

## Overview of the structural framework and hydrocarbon plays in the Penyu Basin, offshore Peninsular Malaysia

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**Abstract:** The Penyu Basin is moderately explored but may still have undiscovered hydrocarbon potential for small to moderate size accumulations. Despite the much publicised Rhu-1 oil discovery made in 1991, the Penyu Basin, with only a couple of sub-economic oil discoveries made, has not had much success ever since. This was generally attributed to the poorly developed generative or immature source rocks most likely present in isolated half-grabens within the basin. The Penyu Basin was formed on continental crust, although the exact formation is not properly understood and most authors generally consider it as a pull-apart or “rift-wrench” basin. This is supported by the presence of major strike-slip and associated normal faults being the main basin-bounding faults. The initial half-graben basins developed into isolated lacustrine systems which provide source-rock facies that may have potentially charged traps in the synrift and post-rift sequences. Trap styles identified include compressional anticlines, basement drape structures and synrift stratigraphic/structural traps. Further data acquisition through the last two decades of exploration activities, such as new 3D seismic, geochemical fingerprinting and fluid inclusion investigations, and full tensor gradiometry (FTG) gravity data adding to the past understanding, has enabled a more refined review of the geology and also of the petroleum potential. Undoubtedly, more detailed mapping of new previously undetected structures, coupled with seismic amplitude analyses and advanced quantitative interpretation (QI) techniques may lead to a better understanding of the structural evolution and, hence, to an increase of hydrocarbon prospectivity by identification of additional plays, new leads and to a potential reduction of exploration risk.

**Keywords:** Offshore Peninsular Malaysia, Penyu Basin, petroleum systems, structural framework

### INTRODUCTION

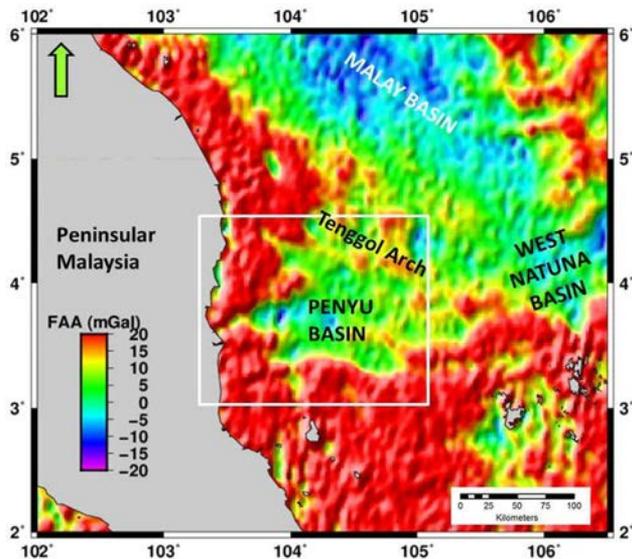
The Penyu<sup>a</sup> Basin, located offshore east of Peninsular Malaysia, is a relatively small (~150 km wide) Tertiary extensional basin filled with more than 5 seconds two-way travel time (TWT) (equivalent to ~7-8 km) of sediment at its deepest parts (Figures 1 and 2). The basin appears to be structurally contiguous with the West Natuna Basin, which lies across the maritime boundary with Indonesia, and therefore some authors regard it as the westward extension of the latter (Haribowo *et al.*, 2013). Separating the basin from the much larger, petroleum-rich Malay Basin to the north is a broad and shallow pre-Tertiary basement high, the “Tenggol Arch”, which has been explored over decades with rather mixed results (Jong *et al.*, 2019a, 2019b). Figure 3 shows the main structural elements and depositional grabens in the basin, the approximate outline of which may be

represented by the 10 mGal contour of the free-air gravity anomaly. The basin comprises a series of E-W and NW-SE trending fault-bounded grabens and half-grabens. A major NW-trending fault zone, named the Trans-Penyu Fault Zone (TPFZ), transects the basin diagonally and is believed to be a major strike-slip fault zone. To the west of the TPFZ are the main grabens, Kuantan and Pekan grabens; whereas to the east of the TPFZ the main grabens are the Jelai, Rompin, Cherating, Rhu, Rumbia and Merchong grabens.

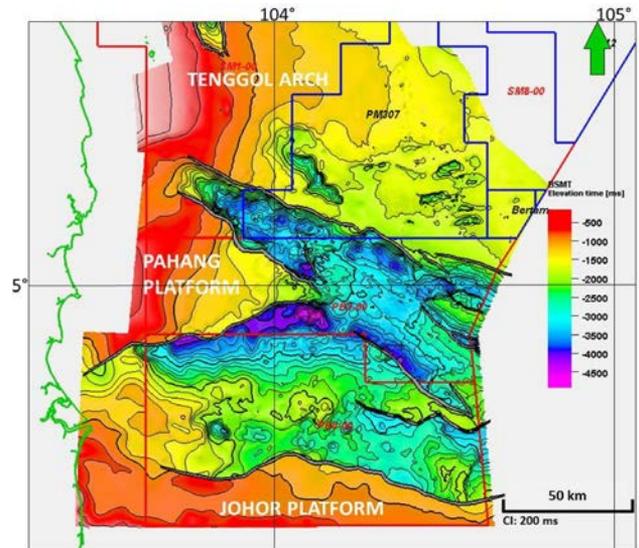
The Penyu Basin is relatively under-explored when compared to the Malay Basin, but quite extensive work has been done on it and some of it has been published (Ngah, 1975; Hamilton, 1979; ASCOPE, 1981; Ngah *et al.*, 1996; Madon *et al.*, 1997; Madon & Anuar, 1999; Restrepo-Pace *et al.*, 2010). Despite a much publicised oil discovery<sup>b</sup> in 1991 by Texaco, the Penyu Basin has not had much success.

<sup>a</sup> “Penyu” is the Malay word for “turtle”, in attribution to common turtle landings on the beaches on the east coast of Peninsular Malaysia.

<sup>b</sup> “Texaco has hefty strike off Malaysia” Oil and Gas Journal, 6 April 1992. According to the report the Rhu-1A wildcat flowed at a combined rate of 6050 bopd of 34-39 API crude from three zones at 2602-2672 m. It was the first, and only significant discovery in the basin.



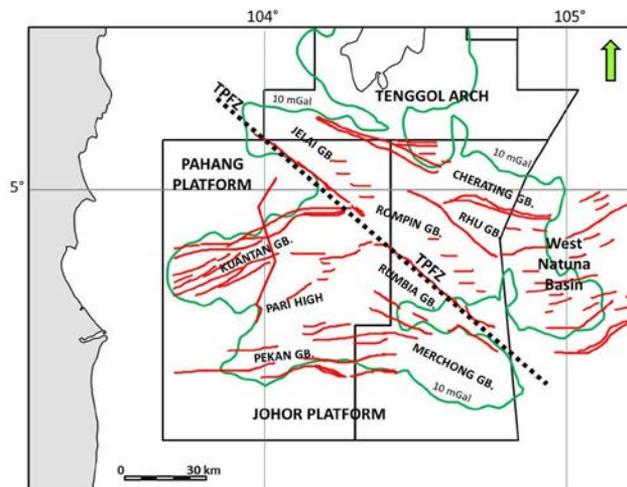
**Figure 1:** Satellite-derived free-air gravity anomaly map of offshore Peninsular Malaysia. Penyu and Malay basins are easily recognised by the low/negative anomalies (-5 to 10 mGal). Rectangle is outline of map in Figure 2 representing the study area. Gravity data from Sandwell *et al.* (2014).



**Figure 2:** Basement structure map of the Penyu Basin based on latest seismic data (including 3D data up to 2013), from Barber (2013).

**Table 1:** Summary of exploration activities in the Penyu Basin. PCSB - Petronas Carigali Sdn. Bhd.

Company	Awarded	Relinquished	Seismic	Wells
Conoco	1970	1976	2D seismic	2 wells
PCSB	1981	1982	2D seismic	0 well
Texaco	1990	1998	2D seismic	6 wells
Santa Fe Energy/Devon Energy	1998	2001	2D seismic	3 wells
PCSB	2001	2004	Rhu 3D	1 well
Lundin Malaysia	2008	2016	2D, 3D seismic	4 wells



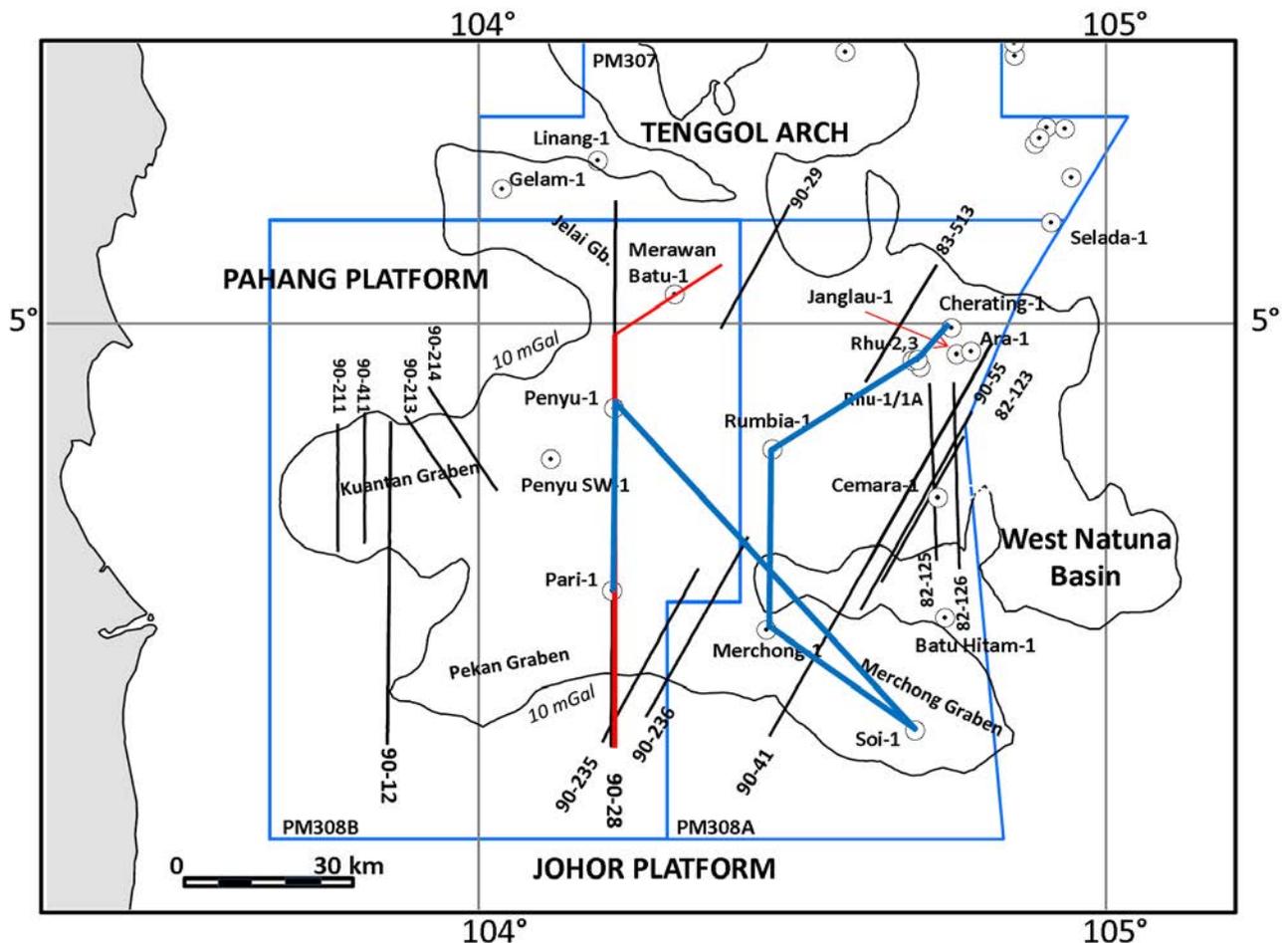
**Figure 3:** Major faults and lineaments in the Penyu Basin (sketched based on Madon *et al.*, 1997 and Barber, 2013). Structural elements (grabens and faults) are named according to Barber, 2013). TPFZ – Trans-Penyu Fault Zone. Green line is 10mGal free-air anomaly contour (see Figure 4). Black lines are exploration block boundaries.

This was generally associated with poorly developed generative or immature source rocks which are assumed to be present in isolated half-grabens within the basin. In the past the understanding of the geology and the petroleum systems was hindered by a poor data base. Additional data acquisition due to further exploration activities, however, has led to a more detailed observation of the geology and the petroleum potential (Table 1). Recent findings suggest that other geological risk factors, including the timing of trap formation relative to hydrocarbon generation, trap effectiveness and trap definition (Restrepo-Pace *et al.*, 2010)

are of equal importance to hydrocarbon charge. This paper provides an overview of the geology and the remaining hydrocarbon potential of the Penyu Basin based on some results of recent exploration effort.

