

Pre-Tertiary basement subcrops beneath the Malay and Penyu basins, offshore Peninsular Malaysia: Their recognition and hydrocarbon potential

MAZLAN MADON^{1,2,*}, JOHN JONG³, FRANZ L. KESSLER⁴, M. HAFIZ DAMANHURI⁵,
MOHD KHAIRIL AZRAFY AMIN⁶

¹ Malaysian Continental Shelf Project, National Security Council, Malaysia

² Department of Geology, Universiti Malaya, 50603 Kuala Lumpur, Malaysia

³ JX Nippon and Gas Exploration (Malaysia) Limited, Kuala Lumpur, Malaysia

⁴ Goldbach Geoconsultants O&G and Lithium Exploration, Germany

⁵ PETRONAS Carigali Sdn. Bhd., Malaysia

⁶ Malaysia Petroleum Management, PETRONAS, Malaysia

* Corresponding author email address: mazlan.madon@gmail.com

Abstract: Following the successful production from fractured basement in similar Tertiary basins, the basement play was pursued in the Malay Basin, particularly during the 2000-2010 period but, unfortunately, that effort fell short of expectations. The only oil discovery in fractured basement reservoir was Anding in the southwestern part of the basin. Despite its development being delayed due to economic reasons, the Anding discovery had been the basis for the basement play concept: namely, a fractured reservoir formed of pre-Tertiary metamorphic rock, charged from overlying Tertiary lacustrine source rocks in an adjacent half-graben and sealed by a transgressive shale unit. This paper examines seismic, gravity and well evidences on the pre-Tertiary basement geology, with the aim of assessing further the hydrocarbon potential of pre-Tertiary basement. The pre-Tertiary basement subcrops beneath the Malay and Penyu basins represent a continuation of the onshore geology of Sundaland Mesozoic terrane. Wells that penetrate the Base-Tertiary Unconformity (BTU) indicate a variety of rock types including igneous, metamorphic and sedimentary. Seismic data show the widespread presence of layered rocks beneath the BTU which could include potential new plays. Gravity modelling was carried out to help distinguish between pre-Tertiary layered rocks and Tertiary synrift sediments. Fractured reservoirs, like those discovered at Anding, seem to be associated with major strike-slip fault zones which are identifiable on high-quality seismic. Carbonate structures such as paleokarsts and buried hills are also recognisable and could potentially be mapped with seismic. These pre-Tertiary plays also rely on hydrocarbon charge mainly from the overlying Tertiary source rocks. Although Palaeozoic-Mesozoic source rocks may have passed their hydrocarbon generation stage, their gas potential cannot be ruled out.

Keywords: Pre-Tertiary basement, Malay Basin, Penyu Basin, Palaeozoic, Mesozoic, fractured reservoir, paleokarst

INTRODUCTION

Out of 700 exploration wells drilled in the Tertiary basins off the east coast of Peninsular Malaysia, namely Malay and Penyu basins (Figure 1), more than 70 wells (about 10%) had penetrated pre-Tertiary basement. The latter comprises a variety of rock types, including igneous, metamorphic and sedimentary. These rocks represent a continuation of the pre-Tertiary geology of the surrounding landmasses which may be regarded as the “pre-rift” subcrop of a peneplain above a Late Mesozoic orogen (Sundaland), which had remained emergent probably until Mid-Eocene times. Based on the regional geology and available well data, and the integration of seismic reflection and gravity data interpretation in the Tenggol Arch area, rocks beneath the Base-Tertiary Unconformity are likely to include sedimentary rocks (some probably low-grade metamorphic) of Palaeozoic and Mesozoic age. The heterogeneous nature of the pre-Tertiary basement subcrops presents a challenge in the search for potential exploration targets. While fractured

basement could be identified by its close association with fault or shear zones, the ability to distinguish between carbonates and siliciclastics in the pre-Tertiary would be an important step towards identifying prospective drilling targets. Despite its heterogenous nature, the pre-Tertiary in this region is traditionally referred to as “basement”; a practice that is followed here.

From a petroleum geology standpoint, the pre-Tertiary reservoir potential is relatively high risk, as mineral transformation during late-stage diagenesis (e.g., Madon, 1994; Maga *et al.*, 2015; Kessler & Jong, 2018) to early metamorphism may have obliterated much of the original porosity and, more so, permeability. In addition to tectonic fracturing associated with faults and shear zones, post-diagenetic and post-burial processes, including paleo-weathering and karst formation in carbonates sequences, may also be important in enhancing the porosity of otherwise non-reservoir rock. Hence, the key to basement exploration is identifying basement rock type, as well as locating faults

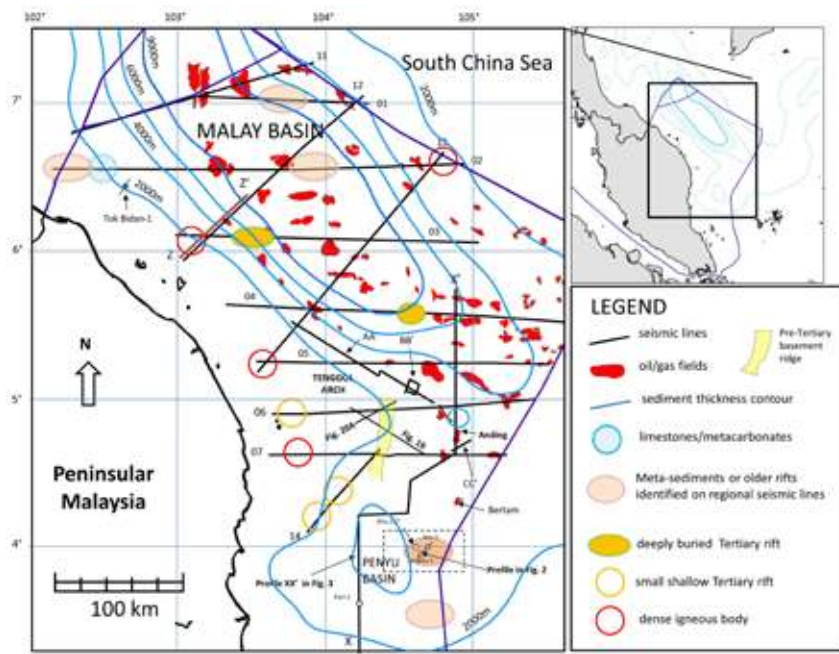


Figure 1: Location map of study area in the Malay and Penyu basins, offshore Peninsular Malaysia. Black lines are seismic profiles mentioned in this paper. Also shown, based on the present study, are the locations of pre-Tertiary basement features identified on those seismic lines, supported by gravity data, such as layered metasediments or older rifts, dense igneous bodies and limestones/metacarbonates. There are also small Tertiary rifts, both on the flanks and in the central basin part of the Malay Basin. Line XX' is a composite seismic profile shown in Figure 3. Sediment thickness contoured at 2000, 4000, 6000 and 9000 m to show the overall geometry of the basins. Pre-Tertiary basement ridge on Tenggol Arch is the feature identified in profiles shown in Figures 12, 13, 16, 17, 19 and 20.

or shear deformation zones using modern 3D seismic data and appropriate technologies.

As the basins approach exploration maturity, the “traditional” hydrocarbon plays are being depleted and the current inventory of prospects and leads consists of only small and subtle stratigraphic, structural or combination traps. Oil companies have started to drill into deeper, over-pressured reservoirs beneath the existing oil and gas fields. Exploration activities have also been extended further outward onto the basin flanks in the search for new plays in the smaller half-graben basins. Occasionally, since the mid-1980s, some of those wells had penetrated the pre-Tertiary basement as secondary objectives. Since the early 2000s, however, deliberate effort was made to explore for hydrocarbon traps in the pre-Tertiary and has resulted in a few minor discoveries, so far none of which are commercial. Nevertheless, the “fractured basement play” still remain as one of the future exploration targets along with other technically challenging “non-traditional” plays such as basin-centre gas and high-pressure-high-temperature (HPHT) reservoirs.

As indicated above, “basement” in this paper refers to rocks beneath the major erosional unconformity at the base of the Tertiary in both the Malay and Penyu basins. That unconformity, referred to herein as the “Base-Tertiary Unconformity” (BTU), is clearly identifiable on seismic in most places except in the deepest parts of the basin where seismic resolution is poorer. The BTU is easily recognized especially on the basin flanks as a prominent high-amplitude reflector that marks a significant contrast in acoustic impedance (due to contrast in density and velocity) between Tertiary sediments and pre-Tertiary rocks. The unconformity is interpreted to represent the eroded Mesozoic to Early Tertiary penneplain surface that existed prior to crustal extension and subsidence during Early Tertiary.

Although most accounts of the stratigraphy of the Malay and Penyu basins have reported that the oldest sediment is Oligocene (e.g., Azmi *et al.*, 1994), the presence of sediments older than Oligocene has never been ruled out. Seismic evidence suggests that pre-Oligocene sediments may be widespread; many of the deep half-grabens that are seen on seismic have not been penetrated but could well be filled with Eocene sediments. At those depths (>3.5 km), the poor seismic resolution and lack of biostratigraphic information have made it difficult to differentiate between pre-Oligocene Tertiary sediments and pre-Tertiary rocks beneath the BTU. Occasionally, these basal Tertiary sediments have been encountered in exploration wells. Well Janglau-1, drilled by Lundin in 2011 in the Penyu Basin, penetrated 281 m of layered seismic facies in the pre-Tertiary basement which turned out to be low-grade metasediments, probably Jurassic to Cretaceous in age (Figure 2). Well records showed that the first 81 m of rock below the BTU at 3539 m is a weathered zone characterised by chaotic dip-meter readings due to abundant fractures, but with low permeability. The pre-Tertiary metasediments have sparse palynomorph data that suggest Mesozoic age, possibly Late Triassic/Jurassic (Lundin, 2012). Down-dip from Janglau-1, well Ara-1 was drilled to test the stratigraphic equivalent of the oil-bearing Upper Eocene/Oligocene sediments at Janglau-1. Ara-1 did not penetrate the pre-Tertiary basement but was terminated in lacustrine mudstones dated by palynomorphs as Late Eocene (Lundin, 2013; Kessler *et al.*, 2020). Seismic data (as shown in Figure 2), however, suggest that a thick Eocene section is likely to be present below TD (total depth) at Ara-1, representing the synrift deposits of the deep half-graben at that location. By analogy, many deep half-grabens not yet penetrated in the Malay Basin may have significant thicknesses of Eocene sediments (as indicated in Figure 3A).

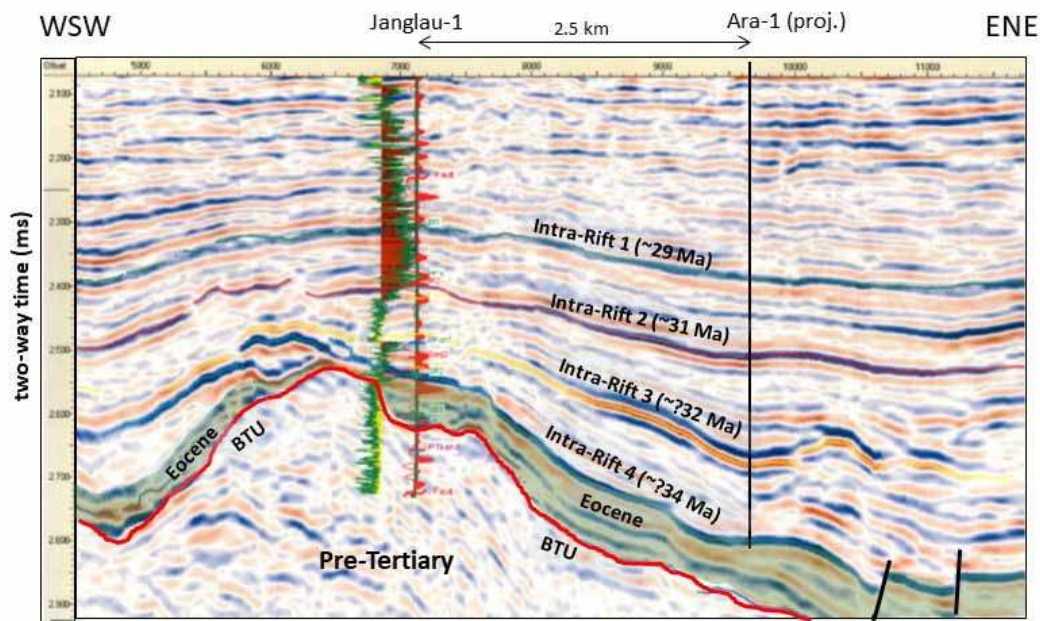


Figure 2: Seismic profile through wells Janglau-1 and Ara-1 (projected) showing a package of Eocene synrift sediments above the Base-Tertiary Unconformity (BTU) in the Rhu half-graben, Penyu Basin. Modified from Lundin (2011). Line location shown in Figure 1. Note that assigned ages of seismic markers are tentative.

The Malay and Penyu basins have similar structural and stratigraphic histories and may be considered as parts of a Tertiary basin complex separated by the Tenggol Arch basement high. A regional composite seismic profile crossing the Tenggol Arch from south to north (Figure 3A) shows the structural style and stratigraphy correlated across the two basins. The profile highlights the rifted geometry of the pre-Tertiary basement underlying the Penyu Basin and southern Malay Basin and a relatively flat BTU on the Tenggol Arch, as a result of the Late Mesozoic peneplanation. It also shows the rarely penetrated, basal synrift sediments of probably Eocene age likely to occur in the deep half-grabens in both basins. The seismic data also indicate the presence of layered rocks beneath the BTU on the Tenggol Arch that are probably Palaeozoic and Mesozoic metasediments, equivalent to those on Peninsular Malaysia. In light of the highly variable onshore geology, it is expected that offshore pre-Tertiary subcrops may include not just igneous rocks, such as granites and basalts, but also layered sedimentary rocks, metamorphosed or otherwise.

This study examines the seismic, well, and gravity evidences on the nature of pre-Tertiary basement rocks beneath the BTU, and reviews the status and potential of the “basement play” in the Malay and Penyu basins. It is hoped that, with this knowledge, along with the application of appropriate seismic technologies to the identification of natural fractures, as well as subtle stratigraphic features in the pre-Tertiary basement, the study provides useful information for the search of basement reservoirs.

REGIONAL GEOLOGICAL FRAMEWORK

The Malay and Penyu basins are two of several major extensional basins developed on Sundaland, the founded Late Mesozoic orogen that represents the continental core of SE Asia. The basins form part of a complex system of

rifts stretching from onshore Thailand to the Natuna area. This rift system includes the onshore Thai basins, the Gulf of Thailand basins (including Pattani Trough), and the Malay-Penyu-West Natuna basin complex, which seem to have developed along the Three Pagodas-Malay-Natuna shear system (Morley, 2004). In similar tectonic models, the Malay and Penyu basins are interpreted to have developed from pull-apart along major NW-SE strike-slip fault zones (Madon & Watts, 1998; Madon *et al.*, 2019).

The Malay Basin developed into a NW-SE trending elongated basin with a steeper western flank and a gently sloping eastern flank. The Tenggol Arch is an inter-basinal high that separates the Malay Basin from the east-west trending Penyu Basin to the south (Figure 1). Both the Malay and Penyu basins seem to merge with West Natuna Basin across the maritime boundary with Indonesia. As mentioned, the basins are generally assumed to have undergone rifting in the Late Oligocene, based on the age of the oldest sediments penetrated by exploration wells to date. Some authors (Ngah *et al.*, 1996, Tjia & Liew, 1996), however, have previously suggested that basin initiation may have started earlier, probably in Middle to Late Eocene. This is now proven by the presence of Eocene synrift sediments in the Penyu Basin wells Janglau-1 and Ara-1 shown earlier in Figure 2 (Kessler *et al.*, 2020). Post-rift sedimentation in both basins during early Miocene to Recent were accompanied by basin inversion from late Early Miocene to Pliocene times (Madon *et al.*, 2006, 2019). A summary of the stratigraphy and major tectonic phases is given in Figure 3B.

Similarly, in both onshore and offshore Thailand, most rift basins are dated as Late Oligocene based on palynological studies (Morley & Racey, 2011), but there have been reports of Eocene sediments in some basins (e.g., Mae Sot, Mae Tun, and Hongsa). Further to the south, the West Natuna Basin has long been regarded as Late Eocene

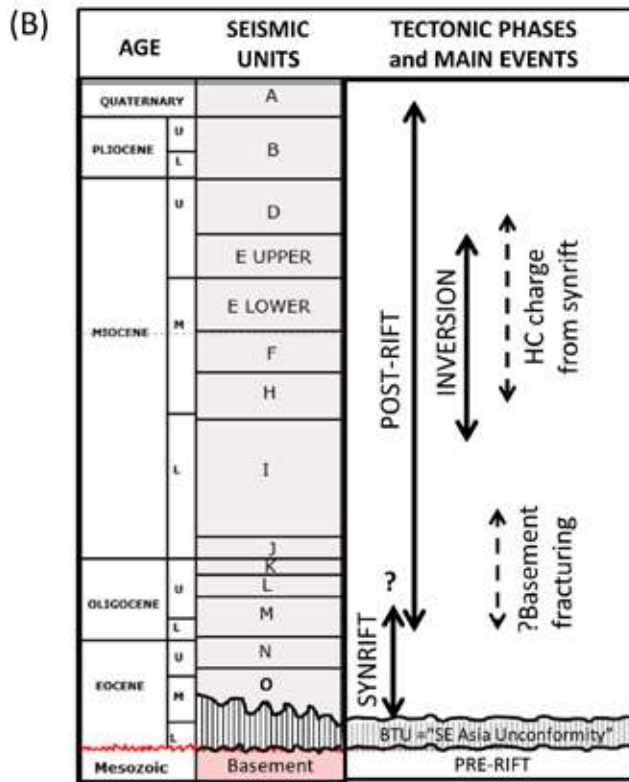
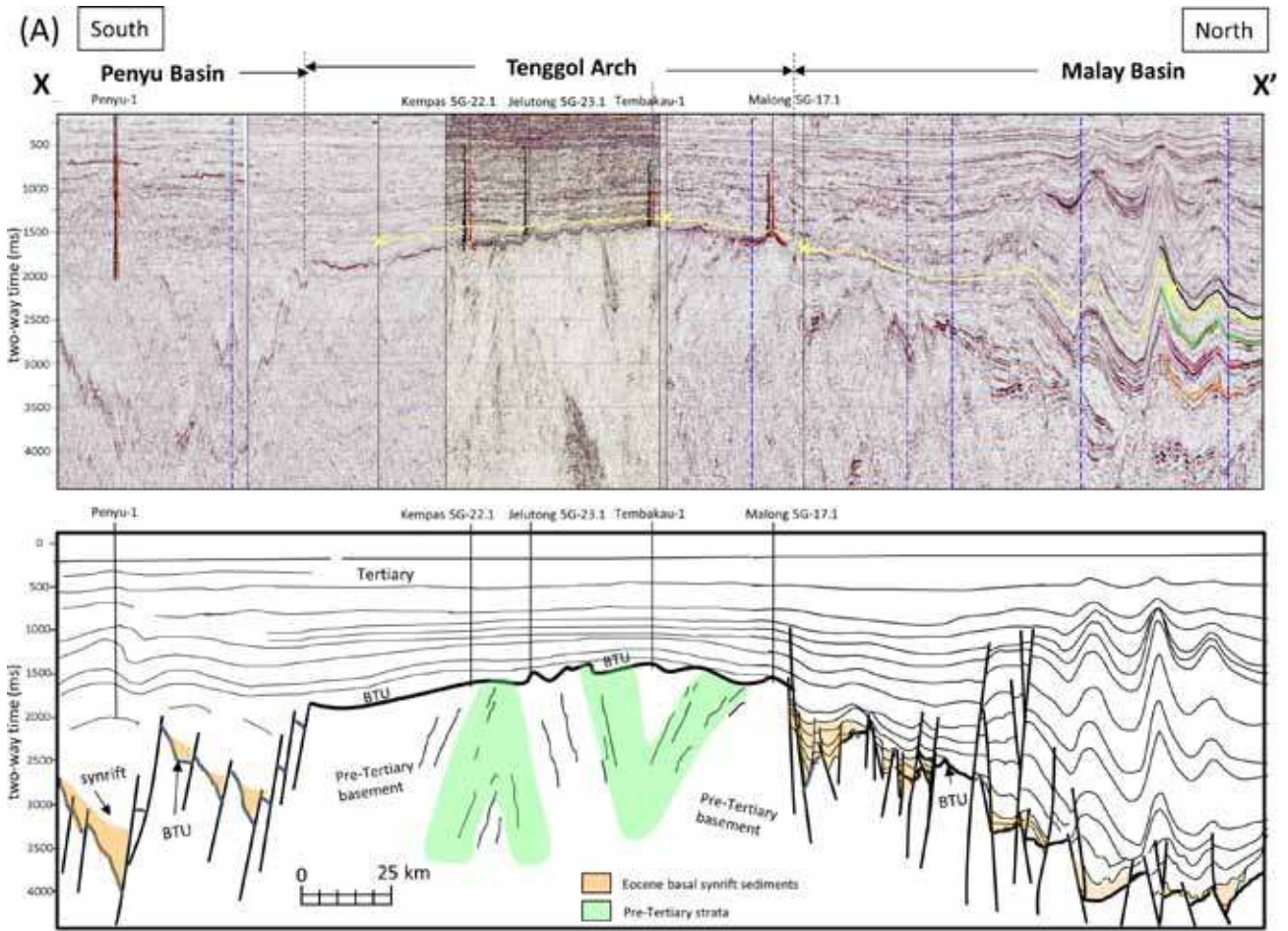


Figure 3: (A) Regional cross-section showing the stratigraphic geometry from Penyu Basin to southern Malay Basin across the Tenggol Arch. Top: Composite seismic profile labelled Line XX' in Figure 1, with key exploration wells. Note the Base-Tertiary Unconformity (BTU) (slightly arched at this vertical exaggeration) is clearly visible across the Tenggol Arch but less so in the deep basins on either side. Bottom: Schematic illustration of above profile based on interpretation of the main seismic markers to show the stratigraphy and structure. Indications of pre-Tertiary layered rocks beneath the Tenggol Arch are shaded green. Synrift sediments (shaded orange) in the deep half-grabens may contain Eocene sediments representing the earliest Tertiary deposits in both basins. (B) Tertiary seismic stratigraphic units based on alphabetical nomenclature used in Malay Basin and extended into Penyu Basin. BTU is Base-Tertiary Unconformity, the unconformity that separates Mesozoic basement from Tertiary basin-fill above; also named "SE Asia Unconformity" by Clements *et al.* (2011). Tectonic phases are partly based on Madon *et al.* (2019), while inversion phase and approximate hydrocarbon charge timing are based on Madon *et al.* (2006). The main phase of fracture generation in the pre-Tertiary basement, based on observations in the Anding-Sotong area (this study), is believed to be during late synrift to early post-rift phases.

in age (e.g., Daines, 1985; Burton & Wood, 2010; Haribowo *et al.*, 2013; Arisandy *et al.*, 2019). Hence, it seems that in all these Tertiary rift basins the sediments are likely no older than Eocene but the pre-rift basement includes a variety of rock types from granites to metasediments of Mesozoic and/or Palaeozoic age (e.g., Achalabhuti, 1974; Tjia, 1999). An important feature that these basins have in common is the major erosional unconformity at the base of the Tertiary sediment-fill which is correlated with the BTU in the Malay and Penyu basins. This unconformity marks a hiatus spanning the Cretaceous to Middle Eocene (e.g., Longley, 1997; Doust & Sumner, 2007; Clements *et al.*, 2011; Kessler & Jong, 2016; Morley, 2016). As a result, there are no Upper Cretaceous and (probably also) Paleocene deposits in Sundaland. The areal and temporal extents of this regional unconformity were so significant that it was named by Clements *et al.* (2011) as the “SE Asia Regional Unconformity”.

