in the Bunguran Trough. A few notable regional erosional events in the well suggest that the rate of sedimentation may actually have been even higher as the eroded sections were not estimated and therefore not taken into consideration for this plot.*

Whether clay is distributed within the sand matrix, or is layered in thin-bedded sequences, cannot be fully addressed at this point, as a consequence of limited wireline coverage, poor logging resolution and an absence of core and/or image logs. However, when dealing with distal turbidite sequences, there is always a very sharp division between clay and sand/silt layers, and a homogeneous mixture of clay and coarser material appears to be extremely unlikely as a consequent of different high and low density flow deposits.

The majority of grains consist of quartz (Figure 36), but plagioclase and orthoclase are also present and may have biased the wireline interpretation towards higher clay content, for example in the layer at *ca.* 2,340m, through its strong K40 content. More importantly, the presence of feldspar indicates a proximate sand source, given that feldspars weather quickly in salt water and do not survive multiple phases of reworking. In addition, all sandy intervals contain carbonate cement and fossil fragments; which are indicative: (i) for the proximity of nearby carbonate platforms that were developed on pre-MMU basement highs acting as clastic sediment source and, (ii) a moderate water depth of less than *ca.* 800m of water depth (CCD). The present-day Natuna Island (Riau) archipelago, is formed by crystalline rocks, but is surrounded by shallow water where carbonates are accumulating (Figure 37). Interestingly, the content of carbonate in Jelawat-1ST1 cuttings does not vary significantly from the Late Miocene to the Pleistocene, which suggests that shoals lay nearby throughout the Neogene. Recently published palaeogeographic maps of Southeast Asia by Shoup et al. (2012, Figure 36 inset) indicate that during the Late Miocene to Early Pliocene, the Natuna Arch was an exposed area connected to the Borneo landmass and therefore formed a potential sediment source area for the Bunguran Trough.

X-Ray Diffraction (XRD) and petrological analyses on cuttings from the recent "T-1" exploration well (Figure 38), confirmed dominant claystone lithology in the Plio-Pleistocene intervals. Some thin sandstone intervals were identified based on Gamma-Ray responses, but they were not detected in XRD and petrological analyses, possibly due to the thin bed thickness and limitations of cutting analyses. Individual detrital grains range from fine silt to very fine-grained sand in the claystone and silty claystone; they are generally angular to sub-angular in shape suggesting a short transport distance and/or rapid deposition from the source. XRD reports clays (37.0-70.3% by weight) and quartz (20.2-56.0% by weight - with maximum quartz at 1,445-1,450m MD) are the most common minerals (Figure 38).