### EXPLORATION HISTORY

Figure 4 shows the location of wells drilled in the Penyu Basin. The well results are summarised in Figure 5 and Table 2. During the 1970s, Conoco drilled the first two wildcat wells in the basin, Penyu-1 (1970) and Pari-1 (1973). Penyu-1 tested the largest inversion anticline overlying the Kuantan Graben (Figures 3 and 4). Pari-1 tested a basement drape feature over a basement high (Pari High) separating the Pekan and Kuantan grabens (Figure 3). These exploration wells were representative of the two important play types that became the target of exploration during the years that followed. The exploration license for the block, then known as PM14, covered the entire Penyu Basin and changed hands, first in 1978 to Petronas Carigali and then in 1990



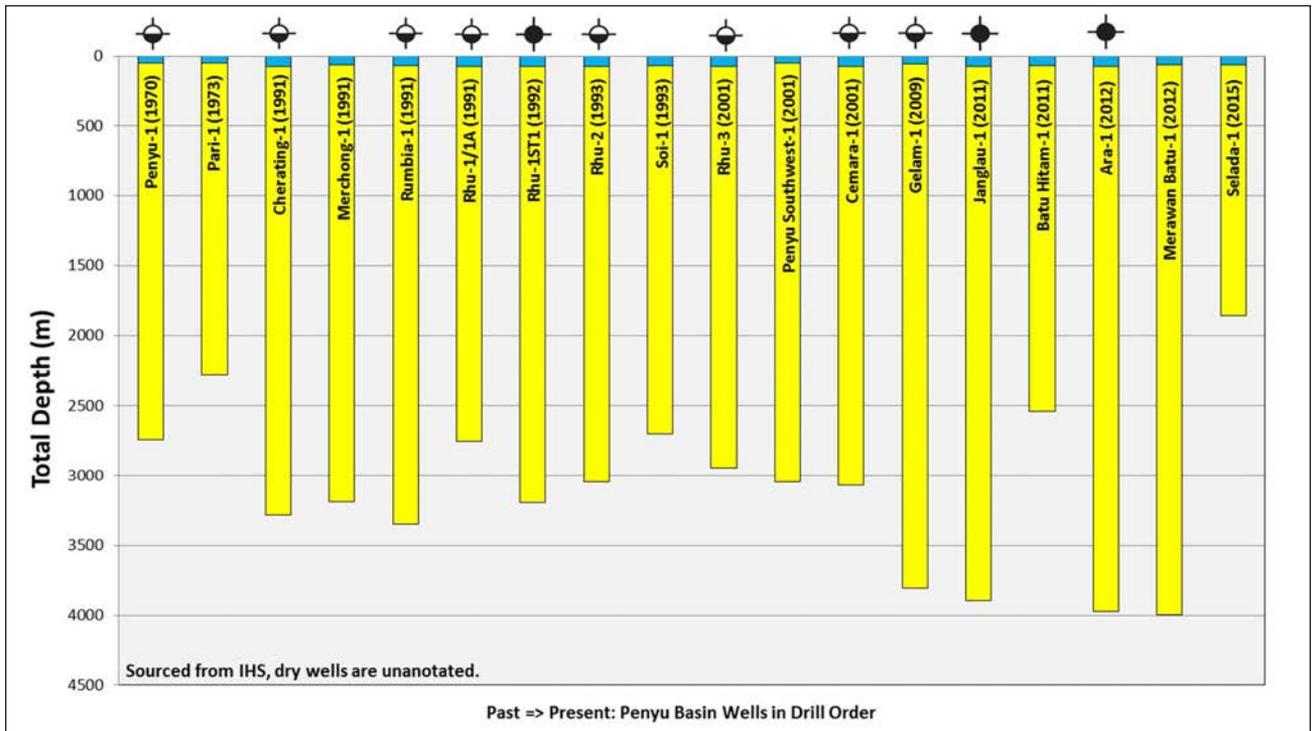
**Figure 4:** Exploration wells in the Penyu Basin drilled between 1970 and 2015. Outline of basin depocentres is marked by the 10 mGal contour line based on free-air gravity anomaly map in Figure 1. Also shown (blue lines) are the outline of exploration Blocks PM308A and PM308B during the Lundin Malaysia 2008-2016 exploration period. Black lines are seismic profiles mentioned in the figures and text. Red line is Line 90-28 through Pari-1 to Merawan Batu-1 (Figure 10). Bold blue line is the location of the stratigraphic well-correlation panel shown in Figure 6.

to Texaco. The latter drilled four exploration wells in 1991, namely Cherating-1, Merchong-1, Rumbia-1, and Rhu-1. The first three, Cherating-1, Merchong-1 and Rumbia-1 tested inversion anticlines (essentially Penyu look-alikes) without success. The Cherating-1 well, drilled on a gentle inversion structure within the central Cherating Graben, found 15 m of gross oil-bearing sands in late synrift Oligocene sediments, but the estimated recoverable hydrocarbon volume appeared to be non-commercial.

Texaco's fourth well, Rhu-1/1A well, originally targeted Oligocene synrift sandstones onlapping on a basement ridge, but found instead oil in basal Miocene sands of the Upper Penyu Formation in a post-rift compactional drape structure. The basement ridge, which is essentially the crest of the footwall block to the Cherating Graben (Figure 3) was found to be composed of basaltic and volcanic tuff. Moderately waxy (35° API gravity) oil was encountered at depths of between 2544 and 2815 m (Madon & Anuar, 1999). The Rhu-1/1A discovery was a breakthrough, since it proved a new play concept whereby the deep synrift lacustrine source

rock is likely to have sourced reservoir sands in the post-rift as well as the synrift sedimentary sequences.

In 1993, Texaco drilled the Rhu-2 well to appraise the stratigraphic continuity and structural geometry of the hydrocarbon column discovered at Rhu-1/1A. Unfortunately, the well failed to produce any oil from the targeted zones; the key oil-bearing "M" sand encountered in Rhu-1/1A was found to be mostly water wet. The company then drilled another wildcat well, Soi-1, to test a so-called "ramp play", in which the drilling target is on a basement high formed by the hanging-wall "ramp" of the two bounding faults of the Merchong Graben (see later Figure 9B). Soi-1 was drilled in the deepest, southeastern part of the Merchong Graben (Figure 4) where the geometry is similar to that of the Pekan Graben shown in later Figure 9C and hydrocarbons could have migrated from the deep grabens to the north and south of the basement high. The well was drilled to a depth of 2630 m but did not prove any hydrocarbons. After declaring the Rhu discovery as sub-commercial, Texaco eventually relinquished the area (Block PM14) in 1996.



**Figure 5:** Exploration well summary (with well symbols) of the Penyu Basin: Penyu-1 (1970), Pari-1 (1973), Cherating-1 (1991), Merchong-1 (1991), Rumbia-1 (1991), Rhu-1/1A (1991), Rhu-2 (1993), Soi-1 (1993), Rhu-3 (2001), Penyu Southwest-1 (2001), Cemara-1 (2001), Gelam-1 (2009), Janglau-1 (2011), Batu Hitam-1 (2011), Ara-1 (2012), Merawan Batu-1 (2012), Selada-1 (2015).

**Table 2:** Wells drilled in the Penyu Basin (see map in Figure 4 for location), with well results compiled based on an internal look-back study conducted by Lundin Malaysia in 2016. The play targets J, K, L and M are following the Malay Basin’s group nomenclature of the synrift section in the Penyu Basin (see Figure 6 for further information).

Well	Year	Operator	Play Target	Results	Reason for Failure	Play Type	
1	Penyu-1	1970	Conoco	K, L, M	Dry	Charge	Post-rift and synrift in inverted half-graben fill (Sunda fold)
2	Pari-1	1973	Conoco	Post-rift	Dry	Trap	Post-rift drape on structural high
3	Cherating-1	1991	Texaco	K, L, M	Dry	Trap	Post-rift in inverted half-graben fill (Sunda fold)
4	Rhu-1/1A	1991	Texaco	Post-rift	Oil discovery	-	Post-rift drape on basement high
5	Rumbia-1	1991	Texaco	Post-rift	Dry	Charge	Miocene transpressional fold
6	Merchong-1	1991	Texaco	Post-rift	Dry	Charge	Miocene transpressional fold
7	Rhu-2	1993	Texaco	Post-rift	Dry	Charge	Basement drape feature (appraisal)
8	Soi-1	1993	Texaco	Post-rift	Dry	Charge	“ramp” margin play
9	Linang-1	1995	PCSB (block 307)	Synrift	Dry	Charge	Alluvial fan sediments truncated by top-synrift unconformity
10	Rhu-3	2001	Santa Fe/Devon	Post-rift	Oil show	Charge	Basement drape feature (appraisal)
11	Cemara-1	2001	Devon	K, L, M	Dry	Charge	Four-way structural closure
12	Penyu SW-1	2001	Devon	K, L, M	Dry	Charge	Synrift in ramp margin
13	Gelam-1	2009	PCSB (block 307)	Synrift	Dry	Charge	Synrift sediments truncated by top-synrift unconformity
14	Janglau-1	2011	Lundin Malaysia	Synrift	Oil shows	-	Synrift sediments against bounding normal fault.
15	Batu Hitam-1	2011	Lundin Malaysia	Post-rift	Gas show (99% CO <sub>2</sub> )	Charge	Basement drape feature
16	Ara-1	2012	Lundin Malaysia	Synrift	Oil shows	-	Deep synrift section
17	Merawan Batu-1	2012	Lundin Malaysia	Synrift	Dry	Trap	Early Oligocene intrarift alluvial sands and late stage synrift fluvial sands over basement high
18	Selada-1	2015	Lundin Malaysia	J, K	Dry	Charge	Basement drape feature

In 1998, Santa Fe<sup>c</sup> assumed operatorship of the block, which had been renamed PM308, and in 2001 drilled Rhu-3 appraisal well but had only some oil shows. Santa Fe, which became Devon Energy due to the merger of Devon Energy with Santa Fe-Snyder<sup>d</sup>, drilled two more wells in that same year: Cemara-1 and Penyu Southwest-1. Both had some insignificant oil shows. Whilst Devon Energy was operating in Block PM308, Petronas Carigali drilled two wells in another part of the Penyu Basin that lie in an adjacent block to the north, Block PM307. Both those wells, Linang-1 and Gelam-1, tested the synrift play in the Jelai Graben (Figure 4) but were unsuccessful.

In 2008, Lundin Malaysia BV<sup>e</sup> was awarded production-sharing contracts for the re-delineated blocks PM308A and PM308B covering the Penyu Basin. During this latest phase of exploration in the basin up to 2015, five wells were drilled – Janglau-1, Batu Hitam-1, Ara-1, Merawan Batu-1 and Selada-1<sup>f</sup> (Figure 4). Lundin Malaysia relinquished blocks PM 308A, 308B and the Tenggol Arch blocks (PM307 and 319) in 2016. By the end of Lundin Malaysia's exploration campaign, altogether 18 exploration wells had been drilled in the basin, including the two appraisal wells on the Rhu structure (Table 2). The poor overall drilling results were thought to be due to mainly insufficient hydrocarbon charge from the adjacent kitchen areas, as well as ineffective trapping. This, however, requires further investigation.

A recent study by Restrepo-Pace *et al.* (2010) suggested that the basin remains prospective, as not all the mapped structures have been tested. About half the basin area including areas adjacent to the maritime boundary with Indonesia is now covered by 3D seismic data. However, full interpretation and utilization of the data is still lacking. Recently acquired gravity/magnetics data, including full-tensor gradiometry (FTG) gravity data may also significantly improve the structural definition and interpretations supporting play and trap definition.

## GEOLOGICAL SETTING

Stratigraphically, the Penyu Basin appears to be a “condensed” version of the Malay Basin; with less than half the total thickness of sediment deposited over the same period of geologic time. Figure 6 shows the stratigraphic subdivision of the Penyu Basin. Like the Malay Basin, the sediments in the basin are entirely siliciclastics, consisting of interbedded shale, siltstone, sandstone and, in the middle, coaly sequences. Sedimentation was initially characterised by non-marine fluvial-lacustrine facies in the synrift half-graben and pull-apart basins, which developed as land-locked basins, passing into upper coastal plain deposits

(Penyu Formation) (Figure 7). Two phases of synrift sedimentation (early and late) during active faulting and subsidence of the half-grabens are identified from seismic interpretation. The synrift sequences are overlain, in places with unconformity (“Base-Pari Unconformity”; Madon *et al.*, 1999), by coal-bearing lower coastal plain sediments indicating increasing marine influence during the post-rift phase of sedimentation (Pari Formation). This overall transgressive marine sedimentation started in the Late Oligocene, concomitant with the regional transgression in the Malay Basin associated with the “K” shale. The post-rift phase is accompanied by a basin inversion phase during the Late Miocene which resulted in unconformities, the most significant one being the Late Miocene “Top-Pari Unconformity”, which effectively subdivides the post-rift section into two sub-phases. This unconformity is a regional unconformity that is correlated with the major erosional unconformity at the base of seismic Group B in the Malay Basin (Madon *et al.*, 2006). The post-unconformity sequence in the Penyu Basin is referred to as the Pilog Formation.

The post-rift sequence represents Miocene to Quaternary sedimentation in a much wider thermal sag basin, which by that time was probably intermittently connected to and influenced by the ancestral South China Sea, *via* the West Natuna basin. As a result of the partial connection to the open ocean, the sedimentary sequences were affected by fluctuating sea levels. Whereas the thickness of synrift sequences in the half-graben fills is determined by the amount of extension along the bounding faults, the post-rift sequence has a relatively uniform thickness across the entire basin as a result of gentle sagging due to non-fault-related thermal subsidence.

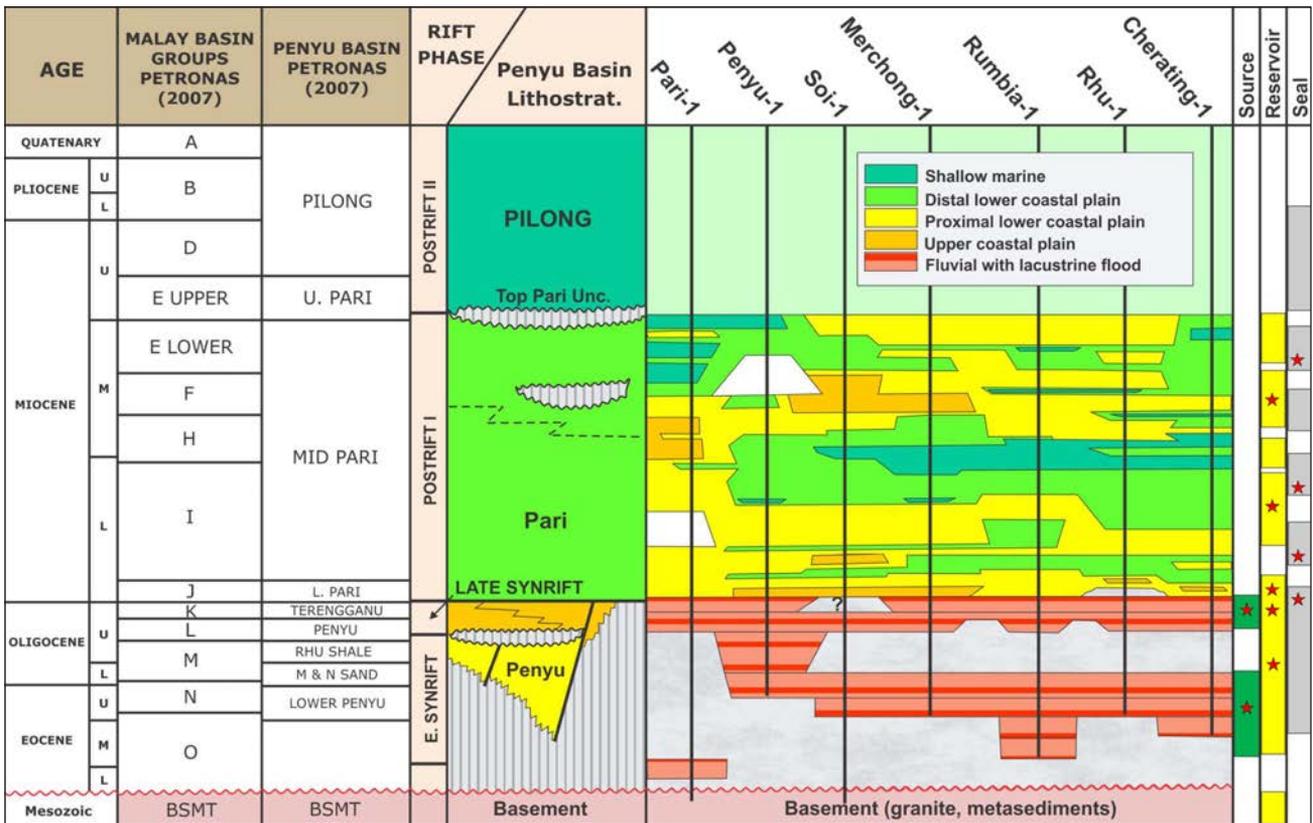
The Penyu Basin is the smallest of the three offshore Tertiary extensional basins of central Sundaland (Figure 1). Undoubtedly, the basin developed in continental crust, although the exact formation is not properly understood and most authors generally considered it as a pull-apart or “rift-wrench” basin (Madon & Anuar, 1999; Haribowo *et al.*, 2013). Early Tertiary crustal extension initiated the development of NW-SE and E-W trending grabens, synchronous with the break-up and opening of the South China Sea marginal basin. Simultaneously, the Malay Basin developed to the north, probably as a series of pull-apart basins along a major NW-trending shear zone that was reactivated by the India-Asia collision during the Late Eocene, as is envisaged in regional tectonic models (e.g. Tapponnier *et al.*, 1982; Daines, 1985; Hall, 2002) (Figure 8). The exact timing of basin formation is unknown but by analogy with the Malay and West Natuna and other

<sup>c</sup> Santa Fe Energy Resources Malaysia Ltd.