The BTU is the result of uplift and erosion following the amalgamation of Sundaland continental terranes at the end of the Indosinian Orogeny in Late Triassic-Early Jurassic times (Metcalf, 2017). Sundaland must have remained emergent as a continental landmass until the Early Tertiary rifting, for there is no record of marine sediments in Peninsular Malaysia younger than the Triassic (Hutchison, 2007). Based on current understanding (Nuraiteng, 2009), sedimentation during the Late Jurassic to Early Cretaceous was mainly in continental extensional or pull-apart basins, controlled by major NW-SE or north-south trending strike-slip faults mainly in the Central Belt of Peninsular Malaysia. These basins were subjected to Late Cretaceous-Early Tertiary tectonism which resulted in isolated outcrops of post-Triassic non-marine sediments that are often referred to in the literature as “red beds” (e.g., Nuraiteng, 2009), or post-orogenic “molasse” formations (Hutchison, 2007). Unfortunately, due to lack of fossils, the age of these rocks is poorly constrained and traditionally they have been assigned a broad “Jurassic-Cretaceous” age, apparently based on long-ranging plant fossils (Koopmans, 1968; Khoo, 1977). Based on the most recent review by Nuraiteng (2009, p.119), several palynological of the various formations since 2007 have yielded an Early Cretaceous age. This problem is still unresolved.

To understand what is above and below the BTU, it is important to note its three most important characteristics: 1) On the basin flanks and on the intra- and inter-basinal highs, the BTU represents the most prominent reflector separating, in most places, stratified Tertiary sediments from unreflective or acoustically opaque “basement”. In the deep basin centre the BTU is a much less prominent reflector (Figure 3A), so the actual basin depth is not always known with certainty. 2) No sediments older than the Eocene are known to exist above the BTU and no older Tertiary sediments occur below it (e.g., Azmi *et al.*, 1996; Morley & Shamsudin, 2006; Shamsudin *et al.*, 2010). Hence, the BTU represents the base of Tertiary sediments overlying the pre-rift basement and filling the basins (Figures 2, 3). On

the basin flanks, particularly of the Malay Basin, the BTU represents a well-defined surface onto which increasingly younger sediments of the post-rift sequence onlap, as is typically observed in basins formed by crustal/lithospheric extension (McKenzie, 1978; Watts *et al.*, 1982). This is illustrated in Figure 4A, an interpretation of the western segment of regional seismic Line 12 (location in Figure 1), where post-rift Miocene sediments strongly onlap onto the pre-Tertiary basement. Since the pre-Tertiary geology of onshore Peninsular Malaysia extends offshore beneath the Malay and Penyu basins, it is expected for the pre-Tertiary rocks to be also present under the BTU. Small half-grabens or pull-apart basins commonly occur on the basin flanks as the result of extensional/strike-slip tectonics during the Early Tertiary. Pre-Tertiary sedimentary rocks that outcrop on the Mesozoic peneplain surface may form the “pre-rift” basement to these small basins (Figure 4B). The recognition of pre-Tertiary basement is dependent upon the clear identification of the BTU. In places where the BTU is also underlain by sedimentary rocks (albeit pre-Tertiary), the unconformity may not be easily recognised if there is insignificant density contrast between the rocks above and below. In such cases, layered rocks truncated by the BTU may look like Tertiary half-graben fill beneath a “top-of-synrift” unconformity, as commonly observed in rift basins. In those cases, other evidences (e.g., velocity, gravity) may be required to distinguish between the two.

PRE-TERTIARY BASEMENT PENETRATIONS

While exploring for the traditional reservoir targets, beginning in the late 1960s, more than 70 exploration wells have penetrated the pre-Tertiary basement (i.e., sub-BTU rocks). Figure 5 shows a pre-Tertiary basement lithology map compiled from previous workers and updated with available data from PETRONAS (Tjia, 1999; Madon, 1999; Hutchison, 2007). The first two wells that hit basement were Belumut-1 and Belumut-2 in the southeastern end of the Malay Basin. Both wells, drilled in 1970 by Esso, encountered granite which was dated Late Cretaceous (80 Ma; Esso, 1985). In 1971, the well Tok Bidan-1 was drilled in the northwestern corner of the Malay Basin and encountered Jurassic-Cretaceous fluvio-lacustrine sediments in the lower part of a half-graben fill sequence, overlying quartzites quoted as Permian to Carboniferous age (Liew, 1994; Hutchison, 2007) (Figure 6). These Jurassic-Cretaceous sediments are believed to be equivalent to the Jurassic-Cretaceous Tembeling Formation and Cretaceous Gagau Group (Hutchison, 2007).

During the subsequent period from 1973 to 1987 all the basement penetrations were in the southwestern part of the Malay Basin and Tenggol Arch area and were drilled by Conoco (10 wells in 1973-74) and subsequently PETRONAS Carigali (5 wells in 1981-87). All those wells, except Pari-1 (1970), which was drilled in the Penyu Basin, were located within the Anding-Sotong-Malong area (Figure 5). Starting in 1990 more wells were drilled into the basement

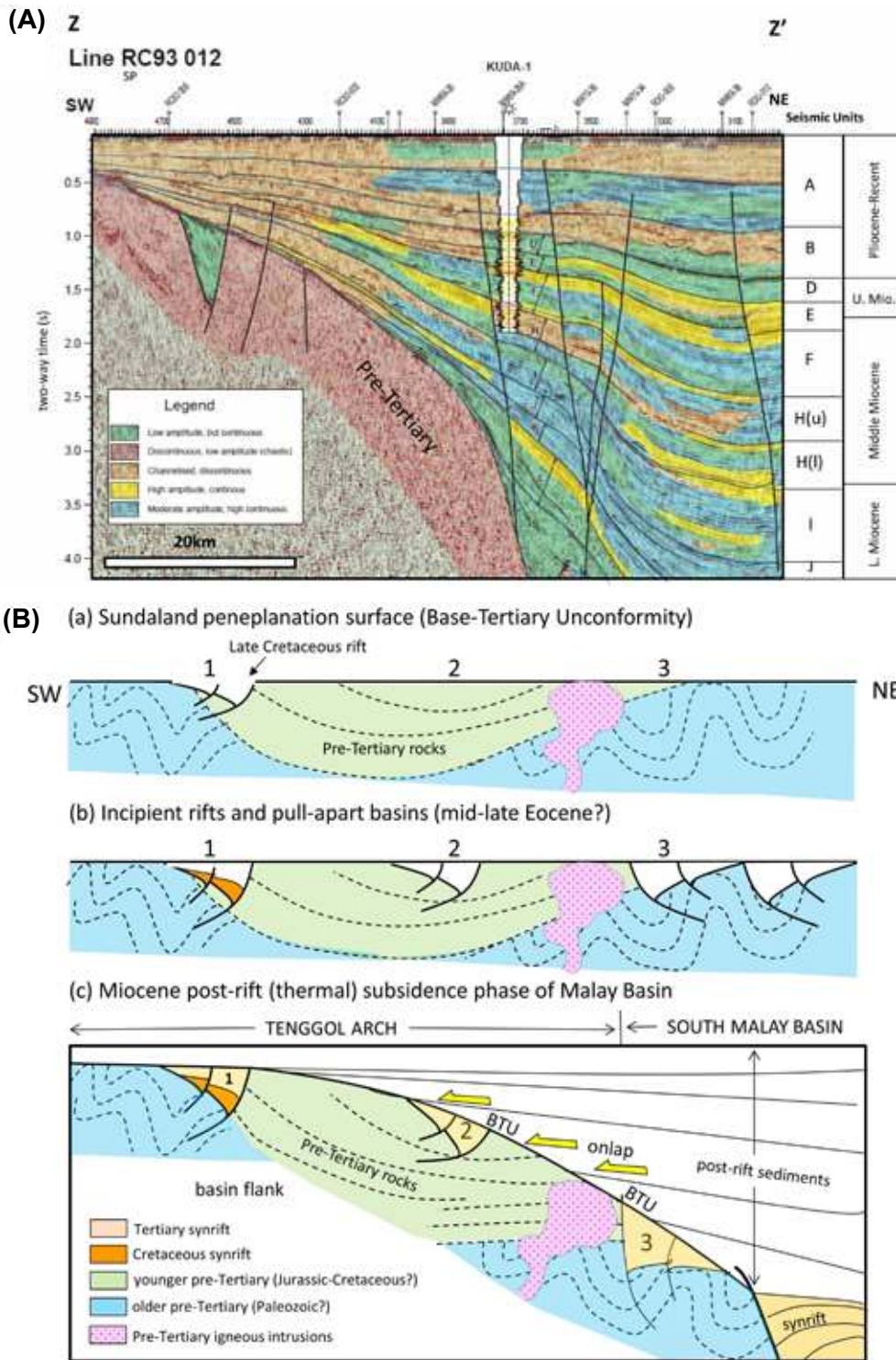


Figure 4: (A) Profile ZZ', part of seismic Line 12, showing the western flank of Malay Basin characterised by stratigraphic onlap onto the prominent Base-Tertiary unconformity (BTU) by increasingly younger sedimentary packages, as is typically observed in the post-rift sequences in extensional basins. Redrawn from ISIS (2006). Line location in Figure 1. Colours represent different seismic facies. Seismic stratigraphic units indicated on the right column. (B) Schematic summary of the geological events surrounding the Base-Tertiary Unconformity (BTU) on the western flank of the Malay Basin, based on the findings of this study. (a) Varied Late Mesozoic geology of Sundaland representing the peneplanation surface prior to Tertiary basin formation. Locations 1, 2 and 3 are the sites of rift and pull-apart basins. Isolated rifts may have started to form during the Late Cretaceous (e.g., at loc. 1, based on knowledge of Tok Bidan Graben). (b) Formation of rifts and pull-aparts during Early Tertiary; some rifts make use of older rifts (loc. 1), while some are created new (locs. 2, 3). (c) As the Malay Basin developed, with its Eocene to Oligocene synrift in the main depocenter (loc. 3), the entire western flank subsided and tilted eastwards during the Miocene and the peneplanation surface that is now the BTU is onlapped upon by post-rift sediments.

on the eastern and northeastern flanks of the Malay Basin, mainly by Esso, the main operator at the time. During that same period, Texaco drilled more wells in the Penyu Basin, including several on the Rhu and Soi structures, and encountered volcanic basement. In 2011-2012 Lundin drilled a few more wells in the basin (Batu Hitam-1, Janglau-1, and Merawan Batu-1) and penetrated pre-Tertiary granite and metasediments (Madon *et al.*, 2019).

Most of the pre-Tertiary basement penetrations (at depths ranging from 1100 m to 4000 m) were secondary drilling objectives, and only a few of them found hydrocarbons. Most wells were drilled on the shallow flank areas in the northeast and southwest, including the Tenggol Arch. The wells sampled a variety of rock types which include igneous, metamorphic and sedimentary rocks. This is not unexpected, since the pre-Tertiary basement is part of the Mesozoic landmass (Sundaland) that was uplifted at the end of the Indosinian Orogeny (Hutchison, 2007). Besides the Jurassic-Cretaceous sediments and Palaeozoic quartzites found at Tok Bidan-1, mentioned above, other notable penetrations of pre-Tertiary basement rocks include unmetamorphosed Late Triassic fossiliferous limestones described in cores from well Sotong B-1 in the southern Malay Basin (Fontaine *et al.*, 1990) and porphyritic rhyolite and dolerite at well Malong 5G-17.2 on the Tenggol Arch (Madon, 1992). Some specimens of pre-Tertiary rocks recovered from wells are shown in Figure 7, including fractured metamorphic rocks at the Anding basement structure, southern Malay Basin, and basalt at well Rhu-1ST in the Penyu Basin. From the well database, it can be deduced that the pre-Tertiary basement rocks in the eastern and southeastern flanks of the Malay Basin are mainly granites, whereas in the southwestern flank of the Malay Basin and in the Penyu Basin, they include

mainly metasediments (phyllites and schists), some plutonic (granitic) and volcanic rocks, and limestones (Figure 5). The pertinent question is how can this information be used in the search for basement reservoir/play.

SEISMIC RECOGNITION OF PRE-TERTIARY SUBCROPS

The presence of sedimentary rocks beneath the BTU has been inferred from seismic data since the early 1990s despite the lower quality of data available at the time. With the more recently acquired higher-quality data, the seismic character and structural style of those rocks are more easily recognized. In this section we examine the seismic character of pre-Tertiary subcrops to have a better understanding of the distribution of the various basement lithologies. A selection of regional seismic lines was used in the study (Figure 1). These are regional seismic lines from PETRONAS Carigali 1993 regional 2D survey. Most of these lines have been published (e.g., Md Yazid *et al.*, 2014; Yu & Yap, 2019), but have been re-interpreted in this study.

As mentioned, most of the occurrences of layered rocks beneath the BTU are observed in the southwestern part of the basin, especially on the Tenggol Arch. Composite seismic profiles, AA' and BB', crossing the Tenggol Arch area (Figure 8), show strongly reflective layered packages suggestive of folded sedimentary rocks that are abruptly truncated by the BTU. Interestingly, in profile AA' the folds are tighter in the southeast compared to the northwest, suggestive of at least two main generations of folds in the pre-Tertiary, separated by a major angular unconformity (Figure 8A). A close-loop composite profile in the southeast end of Line AA' (Figure 8B) emphasises the tight folding. The contrasting deformation styles in the pre-Tertiary seems to

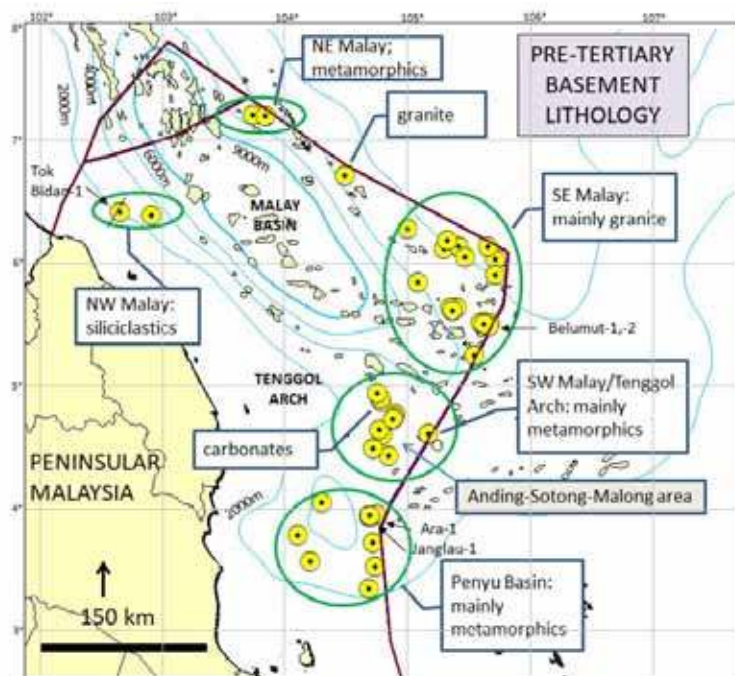


Figure 5: Pre-Tertiary basement penetrations and summary of main lithologies encountered in Malay and Penyu basins. Sediment thickness contours: 2000 m, 4000 m, 6000 m, 9000 m. The wells may be grouped into regions: Northeast (NE), Northwest (NW), Southwest (SW), Southeast (SE), and Penyu Basin. Key wells/field cited in the text: Tok Bidan-1, Belulut-1, Belulut-2 and Anding field.

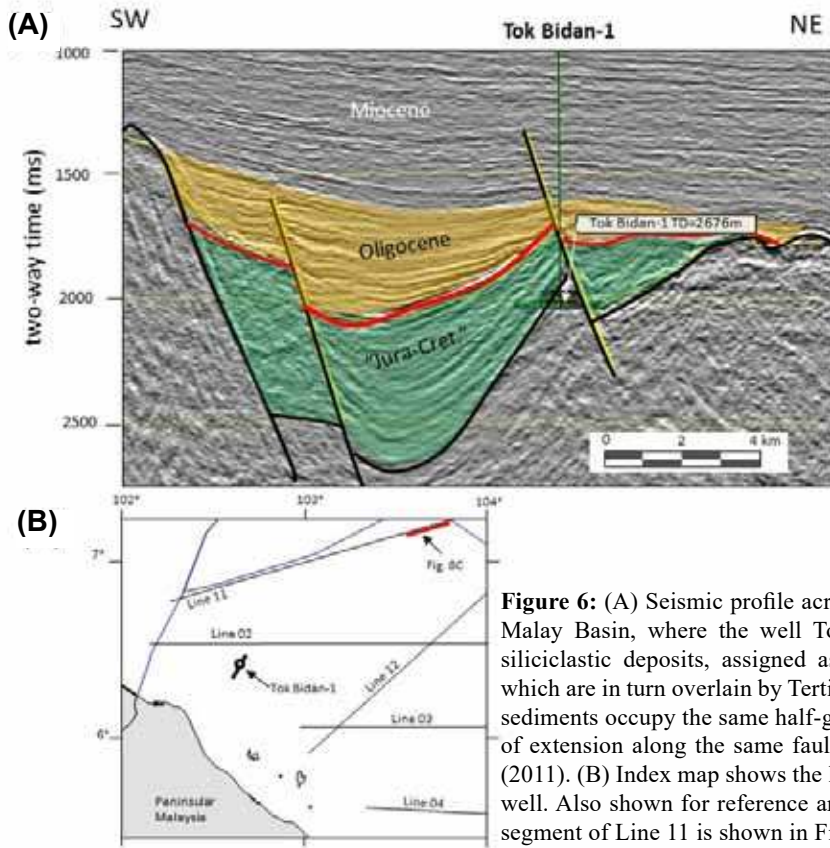


Figure 6: (A) Seismic profile across the Tok Bidan Graben in the northwestern Malay Basin, where the well Tok Bidan-1 penetrated 534 m of non-marine siliciclastic deposits, assigned as “Jurassic-Cretaceous” (Jura-Cret. on map), which are in turn overlain by Tertiary sediments. Both the Mesozoic and Tertiary sediments occupy the same half-graben and probably represent different periods of extension along the same fault systems. Figure modified from PETRONAS (2011). (B) Index map shows the location of the seismic profile and Tok Bidan-1 well. Also shown for reference are key regional seismic lines as in Figure 1. A segment of Line 11 is shown in Figure 8C.

be consistent with our understanding of Peninsular Malaysia geology; generally, Palaeozoic rocks folded during Late Triassic Indosinian Orogeny are overlain unconformably by less-deformed Jurassic-Cretaceous sedimentary basins (Hutchison, in Mustapha, 2009, his figure 13.9). The Late Triassic-Early Jurassic unconformity represents the intervening orogenic phase from Late Permian and Late Triassic (Indosinian Orogeny), which culminated in the collision of western Malaya (Sibumasu) and Indochina terranes (Hutchison, 2009a; Metcalfe, 2017). With the evidences presented in this paper, we interpret the pre-Tertiary subcrops as representing tightly folded Palaeozoic rocks overlain unconformably by a Jurassic-Cretaceous basin. The intervening angular unconformity assigned as the Indosinian “Late Triassic Unconformity” (LTU in Figure 8B).

Seismic data also indicate that subcrops of pre-Tertiary sediments (or metasediments) may extend far beyond the Tenggol Arch region. In the northeastern corner of the Malay Basin near the Vietnamese border, folded pre-Tertiary clastic sediments were also identified on seismic Line 011, near well Bunga Raya-1 which had encountered pre-Tertiary carbonates on the crest of an extensional fault block (Figure 8D). In stark contrast with the unfolded Tertiary post-rift sediments overlying the BTU, the pre-Tertiary fold structures with limbs dipping at $\sim 30^\circ$ (maximum) bear close resemblance to the fold style in the Mesozoic outcrops on Peninsular Malaysia (compare with Figure 9 from Harbury *et al.*, 1990).

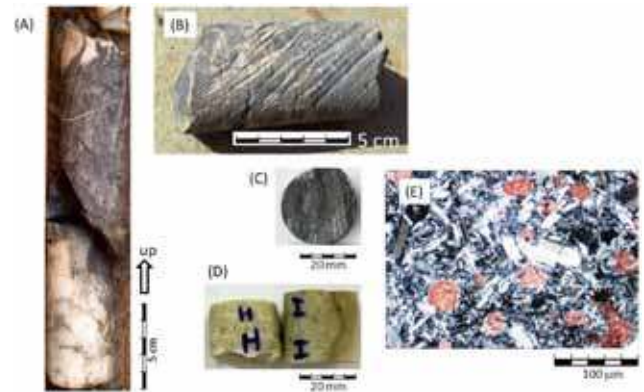


Figure 7: Examples of basement rocks sampled. (A) Phyllite and quartzite from Anding Utara-1, 2852 m. (B) Phyllitic schist from Anding Utara Basement-1, 2948 m. (C) Phyllite, Anding Utara-2, 2788 m. (D) Quartzite, Anding Tengah-1, side-wall core @ 3066.5, 3089.5 m. (E) Amygdaloidal basalt, Rhu-1 ST, 3108.4 m, thin section in cross-polarised light, showing the amygdales filled with calcite (stained red).