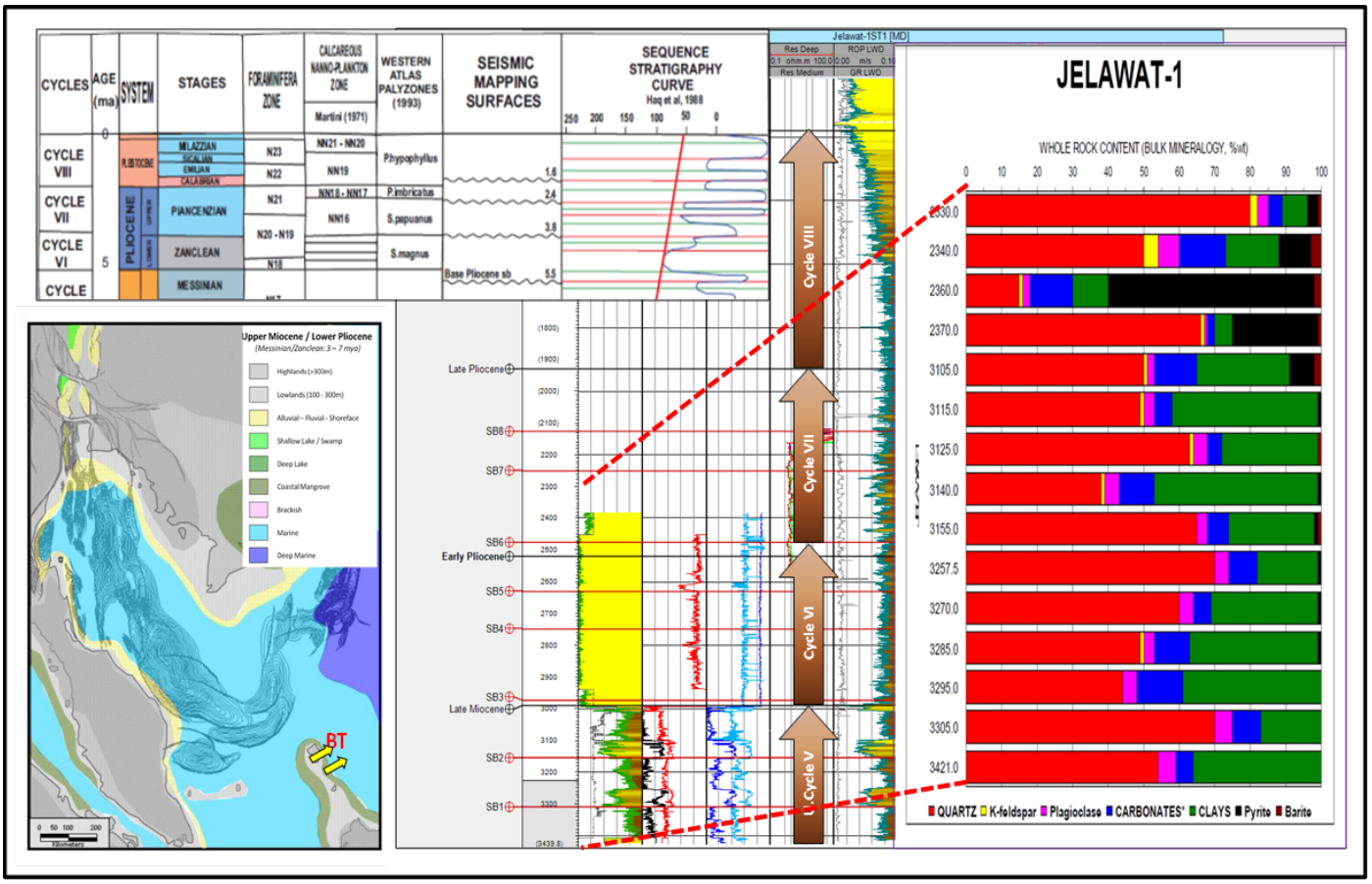


Figure 36: *Right - bulk mineralogical composition of ditch cuttings from Jelawat-1ST1 well intervals 2,330-3,421m (Late Miocene - Early Pliocene). Lower left - Upper Miocene to Lower Pliocene palaeogeographic map by Shoup et al. (2012).*

Other minerals are uncommon but include plagioclase, K-feldspar, calcite, dolomite, siderite, and pyrite.

According to Kessler and Jong (2014), the facies environment of the Pleistocene remains essentially the same as that of the Pliocene section, except that the sediments are concentrated increasingly into elongated depocentres parallel to thrust-cored anticlines deformed during the Pliocene. During the Pleistocene, sedimentary material is again reaching the Bunguran Trough from the west and south, with indications of channelised features, turbidites and mass flow complexes/deposits on seismic observable particularly well on the recently acquired 2D/3D seismic data (Figures 3, 25 and 26).



Figure 37: *Aerial view along the east coast of Natuna Island. The big island is formed by a core of crystalline rocks and wave-cut platforms, on which algal biostroma (dark green to brownish patches) are seen growing away from the zones with terrigeneous outflow (orange-brown colour). The picture shows competition between clastic outflow areas directing to the Bunguran Trough to the east. Photo courtesy of Dr. Franz L. Kessler.*

