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On the supposed onshore extension of the Penyu Basin, Peninsular Malaysia

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Abstract: The Penyu Basin is a Tertiary sedimentary basin located offshore Peninsular Malaysia. The basin is assumed to continue westwards beneath the Pahang River delta where as much as 115 m of Quaternary sediments overlie a bedrock of pre-Tertiary granites and metamorphic rocks. No Pliocene or older sediments beneath the delta have been reported. If the Quaternary sediments are considered as part of the Cenozoic Penyu Basin, the basin's western limit may be delineated at the foothills of the coastal plain where those sediments onlap onto pre-Tertiary rocks. Therefore, any sedimentary rock of Tertiary age that may occur to the west of that limit most probably represents a separate basin.

Keywords: Penyu Basin, Quaternary, Tertiary, gravity, basement

INTRODUCTION

The Penyu Basin is an east-west oriented Tertiary sedimentary basin lying offshore Peninsular Malaysia (Figure 1). It is approximately 150 km long and only 90 km wide at the western end, which is considered small compared to the adjacent West Natuna and Malay basins. Up to 7-8 km of sediments occur in its deepest parts, where Late Eocene to Oligocene syn-rift deposits accumulated in isolated fault-bounded depocentres. Due to its relatively small size, the basin has been extensively explored, even though not yet commercially productive. Through seismic data acquisition and exploratory drilling, the basin had been relatively well studied by the mid-1990s and its structural geometry is fairly well established. This was achieved through detailed mapping based on an almost complete coverage by seismic and gravity data, as well as information from 18 exploration wells in the basin. Some of those wells penetrate the pre-Tertiary basement of igneous and metamorphic rocks (Figure 2A), which represent a continuation of the onshore geology of the Malay Peninsula. The top of the pre-Tertiary basement represents the Late Mesozoic to Early Tertiary erosional unconformity surface upon which Tertiary basins developed. Although the seismic line spacing on the western side is rather coarse, both the seismic and gravity data clearly indicate shallowing of the basement westwards as the basin-bounding faults die out towards the peninsular coastline (Figure 2B). A recent review of the geology and exploration history was given by Madon *et al*. (2019).

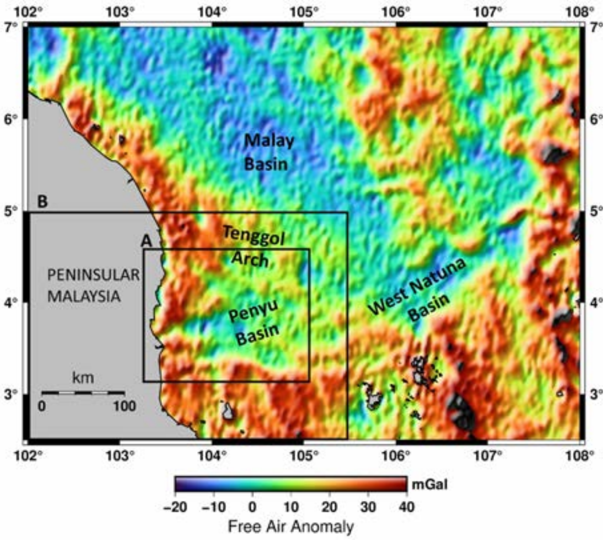

Figure 1: Free-air gravity anomaly map of offshore Peninsular Malaysia, based on satellite-derived gravity grid of Sandwell *et al.* (2014). Colours were applied to accentuate the outline of Tertiary basins which are characterised by low anomalies of <10 mGal. Small rectangle A refers to map area in Figure 2. Larger rectangle B refers to map area in Figures 3 and 5.