Line 05 (Figures 10, 11)

The seismic characteristics of the stratified rocks beneath the BTU were examined in detail along three east-west profiles across the Tenggol Arch: Lines 05, 06, and 07 (see Figure 1 for locations). Line 05 crosses the region from west to east and shows the BTU gradually increasing in depth from less than 1000 m to more than 7000 m at the

basin centre, where the Tertiary basin fill has been folded and uplifted in a compressional anticline (Figure 10A). The BTU is identified as a strong planar reflector that can be traced all the way across the basin margin to the west. In

the middle of the profile, between km 60 and 100, we see strong reflections beneath the BTU. One may be tempted to trace the BTU downwards and interpret those reflections as part of a Tertiary synrift package in a half-graben on

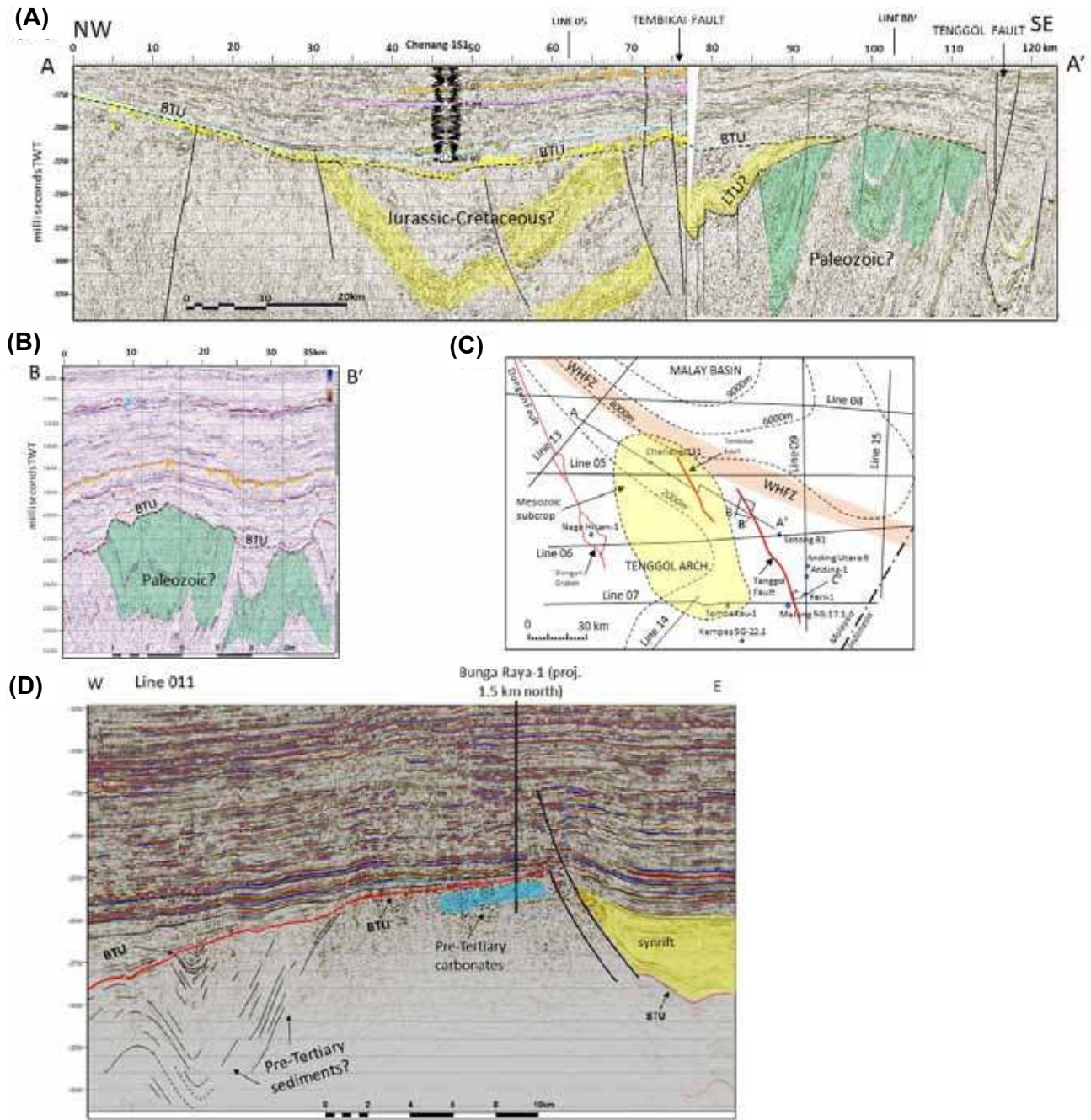


Figure 8: Selected composite profiles across the Tenggol Arch area (Figure 1 for location) showing folded pre-Tertiary rocks beneath the Base-Tertiary Unconformity (BTU). (A) Profile AA', NW-SE cross section through Chenang-1 well and Tembakai Fault, showing broadly folded rocks (Jurassic-Cretaceous?) in the northern part overlying tightly folded rocks (Paleozoic) in the southeastern end. The broadly folded sequence is also intersected by the seismic Line 05 (Figure 10). A possible Late Triassic-Early Jurassic Unconformity (LTU) between the two folded sequences could represent the Indosinian orogenic event. (B) Profile BB', a looped composite seismic in the southeastern end of profile AA', emphasizing the intensity of deformation in the pre-Tertiary (?Paleozoic) rocks. (C) Index map showing the location of the profiles AA' and BB', as well as other key lines in the study area and wells mentioned in the text. Yellow shaded area marks the approximate extent of the Mesozoic (J-K) basin subcrop identified in (A). To the east, and possibly south, of the J-K basin are subcrops of tightly folded Paleozoic metasediments, as indicated by the seismic profile in A and B. (D) Folded pre-Tertiary sediments in the basement near the Bunga Raya Graben, close to the Malaysia-Vietnam maritime boundary (location of profile is shown in Figure 6B). Well Bunga Raya-1 penetrated 493 m of limestone of probable Triassic age (Tjia, 1999). Shaded yellow are the interpreted synrift sediments above the BTU.

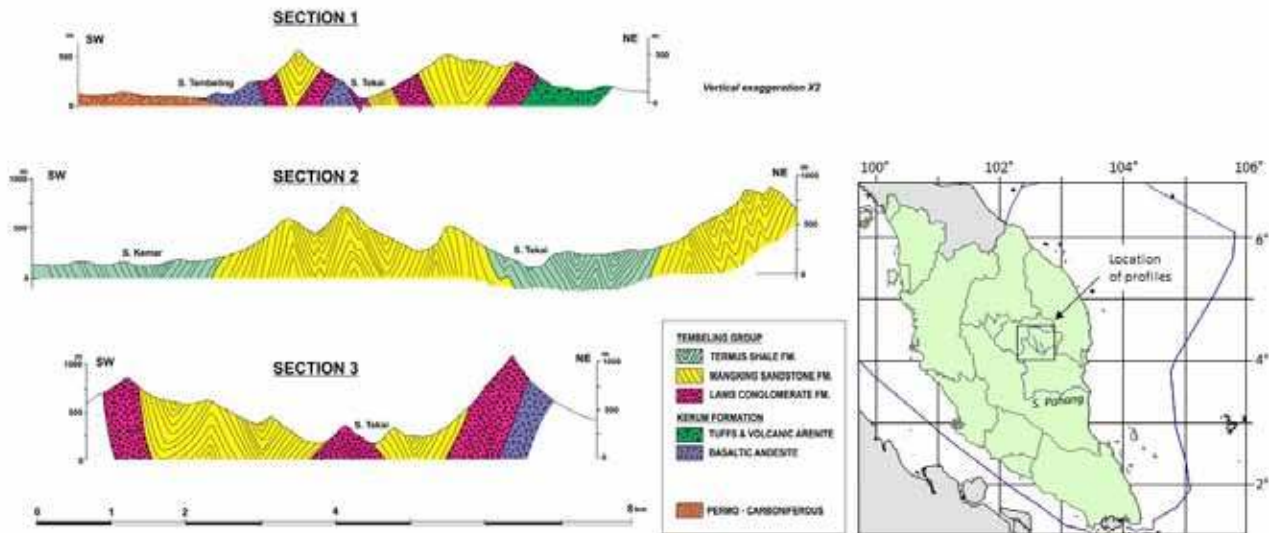


Figure 9: Structural styles of Mesozoic sedimentary rocks of the Tembeling Group (Jurassic – Upper Cretaceous) in the Sg. Tekai region, central Pahang (redrawn from Harbury *et al.*, 1990).

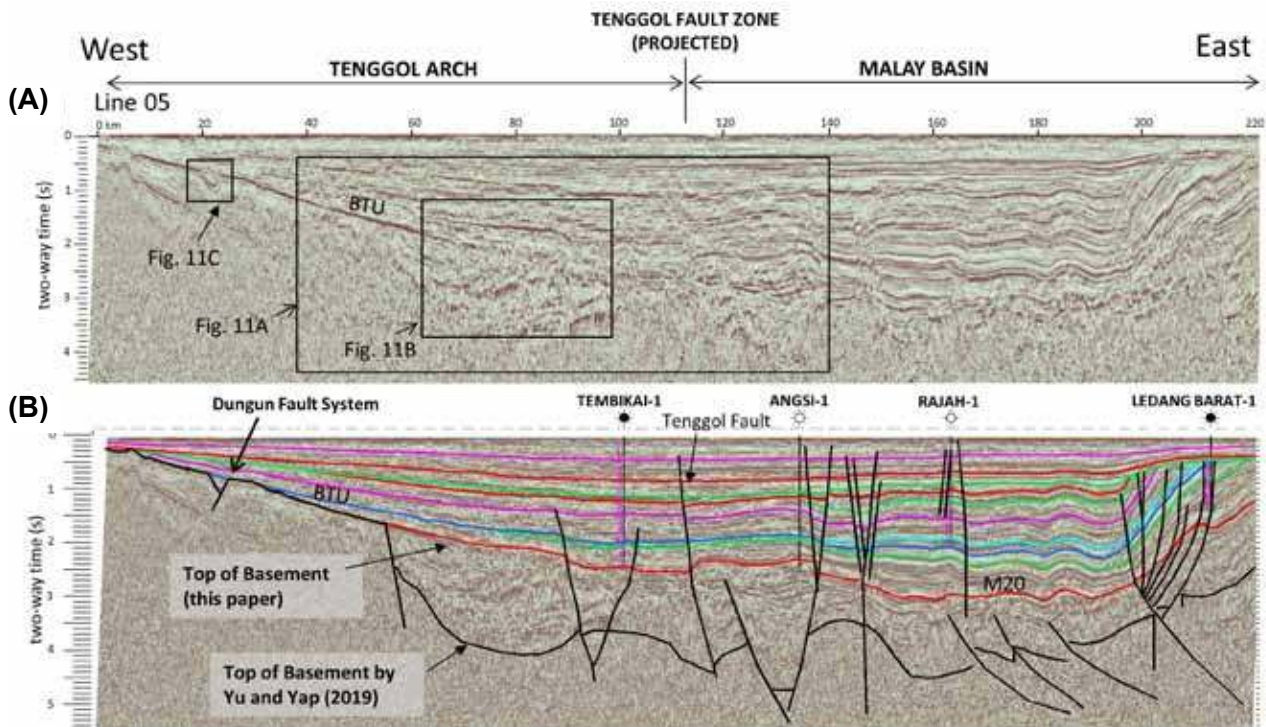


Figure 10: Line 05 across study area (Figure 1 for location). (A) Uninterpreted Line 05 crossing the Tenggol Arch and western flank of the Malay Basin into the central basin area where a compressional anticline is clearly observed (Ledang Barat structure). The BTU is clearly seen as a strong reflector starting at the western end of the line to around km 80 where it starts to be less obvious. A package of seismic reflectors can be seen beneath the BTU. Rectangle is a close-up shown in Figure 11A. (B) Seismic Line 05 from Yu & Yap (2019) shows their interpretation of the top of pre-Tertiary basement which included the reflective package between km 60 and km 100 as part of the Tertiary sediment fill. This study shows that these are pre-Tertiary sediments. These rocks are also intersected by profile AA' shown in Figure 8A.

the basin flank (e.g., see the interpretation of the same line by Yu & Yap, 2019, Figure 10B). A closer inspection of this segment of the profile, however, reveals a pronounced angular truncation of the reflective package by the BTU (Figure 11A), indicating that a major deformational event had occurred prior to erosion that resulted in the unconformity

(Figure 11B). This strongly suggests that the reflective package belongs to an older sedimentary sequence that is unrelated to the overlying Tertiary basin fill.

It is noted that the BTU is particularly clear in the western part of profile, where it is shallower and there is angular discordance between the strata above and below. Eastwards,

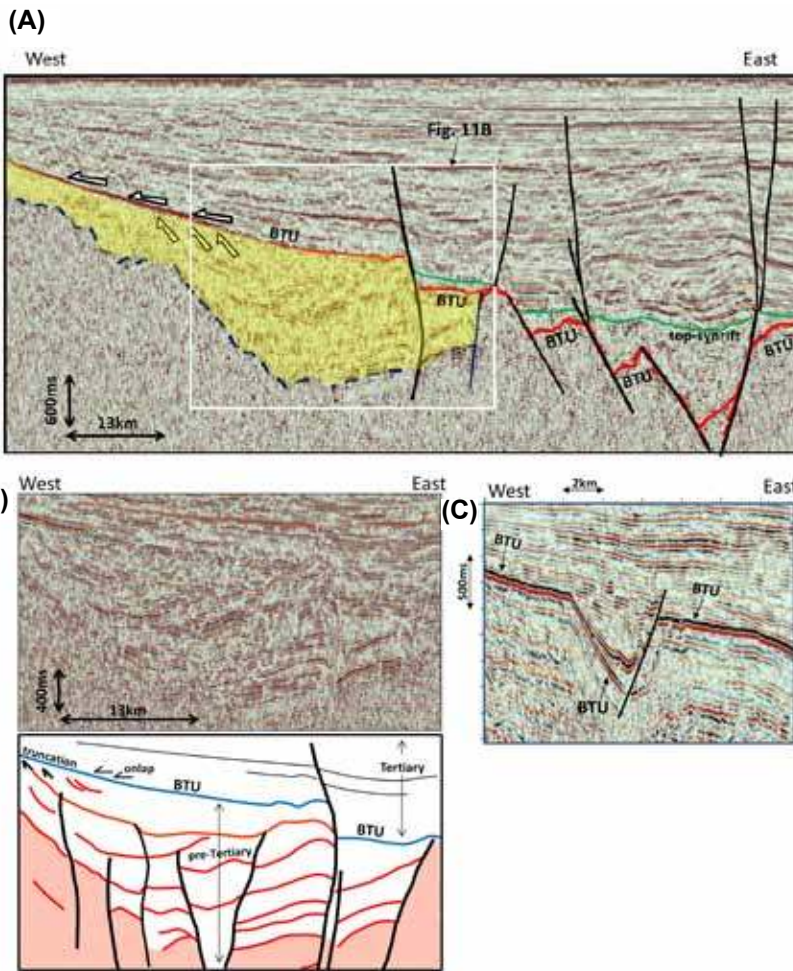


Figure 11: (A) Part of Line 05 (the rectangle in Figure 11B) along which a reflective package is seen beneath the Base Tertiary Unconformity (BTU). The truncation of the layers by the BTU and onlap of Tertiary strata onto it suggests that the reflective package does not belong to the Tertiary sedimentary fill. The likely interpretation of BTU is shown by red lines. Probable top of synrift package is indicated by green lines. (B) Detailed interpretation of rectangle shown in A from Line 05. Top is uninterpreted and bottom is interpreted section of the pre-Tertiary reflections below the BTU, which also shows multiple unconformities within the pre-Tertiary sequences. The entire sequence is truncated by the BTU. (C) A segment of Line 05 at the western end where a small half-graben is seen with the BTU clearly indicated by a strong reflector that continues from the west and dipping underneath the Tertiary synrift.

the BTU reflector tends to be of lower amplitude and continuity due to increased faulting (Figure 11B). The eastern edge of the Tenggol Arch is marked by a major fault, interpreted as the northward continuation of the Tenggol Fault seen in all lines to the south. Here, the BTU is displaced downwards by a series of extensional faults that also affected the overlying Tertiary strata (Figure 11A). In contrast, faults identified within the sub-BTU strata do not penetrate above the BTU and therefore are likely to be pre-Tertiary faults (Figure 11B). The strong amplitude of the BTU (especially to the west) also suggests a major acoustic impedance contrast between the Tertiary post-rift sediments and the sub-BTU strata, indicating that the latter are highly indurated and probably metamorphosed. Along with the structural evidence, this strongly suggests that the reflective package below the BTU belongs to a much older sedimentary sequence, probably Mesozoic. Furthermore, the lack of clearly identifiable bounding faults, as well as a clear basal surface suggests that it is unlikely to be Tertiary rift or pull-apart basin.

Near the western end of the Line 05 (Figure 10A), a small half-graben represents the northern continuation of the Dungun Fault System, a strike-slip fault system along which a series of pull-apart grabens developed. This fault system and its associated grabens, the largest of which is

the Dungun Graben, were initially described by Liew (1994, 1996) and Tjia (1994), and along with the Tembikai and Tenggol faults, seem to be splays off the Western Hinge Fault Zone (see Figure 8C). The Tertiary-age Dungun pull-apart graben is intersected by Line 06, described below (Figure 12), but a closer view of its smaller contemporary is shown in Figure 11C, where the BTU appears as a strong reflector on both sides of the graben but plunges beneath the synrift fill of the half-graben basin. However, unlike in the Dungun Graben (Figure 12B), a clear “top-of-synrift” unconformity (TSU) is absent, suggesting that there was no significant hiatus between the synrift and post-rift phases, as commonly observed in rift basins.

Line 06 (Figure 12)

Similar stratal relationships are seen in consecutive seismic profiles to the south of Line 05, namely Line 06 (Figure 12) and Line 07 (Figure 13). In both these profiles, the BTU is also clearly identified and, in some places, strongly reflective packages are present beneath it. Figure 12A shows Line 06 with the BTU clearly seen as a prominent high-amplitude reflector over much of Tenggol Arch, except above the Dungun Graben between km 20 and 35 (rectangle A in Figure 12A). Also observed at km 12

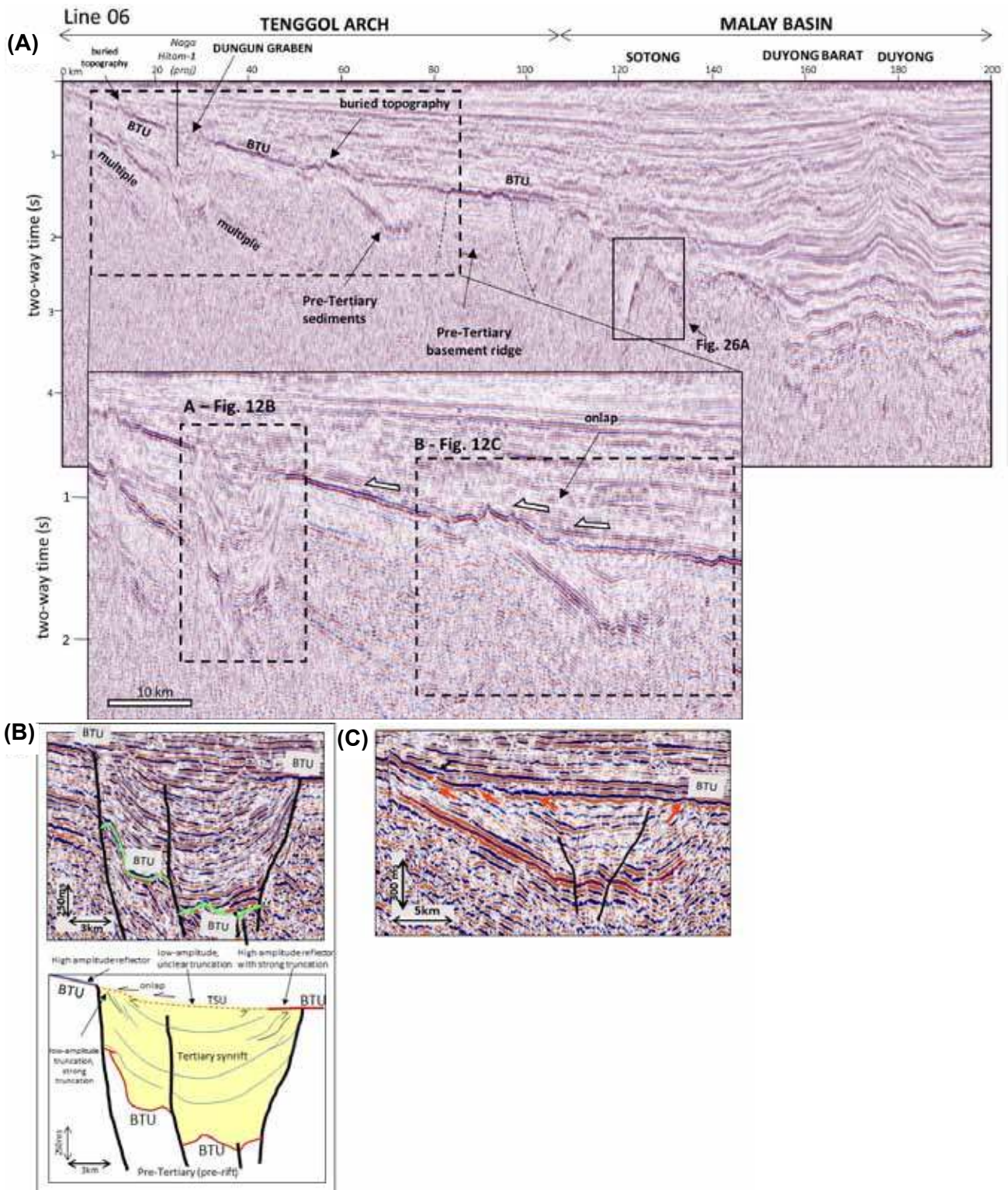


Figure 12: Seismic Line 06 from West to East, showing the main features as discussed in the text. (A) Entire Line 06 with clearly defined Base-Tertiary Unconformity (BTU) particularly in the western half. Some relicts of pre-rift topography can be seen as positive relief on the BTU as well as a pre-Tertiary basement ridge. Close-up segments in rectangles A and B are where the Tertiary Dungun Graben (Figure 12B) and pre-Tertiary sediments (Figure 12C) are identified, respectively. Figure 26A shows a close-up of the Sotong structure. (B) Close-up of Dungun Graben on Line 06. The graben is a pull-apart basin (Liew, 1994) with well-defined eastern and western boundary faults representing the strike-slip margins. The BTU is clear on the footwall of both bounding faults but less pronounced in the basin itself. A top-synrift unconformity (TSU) can be identified by truncational relationship between the graben fill and post-rift sediments (see lower drawing of the main features). (C) Segment of Line 06 (rectangle B in Figure 12A) showing strong pre-Tertiary reflectors truncated by the BTU (red arrows). Above the BTU the post-rift sediments onlap westwards onto the buried topography.

and km 60 are remnants of the eroded pre-rift topography, preserved as positive relief relative to the general depth of the BTU. A westward onlap of Tertiary sediments onto the BTU are also seen, especially over the remnant topography (Figure 12A).