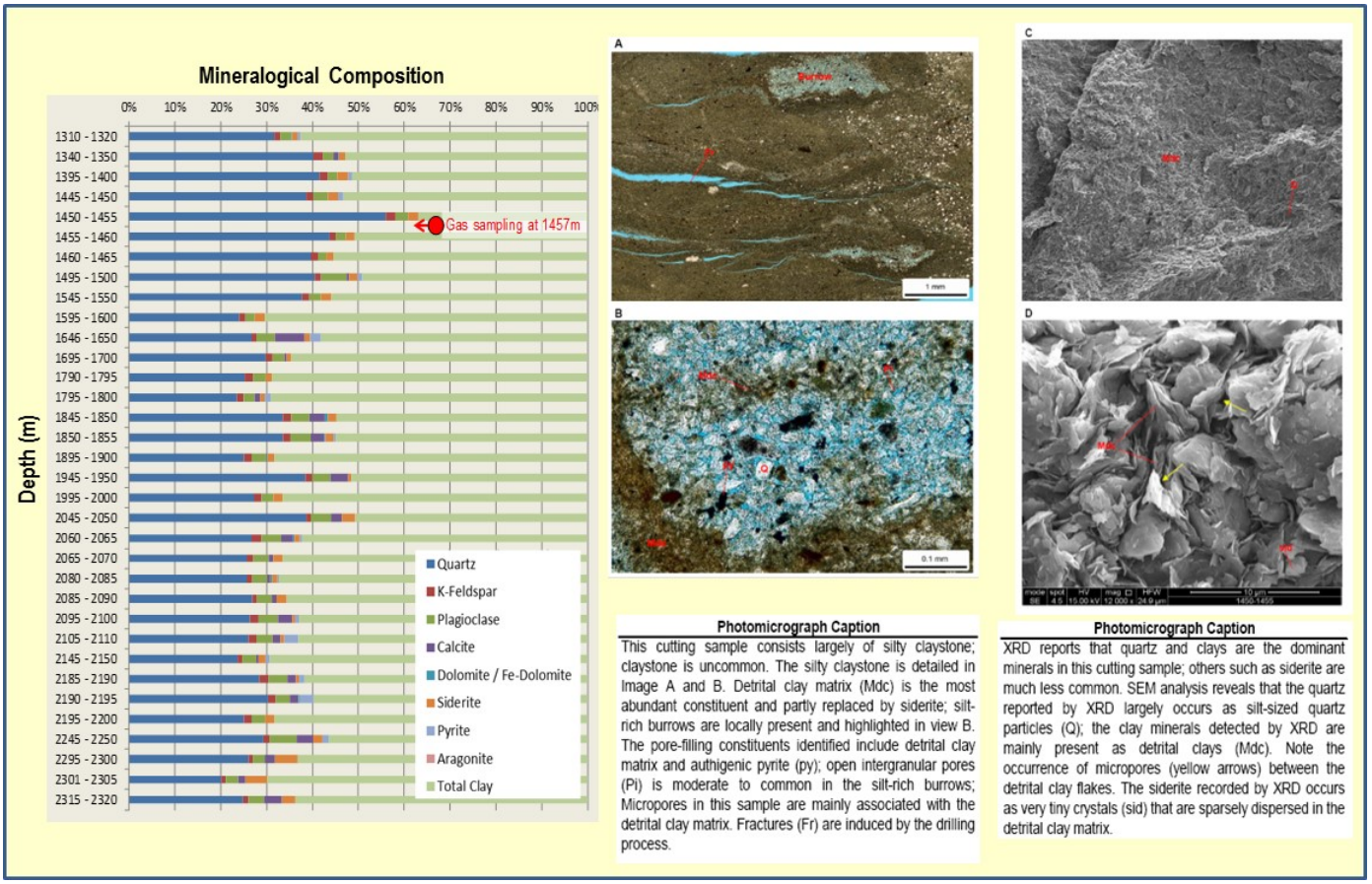


Figure 38: *Left - Mineralogical composition of cuttings samples from "T-1" well based on XRD results. Noted the gas-bearing sample was taken an interval with the highest quartz content recorded in the well. Right - Petrographic and SEM descriptions of the sediments encountered in the well.*