Some authors considered the West Natuna Basin as the eastward continuation of the Penyu Basin (Haribowo *et al*., 2013). This is a reasonable assumption since there is no known structural discontinuity between the two basins and the fault trends appear to continue seamlessly

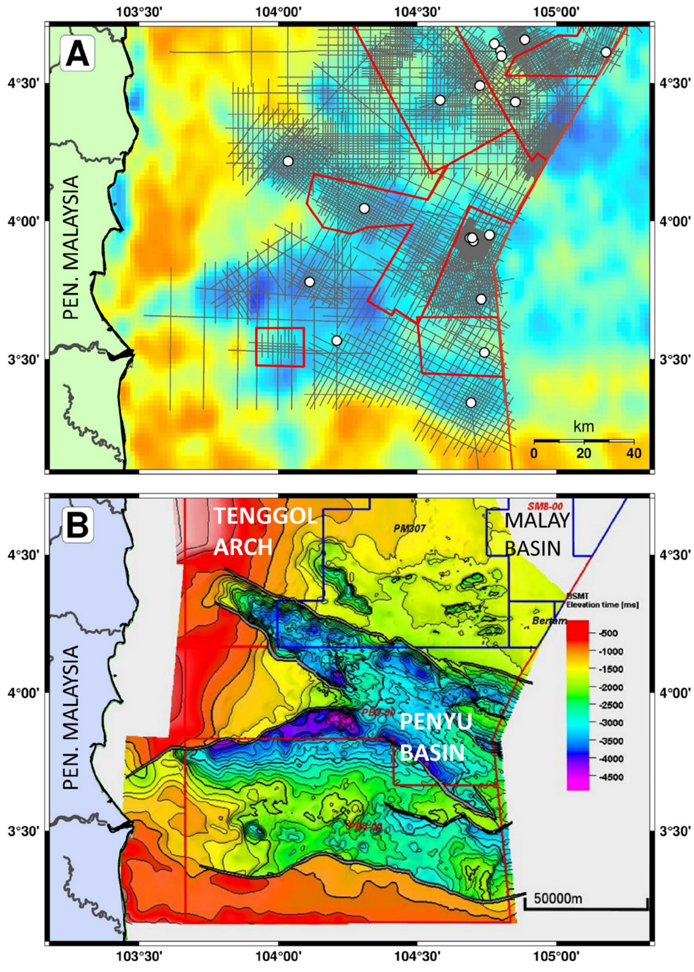

Figure 2: Extensive seismic and gravity data enable the structure of the Penyu Basin to be mapped in detail. (A) Dense coverage of 2D seismic data (grey lines) and 3D data (red polygons), supplemented with wells that penetrate the pre-Tertiary basement (white dots). Plotted with data from Madon (2021). Coloured background in offshore area is gravity anomaly map as in Figure 1; warm colours indicate shallow basement areas, cool colours indicate basin areas. (B) Pre-Tertiary basement elevation map of the Penyu Basin, showing the major faults that define the half-graben depocentres (from Madon *et al*., 2019). Basement elevation in milliseconds (ms).

across the Malaysia-Indonesia maritime boundary. The southern and northern boundaries of the Penyu Basin are generally well-defined by major E-W trending and NW-SE trending faults, which were mapped at the top of the pre-Tertiary basement unconformity (Figure 2B). There is no evidence to support the suggestion that those E-W faults at the northern and southern boundaries of the basin extend all the way to the coastline in the manner shown on the map by Tate *et al*. (2008). The seismic evidence suggests that the normal faults die out before reaching the coastline, indicating proximity to the basin edge (Figure 2B). This brief note further examines the nature of the western edge of the Penyu Basin.

BASIN EDGE

The western edge of the Penyu Basin is not distinct, as there are no known faults that could represent that boundary. The top of the pre-Tertiary basement, which is essentially the basal boundary of the basin, becomes shallower towards the present-day coastline. It is fair to assume that the basement extends beneath the modern Pahang River delta until it reaches the surface further landward. Hence, Hutchison (1989; 2007, p. 118) wrote: the Penyu Basin "is a westwards continuation of the West Natuna basin, and is an east-west directed graben-like structure which extends onshore to include the flat alluvial plain of the Pekan area of Pahang". This is a valid assumption since Hutchison (1989, 2007) considered the Penyu Basin as a Cenozoic basin and therefore includes both Tertiary (i.e., Paleogene and Neogene) and Quaternary sediments.

