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SEISMIC FACIES ANALYSIS AND STRUCTURAL INTERPRETATION OF DEEPWATER NW SABAH

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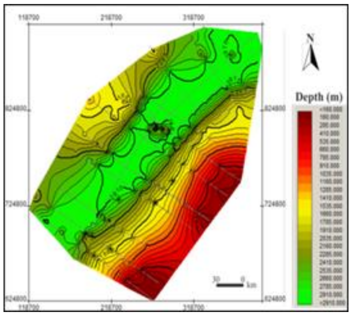
Akhmal Sidek[a*], Umar Hamzah[a], Radzuan Junin[b]

[a]Geology Programme, PPSSSA, Faculty of Science and Technology, UKM, Bangi, Malaysia
[b]Petroleum Engineering Department, FPREE, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author
makhmal@petroleum.utm.my

Graphical abstract



Abstract

The deepwaters of NW Sabah has been an interesting site for deepwater hydrocarbon exploration in Malaysia. Up to now, the exploration in this is mainly focused to the Late Miocene until the Pliocene siliciclastic sediment reservoirs distribution at the shelf edge. This paper shows a gross seismic facies mapping analysis and structural interpretation of regional deepwater NW Sabah especially at Sabah Trough. To convert depth, all seismic lines were picked and tied with selected wells. The results of the interpretation were then summarized and presented with relation to regional tectonic events. Eight seismic stratigraphic units, six seismic facies together with five sequence boundaries were recognized. Multichannel reflection 2D seismic data, gamma ray logs and biostratigraphy description from the three wells at deepwater fold-thrust belt and published tectono-stratigraphic scheme from Dangerous Grounds (Sabah Platform) in South China Sea were selected in this study. The propose of this study is to document the relevance of regional tectonic event between Dangerous Ground and Sabah Trough.

Keywords: 2D multi-channel seismic data, Regional Deepwater NW Sabah, seismic facies mapping, structural interpretation

Abstrak

Perairan laut dalam di Barat Laut Sabah mempunyai kawasan yang menarik untuk penerokaan hidrokarbaon laut dalam di Malaysia. Sehingga kini, penerokaan di rantau ini memberi tumpuan kepada taburan takungan sedimen siliklastik berusia Miosen Akhir hingga Pliosen di pinggiran pelantar (shelf edge). Kajian ini menunjukan beberapa analisis pemetaan fasies seismik dan terjemahan struktur di rantau laut dalam Barat Laut Sabah terutamanya di Palung Sabah. Untuk menukar kedalaman, kesemua garisan sesmik yang dipilih dan disesuaikan dengan telaga yang terpilih. Keputusan terjemahan seterusnya dirumuskan dan dipersembahkan dengan hubungkait peristiwa tektonik rantau. Lapan unit stratigrafi, enam fasies seismik bersama lima sempadan jujukan telah dikenalpasti. Data 2D seismos saluran-berganda, log sinaran gamma dan penjelasan biostratigrafi daripada ketiga-tiga telaga di sekitar jalur lipatan sesar sungkup laut dalam dan skema tektonostratigrafi yang telah diterbitkan daripada 'Dangerous Ground' (Pentas Sabah) di Laut China Selatan telah dipilih untuk kajian ini. Kajian ini bertujuan untuk merekodkan hubungan peristiwa tektonik rantau diantara 'Dangerous Ground' (Pentas Sabah) dan Palung Sabah.

Kata kunci: Data 2D seismos saluran-berganda, Laut Dalam Barat Laut Sabah Rantau, pemetaan fasies seismik, penterjemahan struktur

1.0 INTRODUCTION

The large of scale integrated regional studies from offshore NW Sabah/Borneo required the synthesis of various data to gain a better understanding of its regional geology and structural evolutions. In 1986, PETRONAS (Petroliam Nasional Berhad; a national oil company) set up a seismic campaign, where 3000 km2 seismic surveyed areas were allocated in the NW Sabah region to evaluate its hydrocarbon prospects and provided a good-quality extension of existing seismic data into deepwater. In 2005-2012, several data sets of wildcat wells were established to provide hydrocarbon evaluation, to give a better understanding of regional structural features and also to explore the hydrocarbon potential of deepwater NW Sabah [1]. The NW Sabah Basin is an offshore of predominantly Middle Miocene age sedimentary basin that underlies the continental margin off Western Sabah and continues to the Sabah Trough and the Dangerous Ground provinces [2]. This area had experienced of multiple deformation events during the Cretaceous and Tertiary periods. The complex structures in Sabah offshore had resulted from at least five episodes of deformation that began in the early Cretaceous [3]. This deformation resulted in a reasonably difficult understanding of the chronostratigraphic and depositional history of the area. Over the last decade, intensive exploration and development activities in offshore NW Borneo have led to an abundant amount of new data, especially in deepwater NW Sabah but the large volumes of data was held by oil companies, and therefore not widely accessible by government for open scientific researches.

Despite this limitation, three exploration wells namely Well-A, Well-B and Well-C were used to interpret youngest seismic sequences (Late Miocene- present) against regional tectono-stratigraphic, incorporated with a published stratigraphy scheme and biostratigraphy obtained from the wells in the study area. Additionally, several numbers of seismic data profiles also have been studied from the data files of PETRONAS. Our approach to identify sequence boundaries were mostly based on the seismographic characteristics, including reflection frequency, amplitude continuity and reflection termination (on lap, downlap and truncation). The objectives of this study are to improve present understandings of regional seismic stratigraphy and to review the structural development of the study area.

1.1 Geological Setting

The region of this study lies in the NE-SW margin of the Sabah Trough and surrounding marginal seas which are the South China Sea, Sulu Sea and also between Brunei and Philippines boundaries (Figure 1). It was covered to the western part by the rifted margin of South China Sea, whereas the Dangerous Ground region and the Baram Delta Province covered its southern part. The Sabah Trough is also known as the Borneo Trough/Nansha Trough to the southwestern part and the Palawan Trough/Trench to the northeastern part with bathymetric featuring water depths of the depression that varies from 2410 m to about 2900 m, extends over 300 km in length with an average width of 80 km (Figure 2). From the West Baram Line, the Sabah Trough extends northeastward, but shallows towards it because of the occupying Middle Miocene and younger clastic sediments of the Baram Delta that built out from Sarawak into the Sabah Trough. The delta sediments also were covered over and concealed itself [4]. Nowadays, Sabah Trough was interpreted as a failed rift proto-South China Sea continental margin evolution in the Late Cretaceous to Early Paleogene periods [5,-6].