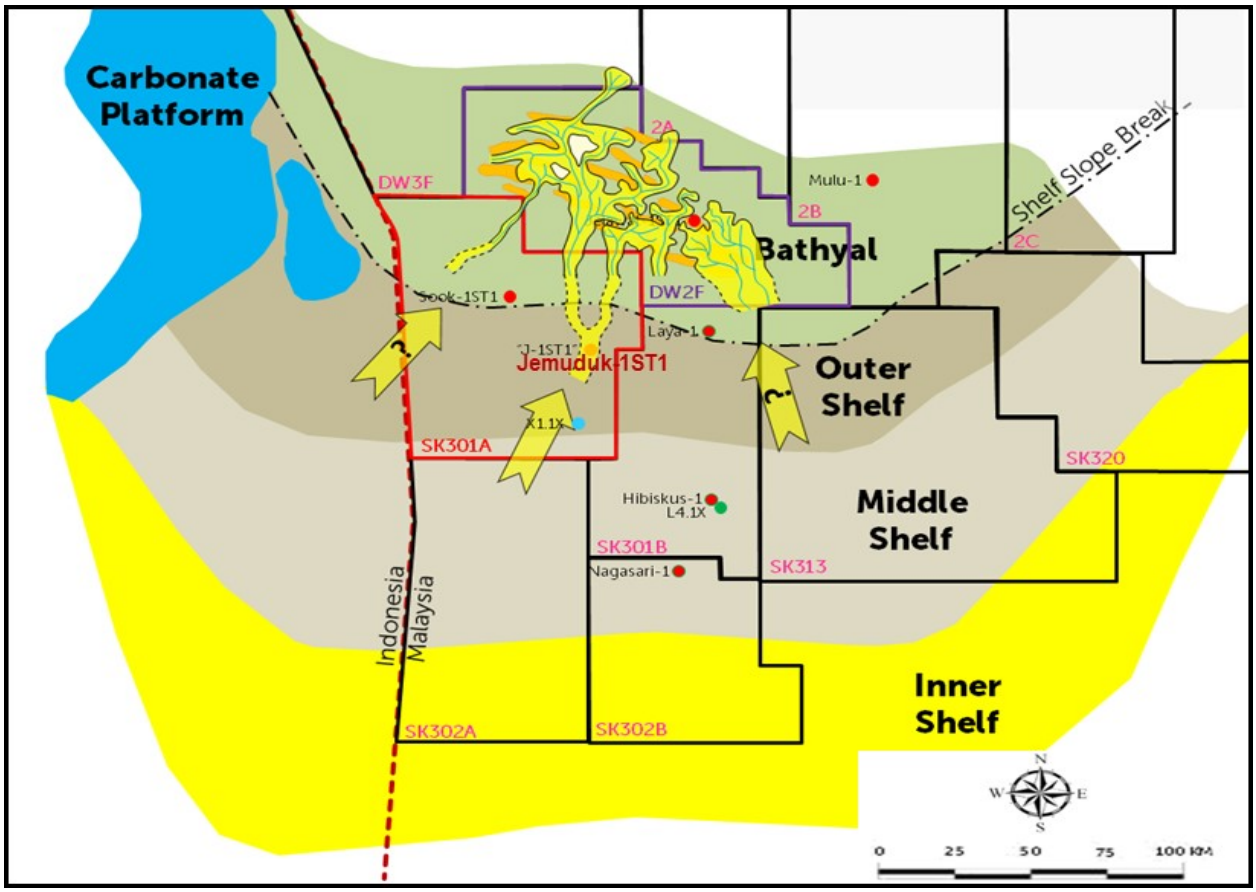


Figure 39: *Palaeogeographic map of Early Pliocene (Cycle VI) where the well Jemuduk-1ST1 found a better than expected sand fairway in a growth fault setting. This could carry sandy sediments downdip to the Bunguran Trough forming viable basin floor turbidite deposits (from Harun Alrashid et al., 2015).*

CONCLUSIONS AND RECOMMENDATIONS

Throughout the Neogene, the Bunguran Trough has been dominated by progradation of the Rajang Delta from the south, with secondary sedimentary inputs from the Natuna Arch to the west. This huge influx of sediment filled a tectonically-induced sag basin, with Neogene sediments reaching a thickness in excess of 7,000m. We see evidence that strong subsidence in the Bunguran Trough was matched by high sedimentation rates. These observations are typical for pull-apart basins but, since a number of lineaments such as the Baram Line and Red River Fault systems converge in the Bunguran Trough, it is not clear what was responsible for the enhanced subsidence and when. We believe that the Bunguran Trough overlies a deep-seated releasing fault bend system in the well-documented dextral stress field induced by the South China Sea evolution.