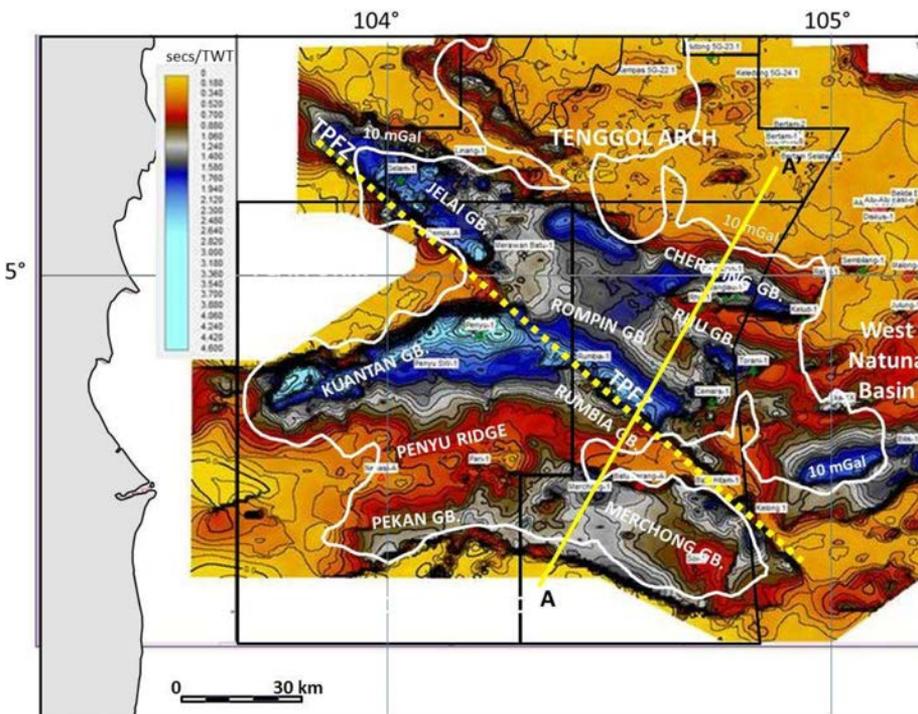
<sup>d</sup> “Devon-Santa Fe Snyder deal tops M&A action”, Oil and Gas Journal, vol. 98, issue 23, 5 June 2000.

<sup>e</sup> The partners were JX Nippon with 40%, Lundin Malaysia with 35% (as operator) and Petronas Carigali with 25% carried interest.

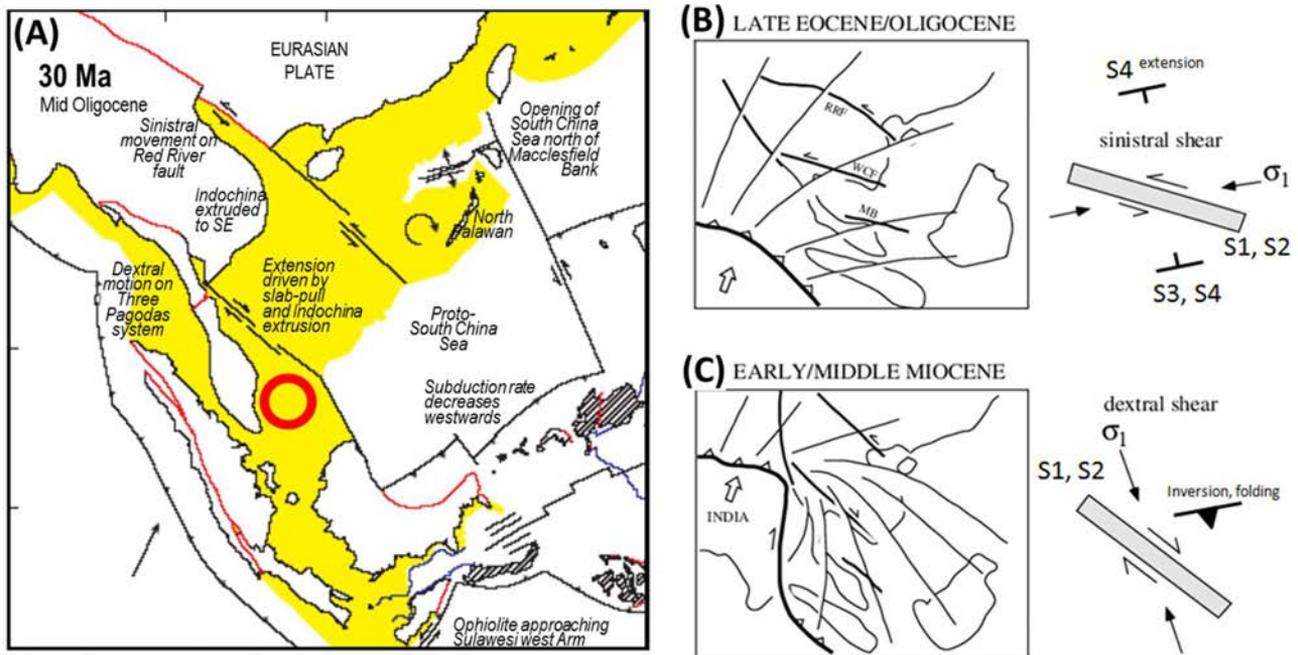
<sup>f</sup> Selada-1 is located on the Tenggol Arch, and strictly speaking not a Penyu Basin well.



**Figure 6:** Stratigraphic summary and paleoenvironments of the Penyu Basin, based on Morley (2009) and Barber (2013). Paleoenvironments based on palyonological and paleontological analyses of selected wells shown, some of which penetrate the basement composed on granite and metasediments. Besides Pari-1 and Soi-1, other wells that penetrated pre-Tertiary basement are Merawan Batu-1, Batu Hitam-1, Janglau-1, Rhu-2, Rhu-3 and Selada-1. Potential source, reservoir and seal rocks indicated on the panel to the right with the best source, reservoir and seal sections annotated by the red stars (see Table 3 for more information). The “Top-Pari” Unconformity marks the end of basin inversion and truncates the “Sunda folds”, as shown in Figure 12.



**Figure 7:** Sediment thickness map in seconds two-way travel time of the Paleogene graben fill (synrift) sequence. Note the main synrift depocentres (blue areas) along the major bounding faults and half-grabens, namely Kuantan Graben, Jelai Graben, Rumbia Graben, Merchong, Cherating and Rhu Grabens. White curve is the 10 mGal gravity anomaly contour from Figure 4. The NW-SE bold dotted line represents the Trans-Penyu Fault Zone (TPFZ) shown in Figure 3. Line A-A' refers to the geological cross-section in Figure 22.

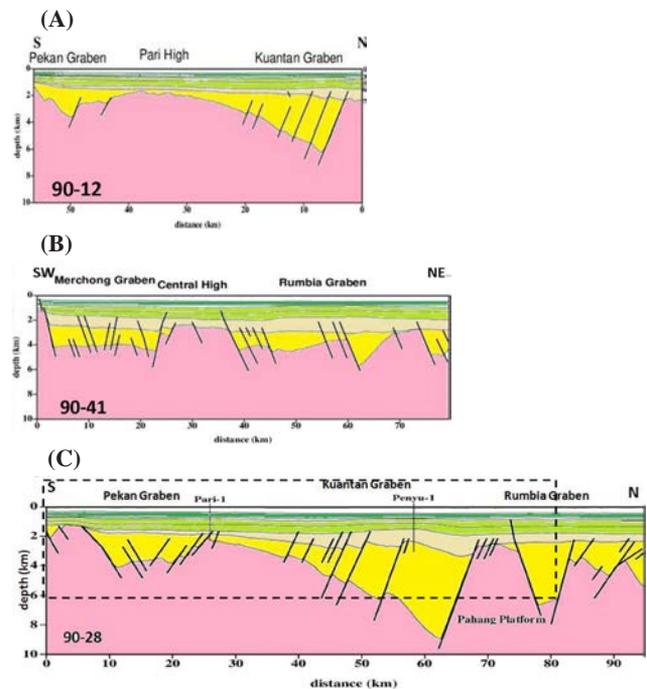


**Figure 8:** Regional tectonic evolution of the Malay/Penyu Basin system in the context of SE Asian tectonics. (A) Tectonic reconstruction at 30 Ma (Mid-Oligocene) by Hall (1997) showing South China Sea opening and its supposed relationship (now controversial and highly debated hypothesis) with NW-SE trending strike-slip faults in Indochina (e.g. Morley, 2012; Hall, 2012). Right-lateral wrench movement along the Three Pagodas Fault through the Gulf of Thailand was depicted, and generally accepted, as the cause of crustal deformation and inversion in the region of the Penyu and Malay basins (red circle) during the post-rift phase. (B) The same shear zone, however, was in sinistral mode during basin initiation stage (before 35 Ma), represented by S1, S2 faults identified from seismic mapping (see Figure 15 later). (C) Clockwise rotation of regional stress, accompanied by reversal of shear direction along the NW-SE shear system causing basin inversion of Malay/Penyu basins. Shear rotation model in (B) and (C) modified after Huchon *et al.* (1994).

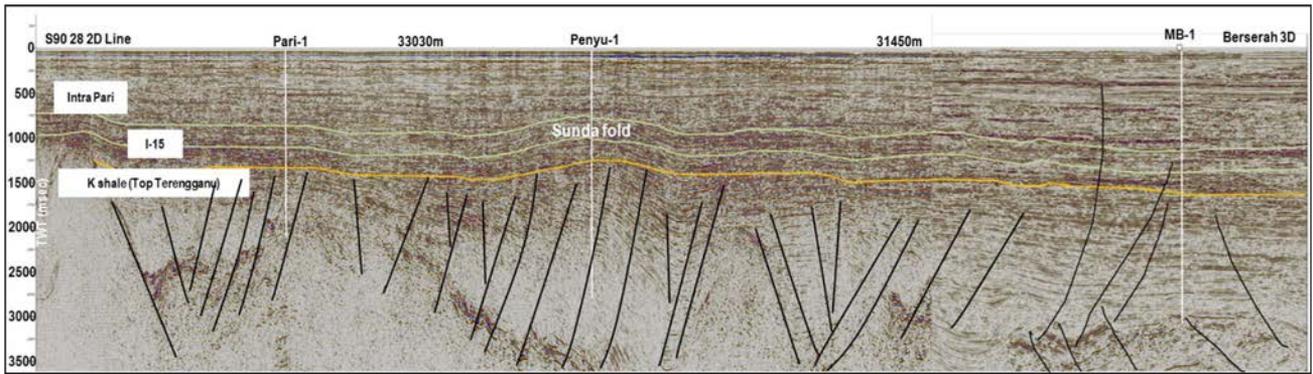
extensional basins of Sundaland (e.g. Morley, 2002), the Penyu Basin was probably formed during the Late Eocene to Mid-Oligocene (~40 – 35 Ma). During this “synrift” phase, small isolated sub-basins developed as extensional half-grabens and releasing-bend basins associated with major E-W and NW-trending faults, respectively (Figure 7).

Figure 9A illustrates the main structural styles in the basin with seismic-based regional cross-sections. The dominant structural style is that of half-graben sub-basins bounded by major normal faults, as also seen in the western part of the basin (Lines 90-12 and 90-28) (see also Figure 10). There, the Pekan and Kuantan grabens have opposite polarities, i.e. with their master border fault dipping in opposite directions. In addition, the hanging-walls of the normal fault systems are cut by mostly synthetic faults, which also deform the entire synrift sequence (Figure 11). This indicates that crustal extension during the synrift phase was contemporaneous with sedimentation and basin filling. Inverted half-grabens and associated anticlines across the major sub-basins, e.g. Cherating Graben are shown in Figure 12.

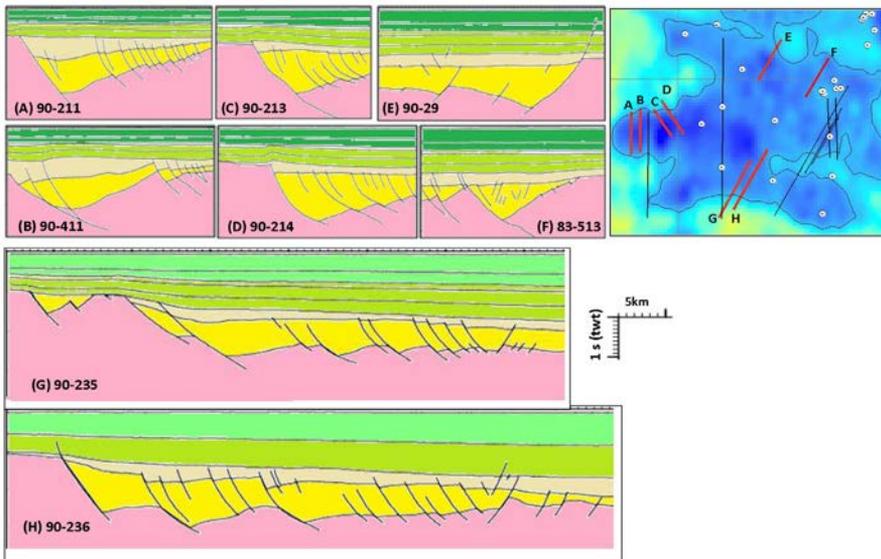
Another dominant structural style is illustrated by Line 90-41 (Figure 9B). The Merchong Graben to the southeast of the basin is characterised by steep basin-bounding faults. This strongly suggests primarily horizontal displacement along those faults in a strike-slip or wrench regime. The



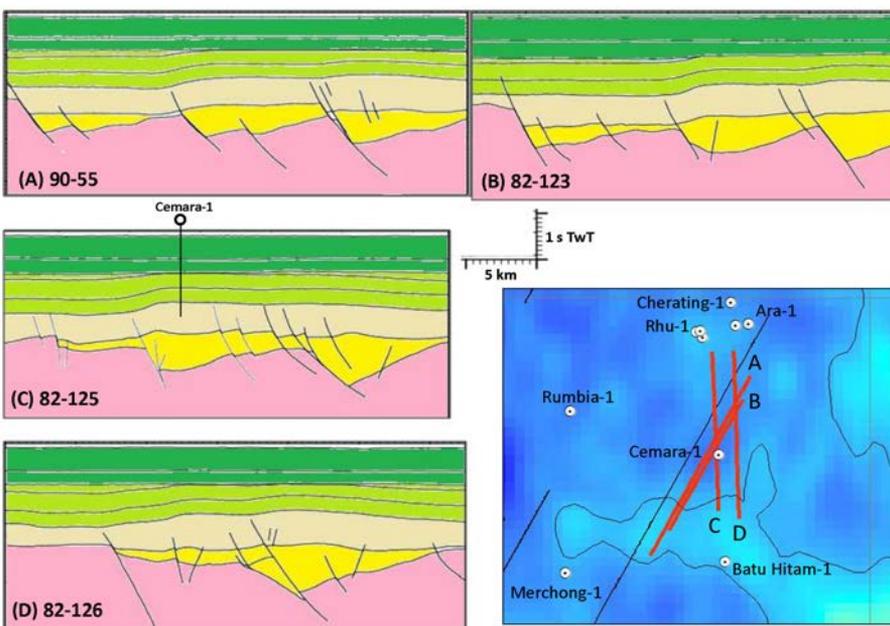
**Figure 9:** Regional geo-seismic sections across the Penyu Basin, showing the main structural elements (modified from Madon & Anuar, 1999). (A) line 90-12. (B) line 90-41. (C) line 90-28. For line locations see Figure 4. Part of the actual seismic section along line 90-28, within the dashed rectangle, is shown in Figure 10.