Beginning in the Late Paleocene to Eocene, thermal event in south Taiwan region extends the continental crust distribution into half graben structures [7] and then the continent continues to thinning followed by sea floor spreading and produced the formation of proto-South China Sea (Rajang Sea) oceanic crust [8]. In the Oligocene to Early Miocene, the opening of South China Sea seafloor spreading occurred in the north-south and in the northwest-southeast directions which caused several micro-continent blocks such as Reed Bank and Luconia Block to drift southwards and collide with northern Borneo. Southern South China Sea seafloor spreading ranges from 30 to 16 Ma. This extensional event also triggered buoyant micro-continental crust of the Dangerous Ground region to rift away from the South China Sea margin and moved towards Borneo, subsequently enhancing the anticlockwise rotation of the West Borneo Basement [9]. In the Early Miocene, part of the Dangerous Ground continental crust continuing subducted beneath the NW Sabah and ceased by the attenuated crust which produced compressional deformation of fold-thrust belts, complex structure and Sabah Orogeny (Figure 2).

Paleocene and Mesozoic compositions of the basement at Sabah Trough are indefinite but it can be suggested that the region continuous to Dangerous Ground, and were once a part of the Southern South China Sea continent, proven by direct evidence from dredge sample rocks which indicated an association with Southeast Asia [10]. The terrain that underlies the Sabah Trough with increasing depth towards the southeast and underlying the mélange wedge is of thinned continental crust continuous to the Dangerous Ground Province and nowadays, it refers to an extinct convergent plate margin [11].

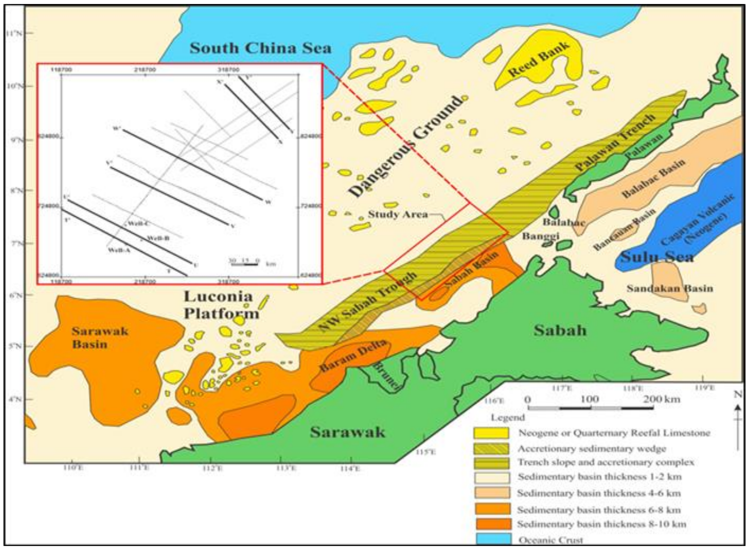


Figure 1 The map shows the geological features of NW Borneo offshore, the sedimentary basin distribution beneath the continental shelf and major features of the region, including Luconia Carbonate Platform, Dangerous Ground and Sabah Trough elongated to Palawan Trench. Upper left inset of the index map shows locations of six seismic lines (black bold lines) trending NW-SE and three exploration wells to establish seismic well converted time to depth

2.0 EXPERIMENTAL

2.1 Seismic Stratigraphy

In order to choose the most prominent seismic reflectors as sequence boundaries, all possible sequence boundaries were initially identified in a high-quality migrated seismic reflection section. The lateral extent of each probable sequence boundary was evaluated through correlation across of the seismic sections. The fundamental concept of seismic sequence analysis is that every seismic section is divided into relatively conformable or concordant seismic reflectors. They were then tied to wells and dated. Then, seismic facies analysis was conducted to correlate reflection attribute, identify stratigraphic sequence characteristics and distribute a correlating framework between seismic and well data. Four characteristics of reflection attributes were used to distinguish between different seismic facies which are frequency, internal reflector configuration, reflector continuity and amplitude strength.

2.2 Well Data

The sequence boundaries identified on seismic reflection data were calibrated, together with three exploration wells. Two out of three exploration wells except Well-C, which penetrated in the early Middle-Miocene (10 Ma) until recent, while Well-A and Well-B penetrated beyond that time and are also confidential in nature so only their general locations are shown in Figure 1. Sequence bounding horizons (seismic unit) on seismic data were depth converted using velocity information derived from well velocity surveys. Every identified seismic facies type was correlated with well data, such as gamma ray and lithofacies from cutting descriptions to establish a relationship between the seismic facies and lithofacies. They were also correlated with biostratigraphic data at every recognized sequence. Time to depth conversion has been done by the average velocity model based on time-depth relationship for the wells. Converted time maps were interpolated with well intersections and corrected accordingly.

3.0 RESULT AND DISCUSSION

3.1 Seismic Stratigraphy Analysis

Consequently, nine distinct seismic markers (horizons) have been identified, including seafloor and the seismic sections were mapped in the study area (Table 1). The mapped horizons are identified by their assigned ages, from 65 Ma up to 0 Ma (seafloor), shown in the chart in Figure 3. The seafloor that was interpreted as the youngest horizon was first to gain a sense of the topography and bathymetry in the study area. The oldest horizon interpreted was the detachment or a basement layer;-hence indicating the basement of the study area NW-SE elongated to the Dangerous Ground. Eight sequence boundaries (seismic units) featured particular reflection patterns and geological ages as shown in Figure 4.

After establishing the key markers, the seismic facies in the units between the horizons were identified. Six seismic facies were recognized in the study area (Table 2). See Figure 5, 6 and 7 for geological interpretation of seismic lines that represents the fold thrust belt of NW Sabah, which was parallel to Palawan Trench. Although from Paleocene to Early Middle Miocene has not been penetrated in the study area, it can be mapped across the Dangerous Ground Province and correlated to carbonate platforms in the Reed Banks area in the north and Luconia (Nyalau Formation) in the south.