Figure 3 shows a map of the depth (z) to the pre-Tertiary basement in the offshore (z<0) and land elevation (z>0) in the adjacent onshore area of the Malay Peninsula. This surface represents a continuous surface of eroded pre-Tertiary Sundaland landmass which was probably elevated above sea level before the Penyu Basin formed during the Late Eocene by extensional faulting and subsidence. We can see that the Penyu Basin is a relatively isolated and confined system of grabens and half-grabens, of Late Eocene to Oligocene age (Madon *et al*., 2019). Its outline can be represented by the 2000 m basement depth contour, as is the boundary between the Tenggol Arch and the Malay Basin to the northeast.

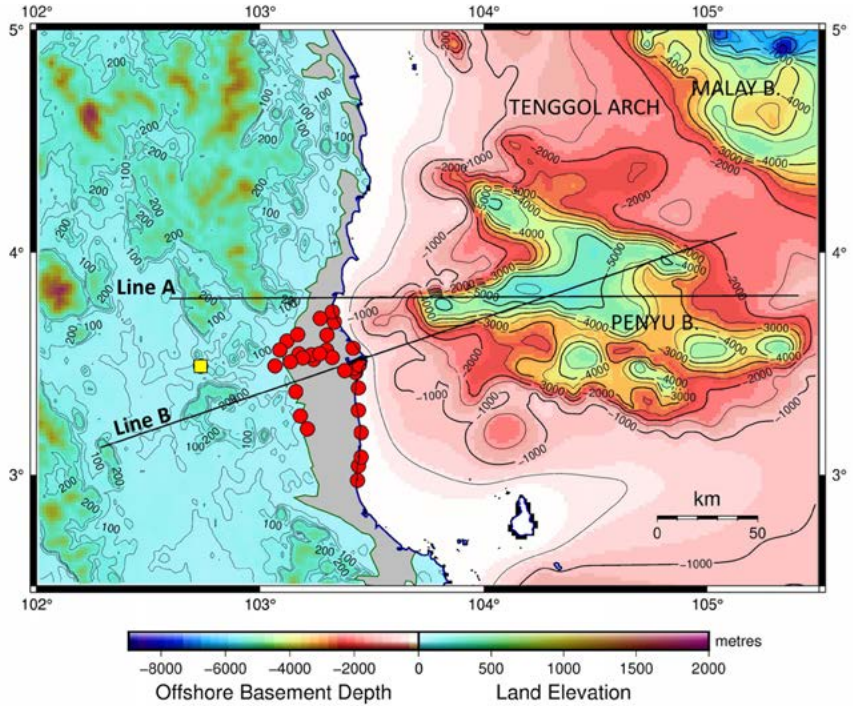

Figure 3: Map of land elevation and pre-Tertiary basement depth (converted from ms to m) in the offshore generated from the data digitised from Figure 2 for the offshore and digital elevation model from GMRT for the onshore (Ryan *et al.*, 2009). For offshore map, time-to-depth conversion was based on velocity data obtained from Madon (1996). Lines A and B represent profiles in Figures 4 and 5. Grey shaded area landward of the coastline represents Quaternary deposits on the coastal plain (Raj *et al.*, 2009). Red circles are the locations of groundwater boreholes from Yoong *et al.* (2018). Yellow square is the location of East Chenor outcrops studied by Makeen *et al.* (2019a, b), as mentioned in the text.

The top-of-basement surface in the Penyu Basin gradually becomes shallower towards the margins to the north, south and west. It probably reaches sea level (depth z=0 m) at some distance landward of the coastline (within the grey shaded area in Figure 3) beneath the coastal plain, which is elevated to more than 30 m above sea level. Figure 4A shows a W-E profile (Line A) extracted from the map in Figure 3 representing the basement surface from land to sea. We can see the great depth of the Penyu Basin relative to the land elevation onshore. At the foothills, landward of the coastal plain, a line may be drawn where the basement reaches the surface and the thickness of Quaternary sediment is zero. This line, which is also above sea level, may be taken as the landward limit of the basin (Figure 4B).

Yoong *et al.* (2018) reported groundwater boreholes that were drilled through the Quaternary sediments in the Pekan area (red dots in Figure 3). The boreholes penetrated as much as 115 m of Quaternary sediments before reaching the bedrock of pre-Tertiary geology comprising weathered granites and metasediments. Similar rocks have been found in the offshore wells on the margins and intrabasinal highs of the Penyu and Malay basins (e.g., Madon *et al.*, 2019, 2020). Similarly, since the pre-Tertiary basement is the offshore continuation of the onshore pre-Tertiary geology, the basin boundary may be drawn where Quaternary sediments onlap and pinch out onto the pre-Tertiary bedrock at the foothills (Figure 4B).