**Figure 10:** Seismic profile 90-28 from South to North across the Pari-1, Penyu-1 and Merawan Batu-1 wells showing the main structural style and basin configuration, with limited faulting observed in the post-rift section (K shale and younger). Line location also shown in Figure 4 (red line).



**Figure 11:** Structural styles in the half-graben sub-basins, drawn from seismic sections. Note the majority of hanging-wall faults are synthetic to the master fault. Index map shows the location of the profiles, based on Figure 4.



**Figure 12:** Inverted half-grabens and associated anticlines, sketched from interpreted seismic profiles across the major sub-basins, e.g. Cherating Graben. Note the truncation of the “Sunda folds” at the Top-Pari unconformity (between dark and light green layers). Index map shows location of lines (see also Figure 4 for regional context of map).

same is observed in the Rumbia Graben to the north and to the west (Line 90-28) (Figure 9C). It seems therefore likely that such early basin structures were developed by crustal extension, by normal faulting and by strike-slip faulting during the Late Eocene to Mid-Oligocene. In contrast, the post-rift sedimentary sequence appears to be unaffected by the faulting in most parts, but was subjected to compressional deformation (Figure 10). The deformation resulted in folding and uplift of the half-graben basin fill in response to either orthogonal compression of the half-grabens or by transpressional deformation associated with movement on the underlying strike-slip faults (Figure 13). It is thought that the basin inversion events that led to the compressional reactivation were coincident with regional changes in stress direction which have been well-documented in SE Asia (Huchon *et al.*, 1994; Tjia & Liew, 1996; Morley *et al.*, 2001) (Figure 8). The exact timing of the change in regional tectonic stress direction is uncertain and difficult to determine but in the adjacent Malay Basin it is believed to have occurred in the Mid-Miocene, corresponding approximately with the boundary between seismic Groups I and H (Madon *et al.*, 2006).

**STRUCTURAL ELEMENTS**

The main structural elements of the basin shown in Figure 3 were recognised very early on, based on sparse 2D seismic data used by Ngah (1975). Subsequently, high quality 2D data acquired since the early 1990s provided better insight into the structural elements, including the major basin-bounding faults and intra-basinal structures. To understand the tectonic history of the basin, it is useful to review the structural evidence provided by the seismic data available thus far. The top-of-basement structural map shown in Figure 2 reveals that the basin consists of two main parts, separated by a remarkably linear fault zone striking at about 130°N (Figure 2). For the purpose of this paper, this unnamed fault zone is referred to as the “Trans-

Penyu Fault Zone” (TPFZ) (Figure 3). The TPFZ marks the southwestern boundary of a NW-trending linear trough, the Jelai-Rumbia Graben, which has steep basin-bounding faults. This graben system widens southeastwards into a series of east-west trending half-graben systems, which characterise the southern and western parts of the basin.

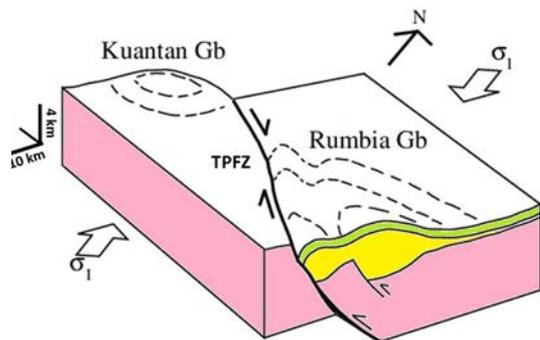
Besides the Jelai and Rumbia graben system, several other grabens or sub-basins (Figure 3), namely the Rompin, Cherating and Rhu grabens in the North and East, and the Merchong, Kuantan and Pekan grabens to the south and west, make up a composite basin complex<sup>§</sup>. The Kuantan and Pekan grabens, in the eastern part of the basin, are bounded by the Pahang and Johor platforms (see also Figure 2), which are the offshore extensions of the Late Mesozoic basement of Peninsular Malaysia. The Kuantan Graben is the deepest in the basin with at least 7 km of sediment, while the Pekan Graben forms a conjugate to the south, separated by the Pari High (Figures 2 and 3). Towards the east, the Rumbia and Merchong grabens are major sub-basins characterised by linear and steep planar bounding faults that appear to be major strike-slip or wrench faults. These faults are associated with wrench-related compressional structures (positive and negative flower structures) overlying reactivated deep-seated basement faults (Figure 14).

**INTERPRETATION OF FAULT SYSTEMS**

Analysis of the basement structural maps revealed four major and one minor set of faults that bound the half-grabens and sub-basins, labeled S1 to S4 for easy reference (Figure 15A). S1 and S2 faults are predominantly strike-slip, whereas S3 and S4 are predominantly dip-slip (normal) faults. Recognition of these different sets of faults and their tectonic implications provides insight into the kinematic development of the basin (Figure 15B):

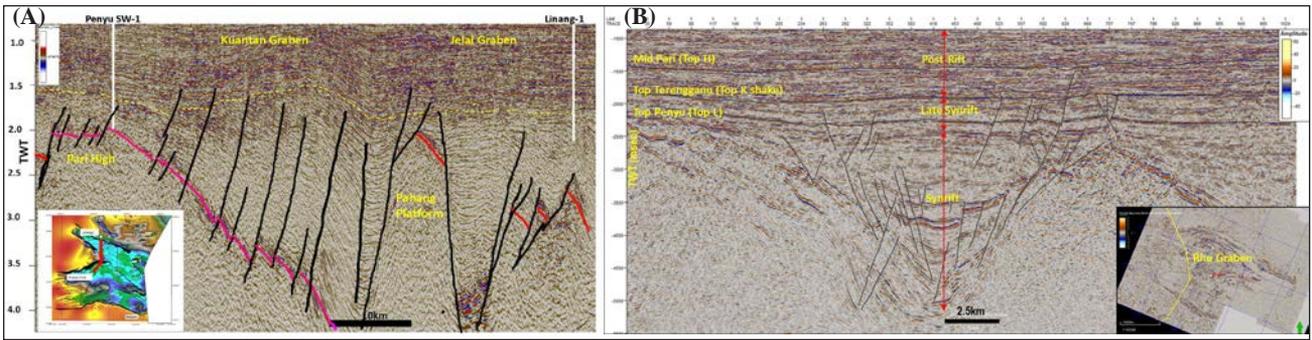
**S1 – NW-SE trending (~130°) faults**

S1 and S2 are the two dominant fault trends. The largest S1 fault is the remarkably linear NW-SE feature, named the Rumbia Fault, which splits the basins into two main parts: the Jelai-Rumbia graben complex to the north and the structurally contiguous Kuantan and Merchong graben complex to the South (Figures 3, 15A). The straight and steep attitude of the fault suggests a significant horizontal (strike-slip) component of displacement in addition to the observed > 4 km of dip slip (throw) in seismic sections (Figures 9 and 10). The mapped fault trace has the same trend as those in the Malay and West Natuna basins, as well as Late Tertiary strike-slip faults in Peninsular Malaysia, e.g. the Lepar and Lebir systems (Tjia, 1989, Figure 16). These faults are mainly left-lateral, as are many regional-scale strike-slip faults in SE Asia, such as in Thailand (Morley, 2002). Those faults are likely



**Figure 13:** Schematic of geometry of inversion structures in the Kuantan and Rumbia grabens resulting from dextral wrench reactivation of the “TPFZ”.

<sup>§</sup> The naming of grabens and faults follows that of Maga *et al.* (2015).



**Figure 14:** (A) Contrasting fault geometries and deformation styles: cross section from SW Penyu-1 (S) to Linang (N) showing the main structural style: Listric faults (master and synthetic faults and hanging-wall rollover) in the Kuantan Graben and transpressional wrench faults in the Jelai Graben, which resulted in a major erosional unconformity (dashed yellow line) at the 28.4 SB level (Top Penyu synrift Mid-Oligocene). (B) Regional cross-section of the Penyu Basin based on composite seismic lines across the Rhu Graben (perpendicular to graben elongation) where there is preponderance of wrench faults. The geometry of faults at depth, although speculative, appears to suggest linkage at mid-crustal levels to a major shear zone. This composite seismic profile is used for FTG 2D forward modelling as shown in Figure 27.

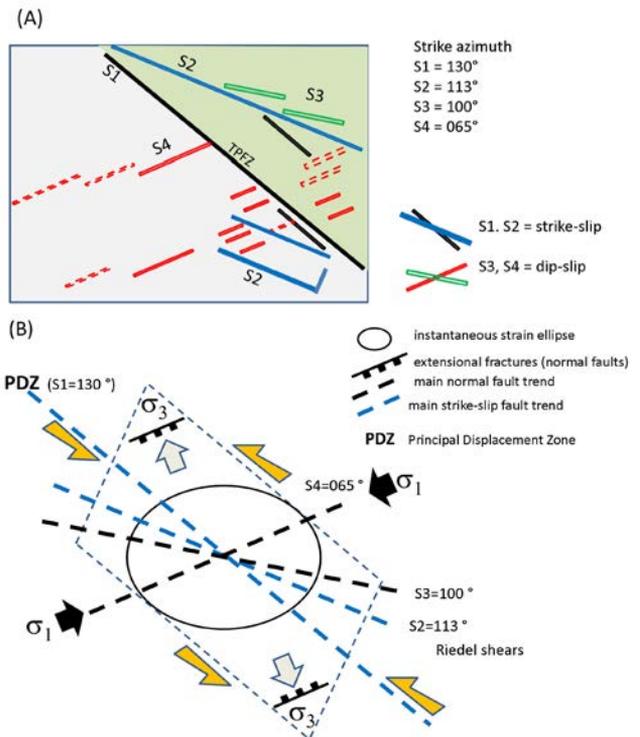
to exist in the pre-Tertiary basement offshore and may have been reactivated during initial phase of the Penyu Basin (Ngah *et al.*, 1996). The E-W trending half-graben extensional faults (S4) in close association with the S1 fault suggest that the former may be the result of a left lateral stress regime acting on a NW-SE shear zone. The principal displacement zone (PDZ) is represented by the NW-trending Rumbia Fault (Figure 15B).

**S2 – WNW-ESE trending (~110°) faults**

The S2 fault is slightly oblique to the S1 fault, and marks the northeastern edge of the Jelai-Rumbia Graben (Figure 15A). S2 fault orientation is also similar to the major faults on Peninsular Malaysia, such as in northeast Johor, suggesting that they have significant strike-slip displacements. In the Jelai Graben, the S1 and S2 faults converge northwestwards to define a narrow steeply bounded sub-basin, which later was subjected to post-rift transpressional deformation (Figure 14A). Like S1, the S2 faults also appear to be mainly strike-slip faults, probably associated with reactivated older basement faults. Large dip-slip movements in the Cherating and Rumbia grabens are also apparent, based on seismic interpretation (Figure 9).

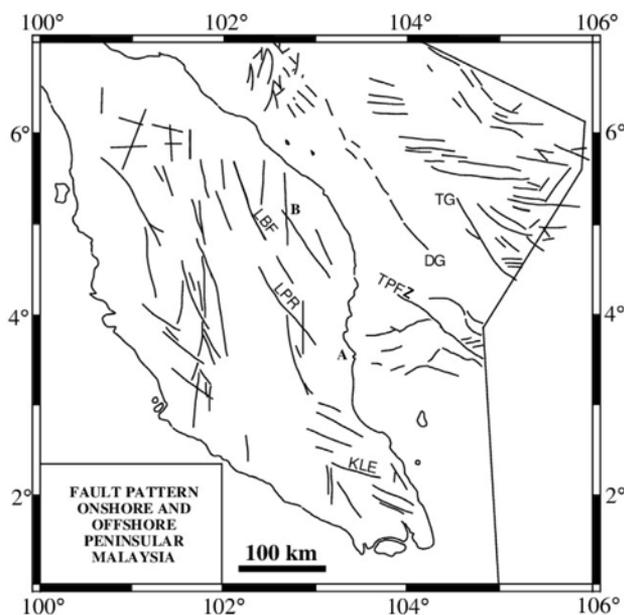
**S3 – WNW-ESE trending (~100°) faults**

S3 faults are present mainly in the northeast, forming the major half-graben bounding faults in the Rompin, Cherating and Rhu grabens (Figures 3 and 10). Those faults appear to be linked to several segments of the NW-trending S2 fault marking the northeastern boundary of the Jelai-Rumbia Graben (Figure 3). This fault pattern strongly suggests left-lateral pull-apart geometry along the NW-trending shear zone. Hence, both S1 and S2 appear to be left-lateral strike-slip fault systems controlling the development of the Penyu Basin, whereas the E-trending S3 and S4 are extensional faults generated by the shear deformation associated with the left-lateral strike-slip



**Figure 15:** (A) Summary of major fault trends based on the interpretation of faults from seismic sections. Compare with maps in Figures 2 and 3. (B) Interpretation of the major structures summarised in Figure 8A, illustrated with the instantaneous strain ellipse representing the time of basin initiation (synrift) phase. The principal displacement zone (PDZ) is interpreted as a left-lateral shear system.

faults (Figure 17A). All these faults have been reactivated during the middle Miocene basin inversion phase due to rotation of the regional stress direction (Figure 8). Figure 18 shows the fault patterns in the context of the right-lateral compressional stress.