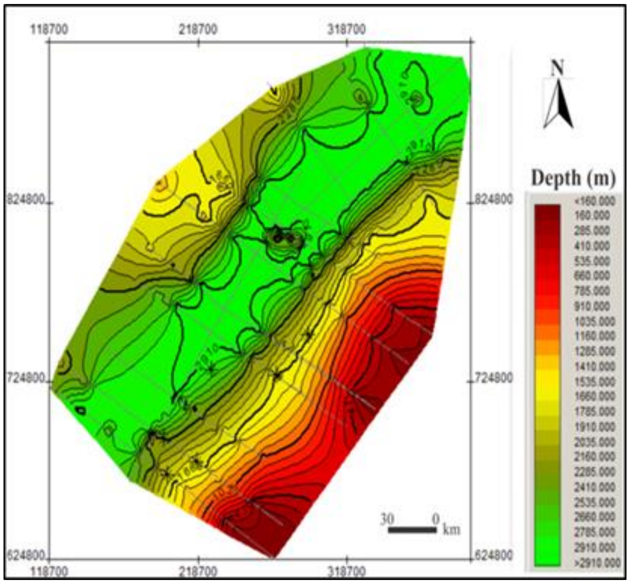


Figure 2 The bathymetry contour map after seismic mapping of the seafloor correlated with wells. The deepest part of the study area, (light green) shows the Sabah Trough, the yellow shows toe-thrust zone area, while in the northwest of the study area, there is the scattered margin of Dangerous Ground while red indicates shallow parts of the Sabah Shelf edge

3.1.1 Paleocene to Early Oligocene Sequence (Unit 8, Early Pre-Rift)

The Paleocene to Early Oligocene sequence was indicated as early pre-rift unit, and is widespread in the Dangerous Grounds and filled with half-grabens. The unit is characterized by chaotic and discontinuous-moderate continuous reflectors with low frequency and various intensities in Seismic Facies C and F (Table 2), indicating rifting-filling clastic sediments (Figure 9). Horizon R8 suggested at the top of the pre-rift basement composite of Mesozoic sedimentary are evidence from samples of 23 sites to the southern and southwestern parts of Reed Bank dredging work [12] with reflectors in moderate-strong, continuous amplitude, and locally diffractive. In Paleocene and Eocene, deeper water marlstones and shales may have been deposited under restricted conditions that are favorable for petroleum source rock generation [11]. Meanwhile, the shallow marine Meligan Formation deposited of the deep marine (marine shales and turbiditic sands) trough in Southern Sabah in Early Miocene, which extended to NW Sabah continental margin translated as Stage III [13]. This unit is sealed by horizon R7. With all selected seismic profiles, R7 shows moderate-strong amplitudes and patchy-continuous reflections and R7 is a regional unconformity and represents the early to syn-rift transition. Horizon R7 was suggested as the base of the carbonate [6, 11, and 14].

3.1.2 Oligocene to Early Miocene Sequence (Unit 7, Syn-Rift)

This sequence is confined to the syn-rift related half-grabens and seismic attributes characterized by sub-parallel reflections of high-intermediate continuity and moderate intensity, referring to Seismic Facies D (Table 2). This unit was deposited parallel with the drifting period of the South China Sea and was also suggested that this unit mainly represents carbonate rocks that were concurrent with a carbonate platform in the Reed Bank and Dangerous Ground. The carbonates were deposited in lagoonal or shallow open marine environment [6]. Horizon R6 was suggested as a top, whereas R7 as a base of carbonate platform extending from the Dangerous Grounds through to and beneath the NW Sabah. This sequence boundary is distinctive in the seismic records with strong and continuous reflections. R6 was suggested at an age of 16 Ma for this unconformity and the deepwater equivalent to the 'Deep Regional Unconformity' (DRU) sedimentation history, which is believed to mark a major break in the sedimentary history and associated with the tilting and the uplift of the margin during the Sabah Orogeny [14, 15 and 16]. The Early Miocene Unconformity (EMU) was caused by relative uplift and predominantly submarine erosion between 19 and 17 Ma ago which is represented by a sedimentary episode hiatus in the Sarawak Basin. EMU can be extended to the entire NW Sabah margin that is probably related to Sabah Orogeny (Figure 3) and occurred at the same age with DRU in the deepwater NW Sabah margin [16]. The term Middle Miocene Unconformity (MMU) in offshore Sarawak was used in Luconia Province [17]. The DRU offshore extended until 40 km off of Sabah's coastline [18]. A study in Baram Delta Basin, marked this sequence and below as South China Sea Unconformity (SCSU) at a diachronous age (19-16 Ma) of this break-up. The collisional deep regional unconformity (DRU) can be seen clearly along with the underthrusting of the Dangerous Grounds crust under NW Sabah [19]. However, since oil companies extended exploration to deeper waters, DRU (Horizon R6) can be traced along the Sabah Trough and marked as a base of the NW Sabah Basin.

3.1.3 Early Miocene to Early Middle Miocene Sequence (Unit 6, Post Rift)

The seismic attribute in this sequence is well continuous, showing low to moderate intensity, locally transparent, and the frequency varies slightly referring to Seismic Facies D (Table 2). The top of this unit is marked by Horizon R5 which was interpreted as Early Middle Miocene (15.3 Ma) in age [10]. The unconformity of Horizon R5 located at upper part of the deformed thrust wedge and in Dangerous Ground shows that the carbonate that continued up to Horizon R5 consisted of a transitional facies between shallow-water and bathyal of the depositional environment thus correlating it with the Pagasa Formation in Palawan. This limestone sequence can be followed from the NW Sabah Trough to the Fold and Thrust Zone.