As mentioned, the northern and southern boundaries of the basin are defined by syn-rift graben-bounding faults, even though Tertiary post-rift sediments extend further onto the basement highs well beyond those faults (Figure 2B). In contrast, the western edge of the basin, as determined above, is at some distance landward of the coastline where Quaternary sediments pinch out to a feather edge. It should be noted that defining the basin limits this way creates a problem. Since Quaternary sediments also occur continuously on the coastal plains of around the entire peninsula (Figure 3), where would the southern and northern limits of the "onshore Penyu Basin" be? Clearly, they would also extend beyond the onshore projections of the fault-bounded limits defined in the offshore. If Quaternary sediments are included, then all basins should be considered as one single basin, which is not helpful for the purpose of basin analysis and the understanding of sedimentary basins. Unfortunately, the Quaternary is of little interest to oil companies which are generally concerned with Pliocene and older sediments. As a result, the Pliocene-Pleistocene (or Tertiary-Quaternary) transition or boundary is rarely investigated and the total thickness of the Quaternary section in the offshore is generally unknown. Images from CHIRP sub-bottom

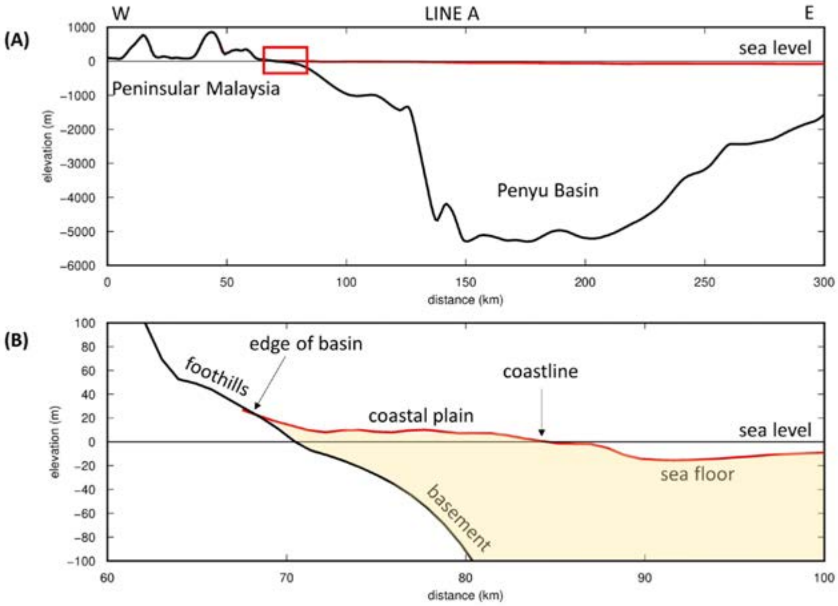

Figure 4: Profile along Line A in Figure 3 which shows (A) the top-of-basement surface in the Penyu Basin continuing onshore as the pre-Tertiary bedrock forming the landscape of Malay Peninsula. (B) Close-up of coastline area marked by red rectangle in A, showing the basement surface rising beneath Quaternary coastal plain sediments and pinching out and onlapping onto the foothills. Note the exaggerated vertical scale to emphasise the elevation of the coastal plain. Technically, where the sediment thickness is 0 represents the edge of the basin.

profiles in the Upper Pleistocene-Holocene section of the basin have revealed some interesting sedimentary features, such as palaeo-fluvial channels and incised valleys (Rahman *et al*., 2016). The lower Pleistocene and its basal transition with the Upper Pliocene section would be worth investigating in the future.