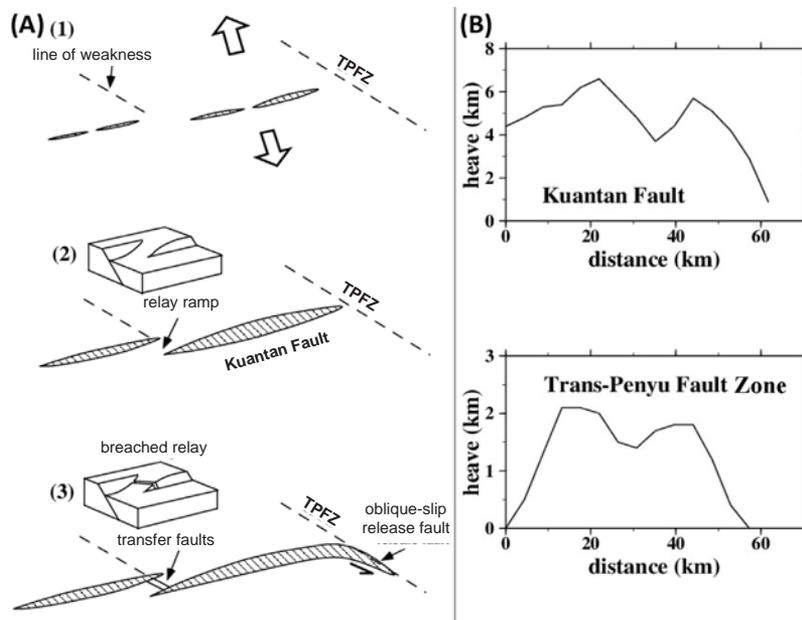


**Figure 16:** Major faults on Peninsular Malaysia and offshore in Malay and Penyu basins. Note the preponderance of NW-trending faults, parallel with those observed offshore. LBF – Lebir Fault, LPR – Lepar Fault, KLE- Kuala Lumpur-Endau Fault. TPFZ – Trans-Penyu Fault Zone, DG – Dungun Fault, TG – Tenggol Fault (modified after Tjia, 1989).

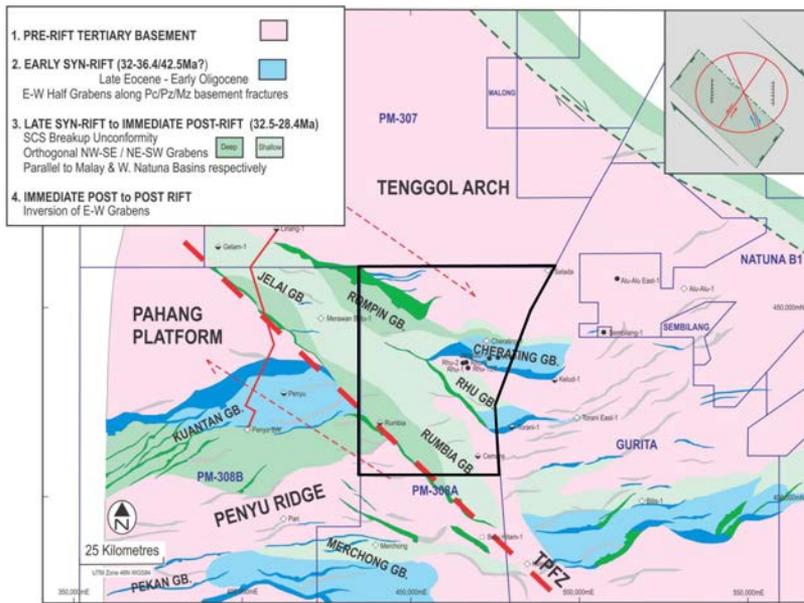
**S4 – ENE-WSW trending (~65°) faults**

This major extensional fault system marks the northern and southern boundaries of the Pekan and Kuantan grabens in the western part of the basin (Figure 15A), and continues westerly towards the Pahang coastline as the basin shallows. The deepest graben in the Penyu Basin is bounded by the largest S4 fault, the Kuantan Fault, which is a major half-graben bounding normal fault, down-throwing to the South. Displacement along the Kuantan Fault appears to have contemporaneous with strike-slip movement along the TPFZ (Figure 17A). The fault has a cumulative displacement in excess of 6 km. Studies of fault displacements have shown that large faults may result from growth by linkage of smaller fault segments (e.g. Peacock & Sanderson, 1994). Plots of fault displacement along strike of the Kuantan Fault and TPFZ (Figure 17B) seem to suggest fault growth by segment linkage. The Kuantan Fault is also a normal fault that is characteristically listric and appears to sole out at depth, probably along a mid-crustal detachment surface near the brittle-ductile transition zone.

Associated with the syn-sedimentary displacements on these faults is deformation of the hanging-wall pre-rift basement block (*via* synthetic normal faults), as well as flexural deformation resulting in typical rollover towards the master fault. Above the basement, the synrift strata are



**Figure 17:** (A) Model for the evolution of the Kuantan Graben, associated with the left-lateral shear along the Trans-Penyu Fault Zone (TPFZ). (1) incipient faults developed as tension fractures in response to N-S transtension. (2) fault segments merge to become larger faults as crustal extension progresses. Relay ramp develops as fault tip interact. (3) Transfer fault created along lines of weakness breaches the relay ramp. Oblique displacement along TPFZ creates steep basin-bounding faults (e.g. Merchong Graben). (B) Plot of displacement (heave) with distance in the two major faults in (A). Kuantan Fault (top), part of the Trans-Penyu Fault Zone (bottom). The presence of minima in the plots strongly suggest that they formed by linkage of at least two fault segments.



**Figure 18:** Major structures in the Penyu Basin, comprising ENE-trending normal faults and half-grabens, transected by major NW-trending faults, the largest being the Trans-Penyu Fault Zone. The TPFZ appears to be a major structural discontinuity and displacement representing a major NW-SE shear system. The structural pattern is explained by first, left-lateral shear during basin extension (synrift) phase, creating the major half-grabens and grabens (blue and green shaded areas) which later were deformed by transpressional deformation along the reactivated TPFZ in a (reversed) right-lateral shear system. See also Figures 15B and 17.

also deformed by synthetic normal faults emanating from the basement. This suggests that the extensional deformation is coeval with sedimentary accumulation in the half-graben, such that the synrift stratigraphy fans out towards the master fault (Figures 9, 11, 14). This syn-kinematic deformation of the sedimentary fill during the synrift (extensional) phase is probably overprinted by post-rift basin inversion of the half-grabens, resulting in the so-called “Sunda folds”.

Studies of earthquake faulting show that brittle extension of upper crustal normal faults is usually associated with subsidence of the hanging-wall and concomitant uplift of the footwall due to elastic rebound (e.g. Thompson & Parsons, 2016; Meschis *et al.*, 2019). In the Penyu Basin, footwall uplift is indicated by flat-topped, highly eroded, truncated footwalls (e.g. Figures 9C, 11G, 11H). The amount of footwall uplift on these faults appears to have been significant, estimated to be in the order of at least 1 to 1.5 km.

Smaller scale S4 faults are observed within the basement of the major sub-basins or grabens, especially the Merchong Graben (Figure 19). These structures were identified initially based on the 1990 2D seismic as sigmoidal (lazy z-shaped) faults, but the more recent data enabled a more detailed mapping of their geometries. These faults are interpreted as extensional fractures generated by left-lateral shear deformation along an S1 fault system (Figures 15B and 17A).

### STRUCTURAL MODEL OF BASIN DEVELOPMENT

Based on the interpretation of fault patterns, it is apparent that the Penyu Basin is not an orthogonal rift basin but, more likely, a pull-apart basin created by a complex interaction of strike-slip/wrench faults and normal faults. The orientation of the half-graben border faults indicates a predominantly north-south extension direction. Strain

partitioning by movement of the strike-slip faults may have resulted in a complex internal structure, as observed in the Rumbia and Merchong grabens. The northeastern part of the basin appears to be strongly influenced by the NW-SE trending strike-slip faults which are aligned with major regional basement weaknesses that occur onshore in Peninsular Malaysia and offshore in the Malay and West Natuna basins (Figure 16).

It is likely that the larger and deeper grabens may have begun opening earlier than the smaller ones, increasing in size as their bounding normal faults grew and merge (see Figure 17A). This is consistent with our understanding of rift-basin evolution based on fault-growth models of normal faulting (e.g. Schlische, 1991). The basin essentially opened by overall extension in a North-South direction, but the crustal extension propagated in a westerly direction, as indicated by shallowing of the basement westwards toward the Peninsular Malaysian (Pahang) coastline. This latest phase of extension in the western part of the basin was roughly orthogonal. The relative timing of the fault movement indicates that opening of the basin started in the East and generally propagated westwards. The major basin-bounding faults appear to have been active only during the initial opening of the basin (extensional phase) and do not penetrate the strata above the top-synrift unconformity. Some faults may have been reactivated during the post-rift basin inversion phase, but by and large they appear to have remained inactive during the thermal subsidence phase. Basin deformation is manifested in complex internal structures in the basement as well as within the sedimentary fill. Synrift wedges in the half-grabens, for instance, are characterised by hanging-wall rollover structures associated with the penecontemporaneous listric faults (e.g. in the Kuantan Graben). Hanging-wall deformation is mainly caused by synthetic rather than antithetic faults, but both types seem

to affect only the synrift and rarely penetrate the post-rift section (Figures 10, 11, 12). Faulting of the post-rift section may have been caused by reactivation of basement faults.

Basin inversion that affected not just the Penyu Basin, but the entire region of the South China Sea, was probably a response to a change in the regional stress field (e.g. Huchon *et al.*, 1994; Tjia & Liew, 1996; Morley *et al.*, 2001). The compressional structures and unconformities suggest that there were two phases of inversion: one at the end of synrift phase, another at the end of post-rift I phase, which is marked by the regional Mid-Miocene unconformity. When the principal stress direction was N-S, the NW-SE faults (e.g. TPFZ, Figure 13) were reactivated as strike-slip/wrench faults, while the E-W trending faults (especially the half-grabens in the western part of the basin) were subjected to N-S compression and shortening.

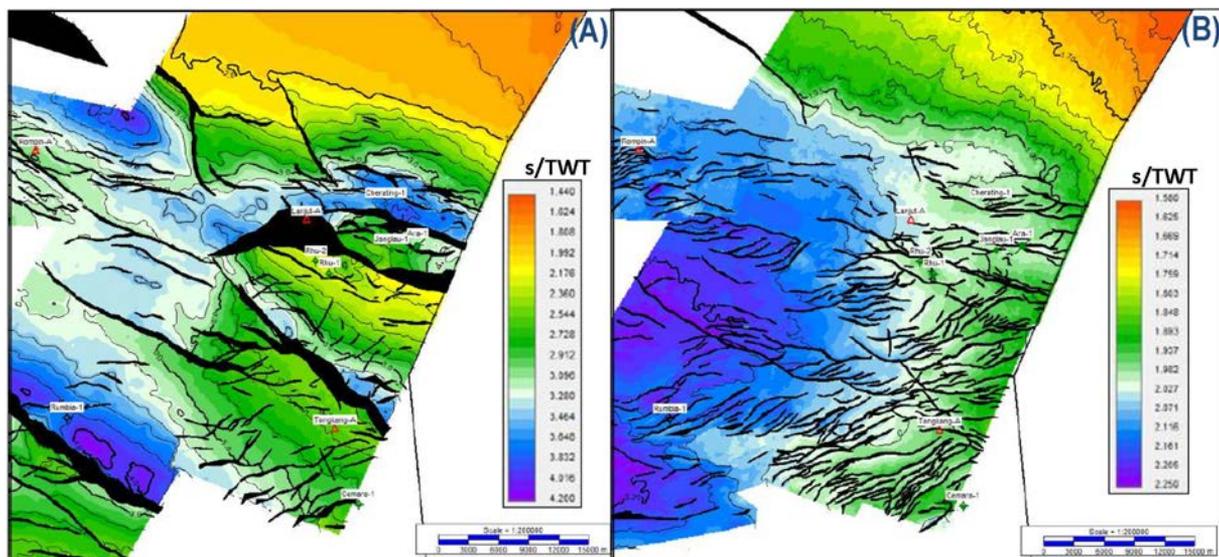
The north-south shortening across the basin resulted in the formation of “Sunda folds”, a series of E-trending, doubly-plunging anticlines formed above the major half-grabens (Figures 12 and 13). The largest inversion anticline occurs above the deepest part of the Kuantan Graben and has been tested by the Penyu-1 well (Figures 9C and 10). The geometry of the inversion structures suggests that they were strongly controlled by the orientation of basement faults that bound the underlying half-grabens. For example, orthogonal N-S contraction of the Kuantan Graben resulted in a simple inverted half-graben, whereas oblique contraction (transpression) in the Rumbia and Merchong grabens produced wrench-fault structures associated with the TPFZ. The wrenching/inversion also affected the graben shoulders resulting in the steepening and uplift of the basin flanks, e.g. in parts of the Tenggol Arch and the Pahang Platform. Post-rift transpressional tectonics along the TPFZ caused “pop-up” structure and erosion along the Jelai Graben (Figure 13).

The stratigraphic level at which the erosion occurred is at the top of Penyu synrift (or SB28.4 Ma, equivalent to SB3 in Petronas Carigali’s nomenclature, or Top K in the Malay Basin), indicating the change in stress regime at the end of the synrift phase in Late Oligocene or early post-rift phase.

The Merchong Graben, in the southwest corner of the basin, has remarkably straight boundaries, marked by steep basin-bounding faults. It is symmetrical and has flat basin floor, which is characteristic of pull-apart basins (Figure 9B). The interior of the graben is characterised by a conjugate normal fault dipping towards the center of the graben. At the south-west boundary of the graben (Figure 18), these faults define sigmoidal traces, which could be interpreted as tension gashes or Riedel shears in a left-lateral transpressive regime (Figure 15B). Detailed mapping of the structures reveals closely spaced tensional fractures indicative of left-lateral wrenching in the basement (Figure 19). The rhombic shape and flat basin floor, steep walls and linear bounding faults suggest strongly that the graben is a pull-apart basin (“rhombochasm”) controlled by two NW-trending strike-slip faults. The northern border fault shows evidence of having been reactivated during the post-rift phase, and resulted in propagation of the basement fault up the sedimentary section with splays producing a flower-structure/palm-tree structure, indicative of a dextral wrench fault in a transpressive regime. Structures within this sub-basin are thoroughly faulted, indicating an initial buckling to form the anticlines which were then sheared apart during pulses of wrench tectonics.