3.1.4 Early Middle Miocene to Late Miocene Sequence (Unit 5-4, Post Rift)

This sequence is characterized by a continuous sub parallel to parallel reflection of low to moderate intensity, showing locally chaotic or wavy patterns which can be referred to Seismic Facies D and E (Table 2). Well-C that operates in deep water NW Sabah toe-thrust folds zone has penetrated in the early Late Miocene (10 Ma). The well penetrated predominantly shale sections with occasional thin sandstone stringers (0.2 – 1.5 m thick) and few limestone stringers just above the top of the R4 event with a massive limestone (~50m thick). Locally, reef growth from R5 that might have continued up to R4 is interpreted as to separate the generally deep marine clastic sedimentation during a pre-Early Middle Miocene phase from a younger clastic shelf or slope deposit in NW Sabah. Therefore, Horizon R4 has been dated back to the early Late Miocene (10 Ma). However, given the time transgressive nature of this horizon in the study area off NW Sabah, this unconformity might be as young as Late Miocene and thus roughly coincided with the top of 'Shallow Regional Unconformity' (SRU) as Horizon R3 (8.5 Ma).

3.1.5 Late Miocene to Recent Sequence (Unit 3-1, Post Rift)

Reflection characteristics of this sequence are represented by parallel, sub-parallel, locally chaotic and divergent reflections of moderate to high amplitude with variable frequencies and high reflection continuity in Seismic Facies A, B and C (Table 2). Well –A and B has penetrated the Late Miocene to present-day (seafloor) of dominantly shale section. The seafloor varies in depth from 2900 m in the Sabah Trough to less than 100 m in shelf regions. From Well-A, the biostratigraphically calibrated age model and recovered from calcareous nannofossil CN 11 at Horizon R1 and has been dated in early Late Pliocene;- (4 Ma) age (Figure 4). In addition, it was also indicated that the Horizon R1 as the shallowest horizon and its depositional environment was in middle-upper bathyal environments because of the present of foraminifera. Furthermore, horizon R1 also represents a base of regional Bottom Simulating Reflection (BSR), nearly parallel to the seafloor and locally chaotic facies below represents the slump mass accumulation (Figure 4). Levell (1987) marked this horizon as Horizon II (3.6 Ma) based on truncation or mild on lap, associated with the formation of open anticlines and synclines with a general NW–SE orientation in the compressional tectonic zone towards the Sabah Basin Shelf. However, Horizon R1 was still used as mentioned above as one of unconformity in this study. Horizon R2 was calibrated with CN9 recovered in Well-A meanwhile NS17 in Well-B, with both nannofossils occurring in the same age, which is 7.12 Ma (late Late Miocene) (Table 3) in middle bathyal to deeper marine environments. Seismic reflection of R2 mapped regionally is represented by moderate amplitude with moderate to semi continuous and truncation below.

3.2 Gas Hydrate Occurrence

In general, the data quality is very good with all the regional horizons and faults are well imaged. However, most of the major deepwater fold-thrust anticlines have associated with shallow amplitudes over the crest under a bottom simulating reflection (BSR) event located 200-300 sec below the seafloor (Figure 8) which was interpreted to be a zone of hydrate concentration and a potential drilling issue. Hydrates, possibly methane trapped occurrences associated with deepwater fold-thrust anticlines at NW Sabah are indicated by BSR (Figure 11), in late-Miocene sediments and water depths ranging between 1100-2800 m. Global estimates of about 43,000 trillion cubic feet (TCF) of gaseous methane, 98 % occur at 300-3000 m (outer shelf and slope) and 2% in continental permafrost [20]. However, further work is needed such as hydrates reservoir assessment, drill and exploitation of technology to utilize gas hydrate that occurs in fold-thrust anticlines in the deepwater NW Sabah.

3.3 Structural Style Response to Regional Tectonic Event

The study area is distinguished by the extensive diversity of slope geometries and structural styles. The regional seismic sections in Figure 5 to 7 illustrate the dominant structural styles in deepwater Sabah. The Sabah Trough was divided into three NW-SE crossings to the regional structure. Figure 5 as the south of the study area is the end of the NW Sabah Trough and divided by NW-SE structure known as West Baram Line. Figure 6 as the central and Figure 7 as the northern are near the Malaysia-Philippines border elongated the NW Sabah Trough to Palawan Trench. The structural framework was built using biostratigraphy in Late Miocene until present-day from selected wells and seismic stratigraphy of Dangerous Ground to NW Sabah with nine horizons that were mapped throughout the study area. Generally, in these study area, the entire Dangerous Grounds were extended as manifested by numerous extensional faults resulting in the formation of half-grabens and rotated fault blocks meanwhile towards the Sabah shelf there is a structural regime, typical of a deepwater fold-thrust belt (DWFTB) system.

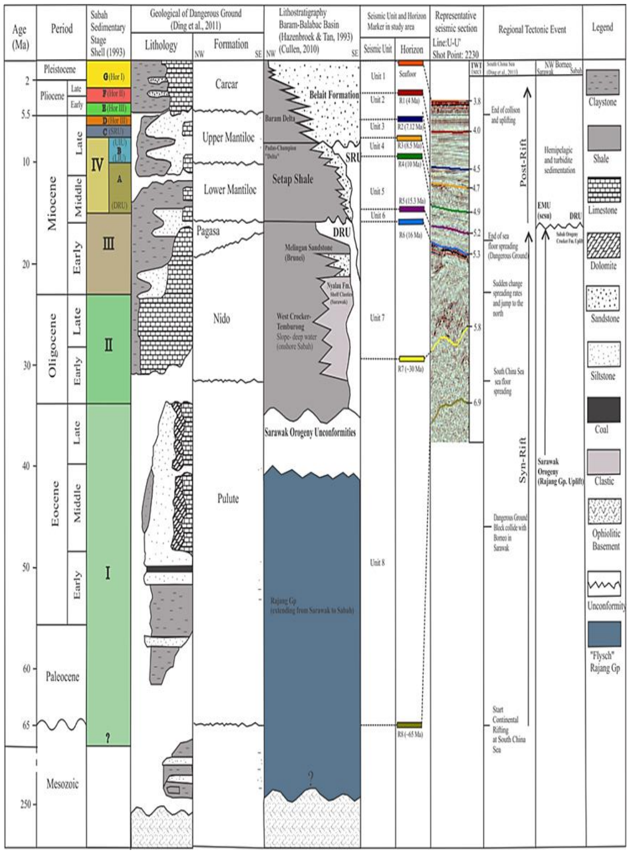


Figure 3 Regional stratigraphy of NW Sabah offshore reviewed by other researchers [10, 19] integrated with seismic horizons and units in this study