Whether the Penyu Basin extends onshore and include the Quaternary sediments of the Pahang coastal plains is "academic". It really depends on whether one considers Penyu Basin as a Cenozoic basin (cf. Hutchison, 1989) or, as most petroleum geologists would, a Tertiary basin (cf. Doust & Sumner, 2007). I suggest that it serves no purpose to "prove" that Penyu Basin extends onshore based on the presence of Quaternary sediment, as attempted by some authors (e.g., Yoong *et al*., 2018). For practical purposes, where direct structural evidence (e.g., faults) is lacking, other practical means may be used to define the approximate limits of sedimentary basins, such as sediment thickness, basement depth, or gravity anomalies. For example, steep gradients in gravity anomalies are usually related to underlying structural discontinuities (faults), as is the case for Penyu Basin (comparing Figures 1 and 2), and would be a useful indicator of basin boundaries.

CHENOR OUTCROPS

In recent years, there have been references made with regard to the "onshore extension" of the Penyu Basin located further inland, as far as Chenor, a sub-district in central Pahang (Makeen *et al*., 2019a, b, yellow square in Figure 3). It is my view that this is taking the "onshore extension" idea too far. Unfortunately, the authors of the paper did not provide the basis for the Oligocene age of the sediments or the reasons why the outcrops were considered part of the Penyu Basin. The authors, however, cited the work of Ahmad Munif *et al*. (2012) who, based on palynomorphs from those outcrops, had determined that the age was Late Miocene and younger, but not Oligocene as quoted. The presence of Tertiary sediments at this location does not necessarily mean that the outcrops represent an "onshore extension" of the Penyu Basin. The outcrop is located ~45 km landward from the basin edge determined above and more than 120 km from the nearest Oligocene syn-rift half-graben in the Penyu Basin. This distance is even wider than the Tenggol Arch which separates Penyu from the Malay Basin (Figures 1, 2). It is more likely that the Chenor outcrops represent a separate, previously unknown, onshore Tertiary basin which is an important addition to the existing list of onshore Tertiary basins described by Raj *et al*. (2009).

Figure 5 is a gravity anomaly map covering the same region shown in Figure 3. It clearly shows free-air anomaly lows corresponding to the grabens of the Penyu Basin (cf. Figure 1). Note that due to the gentle gradient of the Sunda Shelf and shallow water depths (<70 m) in this area, Bouguer anomalies at sea would look similar, reflecting the subsurface density variations due to the presence of a sedimentary basin. On land, the Bouguer gravity anomalies also reflect the subsurface density variations across the Malay Peninsula which are directly related to the underlying geology. In particular, there are two anomaly highs separated by a large negative anomaly. Figure 6 is a profile of the Bouguer gravity anomaly extracted from the map along line B in Figure 5. The profile shows a large negative anomaly with an amplitude of >40 mGal, which is greater than the free-air anomalies associated with the Penyu Basin offshore. It is clear that that negative anomaly is due to sedimentary rocks of lower density compared to the surrounding rocks of the Central Belt in the Malay Peninsula.

Based on the Geological Map of Peninsular Malaysia (JMG, 2021), the abovementioned N-S trending large negative anomaly on land corresponds with an area mapped as Jurassic-Cretaceous formations (Figure 7). The sedimentary formations at the Chenor outcrop locality studied by Ahmad Munif *et al*. (2012) and Makeen *et al*. (2019a, b) are also within this area (yellow square on the map). More importantly, the gravity profile indicates that the Tertiary outcrops at Chenor clearly lie in a basin that is separated from the Penyu Basin by a regional basement high composed of a mixture of Palaeozoic metamorphic and Mesozoic plutonic rocks. This is confirmed by the groundwater boreholes in Figure 7 which penetrated pre-Tertiary basement comprising mainly weathered granites north of Pahang River and mainly metamorphic rocks south of it (Yoong *et al*., 2018).