The post-MMU section in the Bunguran Trough consists of predominantly deepwater slope to basinal deposits (turbidites, mass transport complexes/deposits and mudstone). The central part is filled with Late Pliocene and Pleistocene sediments, and even the Holocene layer is several hundreds of metres thick. This may suggest that the process of tectonically driven subsidence is still active. Considering the distance from continental shorelines and the mud-prone nature of the Rajang Delta, it is logical to find a deepwater mud-dominated environment in the Bunguran Trough, with limited amounts of sand only. However, study of the sedimentation rate and mineralogical composition suggests that sand may be present in the Upper Miocene to Lower Pliocene section as seen in the Jelawat-1ST1 well. Additional feeders from now submerged areas of the Dangerous Grounds/North Luconia and Central Luconia areas could have existed but remain speculative. Overall delivery systems may have changed in transport direction over time, from southwest - northeast during Oligocene time, switching to southeast - northwest during Miocene time, and reverting back to southwest - northeast during Pliocene time.

The latest exploratory drilling suggests that provenance from the Natuna Arch could provide siltier material with some calcareous content to mix with the Rajang Delta fine-grained material. Post-MMU sections (Plio-Pleistocene) penetrated by exploration well “T-1” proved to be siltier than the predicted mud-prone lithology, albeit with very little sand development. The “T-1” well did encounter minor gas-bearing turbidites in the target interval, but these were very fine-grained and chaotic in sedimentary structure, and were non-effective reservoirs. The quality of reservoir sands and their distribution therefore remain the main exploration risk in the Bunguran Trough.

However, the sand potential in the Upper Miocene to Lower Pliocene sections was not properly assessed by "T-1", as the well encountered some fine sands at TD, thought to belong to the uppermost Miocene section. Although structural growth influenced deposition throughout the Plio-Pleistocene, the Late Miocene interval shows less constrained sedimentation and an increased potential for sand development across the study area. A constraint on prospectivity of the potentially more sand-prone Miocene deposits is that they have been buried below an extensive thickness of Plio-Pleistocene and Quaternary deposits, representing a significant risk to reservoir quality.

A more detailed understanding of the timing of structural growth in different parts of the Bunguran Trough may identify prospectivity in areas where the Mio-Pliocene sections are better developed over structures at reasonable depths of burial. Deep-imaging broadband seismic acquisition coupled with the latest techniques in multi-attribute analyses are recommended for the study area to the south and east of the currently available seismic dataset, as there are indications of proximity to sediment input fairways in that region. For instance, if the fairways located downdip of the Jemuduk-1ST1 main fairway can be successfully mapped, this will enhance the chance of finding improved reservoir quality sands (Figure 39). Last but not least, an integrated study approach such as those conducted by Meju et al. (2015), and Noor Farinda Salim et al. (2015) will go a long way to help unravel the prospectivity of the study area.

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Steven Barker is a Senior Geoscientist with more than 12 years of working experience plying his trade predominately in the Europe and SE Asia domains. He specialises in petroleum system analysis with an emphasis on the interactions between structural dynamics and sediment fairway implications for hydrocarbon exploration. Steve attended the renowned Basin Evolution and Dynamics MSc program at Royal Holloway, University of London in the early 2000's after graduating from Birmingham University with a MSci. In the mid 2000's he joined the industry working offshore Kazakhstan as a Consultant Geologist working on the Kashagan megafield and exploring for near-field opportunities. He then joined an Operator by moving to GDF SUEZ E&P in London (2007-2013) working on play fairway analysis drilling numerous successful exploration and pre-development wells in the North Sea. In 2013, he moved to Kuala Lumpur where he joined JX Nippon E&P as a secondee working as Operator on a joint-venture between the two companies on the DW2F block. After taking a short break at the turn of 2017, Steven has recently joined JX Nippon as a Senior Geoscientist working on Sabah deepwater exploration blocks.

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