The Dungun Graben is a relatively small (35 x 10 km), rhomb-shaped pull-apart basin that was formed along a NNW-SSE trending right-lateral strike-slip fault on the western margin of the Malay Basin (Tjia, 1994; Liew, 1994, 1996). Its Tertiary origin was proven by well Naga Hitam-1 (drilled in 2010), which encountered Lower Oligocene (Group M) graben-fill sediments at TD. The geometry and internal structure of Dungun Graben is shown in a close-up seismic in Figure 12B. The graben is bounded by sub-vertical faults whose vertical displacement is more than 1 s two-way time (TWT). It is characterised by well-developed internal stratification – semi-continuous, bowl-shaped concave-up reflections that are truncated at the same level as the BTU, which also coincides with the eroded footwalls of the bounding faults. The upturned and disrupted reflections at the top of the graben fill adjacent to the bounding faults, especially the western one, suggest that the faults were reactivated prior to erosional truncation during the Early Miocene. This erosional unconformity, which is generally of lower amplitude and less pronounced than the BTU, may be interpreted as the “top-of-synrift” unconformity (marked “TSU” in the lower panel of Figure 12B). Only at the eastern boundary fault, where the synrift fill has been upturned to near vertical, the TSU appears as a high-amplitude reflector that merges with, and is indistinguishable from, the BTU.

East of Dungun Graben, starting at around km 60 (Figure 12A), a package of high-amplitude reflectors occurs beneath the irregular BTU topography and dip eastwards to about 2 s TWT at km 75, where it seems to flatten and rise up towards the BTU at km 80. A close-up of this feature is shown in Figure 12C. We can see similar but low-amplitude and less continuous reflections above the high-amplitude reflections, producing an asymmetric synformal structure that is strongly truncated by the BTU. Unlike the Dungun Graben, there are no distinct boundary faults, other than a few minor faults in the middle, to suggest that this feature is a graben (Figure 12C). Also, the BTU is clearly identified as a continuous high-amplitude reflector over the whole breadth of the synform, indicating a marked velocity/density contrast with the Tertiary post-rift strata above. Therefore, as in Line 05, we also interpret this feature as a pre-Tertiary subcrop of sedimentary rocks that were exposed at the Late Mesozoic erosional surface (BTU), and now part of the basement to the Tertiary Malay Basin. The highly reflective sub-BTU package likely represents hard metasediments that were more resistant to erosion and remained as remnant buried topography (Figure 12C).

Line 07 (Figure 13)

The next profile south, Line 07, also shows the BTU as a high-amplitude reflector dipping gently from west to

east to km 70 (Figure 13A). The unconformity surface is almost planar except for a few small bumps, of which the main ones are at km 30 and km 40. Eastwards from km 70, the BTU is abruptly shallower by about 130 ms (equivalent to about 325 m, assuming velocity of 5000 m/s). This sharp step in the BTU probably represents a relict fault scarp in the eroded pre-Tertiary basement surface. Between km 70 and km 150 (where the Tenggol Fault is located), the BTU is again almost planar but with a lower gradient, making this part of the Tenggol Arch appear as a plateau-like intra-basinal high. Figure 13B is a closer view of this “plateau” within which a horst-like feature is clearly identified by steep bounding faults on both sides. The horst-like feature is interpreted as a pre-Tertiary basement ridge. The high-amplitude reflector marking the BTU is continuous throughout the profile, which indicates a strong acoustic impedance contrast between the sub-BTU rocks and the overlying Tertiary post-rift sediments. While some horizontal layers occur within the basement ridge, dipping reflectors indicative of sedimentary layering are observed on either side. To have a clearer view of the stratal truncation of pre-Tertiary rocks at the BTU, the eastern part of Figure 13B is enlarged in Figure 13C. All the layers are strongly truncated by the BTU, consistent with the entire “plateau” feature being pre-Tertiary in origin. The dipping layered rocks truncated by the BTU east of the basement ridge have been penetrated by Lundin’s 2012 well Tembakau-1 from which samples of silty sandstones likely of pre-Tertiary age were reported (Iyer *et al.*, 2019). Further eastwards, core samples recovered from the Malong basement knoll adjacent to the Tenggol Fault revealed a basement of rhyolite and dolerite of unknown age but most likely are also pre-Tertiary in age (Madon, 1992).

GRAVITY MODELLING

Besides the seismic evidence, we modelled the gravity data as an additional means to discriminate between Tertiary and pre-Tertiary rocks and therefore support our interpretation. Since gravity anomalies reflect variations in subsurface densities, they could provide supporting evidence for discriminating pre-Tertiary sediments (which are expected to have relatively higher densities) from Tertiary sediments.

Figure 14 shows the free-air gravity anomaly (FAA) map of the region plotted from Sandwell’s satellite-derived gravity anomaly grid version 24 (Sandwell *et al.*, 2014; Garcia *et al.*, 2014). Shown are three profiles along seismic Lines 05, 06 and 07 used in the modelling. We can see areas with relatively low anomalies intermediate between those of the basinal areas (cool colours in both Malay and Penyu basins) and the basement high areas (warm colours). These lower anomalies (compared to the surroundings) could be due to the presence of slightly lower-density sedimentary rocks in the pre-Tertiary basement on the Tenggol Arch.

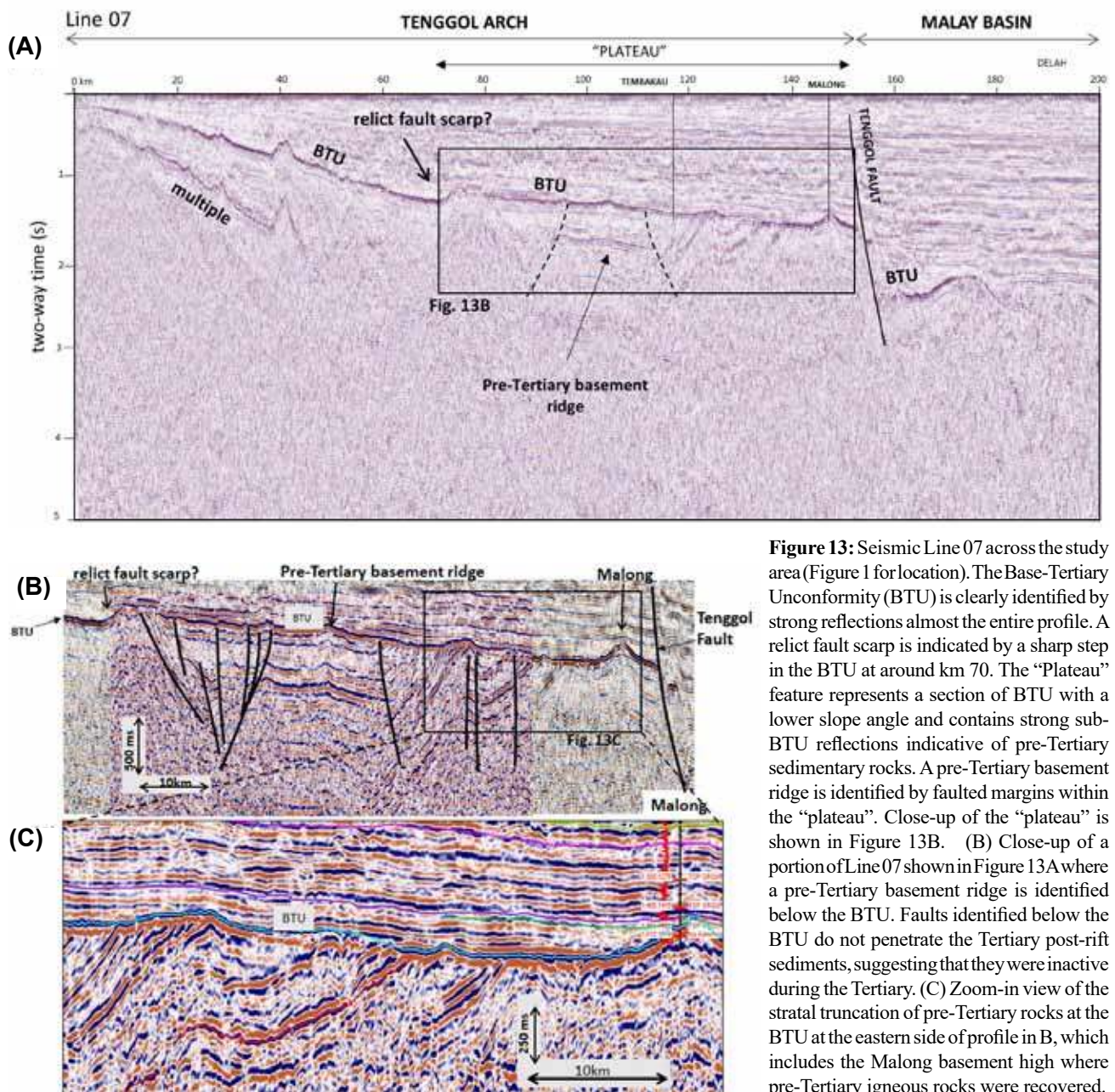


Figure 13: Seismic Line 07 across the study area (Figure 1 for location). The Base-Tertiary Unconformity (BTU) is clearly identified by strong reflections almost the entire profile. A relict fault scarp is indicated by a sharp step in the BTU at around km 70. The “Plateau” feature represents a section of BTU with a lower slope angle and contains strong sub-BTU reflections indicative of pre-Tertiary sedimentary rocks. A pre-Tertiary basement ridge is identified by faulted margins within the “plateau”. Close-up of the “plateau” is shown in Figure 13B. (B) Close-up of a portion of Line 07 shown in Figure 13A where a pre-Tertiary basement ridge is identified below the BTU. Faults identified below the BTU do not penetrate the Tertiary post-rift sediments, suggesting that they were inactive during the Tertiary. (C) Zoom-in view of the stratal truncation of pre-Tertiary rocks at the BTU at the eastern side of profile in B, which includes the Malong basement high where pre-Tertiary igneous rocks were recovered.

For the modelling, the gravity anomalies from Sandwell’s grid were sampled along those seismic lines. Along each profile, the FAA is first normalized by removing the mean (“demeaned”) so that a direct comparison with the calculated anomaly can be made. FAA generally consists of long-wavelength (~100 km) and short-wavelength (<50 km) components. While the former is due to a deeper source, mainly crustal thickness variations, represented by the crust-mantle interface (Moho), the latter is due to shallow sources of density contrasts. Using this knowledge, modelling was done in two main steps:

(i) modelling the isostatic gravity anomaly due to the Tertiary basin-fill (i.e., post-BTU sediments, interpreted from the seismic lines) and the crustal thickness. It is

assumed that the gravity anomaly due to the sedimentary basin-fill is isostatically compensated (applying Airy isostasy) by thinning of the crust (i.e., Moho uplift). This effectively takes care of the long-wavelength component of the anomaly. This modelling technique is similar to the process-oriented gravity modelling approach described by Watts & Fairhead (2010).

(ii) adjusting the calculated isostatic anomaly to match the demeaned observed anomaly by introducing in the crustal model subsurface bodies with appropriate densities, representing pre-Tertiary basement rocks or Tertiary synrift sediments. It was found that where seismic evidence shows the presence of layered pre-Tertiary rocks beneath the BTU, the calculated

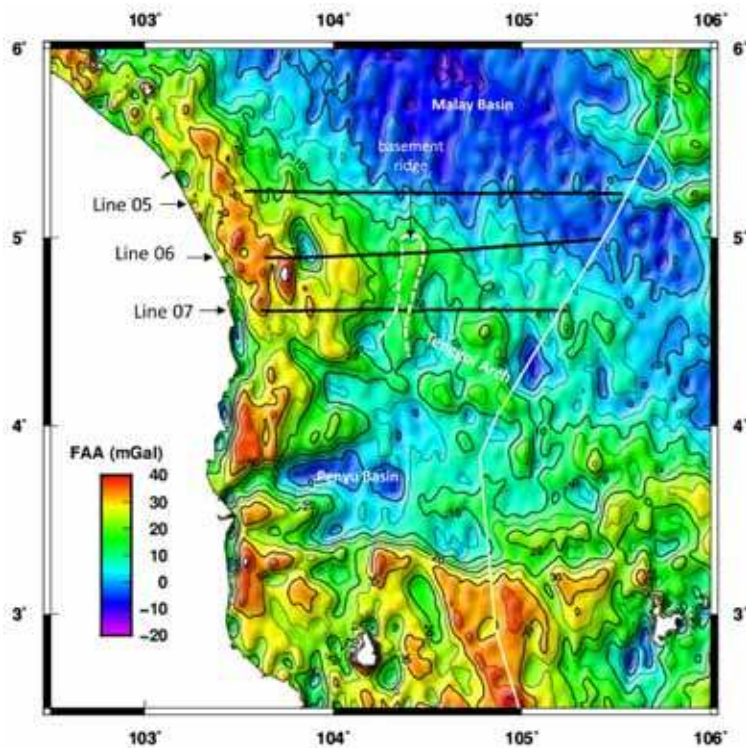


Figure 14: Free-air gravity anomaly (FAA) map of study area, showing the location of three gravity profiles (Lines 05, 06, 07) modelled in this study. Note the intermediate values of FAA in the Tenggol Arch area (green) compared to the deep basins (blue) to the north and south and the basement high areas (red). Map was plotted from Sandwell's satellite-derived gravity anomaly grid version 24 (Sandwell *et al.*, 2014; Garcia *et al.*, 2014). The N-S feature labelled "basement ridge" (white dash line, derived from Iyer *et al.*, 2019), which roughly coincides with the 15 mGal contour, is the pre-Tertiary basement ridge discussed in the text.

anomalies can be easily matched with the observed anomalies by introducing polygons of appropriate densities representing those rocks.

The results of gravity modelling for the three profiles are shown in Figures 15, 16 and 17, corresponding to seismic Lines 05, 06, and 07 (Figures 10A, 12A, 13A), respectively. In each figure, the observed, isostatic and calculated anomalies are plotted (top panel) above the corresponding crustal profile based on interpretation of those seismic lines (bottom panel). Figure 15 shows the results for Line 05 where there is a region with strong reflectors beneath the BTU believed to represent pre-Tertiary sediments, and not Tertiary synrift as interpreted by some authors (Figure 10B). Since dense sedimentary rock and metasediment generally have densities in the range of 2500 to 2650 kg/m³, they often result in a gravity low. In order to honour the observed gravity anomaly, the profile is best modelled by inserting a sub-BTU sediment body (no. 2 in Figure 15) that has a density intermediate between that of the average Tertiary sediment above the BTU (2300 kg/m³), and that of the pre-rift basement or crust (2700 kg/m³). The same was done for other seismic lines which also indicate the presence of layered rocks beneath the BTU: Line 06 (sub-BTU bodies nos. 2 and 3 in Figure 16) and Line 07 (sub-BTU bodies nos. 2 and 3 in Figure 17). It is interesting to note the similarities between these sub-BTU features observed in the three successive E-W lines (05, 06, 07) crossing the Tenggol Arch, suggesting that they are part of the same pre-Tertiary basin subcrop that was intersected by seismic Line AA' through Chenang-1S1, which we believe

are likely to be Jurassic-Cretaceous basin (Figure 8A). This basin has been penetrated by at least two wells, Tembakau-1 and Kempas 5G-22.1 (location shown in Figure 8C), from which sandstones and silty sandstones below the BTU were reported from drill cuttings by M. Hafiz *et al.* (2019) and Hashim *et al.* (2019). These sandstones are similar to the unmetamorphosed siliciclastics overlying quartzites described from Tok Bidan-1 well in the northern Malay Basin, widely believed to be equivalent to the Jurassic-Cretaceous Gagau Group of Peninsular Malaysia (Liew, 1994; Tjia, 1999; Madon *et al.*, 2001). It is important to note that these siliciclastic sediments of presumed Jurassic-Cretaceous age, are unmetamorphosed, in stark contrast with the Palaeozoic rocks that were penetrated by a number of wells to the east of the Tenggol Fault, including at Anding (Figure 5). The presence of a Jurassic-Cretaceous sedimentary basin may also explain the relatively low values of free-air gravity anomaly in the Tenggol Arch area (Figure 14).

The combined seismic and gravity interpretation described above proved to be useful in distinguishing between the synrift fill of Tertiary half-grabens and pre-Tertiary sedimentary rocks below the BTU, especially when there are ambiguities in the seismic interpretation. Gravity anomalies provide useful clues since the Tertiary sediments in the half-grabens on the basin flank tend to have lower densities relative to the surrounding pre-Tertiary basement rocks and therefore show gravity anomaly lows of about -20 mGal, as in the case of Dungun Graben (Figure 16). The sharp faulted boundaries and shallow depths of these relatively narrow Tertiary grabens (~10 km wide) also result in a pronounced negative free-air anomaly.

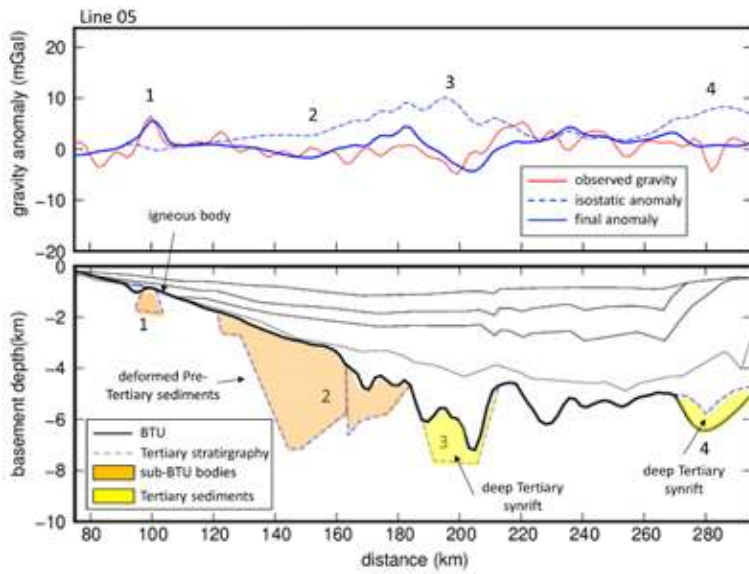


Figure 15: Gravity model for Line 05. Lower panel is crustal model based on interpretation of seismic profile 05. Bold black line is Base-Tertiary Unconformity (BTU). Grey lines are main stratigraphic horizons. Blue dash lines are outline of subsurface bodies added to the gravity model to obtain a reasonable match between observed and calculated gravity anomaly. In upper panel, red line is observed gravity, with regional trend removed for the purpose of modelling. Blue dashed line is calculated isostatic anomaly based on BTU surface assuming density of sediment fill is 2300 kg/m^3 . Note the main mismatch between isostatic and observed anomaly (labelled 1 to 4), which was corrected by adding the effects of corresponding subsurface bodies as identified or inferred from seismic data (numbered 1 to 4, respectively). Appropriate densities were assumed for the different bodies. Note that body 2 is the same one identified in Figures 12A and 13A.

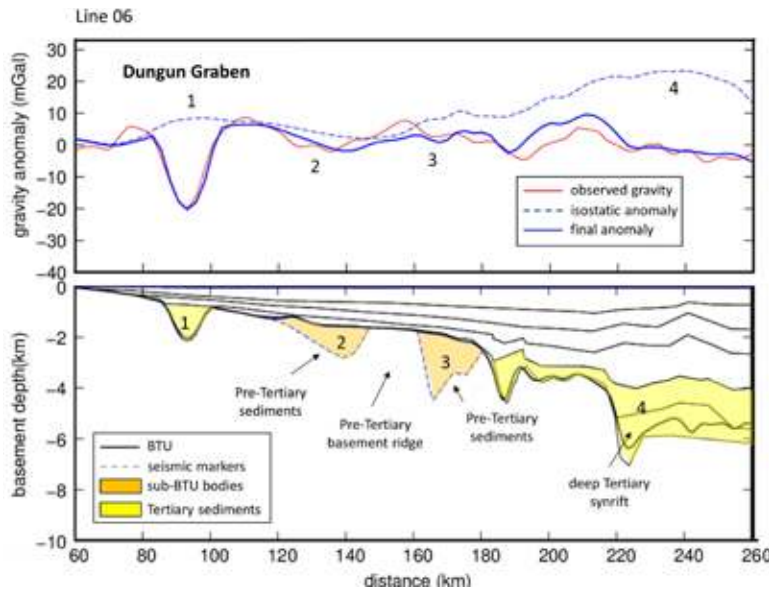


Figure 16: Gravity model for Line 06. As in Figure 15, lower panel is crustal model based on interpretation of seismic Line 04. Bold black line is Base-Tertiary Unconformity (BTU). Grey lines are main stratigraphic horizons. Blue dash lines are outline of subsurface bodies added to the isostatic gravity model to obtain a reasonable match between observed and calculated gravity anomaly. In the upper panel, red line is observed gravity, with regional trend removed. Blue dashed line is calculated isostatic anomaly based on BTU surface assuming density of sediment fill is 2300 kg/m^3 . As in Line 05, the main mismatch between isostatic and observed anomaly (labelled 1 to 4) was corrected by adding the effects of corresponding subsurface bodies (numbered 1 to 4, respectively) with the appropriate density contrasts. Note bodies 2 and 3 are identified in Figures 12A and 13A.