Table 1 Reflection patterns with tentative ages of the main horizons acting as sequence boundaries

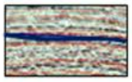
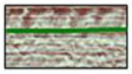
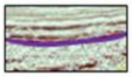
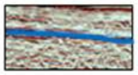
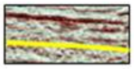
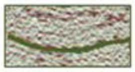
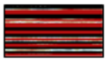
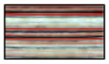
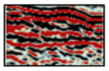
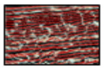
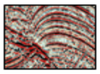
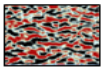
Sequence Boundary and ages		Reflection Pattern	Seismic Profile
R1 (4 Ma)	Red	Nearly Parallel to seafloor, moderate to strong amplitude, high continuous , truncation under boundary	
R2 (7.21 Ma)	Dark Blue	Moderate amplitude, moderate to semi-continuous, truncation below	
R3 (8.5 Ma)	Gold	Moderate to strong amplitude, moderate to high continuous, onlap above and truncation below	
R4 (10 Ma)	Dark Green	Moderate amplitude, moderate continuous, onlap up and truncation below	
R5 (15.3 Ma)	Magenta	Moderate to strong amplitude, moderate to high continuous, truncation below	
R6 (16 Ma)	Slate Blue	Very strong amplitude, High continuous, onlap up and truncation below	
R7 (~30 Ma)	Yellow	Moderate amplitude, patchy to semi-continuous, truncation below	
R8 (~65 Ma) / detachment	Dark Yellow	Moderate to strong amplitude, semi-continuous to disrupted	

Table 2 The six different seismic facies identified in the study area, incorporated with four seismic reflection attributes which were used to classify the facies types

Seismic Facies		Reflection Attributes a) Frequency b) Internal Configuration c) Continuity d) Amplitude strength	
A		a) Uniform b) Parallel to wavy	c) High continuity d) Moderate to strong
B		a) Slightly Variable b) Parallel to wavy	c) High Continuity to semi-continuous d) Low to moderate
C		a) Variable b) Wavy to chaotic	c) Disrupted to discontinuous d) Moderate to strong
D		a) Uniform, locally variable b) Parallel to sub-parallel	c) Semi-continuous to disrupted d) Low to moderate
E		a) Slightly Variable b) Sub parallel to convergent to oblique	c) Semi-continuous to high continuity d) Low to moderate
F		a) Variable b) Wavy to chaotic	c) Discontinuous d) Low to moderate

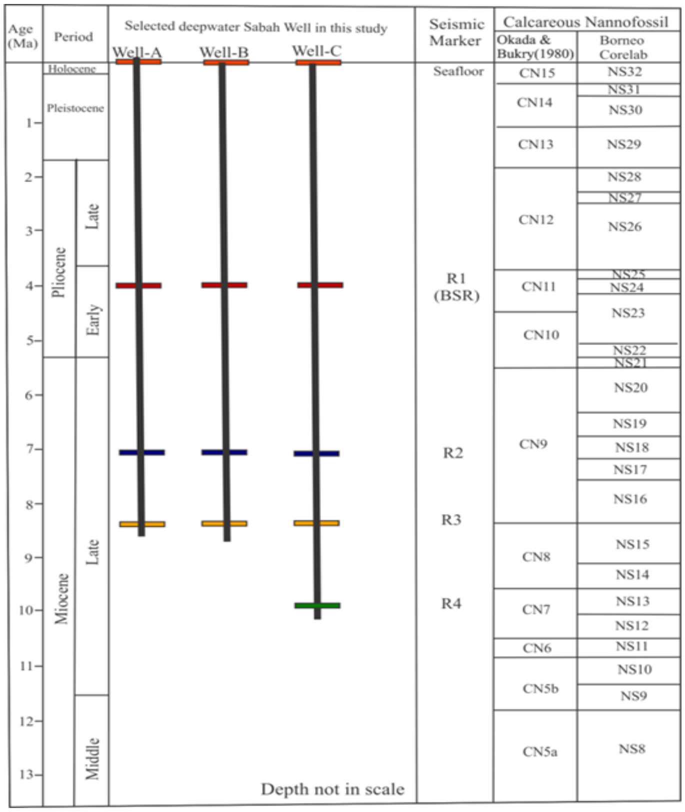


Figure 4 Stratigraphic chart from selected wells, integrated with biostratigraphy in the study area

3.3.1 Southern

The southern region (Figure 5) of the study area shows several steeps caused by folding and thrusting of Baram Delta resulting from tectonic compression [15, 21]. However, some researchers suggested gravity tectonic as the sediments from landward slide to deepwater as mass flow deposits [22, 23]. The southern anticlines are wider spaced (minimum length 4 to a maximum 15 km) and exhibit less bathyal expressions. It is characterized by the association thrust faults with strike toward the SE and range in dip from 15° near the NW Sabah Trough to 40° below the present-day shelf edge. In general, the thrusts tilted into an SE detachment have an average dip of 3.0° and maximum dip of 6.0°. However a further decrease in anticline frequency was found by mapping four deep-water anticlines in the offshore of the Sabah-Brunei border area and at the offshore of the Baram Delta [23]. The West Baram Line connection with a number of major continental strike-slip zones, including the Three Pagodas Fault Zone in the Gulf of Thailand [23], the Mae Ping Fault of Indochina [24], and the Red River Fault Zone [25]. The northeastern part of the Baram Line is an accretionary complex and it comprises of from the Late Cretaceous–Eocene Rajang Group and overlying by deepwater Crocker Formation are exposed onshore [26]. The Crocker Formation was dated as Eocene to lower Miocene by biostratigraphy and of the deep regional unconformity (DRU). However, in this study, biostratigraphy in the southern area reveals that the mappable regional unconformity is in the Late Miocene to Pliocene.