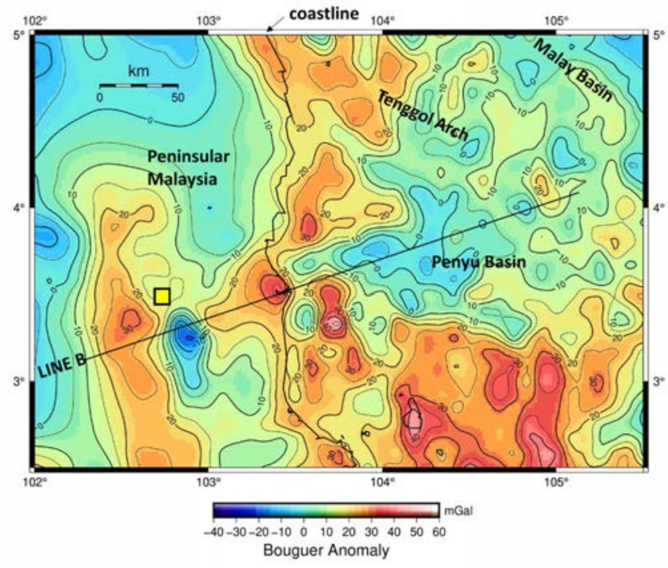

Figure 5: Gravity anomalies over the same map area in Figure 3; Bouguer anomaly on land, free-air anomaly at sea. As in Figure 1, the low negative anomalies in the Penyu Basin are apparent. Note the three distinct anomalies on land crossed by Line B, along which the gravity anomalies are extracted and plotted in Figure 6. Chenor outcrop locality is marked by a yellow square.

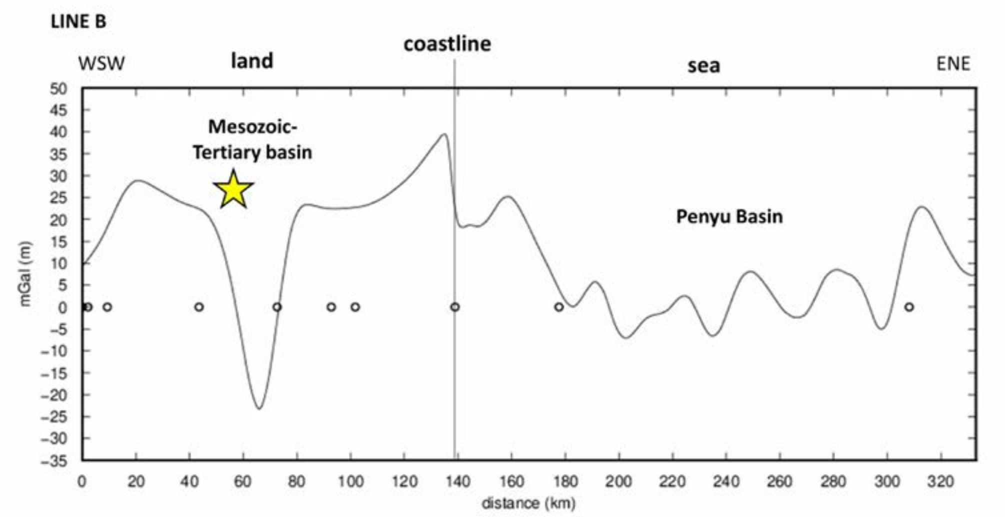

Figure 6: Gravity anomalies along Line B in Figure 5 from land to sea. Note the two main areas of negative anomalies representing sedimentary basins. A single negative peak on land coincides with Jurassic-Cretaceous outcrops (which include the Tertiary outcrop mentioned in the text, marked with a yellow star). The rugged and broad negative anomaly at sea reflects the faulted graben morphology of the Penyu Basin. The small circles at 0 mGal represents the lithological/formation boundaries identified from the geological map of Peninsular Malaysia (see Figure 7).