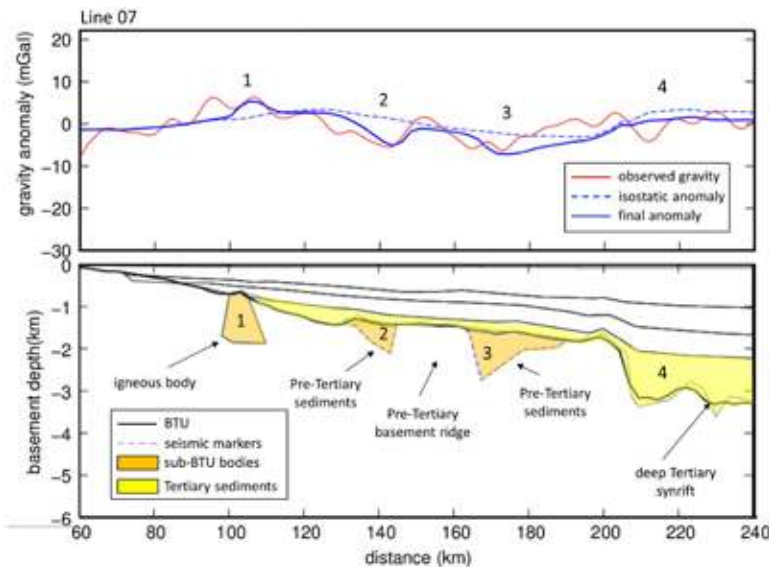


Figure 17: Gravity model for Line 07. As in Figures 15 and 16, lower panel is crustal model based on interpretation of Line 07. Bold black line is Base-Tertiary Unconformity (BTU). Grey lines are main stratigraphic horizons. Blue dash lines are outline of subsurface bodies added to the isostatic gravity model to obtain a reasonable match between observed and calculated gravity anomaly. In the upper panel, red line is observed gravity, with regional trend removed. Blue dashed line is calculated isostatic anomaly based on BTU surface assuming density of sediment fill is 2300 kg/m^3 . Similarly, the main mismatch between isostatic and observed anomalies (labelled 1 to 4) was corrected by adding the gravity effects of corresponding subsurface bodies (numbered 1 to 4, respectively) assuming the appropriate density contrasts. Note bodies 2 and 3 are the same as those identified in Figures 12A and 13A, and are the continuation of bodies 2 and 3 in Line 06 (Figure 16).

To determine if a seismically reflective feature is a pre-Tertiary subcrop or Tertiary half-graben may not always be straight-forward, as it depends on the quality and resolution of the seismic and gravity data, as well as the size of the graben. At the western end of Line 013 (see Figure 1 for location), a half-graben feature can be identified by a well-defined bounding normal fault on its northeastern side due to strong velocity contrast between the graben-fill sediments and the adjacent basement footwall (Figure 18A). This feature is a northward continuation of the Dungun fault system, which is recognisable in seismic Line 06 through

Line 05, and therefore is a Tertiary rift or pull-apart basin. However, although the BTU is clearly identified at the top of the basement footwall it is less distinct in the hangingwall (downthrown) beneath the graben. There, its identification is based on the different seismic character between basement (high-amplitude but discontinuous reflections) and Tertiary basin fill (low-amplitude and discontinuous reflections). As in the case of the Dungun Graben (Figure 11B), there is a pronounced erosional unconformity at the top of a half-graben, marked by a high-amplitude reflector which could be interpreted as TSU. Since along this profile the half-graben is only about 6 km wide, the satellite-derived gravity does not show a distinct anomaly over the feature. Ship-based data, however, confirms the presence of the Tertiary graben (Figure 18B). High-resolution gravity data such as FTG would be useful for future work.

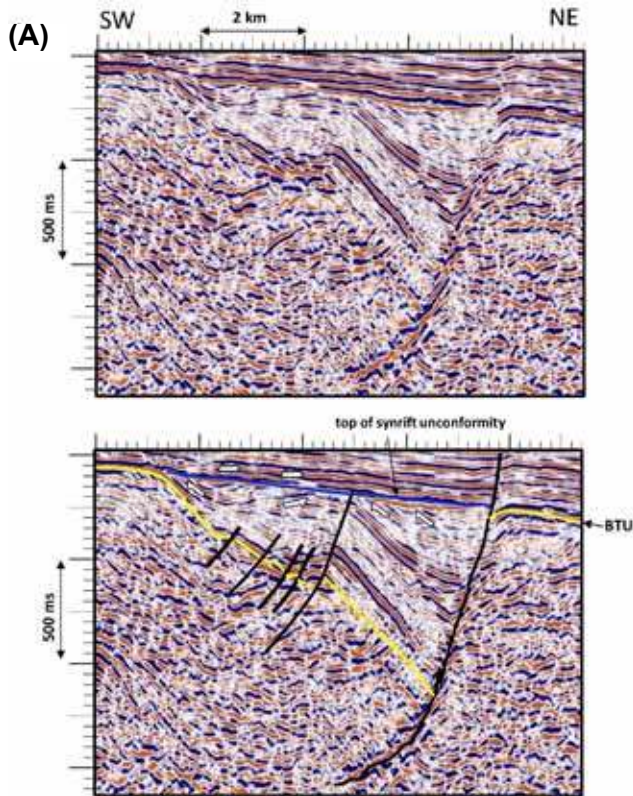
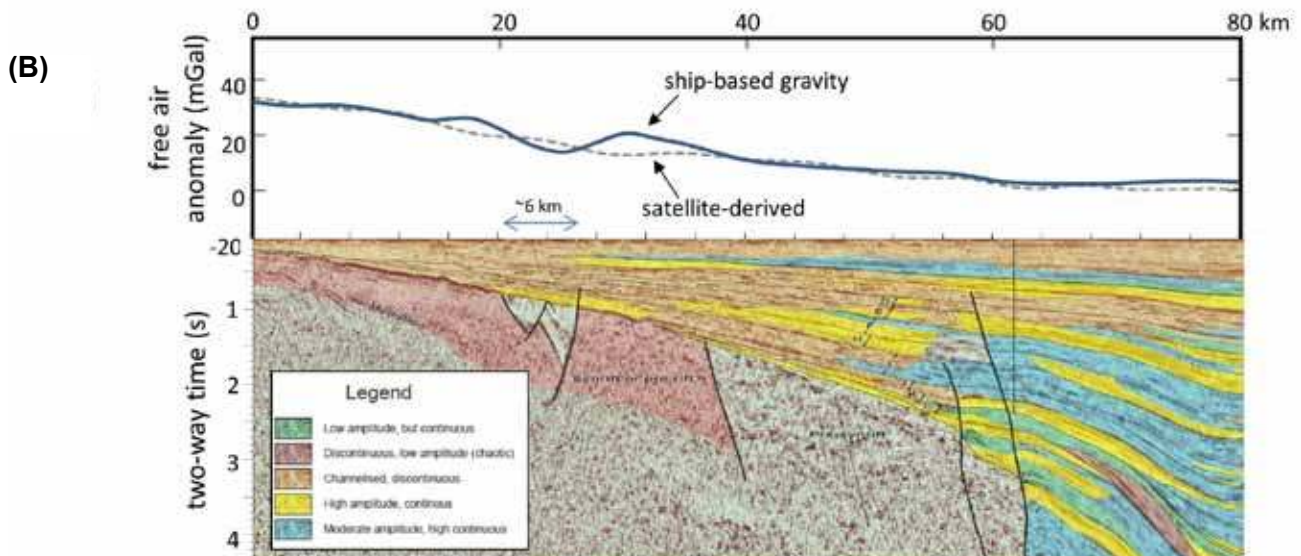


Figure 18: Half-graben structure on the western flank of the Malay Basin identified on seismic Line 13 (location in Figure 1). (A) Uninterpreted (top) and interpreted (bottom) seismic section over the half-graben. The graben has a well-defined bounding fault but less pronounced top of pre-rift basement (BTU). Deformation of the graben-fill resulted in truncation (white arrows) by a top-of-synrift unconformity (TSU) which extends across the graben width as a strong reflector at the base of the post-rift, almost continuous with the BTU on either side of the graben. A pronounced onlap of post-rift sediments is indicated by white arrows above the BTU. The normal fault also appears to sole out at depth (about 1.25 s TWT below the footwall scarp) as well as propagate upwards into the Tertiary strata, suggestive of reactivation sometime during the Miocene. (B) Free-air gravity anomaly over the western part of Line 13 showing the effect of the small half-graben. Satellite-derived gravity (from Sandwell's grid, Figure 14) is compared with ship-based gravity which has a higher resolution and more sensitive to narrower and shallower subsurface density contrasts such as small graben features (6 km wide in this case). The low gravity anomaly above the half-graben suggests that it is more likely a Tertiary graben rather than a pre-Tertiary one.



The pre-Tertiary “basement ridge”

The pre-Tertiary basement ridge identified in the seismic and gravity profiles in Figures 12, 13, 16, and 17 is the same feature interpreted M. Hafiz *et al.* (2019) in a NW-SE seismic profile across the Tenggol Arch, shown here in Figure 19. On the gravity map the feature appears as a linear N-S trending structure roughly outlined by the 15 mGal contour (Figure 14). Reinterpretation of M. Hafiz *et al.*'s line in Figure 19A shows a pre-Tertiary basement ridge bounded on either side by steep reverse faults, as inferred from the “drag” in the hangingwall synclines in the layered rocks. We interpret this as indicative of pre-Tertiary compressional deformation related to those faults prior to the erosional event that culminated with the BTU. Although the previous authors referred to the pre-Tertiary layered rocks flanking the basement ridge as “grabens”, they are not grabens but simply synformal areas of deformed sedimentary pre-Tertiary rocks. Velocity profile from M. Hafiz *et al.* (2019), shown in Figure 19B, indicates that the layered rocks have relatively lower velocities (3500-4500 m/s) than that of the basement ridge (>4500 m/s) but higher than that of the Tertiary sediments on the Tenggol Arch (<3500 m/s). Velocity profile from Tembakau-1 also shows sharp ramp from ~2600 m/s to 4500 m/s at the BTU (M. Hafiz *et al.*, 2019). These evidences suggest that the layered rocks belong with the pre-Tertiary basement and not the Tertiary basin-fill.

As pointed out by M. Hafiz *et al.* (2019), the structure of the basement ridge on the Tenggol Arch is similar to a profile from offshore Cambodia (Fyhn *et al.*, 2010, 2016) where a syncline formed of Cretaceous rocks occur in the footwall of a thrust fault in the pre-Tertiary basement (Figure 20). The Cambodian example is clearly compressional, and not extensional. In the Malaysian case, the north-south linear pre-Tertiary basement feature appears to be a strike-slip or wrench fault-bounded basement structure which is truncated by the BTU along with the folded sedimentary rocks on either side of it. This suggests that the deformation and erosion took place before the initiation of subsidence of the Malay Basin and Tenggol Arch.

DISCUSSION

Nature of pre-Tertiary basement subcrops

The pre-Tertiary basement subcrops beneath the Malay and Penyu basins represent the geologically heterogeneous Mesozoic landmass that existed prior to the formation of the Tertiary extensional basins. As indicated by the basement well penetrations, the lithologies beneath the BTU may comprise Mesozoic and Palaeozoic igneous, metamorphic, and sedimentary rocks that formed part of the Indosinian Orogen prior to Late Cretaceous to Paleocene orogenic collapse, Tertiary extension and basin formation. Tjia (1999) made a distinction between “post-granite” (post-orogenic

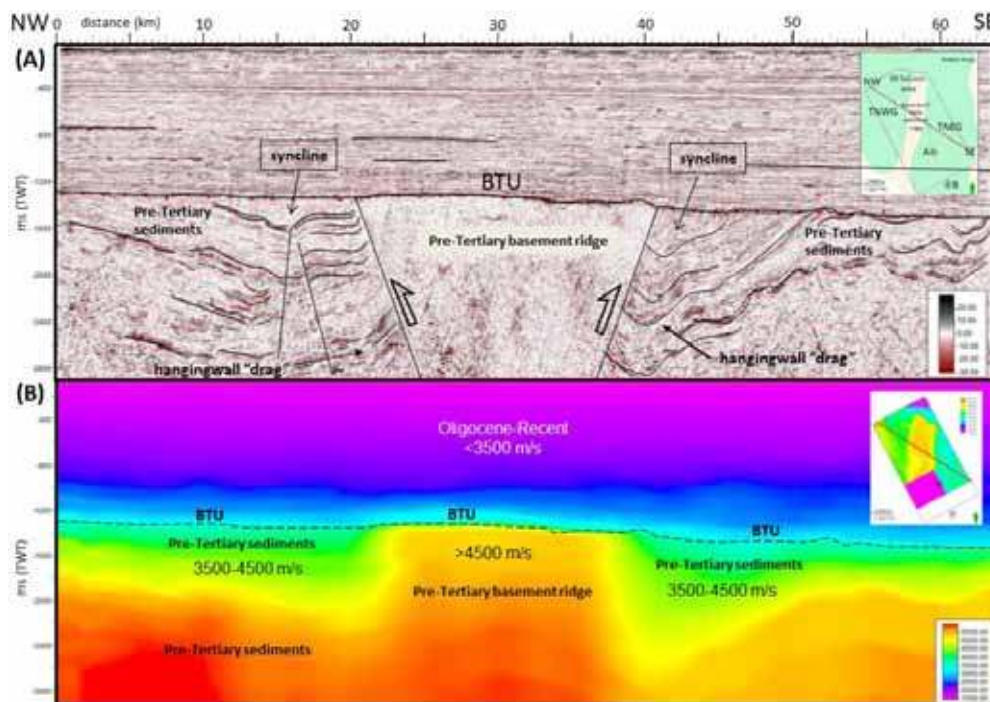


Figure 19: Seismic and velocity profiles across the study area on the Tenggol Arch through a north-south trending basement ridge (see inset in lower figure), modified from M. Hafiz *et al.* (2019). (A) Seismic section with line tracing of major features showing a trapezoidal, non-reflective basement block in the middle bounded by steep reverse faults, flanked by deformed bedded sequences. Both the basement block and deformed sequences are truncated by the Base-Tertiary Unconformity (BTU), which M. Hafiz *et al.* (2019) named as UC-3 Unconformity. For reference, the location of the profile is shown in Figure 1 and Figure 21. (B) Seismic velocity profile along the same line, showing the high velocity of the basement ridge in the middle compared to velocity of the bedded sequences which M. Hafiz *et al.* (2019) identified as “Tenggol NW Graben” (TNWG) and “Tenggol NE Graben” (TNEG). These are not grabens but subcrops of pre-Tertiary sediments in the basement.

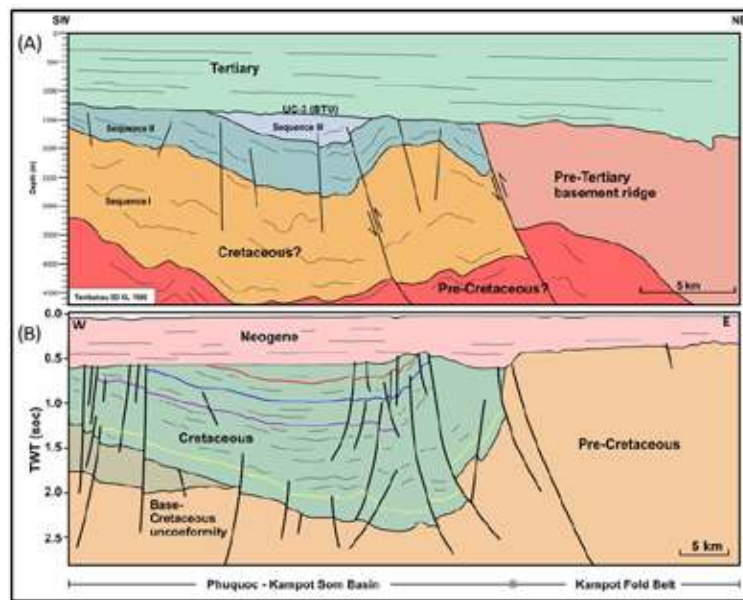


Figure 20: Similarity of structural styles in pre-Tertiary basement of Malay Basin (A) from M. Hafiz *et al.* (2019) with that in offshore Cambodia (B) from Fyhn *et al.* (2016). The location of profiles is shown in Figure 21.

of Hutchison, 2007) sedimentary rocks (which are mainly Jurassic-Cretaceous sediments outcropping in the Central Belt of Peninsular Malaysia) from “pre-granite” sedimentary rocks, which occur almost everywhere else on the Peninsula. These Palaeozoic sedimentary formations form the host rocks to the granitic intrusions that range in age from Late Triassic to Early Jurassic (Hutchison, 2007; Azman, 2009; Searle *et al.*, 2012). The uplifted and exhumed pre-granite sediments, which were affected by very low-grade (anchizone stage) metamorphism (Harbury *et al.*, 1990; Hutchison, 2009b), as well as the granite batholiths that intrude them, form the basement to the Jurassic/Cretaceous and Tertiary basins.

Thus, pre-Tertiary sequences are expected to occur beneath the Malay and Penyu basins, as have been found from seismic and well data presented above. The occurrence and distribution of these rocks support the proposed extent of the Sukhothai Arc from Indochina southwards into the offshore area east of Peninsular Malaysia (Fyhn *et al.*, 2010; Metcalfe, 2017, Figure 21). The outcropping equivalents of the Palaeozoic and Mesozoic rocks in central/northern Thailand and Indochina, as well as in Peninsular Malaysia, including the Semantan Formation and the Tembeling and Gagau groups, provides us with possible analogues for the pre-Tertiary in offshore Malaysia.

Burton (1973) noted that the base of the Cretaceous basins on Peninsular Malaysia lies deeper towards the south, as if the pre-Tertiary Mesozoic landmass is tilted southward. This may be related to the far-field effect of crustal thickening in Central Asia and the compressional tectonics at the Assam Syntax as a consequence of the indentation of India with Eurasia in the Early Tertiary. Madon (1990) argued that while palynological records in the Thai intermontane basins show evidence of marine incursions

by Early Miocene, those basins now lie more than 1000 m above sea level, far exceeding the magnitude of sea level fluctuations during the Late Oligocene to Early Miocene (*ca.* 150 m). This means that the “intermontane” basins of Thailand have been significantly uplifted. Hutchison (2009b) also noted that since high-grade metamorphic rocks are confined to the northern part of the Malay Peninsula, the uplift/exhumation had been greater in the north and the peninsula is generally tilting to the south.

While the pre-Tertiary was dominated by compressional tectonics, as documented in the Late Carboniferous to Triassic and Cretaceous Khorat Group of the Khorat Plateau (Morley *et al.*, 2011), the structural evidences also suggest that there may have also been multiple rifting events during the Late Cretaceous to Tertiary. Some Tertiary half-grabens were initiated along pre-existing, older rift zones and were reactivated during the Tertiary. An example is the Tok Bidan graben (Figure 6) in which Jurassic-Cretaceous synrift sediments occur at the base of the half-graben which is then overlain by an almost equal thickness of Tertiary synrift sediments. This strongly suggests that Tertiary extension may have taken place along pre-existing (Cretaceous or older) extensional faults and sub-basins. The importance of pre-existing basement faults in influencing Tertiary deformation and basin formation has been discussed by Ngah *et al.* (1996). As in the Jurassic-Cretaceous rifts, which often include volcanics (Rishworth, 1974), some Tertiary rifts may also have been associated with volcanism, as evident by the tuffaceous layers within in the Eocene-Oligocene sediments intersected by wells Janglau-1 and Ara-1, Penyu Basin (Figure 2).