3.3.2 Central

Structural interpretation for central of deepwater NW Sabah Trough margin (Figure 6) shows that the folds are more symmetrical and is very thick towards the shelf and the Early Middle Miocene (R5) with wedge draped by younger (Middle Miocene–Present-day) sediments apparent. The central line section extends into the thrust sheet or allochton [5]. The term thrust sheet had a different term used by other researchers as a mélange wedge [14, 27]. The high-velocity body at the shelf edge shows a possible appearance of a large carbonate body enclosed in siliciclastic sediment or Paleogene sediments encircled by ophiolites during the subduction of the Rajang Sea (Proto-SCS) plate [28]. Overall, the observed thrust ranging in dip from 3° near the NW Sabah Trough to 6°, 10 km of present-day shelf edge (Figure 6C). As the central part of the study area, the anticlines are asymmetric and exhibit steep forelimbs above the upper tip of the base thrust fault. Every thrust fault falls into a gently dipping detachment with an average dip of 4° and a maximum of 10°, that is imaged at two-way-time (TWT) at about 5 and 7 sec (approximately depth ranges of 6 to 10 km respectively). High-amplitude reflector strips further SE was interpreted as an extension of the detachment to TWT at 8 Sec (depths of ~12 km) below the NW Sabah shelf edge (Figure 6D).

3.3.3 Northern

The northern seismic lines (Figure 7) show a southeastward slope downward of the fold-thrust and located anticlines exhibit a clear bathyal expression. The northern anticline was exhibited to be less wide (about 3 to 5 km) than in the southern part of the study area. Extensional structure with normal faulting resulted in the formation of half-graben at Dangerous Ground and beneath of the thrust sheet zone in deepwater NW Sabah which is bound to Palawan Trench. R6 as the top carbonate dips down (3~4^0) to the SE from approximately 5 to 6 sec (TWT) (depth range 6 to 8 km respectively) and represent the continuity of a major detachment for Sabah Thrust Sheet. Individual anticlines showed less steep forelimbs that developed above the upper tip of the associated thrust fault. Sediments above R5 in the Sabah Thrust Sheet zone appeared horizontally to sub-horizontally, layered in high lateral continuity, but thickening towards a thrust sheet system which indicated that sediments are close to the surface.

3.4 Carbonate Build-up

The NW Sabah Trough contains several spectacular culminations that have been interpreted as volcanoes or sea-floor mud volcanoes [29]. However, their interpretation differed from strong resolution seismic that shows all the seamounts are actually carbonate build-ups (Figure 9) of similar size to presently active reefs of the Spratly Islands [30]. Figure 9 (A), shows that there is no seismic resolution underneath the carbonate build up, but features likely of half-graben having a crest whereas, Figure 9 (B) is the highest resolution of the seismic record which clearly shows that build up was drowned with the sediment draped over the crest during the early Late Miocene. In some areas under these zones, there is almost a complete loss of amplitude and frequency within the seismic data. The sediment supply that was possibly from the front of Baram and Padas River was sufficient enough to cover this build up in the Sabah Trough by the progradation of the shelf slope which resulted in the deposition of shallower marine sediments in the inboard areas of the basin [17, 24]. Oldest shallow-water carbonate platforms of the latest Eocene to earliest Oligocene age are known to occur offshore of Palawan and neighboring islands. They continue to grow and expand until the late Oligocene or early Miocene before these areas intermittently subsided due to seafloor spreading and subduction drowned platform formed a prominent feature under the Dangerous Grounds and NW Sabah Trough (Figure 10).

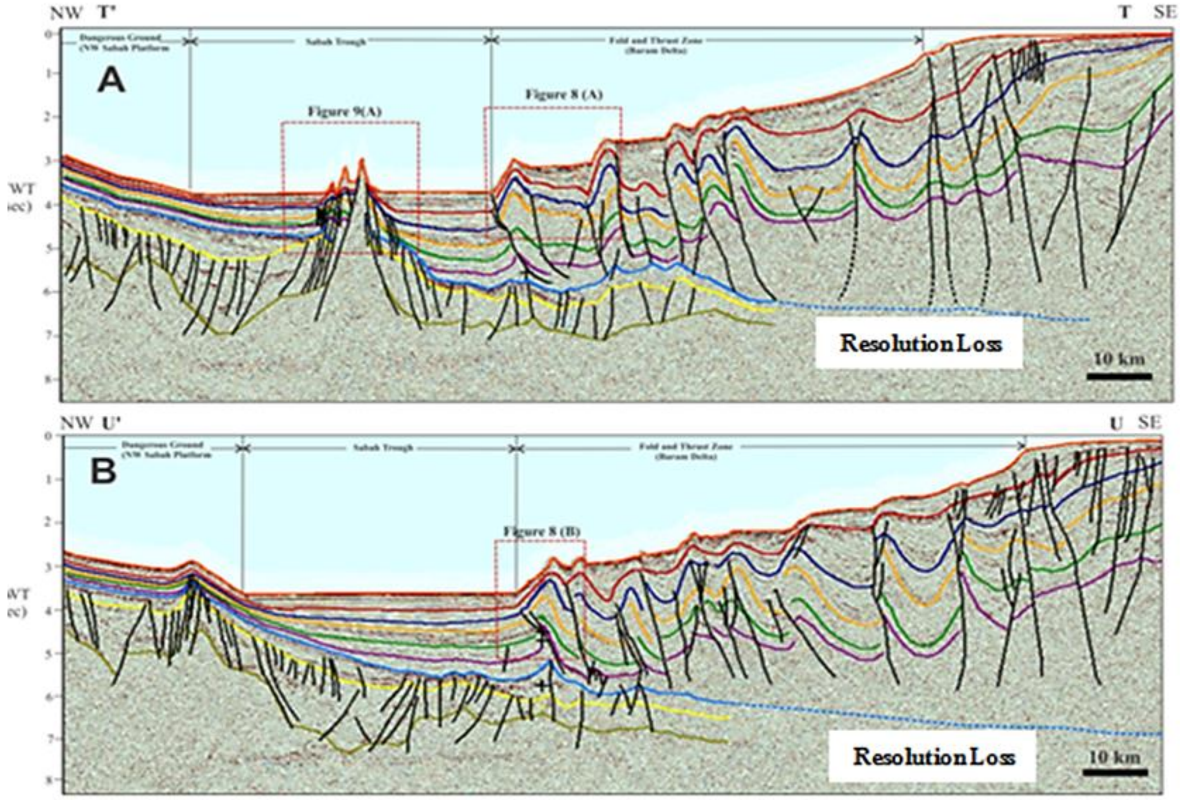


Figure 5 Regional seismic line (T'-T line for image A and U'-U line for image B) in the southern part of study area after interpretation of seismic sequence boundary reveals seamount in deepwater. See Figure 1 for locations of the line