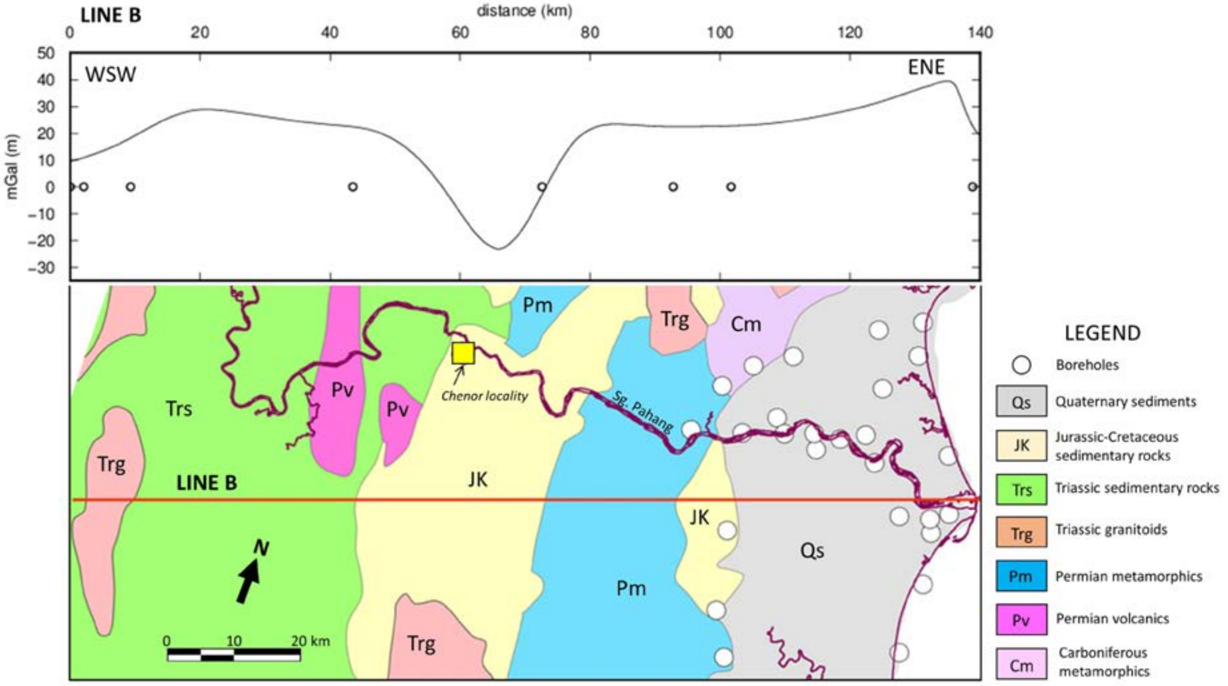

Figure 7: Bouguer gravity anomalies (upper panel) along the onshore portion of Line B in Figure 5 showing the correlation with pre-Tertiary outcrop geology (lower panel). The geological map (modified from JMG, 2021) is slightly rotated clockwise and plotted at the same horizontal scale as the gravity profile. The small circles at 0 mGal on the gravity plot correspond to the boundaries between the lithological groupings shown on the map below. Note the location of the Chenor outcrops (yellow square) within an area mapped as Jurassic-Cretaceous sedimentary rocks (JK). Groundwater borehole locations (large white circles on map) are from Yoong *et al*. (2018).

CONCLUDING REMARKS

For all intents and purposes, the Tertiary Penyu Basin is located entirely offshore. Its supposed western extension onshore seems to comprise mainly Quaternary deposits that underlie the coastal plains of the Pahang River delta. Tertiary sedimentary rocks are not known from the coastal plains of the Malay Peninsula but are well known to occur as isolated pockets or outliers in the interior of the peninsula (Raj *et al*., 2009). If the outcrops at Chenor are indeed Tertiary in age, further work should be done to delineate the extent of the Tertiary basin.

Within the general vicinity of the supposed Tertiary outcrops at Chenor, there have been studies on fluvial sediments that were assumed to be of Jurassic-Cretaceous age (Madon *et al*., 2010; Baioumy *et al*., 2020), since this region of the Central Belt has been mapped as Jurassic-Cretaceous (Figure 7). The discovery of Tertiary deposits in the area casts doubt on the age of these undated "Jurassic-Cretaceous" sediments, and should be further investigated.

Indeed, the Chenor outcrops were initially thought to be Jurassic-Cretaceous (Zainey *et al*., 2007) but later found to be no older than Late Miocene (Ahmad Munif *et al*., 2012). Unlike the Mesozoic deposits of the Central Belt, the moderately dipping (~30°) to flat-lying strata at Chenor do not appear to have been highly deformed. Furthermore, the paleocurrent data indicate west and north-westerly transport directions (Zainey *et al*., 2007), opposite to that in the main Penyu Basin. In any case, the Chenor outcrops represent an entirely separate basin located within the Central Belt of the Malay Peninsula and not an "onshore extension" of the Penyu Basin.

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