Outcrops of Jurassic-Cretaceous Tembeling and Gagau groups in the Central Belt of Peninsular Malaysia are believed to be good analogues for some of the Mesozoic

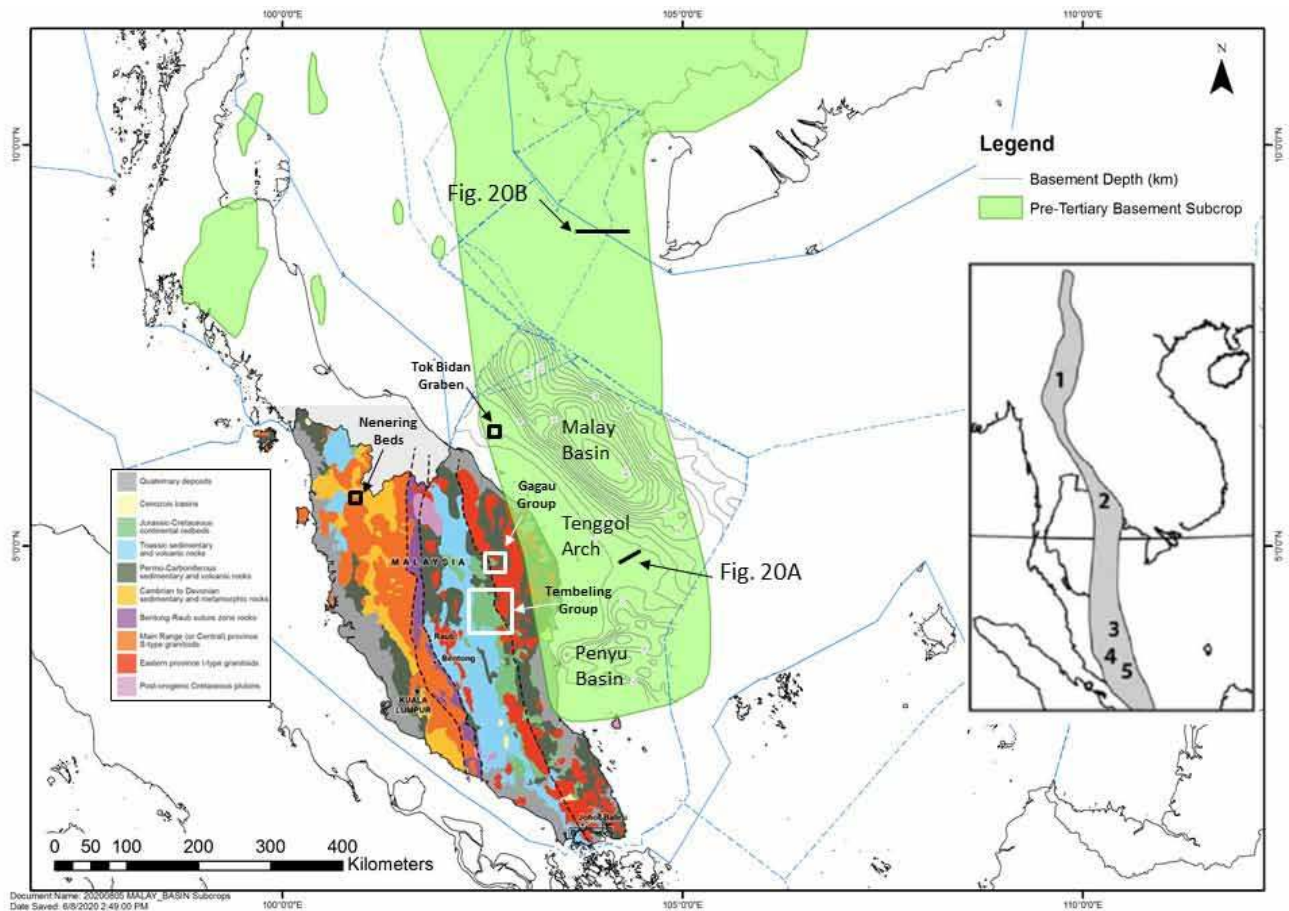


Figure 21: Map of Mesozoic sediments in the central SE Asian region, including beneath the Malay Basin (shaded green areas), compiled from various sources. Inset - Sukhothai Arc terrane showing the distribution of Jurassic-Cretaceous redbeds. Overlain on Peninsular Malaysia is a simplified regional geological map including the tectono-stratigraphical Western, Central and Eastern belts (from Leslie *et al.*, 2019). Terrane identification: 1. Sukhothai 2. Chanthaburi 3. East Malaya (East Pahang) 4. East Malaya (West and Central Pahang) 5. East Malaya (South Pahang and Johor) (from Metcalfe, 2017). Also shown are the locations of profiles in Figure 20, the main Jurassic-Cretaceous formations in Peninsular Malaysia mentioned in the text, and Tok Bidan Graben.

sediments beneath the offshore basins. Besides those, the Cretaceous (Aptian-Albian) Nenering beds in the NW Peninsular Malaysia, which sit in fault-bounded grabens and unconformably overlie Ordovician-Devonian Kroh Formation (Nuraiteng, 2009), may also serve as analogue for offshore Mesozoic basins such as the Tok Bidan graben. The Nenering beds are relatively flat-lying, whereas Late Jurassic-Early Cretaceous sediments (Tembeling Group) are tightly folded (Figure 9), and would be a better analogue for the layered pre-Tertiary rocks observed beneath the BTU under the Tenggol Arch (Figures 10-13). It seems that the deformation intensity in the Mesozoic sequences is quite variable or they represent different stratigraphic groups of different ages separated by a major unconformity. As a result of the widespread extensional event in the Early Tertiary, the Sundaland landmass founded by faulting and extension, resulting in rift basins that initially occurred at different elevations and ended up subsiding to different depths. Some basins remained above sea level, like those on Peninsular Malaysia, sitting directly on top of exhumed

Palaeozoic metasediments, e.g., Batu Arang Basin (Tjia, 1999; Raj *et al.*, 2009).

Pre-Tertiary plays

There are two main potential reservoir types in the pre-Tertiary basement: fractured basement and paleokarsts. While the former can to some extent be predicted or mapped based on seismic recognition and interpretation, the latter may possibly be predicted based on seismic and knowledge of pre-Tertiary limestones distribution in Peninsular Malaysia.

Although it may be possible, with good 2D and 3D data coverage, to map the extent of Mesozoic sedimentary subcrops or basins, as indicated in this study, in terms of the reservoir potential the primary matrix porosity might have been obliterated during periods of pre-Tertiary burial, upheaval and peneplanation. The main potential agents that could result in reservoir quality enhancement include natural fracturing of the rocks (e.g., Anding) or, in the case of carbonate bodies or paleokarsts, meteoric water

or hydrothermal dissolution (e.g., Nang Nuan in Thailand; Heward *et al.*, 2000). The deliberate search for a basement plays therefore requires prediction of fracture or karst occurrence, through seismic imaging and characterisation. Regional understanding of fractures and their tectonic controls, coupled with the application of seismic data (especially 3D) is essential for predicting fracture distribution and orientation. Some authors have attempted to do this by relating present-day stress orientations derived from borehole-breakouts and regional fault/fracture patterns (Tjia & Mohd Idrus, 1994; Ngah *et al.*, 1996; Tjia *et al.*, 2010), but these studies suffer from the lack of chronological constraint on the timing of deformation. We propose a more pragmatic approach to basement play exploration utilising all the seismic data available in the basin to identify areas of basement is likely to be fractured.

Critical is the ability to recognize fractured basement in seismic and the use of 3D seismic data has greatly improved the recognition of fractured zones in the basement. It is now possible to identify potential “sweet spots” for fractured basement reservoirs. Some areas in the Malay Basin have been mapped in detail using 3D seismic and may have potential for fractured basement play (Figure 22). Commonly observed are conjugate sets of linear fractures (e.g., Figures 22B, 22C), which suggest that similar patterns may exist at sub-seismic scale. Figure 23 shows selected seismic profiles across those mapped areas where fracturing is clearly visible. The main potential fracture zones are observed as linear high-angle planes of discontinuity often in conjugate sets. We see these fractures in generally mild deformation zones, and they tend to get stronger when located near wrench zones where they are in close association with strike-slip or wrench fault zones, for example near the major NW-SE trending Tenggol Fault and its *en echelon* offset, Tembikai Fault (see Figure 8C), to the north (Figures 23B, 23C). On 2D seismic sections, the fractures appear as high-angle, linear features that extend downwards from the top-of-basement. The fractures do not seem to propagate upwards into the overlying layered sediment. They often occur as conjugate sets with opposing dips with apparent dihedral angles of 45-60°, suggesting that they formed probably as hybrid tensile-shear fractures in a wrench regime (Figure 24). Well data from Anding area have indeed revealed two main fracture sets oriented WNW-ESE and NW-SE, dipping steeply at 50°/90°, and are parallel to the major seismic-scale faults and fractures. With high quality 3D data, it is therefore possible to identify and map prospective areas for fractured basement play.

Fractured basement play: the Anding example

Despite the numerous basement penetrations, the only significant hydrocarbon discovery in the pre-Tertiary basement was at Anding Utara-1¹ which was drilled by

PETRONAS Carigali in September 2004. The well is located 4 km north of the Anding structure in the southwestern part of the Malay Basin adjacent to the Tenggol Arch (Mohd Kadir, 2010) (Figure 1). The discovery has been appraised with several wells (the key ones shown in Figure 24A) to delineate the field and estimate the resources. Anding Utara-1 was drilled to a total depth of 2610 m, and penetrated 120 m of basement, while the side-track well reached a total depth of 2740 m, and penetrated 250 m of basement as the secondary objective. Both the Anding Utara-1 exploration well and its sidetrack tested oil in the basement. Subsequently, in November 2005 and November 2006, PETRONAS Carigali drilled Anding Utara Basement-1 and Anding Tengah-1 wells, respectively, to explore further the basement reservoir complex. Anding Utara Basement-1 was drilled deliberately to test the basement reservoir while Anding Tengah-1 was drilled in a southern structural high and penetrated 267 m of fractured metamorphic rocks comprising phyllites and quartzites and tested oil. Core samples show that the basement reservoir comprises generally dark coloured, heavily quartz-veined metapelites or phyllites, with a strong foliation probably inherited from a precursor bedding fabric of a mud-rich sediment (see examples in Figures 7A-C).

Despite its development being shelved for the time being, the Anding basement discovery has formed the basis for the fractured basement play concept (Figure 25). This play is similar to the “buried hill” play that has been highly successful in Cuulong Basin, offshore Vietnam, e.g., Bach Ho field (Cuong & Warren, 2009). In the Vietnamese example, however, the basement rock is mainly granite. The producibility of basement reservoir, whether granite or metamorphic rock, relies on secondary porosity due to natural fractures and/or paleo-weathering zones. Fractures may have been generated during the Early Tertiary (?Oligocene) or earlier, probably during the main active displacement phase along the Tenggol Fault, which is likely towards the late synrift to early post-rift, prior to the compressional deformation that accompanied the major basin inversion. It was also found that, based on Anding data, weathered metamorphic rocks appear to be of higher reservoir quality than “fresh” (non-weathered) facies. Reservoir quality prediction therefore depends on understanding fracture origin and distribution and the extent of weathered zones on top of the basement.

Regional geological knowledge indicates that pre-Tertiary rocks are thermally over-mature, so the generative source rocks for basement play must occur in the overlying Tertiary sediments, mostly lacustrine shales in Groups L and older deposited within the synrift half-grabens adjacent to the basement highs. This has been proven in the Anding area, where thermally mature L shales may be as much as 300 m thick. The adjacent half-grabens appear to be at

¹ PETRONAS Makes Malaysia's First Basement Oil Discovery: Rigzone, 2005. published 25 April 2005. Viewed 11 June 2020, https://www.rigzone.com/news/oil_gas/a/22053/petronas_makes_malysias_first_basement_oil_discovery/

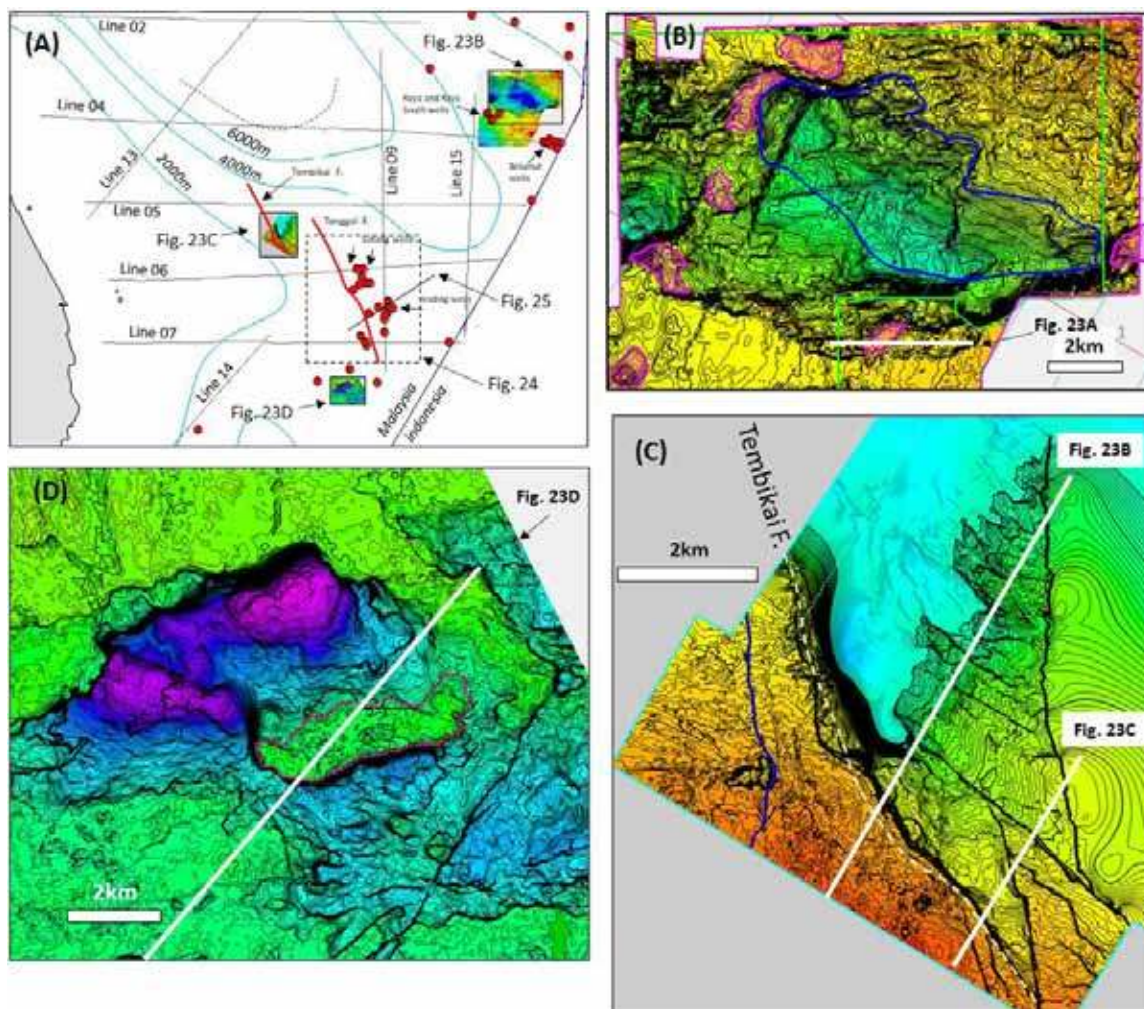


Figure 22: (A) Structure map at Base-Tertiary Unconformity (BTU) based on 3D mapping at selected areas showing conjugate sets of linear fracture patterns which indicate the possible presence of pervasive fracture networks conducive for fractured basement reservoir development. Time structural map drawn at contour intervals at 20 ms. (B) Time structural map of pre-Tertiary basement in the southeastern Malay Basin. A seismic profile across a fractured basement “buried hill” feature is shown in Figure 23A. Rectangular dashed line is the map area in Figure 24A. Figure 25 is the geological cross section across the Tenggol Fault-Anding area summarizing the key elements of the fractured basement play. (C) Complex fracture patterns associated with the Tembikai Fault in the southern Malay Basin (highlighted by white dash line). Note the parallel linear fractures eastward of, and oblique to the Tembikai Fault. (D) BTU depth map on the southern Tenggol Arch area showing remarkably linear conjugate fracture patterns bounding sub-basins (purple areas), which could be the source rock pods for nearby fractured basement highs.

maximum burial depth at present, as supported by basin modelling (Madon, 1997), and are sufficiently mature to have charged the structures. Hydrocarbon migration took place, likely during Late Miocene to Pliocene, after the creation of secondary porosity by fracturing and weathering.

Although pre-Tertiary granites have been encountered in many wells, especially in the SE Malay Basin (Figure 5), no granitic basement reservoir have been found. The Puteri Basement-1 well, drilled by PETRONAS Carigali in 2017, was reportedly the first test of fractured granite in basement in the Malay Basin. Unfortunately, the well did not find any hydrocarbons due to lack of charge and poor top seal, with only 10 m of shale above the basement (Aziz *et al.*, 2019). Some wells on the Tenggol Arch also penetrated basement, and found metasediments as well as

granites. In the Penyu Basin, out of the 18 wells drilled, more than half (11) were reported to have penetrated the pre-Tertiary basement (Figure 1). These include Pari-1, Janglau-1, Ara-1, Soi-1, and all the three wells on the Rhu structure. In well Pari-1, oil stains were observed in the pre-Tertiary silty limestone of the bottom-hole cored section. Igneous rocks (possibly diorite, according to well report) were encountered at Batu Hitam-1, which was drilled on a basement horst block similar to the Rhu structure (Lundin, 2011; Batu Hitam-1 Final Completion Well Report).

Paleokarsts

Limestone outcrops on Peninsular Malaysia provide some insights into the pre-Tertiary potential of this play. They most occur in the western side of Peninsular Malaysia and

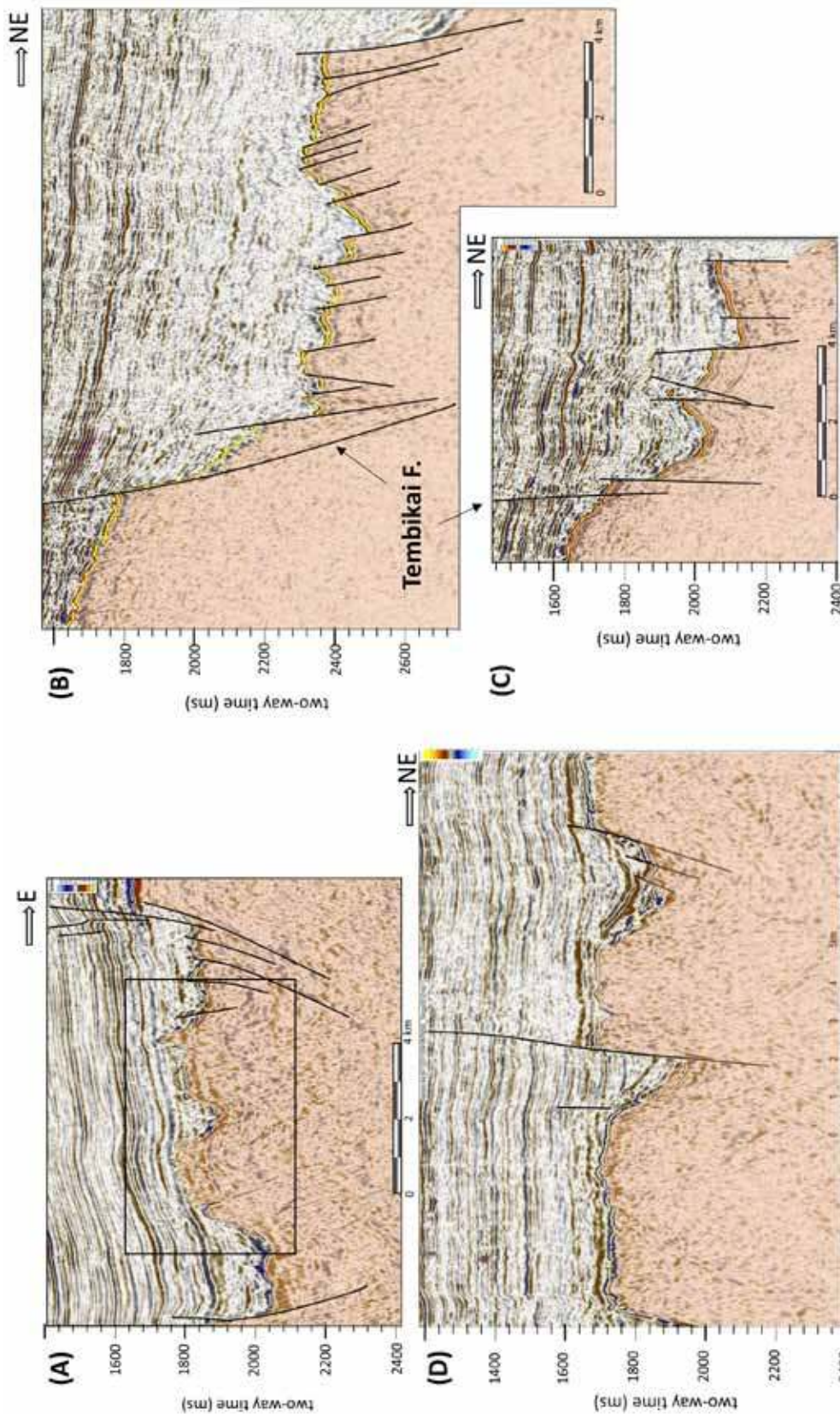


Figure 23: (A) Seismic section in Figure 22B across fractured basement features, highlighted in rectangle. Intense fracturing resulted in closely spaced sub-vertical fractures through the two structural highs visible on seismic. These features look like karst features. However, the pre-Tertiary basement penetrated in this area in the SE corner of the Malay Basin, near the Belumut area (see Figure 5 for location) is mainly granites. (B) and (C) are seismic sections across the Tembikai Fault, which seems to be part of a right-stepping *en echelon* fault system along with the Tenggol Fault (Figure 22A) and have similar geometries: high-angle and linear in NNW-SSE direction. These two NE-SW profiles show the closely-spaced faults which seems to be linked to the main Tembikai Fault zone (see Figure 22C). (D) NE-SW profile across fractured basement highs in the southern part of the Tenggol Arch. Closely spaced fractures can be seen in the flat Base-Tertiary Unconformity on the basement highs separating small half-grabens.

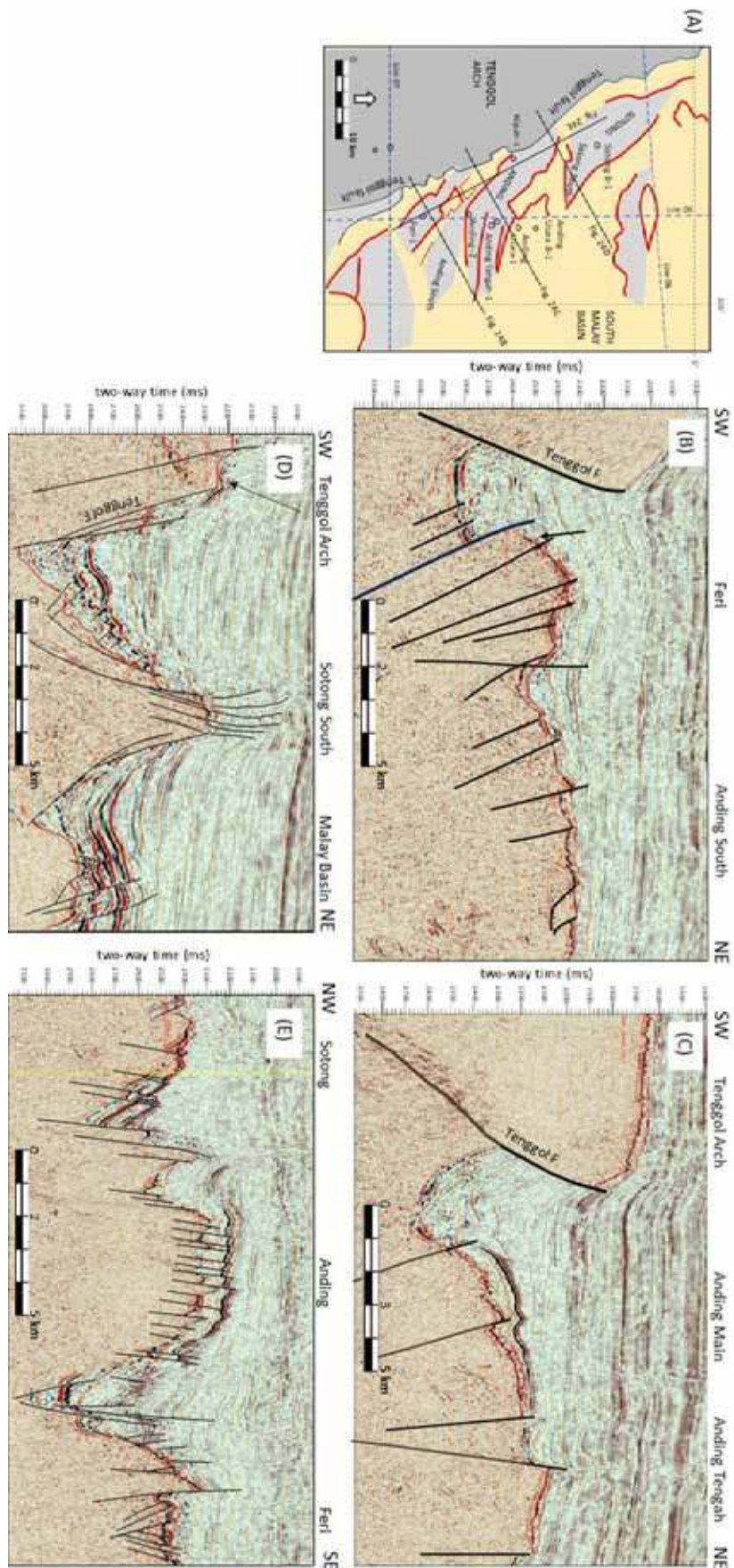


Figure 24: (A) Simplified structural map of the Tenggol Fault and southern Malay Basin showing the key structural elements of the Solong-Anding-Feri area. (B) Dip profile in the southern part of the area through the Feri structure where well Feri-1 encountered fractured metamorphic basement. The transpressional nature of the strike-slip displacement is evident from the steep overthrust of the Tenggol Fault and the “pop-up” flower structure of the Feri high. (C) Profile through the central part of Anding basement high, showing the thrust hangingwall overhang at the Tenggol Fault above an adjacent deep synrift basin. The Anding structure is transected by several NW-SE faults oblique to the main Tenggol Fault strand, resulting in compartmentalization into Anding North, Anding Main and Anding South (see index map in A). (D) The northernmost dip profile shows deep half-graben adjacent to the Tenggol Fault. Basinward is a narrow southward extension of the Solong structure where closely spaced faulting and fracturing resulted in a highly fractured triangular fault-block, which is part of a tilted extensional fault block affected by strike-slip faulting. The fractures seem to propagate into the overlying Tertiary sediments, which indicates that the fracturing event may have been reactivated subsequently, probably during the Miocene. (E) NW-SE profile through the three main basement highs (Solong, Anding and Feri) showing intensely fractured basement. Most of the fractures that are visible at this seismic scale also have vertical displacements (especially at Anding). The fracturing seem to have affected the immediate overlying late synrift to early post-rift strata, thus indicating Late Oligocene-Early Miocene deformation event.