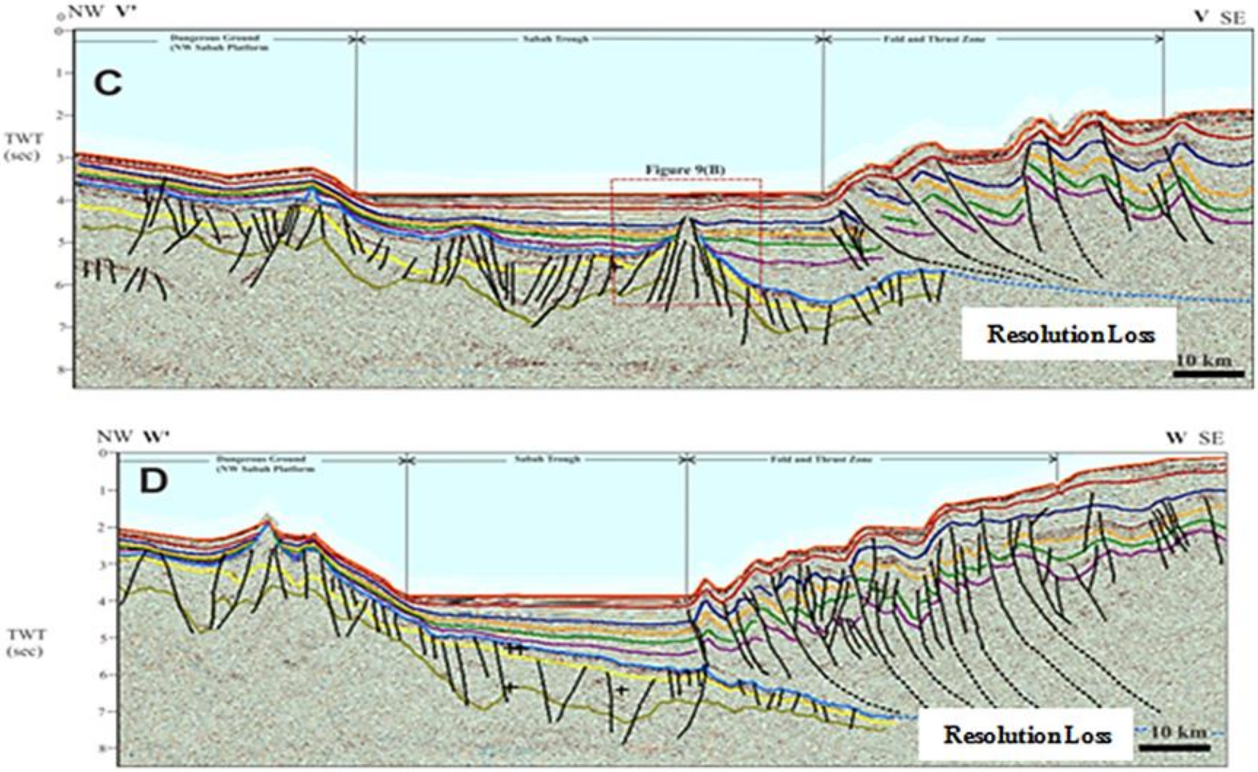


Figure 6 Regional seismic line (V'-V line for image C and W'-W line for image D) in the central part of study area, NW and SE to landward. See Figure 1 for location of the line

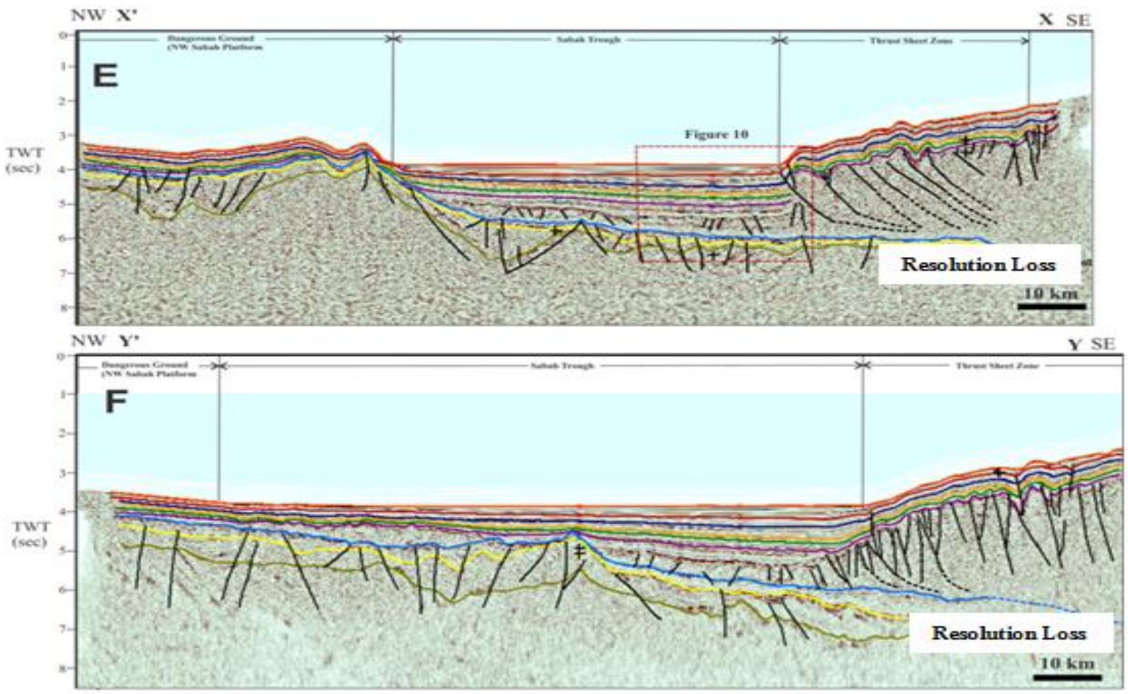


Figure 7 Regional seismic line (X'-X for image E and Y'-Y for image F) in the northern part of study area reveals an extension from Dangerous Ground to Sabah Trough. See Figure 1 for location the line