### SUBSIDENCE HISTORY

Based on the available stratigraphic data, geohistory and tectonic subsidence curves were constructed at selected well locations at the centre of half-grabens (e.g. Penyu-1



**Figure 19:** Detailed mapping of Rumbia, Merchong and Cherating/Rhu grabens reveals en echelon E-W extensional structures in the basement and up the sedimentary section, probably associated with transensional wrench tectonics in the basement. (A) Structural map at “38.4 Ma horizon” (Basement). (B) Structural map at 27.5 Ma horizon (Intra-Penyu marker).

and Rumbia-1, Figures 20A and 20B) and on structural highs (e.g. Rhu-1/1A, Figure 20C). The geohistory curves show greater synrift subsidence and therefore sediment accumulation at graben centre, compared to wells on structural highs, which had remained emergent until the end of the synrift phase. Subsidence clearly started later on the structural highs than in graben centres and, obviously, the main difference between these locations is the significantly greater thickness of synrift section in the latter.

Tectonic subsidence curves, i.e. subsidence of basement minus the effect of sediment loading (Figure 20D), show characteristics of rift basins formed by lithospheric stretching (McKenzie, 1978); rapid subsidence during the synrift phase (up to ~23 Ma B.P., the approximate age of the top of Penyu Formation) and gradual subsidence during the post-rift (thermal) subsidence phase. The curves indicate that structural highs or graben centres have the same post-rift subsidence rates. This is quite expected, as observed in many rift basins, since thermally induced post-rift subsidence usually affect a larger area than the underlying rift zone. As a result, the post-rift sedimentary sequence covers the entire basin.

The magnitudes of synrift subsidence, however, differ from place to place but the deeper half-grabens are the result of greater synrift tectonic subsidence. As mentioned above, it is likely that the deeper half-grabens had opened earlier than the shallower ones. There may have been multiple episodes of extension along the major bounding faults of the deep half-grabens. There is no evidence to suggest that all the half-grabens started to open and subside at the same time, at the presumed age of 40 Ma (Figure 20). Without reliable information on the exact timing of half-graben formation, it may be difficult to estimate synrift subsidence rates.

The magnitude of thermal subsidence may be obtained from the post-rift tectonic subsidence history of wells drilled on the basin inversion structures at the graben centres (e.g. Penyu-1, Cherating-1, Merchong-1 and Rumbia-1). The tectonic subsidence curves (Figure 20D), although at different depths, show gentle gradients characteristic of slow thermal subsidence. Assuming a lithospheric stretching model (McKenzie, 1978), the stretching factor ( $\beta$ ) may be estimated from the thermal subsidence curve by plotting tectonic subsidence against  $1 - e^{-t/\tau}$ , where  $t$  is time since stretching and  $\tau$  is the thermal time constant of the lithosphere (62.75 Ma). The subsidence curves in Figure 20D give an average stretching factor ( $\beta$ ) of 2.0, indicating that there had been crustal thinning underneath the basin to about half the original thickness. This value is similar to that estimated based on gravity modeling ( $\beta=2.3$ ) by Madon & Watts (1998).

An important difference between Penyu and Malay basins is that in Penyu the synrift appears to be dominant, whereas in Malay the post-rift is dominant. Many pull-apart (strike-slip) basins have subsidence histories that are similar to that of Penyu Basin; extremely rapid synrift tectonic subsidence, but little post-rift (thermal relaxation)

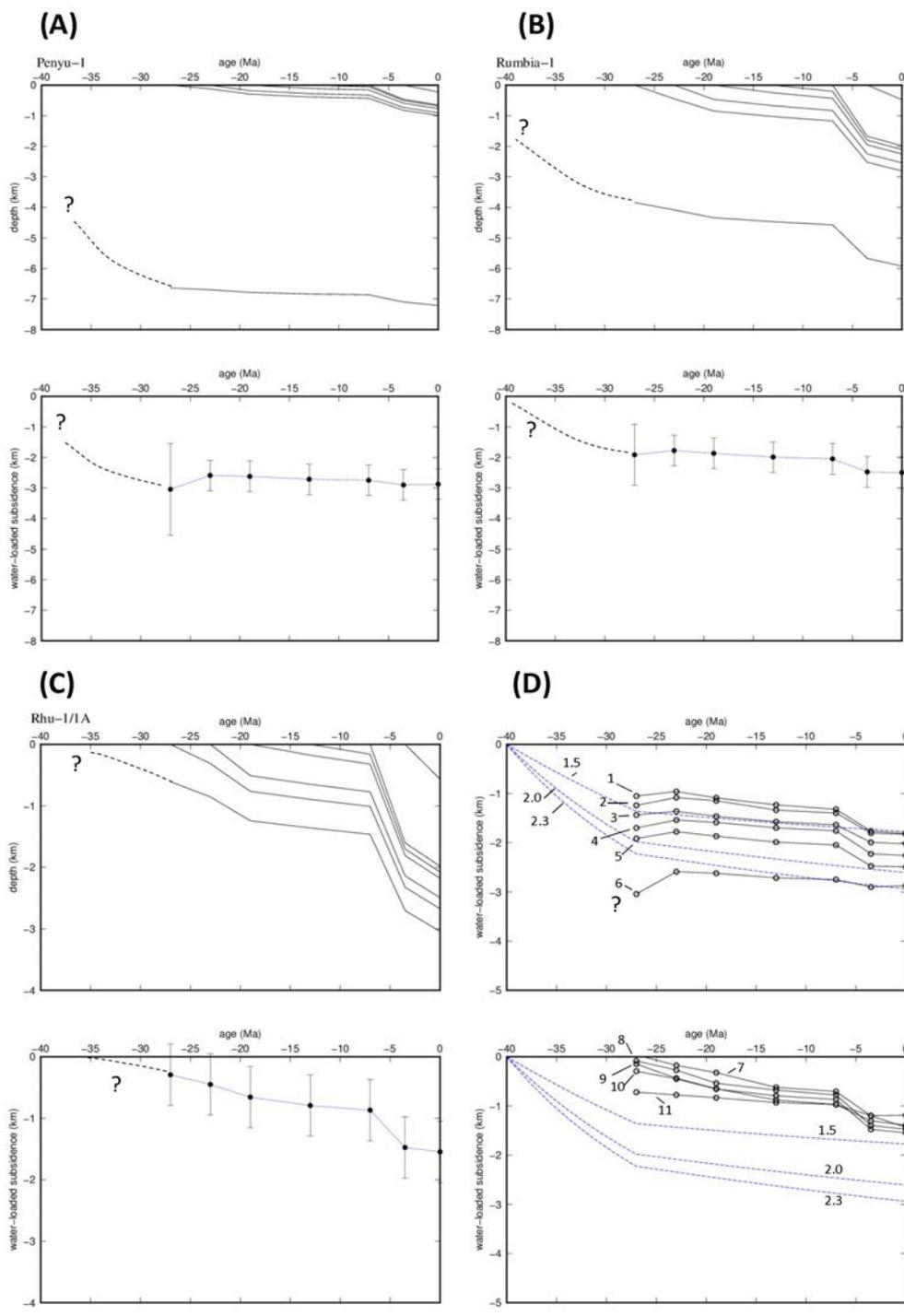
subsidence. This is partly because most studied examples of strike-slip basins are young and short-lived or, in some cases, crustal extension did not involve the mantle and so thermal subsidence is insignificant (Pitman & Andrews, 1985; Xie & Heller, 2009). The synrift appears dominant in Penyu Basin probably because it is a much smaller basin and its synrift sediment-fill is shallow enough to be imaged by seismic. In the Malay Basin, much of the synrift is too deeply buried in the axial zone of the basin and may have been totally obliterated due to extreme shear deformation.

## HYDROCARBON PLAYS

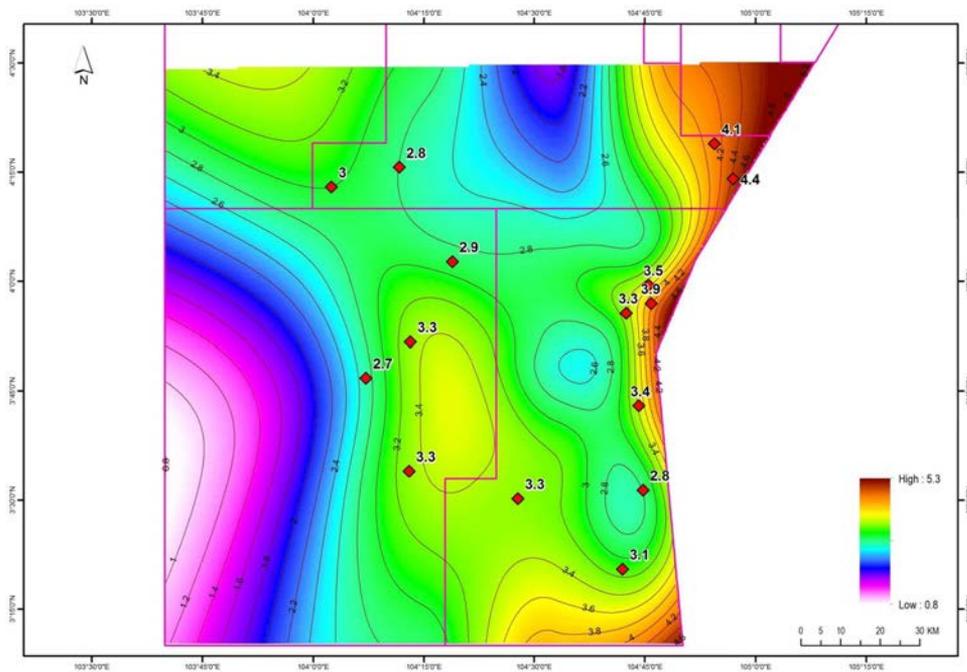
The structural history of the basin provides a framework for understanding the different play types. Structural traps mainly rely on post-rift compressional events related to wrench faulting. The inversion anticlines (Sunda Fold Play) were the most obvious structures that were the drilling targets during the early phase of exploration, and there are likely not many of these left undrilled in the relatively small basin. Trapping is deemed to be achieved by four-way dip closures of these elongate or domal structures, which occur in the post-rift section above the half-graben depocenters. The reservoir targets are within the Pari Formation, comprising coastal plain sediments. The Penyu-1 structure is a classic example for the "Sunda Fold Play". Another example is the Rumbia-1 well, which targeted a late synrift to post-rift Sunda Fold anticlinal structure and inverted half-graben.

The hydrocarbon source rock for this play type is believed to be from lacustrine shale in the synrift section of the half-graben sub-basins, which occur directly beneath the structures and vertical migration is likely to be the key charge mechanism. Geochemical analyses have shown that thermally mature source rocks with mainly Type II/III kerogen may be present in the unpenetrated synrift section in those deep half-graben systems providing the hydrocarbon charge (Madon & Anuar, 1999). The heat flow is also markedly higher in some of the rift branches (Maga *et al.*, 2015; Kessler & Jong, 2018) (Figure 21). Hydrocarbons could migrate along the fault conduits where they propagate upwards into the post-rift strata. It is worth noting, however, that most of the major "Sunda Fold Plays" tested by the drill turned out water bearing (e.g. Penyu-1 well). The main risk to this play is that the faults as migration conduits rarely connect the source facies with the post-rift reservoirs (Jong *et al.*, 2019b). The Top-Pari unconformity which truncates the Sunda folds (Figure 12) may also pose a risk to trap preservation (i.e. top seal risk), especially when the post-unconformity are sandy transgressive sediments.

Another major play type in the post-rift section is the basement drape play, which is essentially comprises compactional drape features in early post-rift or late synrift section over a basement structure. For the late synrift sequence, the play was proven by the Rhu-1/1A oil discovery (Figure 22). The main reservoirs are fluvial sandstones in the Penyu Formation, whereas interbedded claystone/shale intervals in the Terengganu Formation provide the



**Figure 20:** Geohistory and subsidence curves for selected wells in the Penyu Basin. (A) Penyu-1, (B) Rumbia-1, (C) Rhu-1/1A. For each well, the upper plot is sediment accumulation curves (or “geohistory”, Van Hinte, 1978), with each line representing the stratigraphic markers, see Figures 6 and 9). The lower plot is water-loaded subsidence curve for the top of pre-Tertiary basement, calculated using backstripping technique (Watts & Ryan, 1976). Vertical bar over each point represents the uncertainty in the calculation. The water-loaded subsidence curves essentially represents the basement subsidence over time since basin opening with the effect of sediment loading removed, i.e. the basin is filled with water. Note the dashed black lines and question mark represents the uncertainty in the age of start of subsidence (basin opening) which may be between 35 to 45 Ma (Eocene). (D) Upper plot represents water-loaded tectonic subsidence (black circles and lines) for wells at the centre of major half-grabens. The lower plot represents water-loaded tectonic subsidence for wells on the intrabasinal highs. For comparison, blue dotted lines represent tectonic subsidence curves for rift basin based on McKenzie (1978), assuming a rifting phase from 40 Ma to 27 Ma. Three curves represent stretching factor  $b=1.5, 2.0, 2.3$ . Well identification on the plots: 1- Penyu SW-1, 2- Cemara-1, 3- Merchong-1, 4- Rumbia-1, 5- Cherating-1, 6- Penyu-1, 7- Rhu-3, 8- Rhu-2, 9- Soi-1, 10- Rhu-1, 11- Pari-1. For well locations, see Figure 4.



**Figure 21:** Penyu Basin temperature gradients ( $^{\circ}\text{C}/100\text{m}$ ) calculated from borehole measurements (Kessler & Jong, 2018).

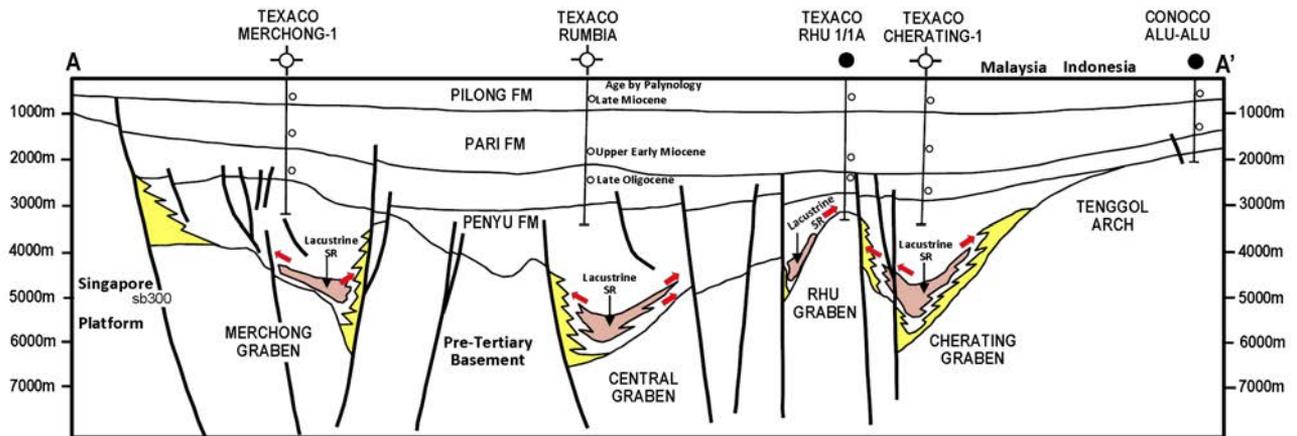
seal. The Rhu-1/1A oil appears to have migrated from a lacustrine source rock in the deep half-graben up the gently dipping hanging-wall ramp margin to the Rhu Graben to the south of the structure, into late synrift sandstone draping an anticlinal high. The anticlinal closure near the Base Pari seismic horizon seems to persist downwards through the Terengganu and Penyu formations. The play works because the sediment drape and the associated fault traps above the Rhu Ridge were in existence before the onset of hydrocarbon migration. Bed-parallel migration rather than vertical migration *via* fault conduits appears to be a key charge element of this play (e.g. Jong *et al.*, 2019b).