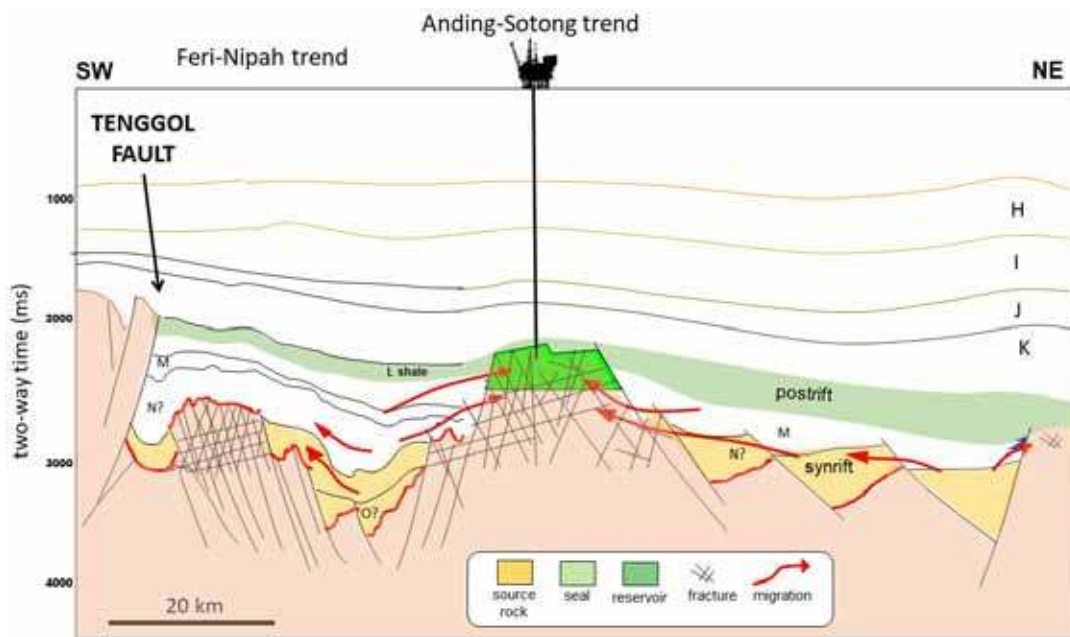


Figure 25: Schematic illustration of basement play concept in the southern Malay Basin, based on actual seismic data in the Tenggol Arch and adjacent Sotong-Anding area where many wells have been drilled to appraise the discovery at Anding area. Approximate line location is shown in Figure 22A. The Anding-Sotong structural trend is essentially a tilted normal fault block that has been affected by subsequent strike-slip (wrench) deformation, which is believed to have generated the fracturing. The main displacement zone of the strike-slip fault activity is along the Tenggol Fault Zone. Evidence of wrenching is seen along the fault as basement-involved “pop-up” or flower structures intensely fractured, forming the Feri-Nipah trend adjacent to the Tenggol Fault (Figure 24B is an actual seismic across the Feri structure). The geometry suggests a transpressional zone associated with the Tenggol Fault system.

range in age from Late Palaeozoic (Permo-Carboniferous) to Triassic rocks. Those in western side are mainly slope carbonates, while to the eastern side of Peninsular Malaysia, they are platform carbonates thought to extend into the basement of the Malay Basin (Pierson *et al.*, 2009). Most of the limestones are not metamorphosed, except locally due to contact metamorphism. These limestones have been affected by karstification (Kassa *et al.*, 2012), that crop out as hills onshore and could form “buried hill” structures in the subsurface. The carbonate bodies are often interbedded with carbonaceous shales that may act as source rocks within the pre-Tertiary basement. The Nang Nuan field in Chumphon Basin, Gulf of Thailand, may be a useful analogue for karstic play (Heward *et al.*, 2000) in which the reservoirs are formed of Permian Ratburi limestones underlying basement buried hills. In this example, however, the karstification process may have taken place in the subsurface, related to deep hydrothermal fluids rather than meteoric water dissolution during subaerial exposure.

Perhaps the obvious place to look is the Tenggol Arch and adjacent southwestern Malay Basin where Sotong B-1 look-alikes are likely to occur as extension of the platform carbonate region postulated by Pierson *et al.* (2009). A detailed facies study by ISIS (2006) indicate that potential carbonate facies can be identified and mapped from seismic in the Sotong-B1 area (Figure 26). This could serve as a type section for pre-Tertiary carbonate and paleokarst play. The carbonates appear to have a distinct seismic facies

signature compared to the overlying Tertiary sediments as well as the surrounding basement rocks, and therefore could be identifiable with good quality seismic data.

Play risk

While the fractured pre-Tertiary basement play relies on hydrocarbon charge from overlying Tertiary source rocks, the unfractured pre-Tertiary play involving the layered sedimentary sequences or karstic, “buried-hill” structures requires a working petroleum system within the Mesozoic and Palaeozoic sequences. Hence, besides the presence of fractures, the likelihood of hydrocarbon charge and the timing of migration have to be determined in order to de-risk the potential drilling candidates. Below we consider the main risk elements for these plays.

Reservoir - Based on the onshore pre-Tertiary geology, potential oil reservoirs may exist in a variety of rock types, since various granitic, basaltic, felsic volcanics, metamorphic, limestone and sedimentary rocks have all been encountered (Fontaine *et al.*, 1990; Madon, 1992; Madon *et al.*, 2019). In the fractured basement play, regardless of rock type, pervasive occurrence of natural fractures is likely to be associated with major strike-slip faults or shear zones. Reservoir quality may be enhanced by secondary porosity associated with paleo-weathering zones. At Anding, for example, it was observed that weathered metamorphic rocks have higher reservoir quality

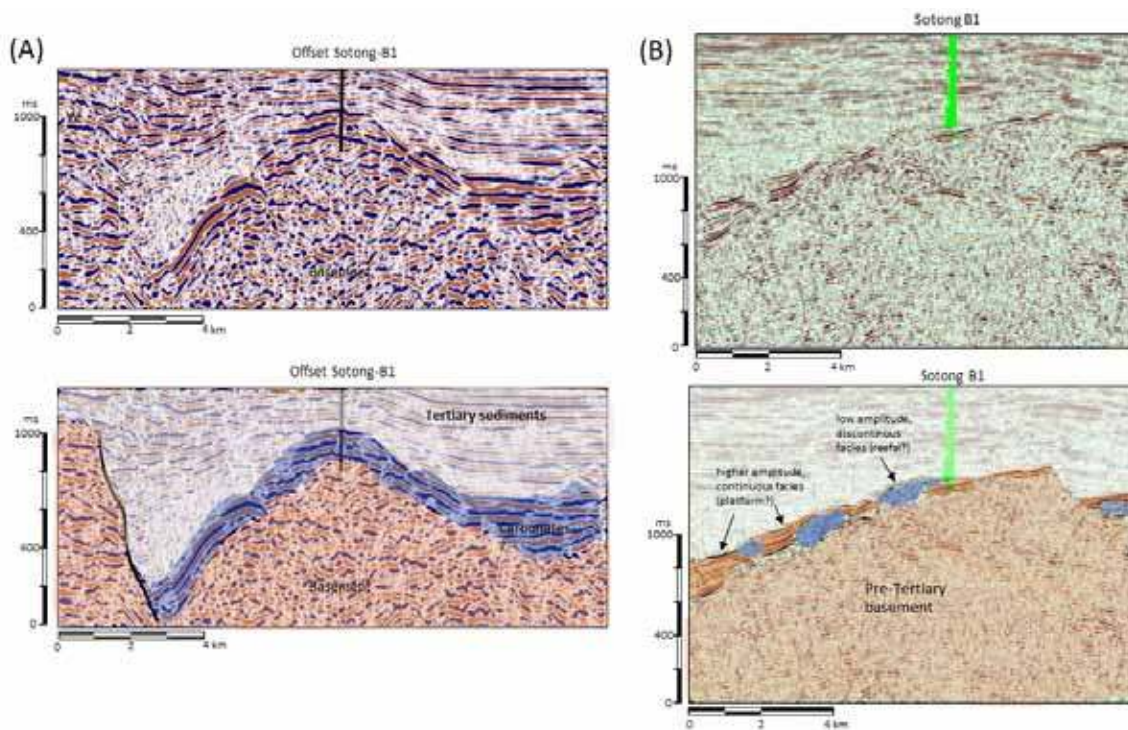


Figure 26: Examples of seismic facies analysis to identify carbonate facies. (A) A segment of Line 06, with offset well Sotong B-1, which encountered Triassic limestone in the pre-Tertiary basement. These rocks have a distinct seismic facies signature compared to the overlying Tertiary sediments as well as the surrounding basement rocks, and therefore could be mapped with good-quality seismic data. (B) Interpretation of seismic facies across Sotong area. Reflection characteristics and attributes may be used to distinguish between reef (transparent, low-amplitude, discontinuous) and off-reef (high-amplitude, continuous, bedded) facies. Based on ISIS (2006).

than “fresh” facies. Reservoir quality prediction therefore depends on regional understanding of fracture origin and distribution, faulting, hydrothermal activity and the extent of weathered zones on top of the basement. Near-surface tectonic fissuring processes due to tensile fracture, associated hydrothermal mineralization and weathering are key controls on the porosity and permeability development of basement reservoirs (Trice *et al.*, 2019). Fracture zones can with some confidence be identified with high-quality seismic with appropriate processing parameters applied (Figure 27). They may appear as relatively closely spaced linear planes of discontinuities at high angles to the horizontal, and are aligned sub-parallel to major faults or fault zones, such as the Tembikai and Tenggol faults. In some instances, amplitude maps may be used to distinguish between metasediments from granites, as well as to identify igneous dykes (Ngoc *et al.*, 2014). The application of the latest deep-imaging 3D seismic acquisition and processing technologies (e.g., Beam-PSDM; Ngoc, 2019) have helped in characterising the subsurface fracture patterns and intensity. Attributes such as amplitudes, coherence, curvature and second derivatives have been shown to be effective in predicting fracture networks, while interpretation techniques such as “ant tracking” for fracture orientation and acoustic impedance (AI) aided fault picking may greatly enhance the subsurface reservoir understanding (Ngoc *et al.*, 2012, 2014; Ngoc, 2019; see sample in Figure 27).

Source rocks - In the Anding-type play, the source rocks occur in the Tertiary (Eocene-Oligocene) shales overlying the fractured pre-Tertiary rocks. For the pre-Tertiary structural-stratigraphic and karstic plays the presence of effective source rocks in the Mesozoic and Palaeozoic sequences have to be considered. Good source rock units exist in the Palaeozoic sequences (Pierson *et al.*, 2009), but their existence is not yet proven in the offshore pre-Tertiary basement.

The source-rock potential of pre-Tertiary rocks can be assessed from geochemical analyses of outcrop samples of Mesozoic and Palaeozoic rocks. Tjia (1999) reported the analyses of 25 samples of Triassic rocks which show low to moderate TOC, but the vitrinite reflectance (R_o) exceeds 2.7%. In addition, fifty-seven (57) Jurassic-Cretaceous samples were analysed, and all exhibit poor TOC (<0.5 wt%), with R_o ranging from late-mature to post-mature (no values reported); maturity readings are higher in proximity to igneous intrusions. The Jurassic Tembeling Group was shown to have attained very low-grade metamorphism based on illite crystallinity (Harbury *et al.*, 1990), and thus may have passed the hydrocarbon generating stage. Carbonaceous black shales with TOC of up to 6% are known to occur in Permo-Carboniferous clastic and carbonate sequences on Peninsular Malaysia (Pierson *et al.*, 2009), and the seismic evidence presented in this paper suggests that some of these sequences may extend eastwards beneath the Malay and Penyu basins.

As mentioned above, pre-Tertiary rocks are thermally over-mature and the generative source rocks occur in the overlying Tertiary sediments within the synrift half-grabens (Figure 25) where thermally mature L shales may be up to 300 m thick. In addition, geochemical results from Janglau-1 has indicated the presence of effective and mature source shales containing oil-prone Type II kerogen in the Cherating Graben (Madon *et al.*, 2019).

Trap formation - The trapping of hydrocarbons in a fractured basement reservoir, as in Anding, relies on two elements – fracture porosity in the basement high and hydrocarbon charge from adjacent/overlying source shales, which also serve as seals. Fracturing was caused by discrete fault or shear zones resulting from wrench tectonics of Oligocene-Miocene age, which affected parts of the Tenggol Arch and southwest Malay Basin, probably contemporaneous with the basin inversion phase that generated the major hydrocarbon-bearing anticlinal folds in the basin centre. These shear zones are easily recognized on seismic and are mappable with high-density 2D and 3D data (Figures 22-24). The Tenggol Arch is especially well-imaged by 2D and 3D

seismic, as well as by modern full-tensor gradiometry (FTG) gravity. Being at relatively shallow depth, the seismic also contains a high frequency content that would enable subtle stratigraphic features such as paleokarsts and buried hills to be identified in the future.

Seal formation - The fractured basement play requires an effective seal immediately on top of the basement. Such a seal is likely to be formed by transgressive shales in the late-synrift or post-rift sequences, either the Groups K or L shales (Figure 25), which are seismically continuous and have been found to be effective seals. The Group L shale is sealing formations of tight sands with petroleum occurrences, and the Group K shale is proven effective top seal in the Bertam Field, as well as the Alu Field over the border in Indonesia. A pressure communication in the common aquifer between the Bertam and Alu fields is reported. Both regional clay sequences would qualify as top seals, where fractured basement is seen to form horsts, with onlapping Oligocene and the Group M and lower L sequences being absent. Group K sequence is very interesting because it contains a *ca.* 10-30 m of massive, often organic claystone and

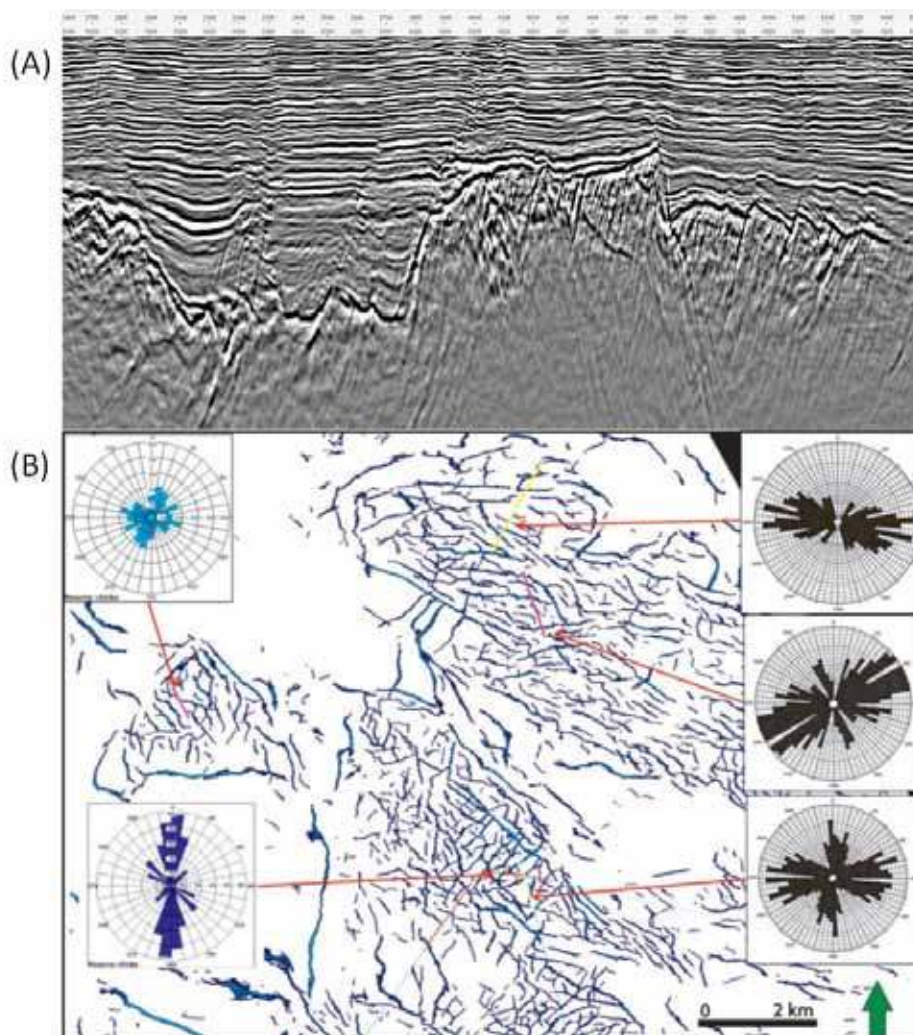


Figure 27: Geophysical applications to enhance basement fracture identification and characterisation in southern Malay Basin. (A) Example of 3D seismic profile (from Ngoc *et al.*, 2012, exact location unknown) processed using BEAM-PSDM, showing likely conjugate set of fractures in the pre-Tertiary basement. (B) Example of ant-tracking results using relative AI time slice 2280 ms through the pre-Tertiary (metasedimentary) basement at Anding. Fracture and fault orientations in the rose diagrams were interpreted from FMI data. From Ngoc *et al.* (2014).

beneath the clay are several good quality reservoirs, which have acted as regional hydrocarbon carrier beds. However, further investigation is needed on the interface between the fractured basement and the mentioned clay units for sealing capacity, and tight sands in between might form waste zones. Nonetheless, within the pre-Tertiary basement itself, the presence of seals is unknown as the detailed stratigraphy of Mesozoic and Palaeozoic strata is yet to be worked out. Analogues from outcrop studies from around the region, both on the Peninsula and in Indochina would be useful (e.g., Harbury *et al.*, 1990; Metcalfe, 2017).

Timing - Effective source-reservoir-trap relationships require that hydrocarbon migration took place after the creation of secondary porosity by fracturing and/or weathering. In the Anding area, the adjacent half-grabens appear to be at maximum burial depth at present (as supported by basin modelling outcomes; Madon, 1997), and are sufficiently mature to have charged the oil accumulations. The basement fractures were mainly generated during the major strike-slip fault activity in the southern Malay Basin (e.g., along the Tenggol Fault and possibly also the Tembakai Fault) during late synrift to early post-rift (Mid-Oligocene to earliest Miocene) before the start of the main basin inversion phase (Middle Miocene), whereas the oil migration was probably much later, during Late Miocene to Pliocene (see Figure 3B).

In the pre-Tertiary basement, it is likely that the Palaeozoic and Mesozoic source rocks reached their hydrocarbon-generation stage very early in their history (Pierson *et al.*, 2009). Despite this, pre-Tertiary shales below the BTU may still be generating some dry gas at depth and contributing to the thermogenic gas encountered on the Tenggol Arch. In the Tembakau gas discovery, although the current model suggests long-distance migration from the nearby basinal areas (Anding-Sotong area) in the Malay Basin to the east (Jong *et al.*, 2019), or even from the central Malay Basin to the north, hydrocarbon charge from a deep-seated source through the steep basement-involved faults may still be a possible alternative.

CONCLUSIONS

Over five decades of exploration effort has resulted in more than 70 well penetrations of the basement in the Malay and Penyu basins. These wells reveal a variety of lithologies in the pre-Tertiary basement including igneous, metamorphic, and sedimentary rocks (siliciclastics, limestones, meta-carbonates) and provide us with some insights into the geology of the Mesozoic landmass prior to Tertiary basin subsidence. Some basement highs made up of intensely fractured rocks have become attractive drilling targets for fractured basement exploration, and a working petroleum system has indeed been proven by the Anding discovery. Based on interpretation of high-quality 2D and 3D seismic and gravity modelling, pre-Tertiary layered sequences could be identified in large parts of the Tenggol Arch and southwestern Malay Basin. These

pre-Tertiary sequences, especially the “Jurassic-Cretaceous” sediments, should be mapped in detail for further investigation of their exploration potential.