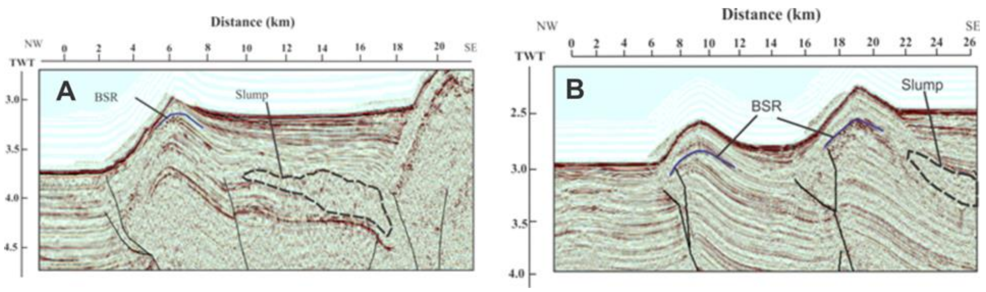


Figure 8 Shallow subsurface expressions indicated strong Bottom Simulating Reflector (BSR) marked as a blue line was identified across the anticline fold in seismic lines T'-T (A) and U'-U (B). The dashed line shows that slump occurs at the hanging wall block of thrust fault

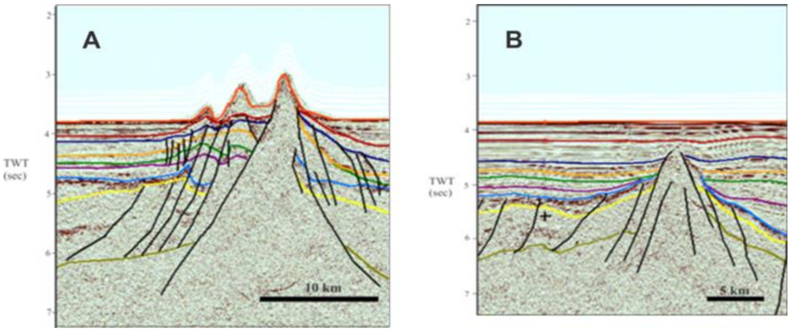


Figure 9 The culminations of seamounts are partly (A) or entirely (B) covered by draping siliciclastic strata

4.0 CONCLUSION

Nine seismic horizon markers (8-0 sec TWT) have recognized from six multi-channel seismic profiles acquired in the NW Sabah Trough, intercepting the eastern part of Dangerous Grounds together with five sequence boundaries that defined the ages. Units above R5 are the post-drift strata with minor tectonic activities at the northern and central parts of study area that were interpreted as tectonic shortening related to a basement collision between Dangerous Ground and NW Borneo-during 16 Ma (marked as R6) ago. Meanwhile, to the south, near West Baram Line, there was tectonic shortening related to gravity driven. Thereby R6 and R7 are the two most important unconformities related to Oligocene to Early Miocene platform carbonates distributes along Dangerous Ground that correlated to subsidence beneath NW Sabah and marked the end of the extension in the southern South China Sea. An integration of this regional stratigraphic framework of the deepwater NW Sabah Basin and Dangerous Ground Province with seismic stratigraphy control along the Dangerous Ground and the Sabah Trough showed that the horizon markers defined in this study fit well into a margin-scale geological framework. The fault trends in the SE shelf that was influenced by both extensional and compressional tectonics. There are three structural styles dominating the study area which are, thrust related to fold, normal faulting and half-graben structures. The half-graben structure was clearly imaged in Oligocene to Early Miocene sequence due to compressional tectonic that took part from the Dangerous Ground that was subducted beneath NW Sabah. The biostratigraphy data of three wells obtained the age in early Miocene until present-day integrated with the seismic profiles. Therefore, it is indicated that along the Sabah Trough to the Palawan Trench,-there was a same sediment accumulation (draping strata) occurring in a fold and thrust zone and was correlated to Dangerous Ground. At present, the deepwater NW Sabah is not an active volcanic-earthquake activity region, but has experienced multiple tectonic histories in the past. The evolution of deepwater NW Sabah folds and thrust structures has a significant impact from the history of South China Sea evolution as suggested by Hutchison (1996) and Schluter *et al*., (1996). In the future, a sub-division of each sequence needs to be considered when existing additional well data are available.

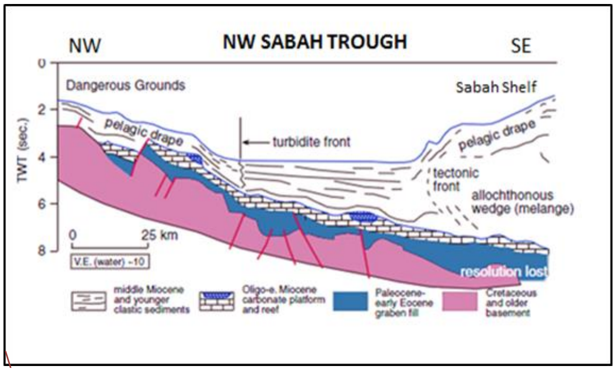


Figure 10 Cross section shows drowned Oligocene–early Miocene carbonate platform and younger turbidite deposition along the NW Sabah Trough (modified from Hutchison 2004)

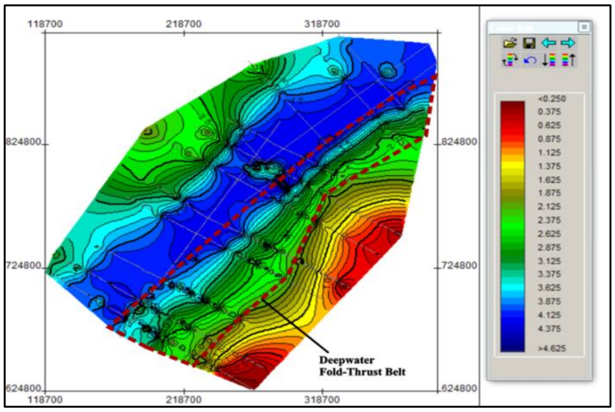


Figure 11 The contour time (TWT) map of Horizon R1 that is related to the BSR distribution in Deepwater Fold-Thrust Belt

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