The Batu Hitam-1 well also tested the basement drape play by drilling a compactional drape structure over a basement high feature, targeting the Upper Penyu reservoir sequence in the synrift section. The secondary target was the pre-Tertiary basement. No hydrocarbons were found in the Penyu reservoir. The well penetrated 150 m of the pre-Tertiary basement of granodiorite with no shows, although the FMI log indicated potentially open fracture network (Lundin Malaysia, 2011).

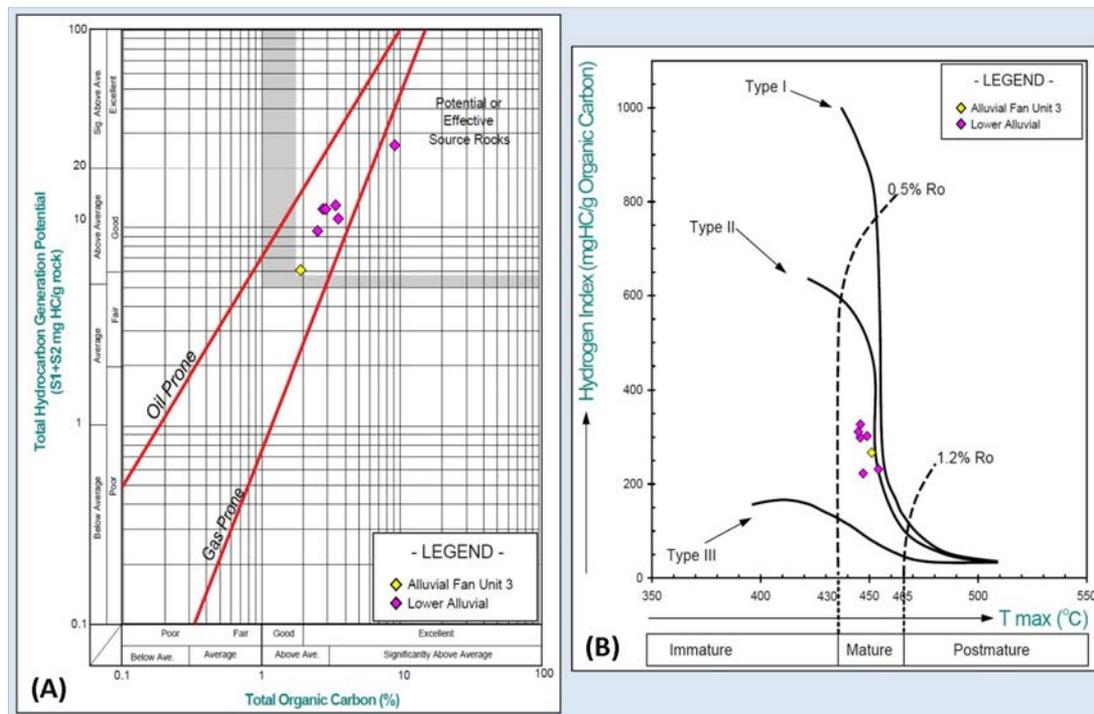
There are additional plays that remain to be tested. Besides conventional structural traps, there are plays such as stratigraphic traps, including fluvial deposits of the lower synrift graben-fill that onlap onto basement highs (Figure 22). In this play type, alluvial fan sediments deposited on the hanging-wall and footwall of half-graben faults could potentially form the reservoirs. In this play, trapping of hydrocarbons may be achieved in alluvial fan sediments sealed at the top of the trap by overlying shale/claystones or intraformational shale units and by a base seal consisting of impervious basement. Such a base seal carries a very high risk, as pointed out earlier from the Batu Hitam-1 well results which suggest potentially open fractures from the FMI log.

Janglau-1 well, Lundin Malaysia's fourth well, was also drilled in 2011 to test Late Eocene to Early Oligocene (synrift) alluvial sands overlying a pre-Tertiary basement high, the latter being the secondary drilling objective. Post-rift sediment drapes over basement highs are usually reservoir-poor compared to the synrift sediments adjacent to the half-graben normal faults. There was a high confidence in the synrift package based on the 3D seismic data but the three-way fault-dependent closure relied on an effective seal against the basement as well as a sealing fault. Geochemical analyses of intra-rift source rocks from Janglau-1 well clearly show the presence of effective source rocks in the Cherating Graben to the north of the structure (Figure 23).

Well Ara-1 also tested intra-rift sands, but in a down-dip location to Janglau-1, about 2600 m to the west. It is a three-way fault-dependent closure, structurally well-defined on 3D seismic data and supported by seismic amplitude anomalies. The well targeted intra-rift (synrift) packages that are equivalent to those encountered at Janglau-1 (Figure 24). It was one of the deepest wells drilled in the basin, and penetrated numerous alluvial fan sequences terminating in the basal synrift section. As Janglau and Ara appear to be located in the same migration path, the hydrocarbon may have originated from the same source rock kitchen in the Cherating Graben to the north of the structures (Figure 22). Janglau-1 and Ara-1 were minor oil discoveries with oil in very tight formations in the Lower Palaeogene. Despite the apparent lack of effective reservoirs, the positive results from Janglau-1, Ara-1 and, in particular the Rhu-1/1A well, suggest that oil has been generated in the synrift sequence and migrated up the flanks of the half-grabens. Arguably, these hydrocarbons occur within low-permeability sediments due to porosity-occluding diagenetic processes at burial depths >



**Figure 22:** Geological cross section along profile AA' in Figure 7 across the main graben systems, showing a schematic model of structural trapping mechanisms and hydrocarbon migration pathways in the Penyau Basin.



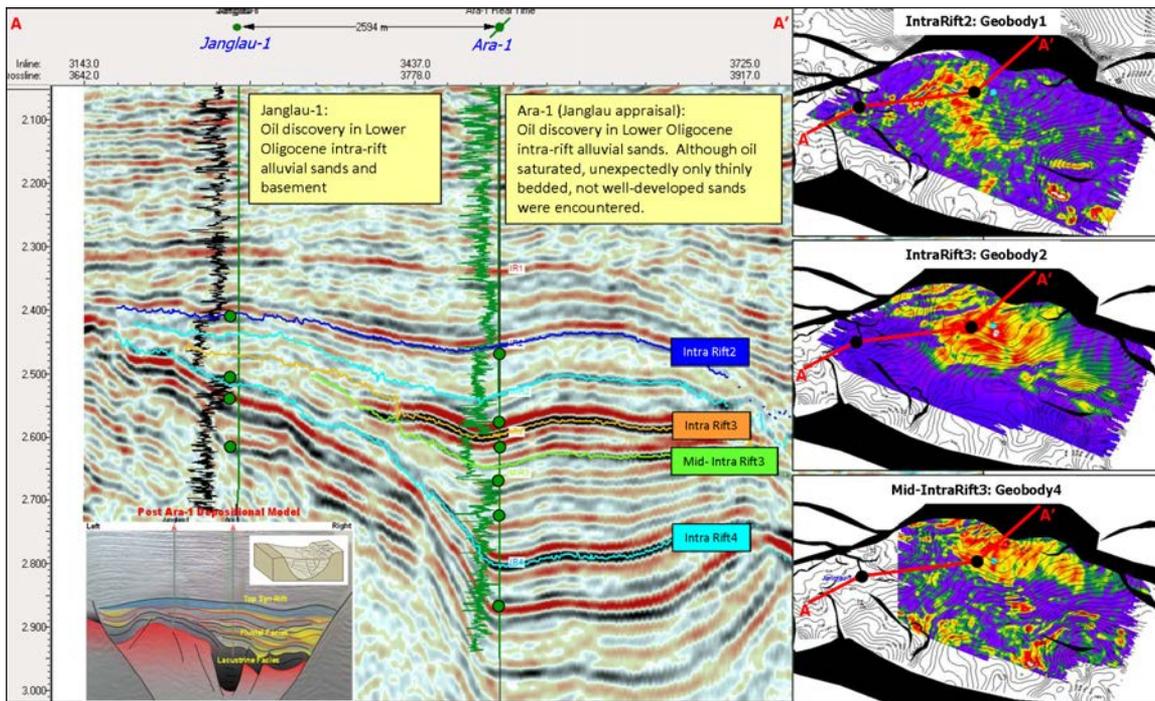
**Figure 23:** Geochemical analytical results of Janglau-1 intra-rift source rocks. (A) RockEval data indicating potential or effective source rocks. (B) Van Krevelen diagram showing the mature source shales containing oil-prone Type II kerogen. These results clearly show the presence of effective mature source rocks in the Cherating Graben.

2000 m such as quartz cementation and clay mineral alteration (Kessler & Jong, 2018). Oil-bearing reservoirs may occur in other parts of the basin where diagenesis has been less severe, but deeper sections of the rift branches may suffer from adverse reservoir diagenesis in thermal hot spots.

Merawan Batu-1 targeted a similar trap style as Janglau-1 but the trap closure appears to have been less well-defined and it turned out water wet. The final well by Lundin Malaysia, Selada-1 was drilled in 2015 on a basement-drape feature (Malong look-alike) but although good-quality reservoirs were found, the prospect was

water-bearing. In this case hydrocarbon charge is thought to be the main risk factor and not trapping.

Besides hydrocarbon charge, reservoir porosity preservation may also be a risk factor, especially if reservoirs are at depths greater than 2000 m and porosity reduction by compaction during shallow burial is overtaken by quartz cementation. Studies in Malay and Penyau basin diagenesis (Chu, 1992; Kessler & Jong, 2018) showed that the onset of quartz cementation occurred at around 1800-2000 m burial depth, slightly deeper than that quoted for the Malay Basin (~1200 m, Chu, 1992; Madon, 1994). Besides quartz



**Figure 24:** Latest exploration wells Janglau-1 and Ara-1 in the Rhu Graben have resulted in oil discoveries in the intra-rift section of the graben. The geobodies as highlighted on the left based on amplitude extraction suggest potential better reservoir development areas which were proven tight and therefore bright amplitudes do not necessarily indicate good reservoir sections in the Rhu Graben. Further lithology and fluid prediction based on quantitative interpretation (QI) and seismic inversion studies incorporating well outcomes are recommended to help differentiate zones of better reservoir development. However, it is also noted that the intra-rift section in the graben area might have been affected by burial diagenesis resulted in deteriorating reservoir characters (Maga *et al.*, 2015; Kessler & Jong, 2018).

cements, pore-filling clays such as kaolinite also have impact on reservoir quality, especially in feldspar-bearing sandstones. Kessler & Jong (2018) predicted that complete obliteration of porosity may occur at burial depths of about 3250 m. The porosity trend does not appear to be related to heat flow or temperature gradient (Figure 21) but requires further investigation.

To assist in the assessment of the hydrocarbon potential in the basin, the concept of “play segments” was applied by mapping discrete areas of the basin that possess a common charge and timing or migration risk for a particular reservoir target (Figure 25). This involves several steps: (i) overlay the reservoir-trap intervals with the source rock pods or kitchens, (ii) identify the migration path between the source rock and the reservoir/trap, (iii) for each play segment identify the sealing mechanism, which may be one of several possible mechanisms such as regional shale seal, fault-assisted trap or basement juxtaposition

The K-shale map in Figure 25 shows the various play segments identified, given that it is one of the unambiguous interpretation events and also roughly coincides with the Oligocene to Miocene boundary. Furthermore, it shows a drainage pattern which developed within the Late Oligocene and focused charge towards the edges of the Penyu Basin. The key components of petroleum system elements of the identified play segments in the basin are briefly summarised below (Table 3; also see Figure 6 for stratigraphic nomenclature):

### Segment 1

There is potential for stratigraphic (pinchout) traps, with oil charge from the Malay/Natuna basins particularly in the K group but reservoir continuity may be a risk factor. Good reservoirs are expected in upper Penyu and lower Pari formations (equivalent to I, J, and K groups). Seal rocks may become discontinuous NW of Tembakau discovery.

### Segment 2

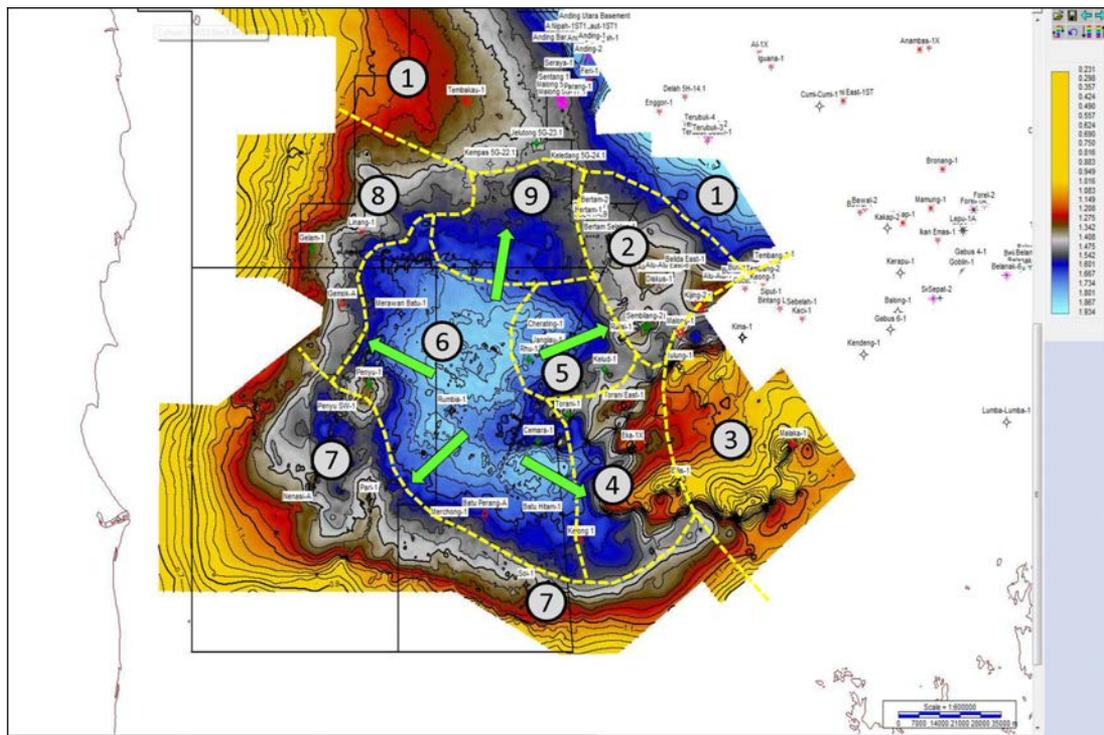
There is good potential for relatively small drape structures, like Bertam or Malong fields, with oil in upper Penyu (Group K) reservoirs charged from either the Malay or Penyu basins. Reservoir pressure may be contiguous with the Bertam and Belida fields (in Indonesian waters).