Pre-Tertiary reservoirs appear to be of high risk, as diagenesis may have obliterated much of the porosity and, more so, permeability (e.g., Madon, 1994; Maga *et al.*, 2015; Kessler & Jong, 2018). Therefore, the identification of enhanced porosity and permeability in the basement rocks due to intense fracturing is critical, while seismic recognition of fracture and fault orientations will be a key factor in finding new prospects. The use of high-quality 3D seismic with the latest deep-imaging AI technologies and specialist interpretation techniques such as “ant tracking” can enable the recognition of potential fractured zones in the basement that could form fractured reservoirs and traps if the right conditions for a working petroleum system exist. These criteria include juxtaposition of the fractured rocks against carrier beds with direct access to a thermally mature source kitchen, and an effective top seal to retain the migrated hydrocarbons. Based on seismic data examined in this study, potential areas of fractured basement reservoirs have been identified for further investigations.

ACKNOWLEDGEMENTS

We thank PETRONAS for providing seismic examples and permission to publish this paper, which has benefited greatly from the published work of past and present authors who contributed to the ideas presented, and to whom we are indebted. However, any mistakes or shortcomings remain the responsibility of the authors. MM would like to specially acknowledge the contribution by James Liu, a former colleague at PETRONAS who had worked on the seismic dataset and prepared some of the structural maps and profiles used in this paper. We thank Dayang Aimi Nuraini for helping to redraft some of the figures. Our appreciation is extended to our reviewers for their constructive comments that help to improve the quality of the manuscript.

REFERENCES

- Achalabhuti. C., 1974. Petroleum geology of Gulf of Thailand. American Association of Petroleum Geologists Bulletin, 58(7), 1430 (Abstract).
- Arisandy, M., Farida, W.N., Putra, B.P., Iriansyah, H., Nasifi, W., Ozza, T. & Korah, F.H., 2019. New insight of hydrocarbon play concept in West Natuna Basin related to tectonic and stratigraphic framework. Asia Petroleum Geoscience Conference & Exhibition 2019, 29 - 30 October, KLCC, Kuala Lumpur.
- Aziz, S.S., Tukimin, N., Dasgupta, S., Lai Kee, Y. & Mohamad Idris, H.A., 2019. Maturing potential fractured basement play in Malay Basin Through regional integrated approach. Asia Petroleum Geoscience Conference & Exhibition 2019, 29 - 30 October, KLCC, Kuala Lumpur.
- Azman A. Ghani, 2009. Plutonism. In: Hutchison, C.S. & Tan, D.N.K., (Eds.), Geology of Peninsular Malaysia. Universiti Malaya & Geological Society of Malaysia, Kuala Lumpur, 211-232.
- Azmi, M. Y., Harun, A., Md Nasib, B. & Morley, R., 1996. Integrated

- biostratigraphic zonation for the Malay Basin. *Bulletin of the Geological Society of Malaysia*, 39, 157-184.
- Burton, C.K., 1973. Mesozoic. In: Gobbett, D.J. & Hutchison, C.S., (Eds.), *Geology of the Malay Peninsula*. Wiley-Interscience, New York, 91-141.
- Burton, D. & Wood, L.J., 2010. Seismic geomorphology and tectonostratigraphic fill of half grabens, West Natuna Basin, Indonesia. *American Association of Petroleum Geologists Bulletin*, 94(11), 1695-1712. DOI:10.1306/06301010003.
- Clements, B., Burgess, P.M., Hall, R. & Cottam, M.A., 2011. Subsidence and uplift by slab-related mantle dynamics: A driving mechanism for the Late Cretaceous and Cenozoic evolution of continental SE Asia? In: R., Hall, M.A., Cottam, & M.E.J., Wilson, (Eds.), *The SE Asian Gateway: History and Tectonics of the Australia-Asia Collision*. Geological Society of London Special Publications, 355, 37-51. <http://dx.doi.org/10.1144/SP355.3>
- Cuong, T.X. & Warren, J.K., 2009. Bach Ho field, a fractured granitic basement reservoir, Cuu Long Basin, offshore SE Vietnam: a "buried-hill" play. *Journal of Petroleum Geology*, 32, 129-156.
- Daines, S.R., 1985. Structural history of the West Natuna Basin and the tectonic evolution of the Sunda region. *Proceedings of the Indonesian Petroleum Association 14th Annual Convention*, Jakarta, 8 - 10 October, 39-61.
- Doust, H. & Sumner, H.S., 2007. Petroleum systems in rift basins - A collective approach in Southeast Asian basins. *Petroleum Geoscience*, 13, 127-144.
- Esso, 1985. Petroleum geology of the Malay Basin. Unpublished internal report, held by PETRONAS. 87 p.
- Fontaine, H., Rodziah Daud & Singh, U., 1990. A Triassic "reefal" limestone in the basement of the Malay Basin, South China Sea: regional implications. *Bulletin of the Geological Society of Malaysia*, 27, 1-25.
- Fyhn, M.B.W., Boldreel, L.O. & Nielsen, L.H., 2010. Escape tectonism in the Gulf of Thailand: Paleogene left-lateral pull-apart rifting in the Vietnamese part of the Malay basin. *Tectonophysics*, 483, 365-376.
- Fyhn M.B.W., Green, P.F., Bergman, S.C., Van Itterbeeck, J., Tri, T.V., Dien, P.T., Abatzis, I., Thomsen, T.B., Chea, S., Pedersen, S.A.S., Mai, L.C., Tuan, H.A. & Nielsen, L.H., 2016. Cenozoic deformation and exhumation of the Kampot Fold Belt and implications for south Indochina tectonics. *Journal of Geophysical Research: Solid Earth*, 121, doi:10.1002/2016JB012847.
- Garcia, E.S., Sandwell, D.T. & Smith, W.H.F., 2014. Retracking CryoSat-2, Envisat and Jason-1 radar altimetry waveforms for improved gravity field recovery. *Geophysical Journal International*, 196, 1402-22. doi: 10.1093/gji/ggt469.
- Harbury N.A., Jones, M.E., Audley-Chaeles, M.G., Metcalfe, I. & Mohamed, K.R., 1990. Structural evolution of Mesozoic Peninsular Malaysia. *Journal of the Geological Society*, London, 147, 11-26.
- Haribowo, N., S. Carmody & J. Cherdasa, 2013. Active petroleum system in the Penyu Basin: exploration potential syn rift and basement-drape plays. *Proceedings of the Indonesian Petroleum Association 37th Annual Convention*, Jakarta, IPA13-G-041, pp. 1-16.
- Hashim, A.H., Konjing, Z, Pendkar, N., Iyer, S.I.R., Dahmanuri, M.H., 2019. The occurrence of clastic successions below UC-3 unconformity in South Malay Basin: a new insight from petrography, XRD and SEM analyses. *Asia Petroleum Geoscience Conference & Exhibition 2019*, 29 - 30 October, Kuala Lumpur.
- Heward, A.P., Chuenbunchom, S., Makel, G., Marsland, D. & Spring, L., 2000. Nang Nuan oil field, B6/27, Gulf of Thailand: Karst reservoirs of meteoric or deep-burial origin? *Petroleum Geoscience* 6(1), 15-27. DOI: 10.1144/petgeo.6.1.15
- Hutchison, C.S., 2007. Geological evolution of South-East Asia. *Geological Society of Malaysia*, Kuala Lumpur. 368 p.
- Hutchison, C.S., 2009a. Tectonic evolution. In: Hutchison, C.S. & Tan, D.N.K., (Eds.), *Geology of Peninsular Malaysia*. Universiti Malaya & Geological Society of Malaysia, Kuala Lumpur, 309-330.
- Hutchison, C.S., 2009b. Metamorphism. In: Hutchison, C.S. & Tan, D.N.K., (Eds.), *Geology of Peninsular Malaysia*. Universiti Malaya & Geological Society of Malaysia, Kuala Lumpur, 233-247.
- ISIS Petroleum Consultants Pty Ltd, 2006. Integrated Regional Study of the Malay Basin - Sequence Stratigraphy Study. Unpublished Internal Report by ISIS Petroleum Consultants Pty Ltd. for PETRONAS Research Sdn Bhd.
- Iyer, S.R., M. Hafiz Dahmanuri, Azman, A.A. & Ilias, F., 2019. The Pre-Oligocene new play concept of Peninsular Malaysia basin within the regional geological framework of Southeast Asia. *Asia Petroleum Geoscience Conference & Exhibition 2019*, 29 - 30 October, Kuala Lumpur.
- Jong, J., Kessler, F.L., Madon, M. & Your, L., 2019. The Tembakau gas accumulation, Tenggol Arch, offshore Peninsular Malaysia: Petroleum system, gas composition and gas migration. *Bulletin of the Geological Society of Malaysia*, 68, 63-77.
- Kassa, S., Pierson, B.J., Chow, W.S. & Jasmi, B.A.T., 2012. Mapping the Kinta Valley Karst System, Peninsular Malaysia: Implications for better insight of subsurface karst features. *Petroleum Geoscience Conference and Exhibition 2012*, Warta Geologi, 38(2), 98-99.
- Kessler, F.L. & Jong, J., 2016. The South China Sea: Sub-basins, regional unconformities and uplift of the peripheral mountain ranges since the Eocene. *Berita Sedimentologi*, 35, 5-54.
- Kessler, F.L. & Jong, J., 2018. Sandstone diagenesis: Establishing threshold temperature and depth of porosity deterioration, Penyu Basin and Tenggol Arch, offshore Peninsular Malaysia. *Berita Sedimentologi*, 41, 4-21.
- Kessler, F.L., Jong, J. & Madon, M., 2020. Sedimentary record of Paleogene sequences in Penyu and Malay basins, offshore Peninsular Malaysia. *Berita Sedimentologi*, 46 (November), in press.
- Khoo, H.P., 1977. The geology of Sungai Tekai area. *Annual Report of Geological Survey of Malaysia*, 93-103.
- Koopmans, B., 1968. The Tembeling Formation-Alitho-stratigraphic description (West Malaysia). *Bulletin of the Geological Society of Malaysia*, 1, 23-43.
- Leslie, G.A., Dodd, T.J.H., Gillespie, M.R., Kendall, R.S., Bide, T.P., Kearsy, T.I., Dobbs, M.R., Lee, M. K-W. & Chiam, K., 2019. Ductile and brittle deformation in Singapore: A record of Mesozoic orogeny and amalgamation in Sundaland, and of post-orogenic faulting. *Journal of Asian Earth Sciences*, 181, 103890. <https://doi.org/10.1016/j.jseae.2019.103890>
- Liew, K.K., 1994. Structural development at the west-central margin of the Malay Basin. *Bulletin of the Geological Society of Malaysia*, 36, 67-80.
- Liew, K.K., 1996. Structural history of Hinge fault system of the Malay Basin. *Bulletin of the Geological Society of Malaysia*, 39, 33-50.
- Longley, I. M., 1997, The tectonostratigraphic evolution of SE Asia.

- In: A. J. Fraser, S. J. Matthews, and R. W. Murphy, (Eds.), Petroleum geology of Southeast Asia: Geological Society of London, Special Publication, 126, 311–339.
- Lundin Malaysia, 2011. Batu Hitam Final Well Completion Report. Unpublished Internal Report.
- Lundin Malaysia, 2012. Janglau-1 Well, Block PM308A, Offshore East Coast of Peninsular Malaysia. Biostratigraphy and Paleoenvironmental of the Interval 2545 to 3805m. Unpublished Internal Report.
- Lundin Malaysia, 2013. Ara-1 Well, Block PM308A, Offshore Terengganu of Peninsular Malaysia. Biostratigraphy and Paleoenvironmental of the Interval 2565 to 4020m. Unpublished Internal Report.
- M. Hafiz Damanhuri, Azman, A.A., Iyer, S.I.R. & Ilias, F., 2019. Maturation of a new play concept in the pre-Oligocene stratigraphy to rejuvenate exploration in Peninsular Malaysia basin. Asia Petroleum Geoscience Conference & Exhibition 2019, 29 - 30 October, Kuala Lumpur.
- Madon, M., 1990. The southward tilting of Sundaland: tectonic vs eustatic control on sedimentation in the Cenozoic basins in Thailand and offshore Malaysia. Geological Society of Malaysia, Petroleum Geology Seminar, Kuala Lumpur, 27-28 Nov. 1990.
- Madon, M., 1992. Note on dolerite, rhyolite, and granophyre in the basement of the Tenggol Arch, offshore Terengganu. Bulletin of the Geological Society of Malaysia, 31, 133-143.
- Madon, M., 1994. Depositional and diagenetic histories of reservoir sandstones in the Jerneh Field, central Malay Basin, Malaysia. Bulletin of the Geological Society of Malaysia, 36, 31-53.
- Madon, M., 1997. Analysis of tectonic subsidence and heat flow in the Malay Basin (offshore Peninsular Malaysia). Bulletin of the Geological Society of Malaysia, 41, 95-108.
- Madon, M., 1999. Basin Types, Tectonostratigraphic Provinces and Structural Styles. In: PETRONAS "The Petroleum Geology and Resources of Malaysia", 78-105.
- Madon, M. & Watts, A.B., 1998. Gravity anomalies, subsidence history, and the tectonic evolution of the Malay and Penyu Basins. Basin Research, 10, 375-392.
- Madon, M., Azmi Mohd Yakzan, Mahani Mohamed, Mohd Fauzi Abdul Kadir, Mohd Rapi Md Som, Redzuan Abu Hassan, H.D. Tjia, Anyi Ngau, Ooi Chit Meng & Denis N.K. Tan, 2001. North Malay Basin PM303 Petroleum System Study. Unpublished report, SEPM-PRSS Joint Study. PRSS-L1-01-25.
- Madon, M., Jiu-Shan Yang, Abolins, P., Redzuan Abu Hassan, Azmi M. Yakzan & Saiful Bahari Zainal, 2006. Petroleum systems of the Northern Malay Basin. Bulletin of the Geological Society of Malaysia, 49, 125-134.
- Madon, M., Jong, J., Kessler, F.L., Murphy, C., Your, L. Mursyidah A Hamid & Nurfadhila M Sharef, 2019. Overview of the structural framework and hydrocarbon plays in the Penyu Basin, offshore Peninsular Malaysia. Bulletin of the Geological Society of Malaysia, 68, 1-23.
- Maga, D., Jong, J., Madon, M. & Kessler, F.L., 2015. Fluid inclusions in quartz: implications for hydrocarbon charge, migration and reservoir diagenetic history of the Penyu Basin and Tenggol Arch, offshore Peninsular Malaysia. Bulletin of the Geological Society of Malaysia, 61, 59-73.
- McKenzie, D., 1978. Some remarks on the development of sedimentary basins. Earth Planet. Sci. Lett., 40, 25-32.
- Md Yazid Mansor, A. Hadi A. Rahman, Menier, D. & Pubellier, M., 2014. Structural evolution of Malay Basin, its link to Sunda Block Tectonics. Marine and Petroleum Geology, 58, 736-748.
- Metcalfe, I., 2017. Tectonic evolution of Sundaland. Bulletin of the Geological Society of Malaysia, 63, 27 – 60.
- Mohd Kadir, 2010. Fractured basement exploration case study in Malay Basin. Petroleum Geology Conference and Exhibition, 2010. 29-30 March, Kuala Lumpur.
- Morley, C.K., 2004. Nested strike-slip duplexes, and other evidence for Late Cretaceous–Palaeogene transpressional tectonics before and during India-Eurasia collision, in Thailand, Myanmar and Malaysia. Journal of the Geological Society of London, 161, 799–812.
- Morley, C.K., 2016. Major unconformities/termination of extension events and associated surfaces in the South China Seas: Review and implications for tectonic development. Journal of Asian Earth Sciences, 120, 62-86.
- Morley C.K. & Racey, A., 2011. Tertiary stratigraphy. In: M. F. Ridd, A.J. Barber & M.J. Crow, (Eds.), The Geology of Thailand, 223-371.
- Morley, C.K., Charusiri, P. & Watkinson, I.M., 2011. Structural geology of Thailand during the Cenozoic. In: M. F. Ridd, A.J. Barber & M.J. Crow, (Eds.), The Geology of Thailand, 273-334.
- Morley, R. & Shamsudin Jirin, 2006. Integrating Biostratigraphy with Seismic for Sequence Stratigraphic Interpretation in The Malay Basin. Petroleum Geology Conference and Exhibition, 2006. 27-28 November, Kuala Lumpur.
- Mustapha Kamal Shuib, 2009. Structures and deformation. In: Hutchison, C.S. & Tan, D.N.K., (Eds.), Geology of Peninsular Malaysia. Universiti Malaya & Geological Society of Malaysia, Kuala Lumpur, 271-308.
- Ngah, K., Madon, M. & Tjia, H.D., 1996. Role of pre-Tertiary fractures in formation and development of the Malay and Penyu basins. In: Hall, R. and Blundell, D., (Eds.), Tectonic Evolution of Southeast Asia. Geological Society of London Special Publication, 106, 281-289.
- Ngoc, N.H., 2019. Malay Basin Tertiary fracture system and analysis. In: Geophysical Applications in Malaysian Basins. PETRONAS, Kuala Lumpur, 91-104.
- Ngoc, N.H., Aziz, S.A. & Mokhtar, P.N.Bt., 2012. Pre-Tertiary fractured basement of Mega Horst Block A, Malay Basin in light of current 3D seismic Data interpretation. Petroleum Geology Conference and Exhibition, 2012. 23-24 April, Kuala Lumpur.
- Ngoc, N.H., Aziz, S.B. & Duc, N.A., 2014. The application of seismic attributes for reservoir characterization in pre-Tertiary fractured basement, Vietnam-Malaysia offshore. Interpretation, 2(1), 57–66. <http://dx.doi.org/10.1190/INT-2013-0081.1>.
- Nuraiteng Tee Abdullah, 2009. Mesozoic. In: Hutchison, C.S. & Tan, D.N.K., (Eds.), Geology of Peninsular Malaysia. Universiti Malaya & Geological Society of Malaysia, Kuala Lumpur, 87-131.
- PETRONAS, 2011. Integrated Regional Studies of the Malay Basin. Unpublished internal report, PETRONAS.
- Pierson, B.J., Askury A. Kadir, Chow, W.S. & Zuhar Z.T. Harith, 2009. Paleozoic hydrocarbon plays in and around Peninsular Malaysia. PETRONAS Technology Journal, 2(2), 16-25.
- Raj, J.K., Tan, D.N.K. & Wan Hasiah Abdullah, 2009. Cenozoic stratigraphy. In: Hutchison, C.S. & Tan, D.N.K., (Eds.), Geology of Peninsular Malaysia. Universiti Malaya & Geological Society of Malaysia, Kuala Lumpur, 134-173.
- Rishworth, D.E.H., 1974. The Upper Mesozoic terrigenous Gagau Group of Peninsular Malaysia. Geological Survey of Malaysia, Specia Paper 1. 78 p.
- Sandwell, D.T., Muller, R.D., Smith, W.H.F., Garcia, E. & Francis, R., 2014. New global marine gravity model from CryoSat-2

- and Jason-1 reveals buried tectonic structure. *Science*, 346 (6205), 65-67. DOI: 10.1126/science.1258213.
- Searle, M.P., Whitehouse, M.J., Robb, L.J., Ghani, A.A., Hutchison, C.S., Sone, M., Ng, S.W.-P., Roselee, M.H., Chung, S.-L. & Oliver, G.J.H., 2012. Tectonic evolution of the Sibumasu–Indochina terrane collision zone in Thailand and Malaysia: constraints from new U–Pb zircon chronology of SE Asian tin granitoids. *Journal of the Geological Society London*, 169, 489–500. doi: 10.1144/0016-76492011-107.
- Shamsudin Jirin, Azmi M. Yakzan, Mohd Fauzi Abdul Kadir, Mahani Mohamed, Sanatul Salwa Hasan, A. Jalid Mukamad, A. Sapawi A. Jamil & Morley, R., 2010. Application of high-resolution biofacies for better depositional environment interpretation in the Malay Basin Tertiary sedimentary successions. *Petroleum Geology Conference and Exhibition, 2010. 29-30 March, Kuala Lumpur*.
- Tjia, H.D., 1994. Inversion tectonics in the Malay Basin: evidence and timing of events. *Bulletin of the Geological Society of Malaysia*, 36, 119-126.
- Tjia, H.D., 1999. Pre-Tertiary hydrocarbon potential. Chapter 26. In: PETRONAS “The Petroleum Geology and Resources of Malaysia”, 605-635.
- Tjia, H.D. & Mohd Idrus Ismail, 1994. Tectonic implications of well-bore breakouts in Malaysian basins. *Bulletin of the Geological Society of Malaysia*, 36, 175-186
- Tjia, H.D. & Liew, K.K., 1996. Changes in tectonic stress field in northern Sunda Shelf basins. In: Hall, R. and Blundell, D.J., (Eds.), *Tectonic Evolution of Southeast Asia*. Geological Society of London Special Publication, 106, 291-306.
- Tjia, H.D., Zuhaini Mohamed, Ariffin Suhaidi Mat Saad, Ahmad Ridhwan Abd Rahim, Jusmila Baharom, Mazlan Md Tahir, Shahril Jamil, Nurul Fizziyana Ismail & Azani Abdul Manaf, 2010. In the quest of open fractures in the crystalline basement of the Malay and Penyu basins. *Petroleum Geology Conference and Exhibition, 2010, 29-30 March, Kuala Lumpur*.
- Trice, R., Hiorth, C. & Holdsworth, R., 2019. Fractured basement play development on the UK and Norwegian rifted margins. In: Chiarella, D., Archer, S. G., Howell, J. A., Jackson, C. A.-L., Kombrink, H. & Patruno, S. (Eds.), *Cross-Border Themes in Petroleum Geology II: Atlantic Margin and Barents Sea*. Geological Society of London, Special Publications, 495, <https://doi.org/10.1144/SP495-2018-174>.
- Watts, A.B. & Fairhead, J.D., 2010. A process-oriented approach to modeling the gravity signature of continental margins. *The Leading Edge*, 18, 258-263. <https://doi.org/10.1190/1.1438270>.
- Watts, A.B., Karner, G.D. & Steckler, M.S., 1982. Lithospheric flexure and the evolution of sedimentary basins. *Philosophical Transactions of the Royal Society of London*, A 305(1489), 249-281.
- Yu Sheng Mo & Yap Kok Thye, 2019. Malay and Penyu basins: seismic stratigraphy and structural styles. In: *Geophysical Applications in Malaysian Basins*. PETRONAS, Kuala Lumpur, 51-68.

Manuscript received 20 July 2020

Revised manuscript received 11 September 2020

Manuscript accepted 15 September 2020