### Segment 3

This is an area of relatively small, complex and wrench-induced and/or inversion traps. Hydrocarbon charge could be from mature gas kitchen in (Groups I and K) carrier beds, with good reservoir properties in Group K equivalent sands. Overall, Segment 3 has good prospectivity for gas.

### Segment 4

Small wrench-induced and/or inversion traps in this segment have mostly been tested. The main reservoirs occur



**Figure 25:** Play segments defined by Lundin Malaysia, overlay on regional time structure map of K shale which roughly coincides with the Oligocene to Miocene boundary showing a drainage pattern (green arrows) developed within the Late Oligocene and focused charge towards the edges of the Penyu Basin. Light blue to dark blue = depocentres, light grey to brown = basin fringes, orange to red = structurally high areas.

in the late synrift upper Penyu (Group K) and possibly also in the older section.

**Segment 5**

Charge has been proven in at least two levels in the lower Penyu (Group M) section, with both structural and stratigraphic trapping mechanisms. As an example, the Rhu oil discovery was tested with producible oil, but with a small accumulation mainly in the M sand as mentioned earlier. In addition, there were strong oil shows in Ara and Janglau in the pre-Oligocene reservoirs, but oil may not easily producible (lack of reservoir permeability).

**Segment 6**

This is an area of relatively small, complex and wrench-induced and/or inversion traps. Hydrocarbons are expected from mature gas kitchen in the Groups I and K carrier beds, with good reservoir properties in Group K equivalent sand. Overall, the segment has good prospectivity for gas, with remaining potential in a few intra-basinal highs, of which several have been drilled. The northern area near Merawan Batu hosts several highly tectonised structures and broken-up Oligocene reservoir with sporadic charge.

**Segment 7**

This segment has good potential for pinchout and drape structures. There are two active kitchens, which

provide the charge for oil in the Group I and J equivalent units. Potential seeps are indicated by the observed gas chimneys.

**Segment 8**

Potential for very minor pinch-out traps occur in this segment. However, there may be limited access to hydrocarbon charge from the Kuantan and Jelai grabens (Figure 3).

**Segment 9**

This segment is yet to be drilled, with potential for pinchout traps (Oligocene upper Penyu sands). Seal effective may be a major risk, with oil migration likely to be from Cherating Graben (Figure 3).

**FULL-TENSOR GRADIOMETRY (FTG) DATA**

Since 2012 there have been efforts to enhance the exploration potential of the offshore basins in Malaysia, through improved basin definition and structural interpretation, by acquiring full-tensor gradiometry gravity and magnetic data. In collaboration with Malaysia Petroleum Management (MPM), Bell Geospace has acquired FTG data that would enable re-evaluation of the structural interpretation, particularly in areas that are poorly covered by seismic. In the Penyu Basin, improved imaging of the major faults and pull-apart grabens as well as the identification of

**Table 3:** Summary of petroleum system elements and exploration potential of the defined play segments in the Penyu Basin (see Figure 25). The I, J (post-rift) and K, L and M (synrift) units are following the Malay Basin's group nomenclature (see Figure 6 for further information).

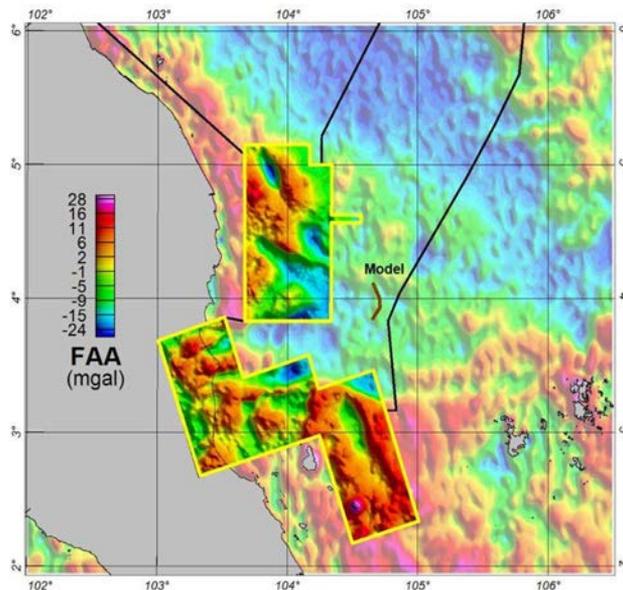
Play Aspects	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	Segment 7	Segment 8	Segment 9
<b>Charge - Mature SR</b>	none	none	none	Potential spotty mature SR in synrift	Proven lacustrine source rock mature for oil (Pari to recent)	Suspected SR in local depressions, some continuous and some spotty.	Major source rock North and South of Nenasi	SR patches at Penyu graben margin, low lateral extent.	SR in Cherating Graben, potentially extending North to edge of graben.
<b>Lateral migration in units</b>	Oil from Malay/ Natuna basins in K, sometimes oil/gas in J, and I.	Oil from both Malay Basin and Penyu grabens in K and Rhu carrier beds.	Gas from mature gas kitchen I, K carrier beds.	Mainly synrift section occasionally younger, migration West to East.	Oil in locally charged synrift reservoirs, no major lateral migration	Oil traces mostly in K and J sands; migration of oil mainly in South direction.	Good oil indications in I, J levels; two active kitchens, Migration towards Nenasi.	Minor I, J, no K, some shows in synrift; gas migration.	No well results, undrilled; migration updip from Cherating Graben.
<b>Reservoir characteristics</b>	Excellent sand in I, J, good K.	Good sand in K	Good sand in K	Reservoir in K and older	Good sands in M unit in Rhu discovery. Very poor poroperm in Penyu.	Expected fairways of sands in I, J.	Expected fairways of sand in I, J, K.	Expected minor fairways of sand in I, J.	Poor quality Penyu and good Rhu sand.
<b>Seal characteristics</b>	K Shale + some other	K shale + some other	K shale + some other	K shale + some other	Intra-Penyu	Intra-Penyu, Pari I, J, K.	Intra-Penyu, Pari I, J, K.	Intra-Penyu, K	Intra-Penyu, K.
<b>Tectonic dynamics</b>	Quiet since Oligocene	Quiet since Oligocene	Some Miocene inversion tectonism	Some Mio inversion tectonism	Largely quiet since Oligocene	Some inversion, strike-slip in Miocene	Some Miocene inversion tectonism	No major tectonic activity since Oligocene	No major tectonic activity since Oligocene
<b>Subjective appeal low to high</b>	good	good	good	Challenging, Most highs are drilled	Major reservoir problems	Prospective in intra-basinal highs	Good - updip of charge	Low - limited kitchen	Moderate. Very high seal risk.
<b>Status of exploration</b>	Expected drilling 2-3 wells	Development K oil pools	Production of gas	Dropped marginal discoveries	Dropped with marginal oil	Batu Perang proposal	Nenasi proposal	Dropped with no material prospects	Potential candidate well.

low-relief closures would assist in identifying new plays and drilling targets. FTG surveys were conducted by Bell Geospace, under contract with Lundin Malaysia, on the Tenggol Arch north of the Penyu basin in 2013 and in the area around Tioman Island for MPM in 2015. Subsequently, the entire basin was covered by FTG and Magnetic surveys as part of a Pan Malaysia MultiClient FTG programme coordinated by Bell Geospace and MPM (Figure 26).

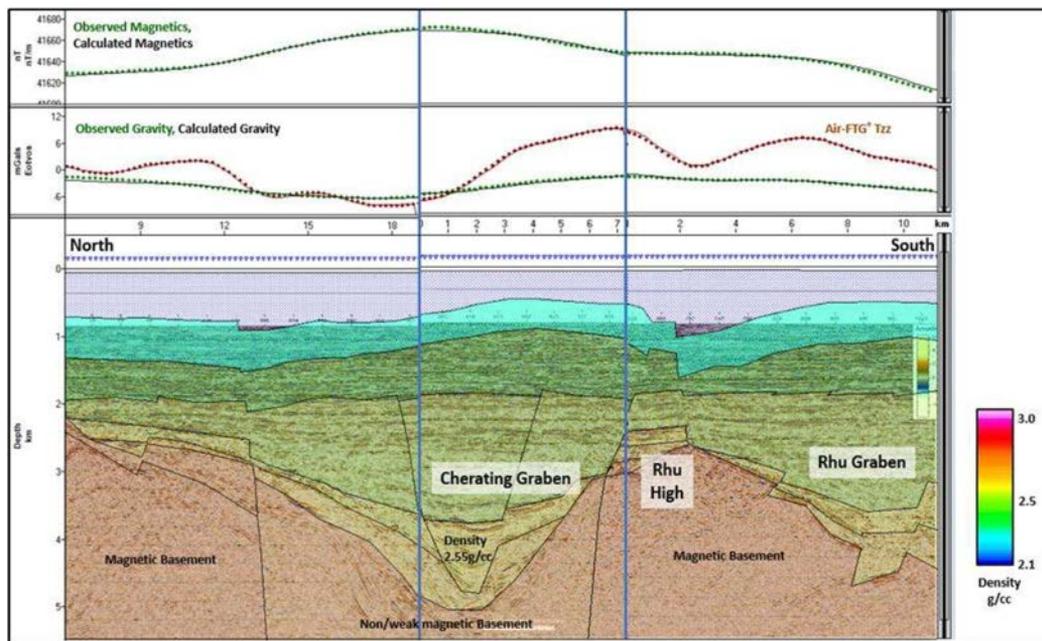
Results from the FTG interpretation showed that gravity anomalies correlate well with basement features observed in seismic on the Tenggol Arch. When applied in combination with 3D seismic, FTG allowed the mapping of graben branches (main boundary faults, grabens and horsts) in the northern Penyu Basin and in the Kuantan Graben. For plays that rely on long-distance migration from the hydrocarbon expulsion areas, identification of low-relief structures could be improved by integrating seismic interpretation with high-resolution potential field data provided by the FTG method.

As an example, a 2D forward model shown in Figure 27 identifies the presence of these low relief structures in NE Penyu Basin. In this model, Free Air anomaly (FTG-Tzz component), satellite-derived gravity and magnetic (TMI) data were extracted along a seismic profile (Figure 14B) from NE Penyu Basin over the Cherating and Rhu graben structures. The composite seismic/gravity profile comprising three separate seismic sections clearly show the presence of the graben structures overlying basement. The basement is modelled with moderate complexity from magnetics (top and lower panels, Figure 27) indicating that a central block of weak magnetic susceptibility resides beneath the Cherating Graben

and is flanked by more magnetically susceptible lithology likely to represent crystalline/igneous rocks. Magnetic data from low latitudes normally show very low magnetic field declination and inclination values, thus yielding low amplitude



**Figure 26:** FTG surveys carried out in the Penyu Basin area. Areas outlined in yellow show the Tenggol Arch (2013) and Tioman Island area (2015) FTG gravity; black outline locates additional FTG surveys acquired as part of the MultiClient programme. The brown polyline locates the 2D forward model shown in Figure 27 with seismic profile as shown Figure 14B. Background is satellite-derived free-air gravity data from Sandwell *et al.*, 2014.



**Figure 27:** 2D forward model along North-South composite seismic line located in NE Penyu Basin (see Figure 14B). Top panel shows observed (green) and calculated (black) magnetic response; Middle panel shows observed (green) and calculated (black) gravity response and observed (brown dotted) and calculated (brown solid) FTG Tzz response; Lower panel shows modelled lithology against seismic backdrop. Colours depict density change.

positive anomalies for non/weakly magnetic sources. The satellite gravity data (middle and lower panels, green/black curves, Figure 27) supports the magnetics insofar as moderate densities of 2.74 to 2.76 g/cc are assumed and suggests the presence of locally higher density material associated with the igneous enriched basement blocks. A non-magnetic layer with density 2.6 g/cc is modelled above the crystalline basement and is interpreted as representing metasedimentary rock; the conventional gravity data requiring a wide distribution of such a layer to fit the model.

The FTG data show greater sensitivity to density contrasts (middle and lower panels, Figure 27) in the shallow section. As a result, the model requires the presence of a shallow layer with a density contrast of 0.2 g/cc at depths of 1 to 1.5 km below sea-level. The low relief structure indicated by the shallow layer is interpreted as inversion related anticlinal feature developed above the Cherating and Rhu grabens, as clearly identified in seismic.

### CONCLUSIONS

The Penyu Basin was formed by crustal extension associated with a zone of major strike-slip faulting in the Early Tertiary. It evolved from a series of isolated non-marine half-graben basins in which lacustrine source rocks were deposited. The basin structure is dominated by ENE-trending normal faults and NW-trending combined dip- and strike-slip faults. Fault geometry and orientation suggest a basin development from regional N-S extension associated with left-lateral strike-slip fault zone. Pre-existing basement faults appear to have had a strong control on basin configuration. Lacustrine claystones and shales in isolated synrift basins are thought to be the main hydrocarbons source for hydrocarbons that may be trapped in both synrift and post-rift structures.

The Penyu Basin has been explored for more than fifty years, and much knowledge has been gained from a wealth of geological, geophysical and geochemical information. Unfortunately, exploration results in the basin have not been highly successful, with the Rhu discovery in 1992 being the only significant find. For future economic evaluation, however, a cluster development concept for the Rhu discovery and Janglau/Ara appraisal, coupled with near field exploration potential, may be a feasible option for development under improved PSC terms.

The main exploration play types in the basin are the compressional fold play (Sunda folds), late synrift basement-drape play, and synrift stratigraphic play. Most of the Sunda folds have been tested by the drill but with little success. The basement-drape play has been proven by the oil discovery at Rhu. The more speculative synrift play holds promise, but detailed understanding of the controls on reservoir distribution and preservation is essential for identifying drilling targets. With further detailed studies and interpretation of newly acquired data (3D seismic and FTG gravity/magnetics), new plays may emerge. It is believed that there still remains a potential for further

leads to be explored. Application of new techniques (e.g. basin modelling, advanced quantitative interpretation, high-resolution potential field techniques such as FTG) is expected to help in the identification of new play types, including subtle stratigraphic traps.

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