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INTEGRATED ANALYSIS FOR ASSESSMENT OF DEEPER HYDROCARBON PLAY POTENTIAL IN REBAB-1, CENTRAL LUCONIA PROVINCE, SARAWAK

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ABSTRACT

The basin history, thermal maturity, and hydrocarbon entrapments of Rebab-1 Well in Central Luconia have been relooked through the study of seismic, well log, and geochemical data to find new hydrocarbon potential in the deeper section of the well. The quality of source rocks in this area was based on assumptions, and hydrocarbon exploitation only occurs on shallow hydrocarbon plays making the potential for deeper plays difficult to ascertain. This study was conducted based on two 2D seismic lines, integrated with well lithological and stratigraphy data and geochemical data such as total organic carbon, pyrolysis, and vitrinite reflectance. Integration of these data was used to determine the deeper hydrocarbon play of Rebab-1 in Central Luconia Province. The seismic data were interpreted using Petrel software with validation from the report. Cross-plots from bulk geochemical analysis data were interpreted for the source rock's organic richness, kerogen quality, hydrocarbon-generating potentials, and thermal maturation levels. The results of seismic interpretations showed that extensional and compressional tectonics shaped the field of Rebab-1, with structures mainly trending to the NW-SE and NE-SW directions. Geochemical analysis showed that the total organic carbon content (TOC) of the samples analysed ranges between 0.06 and 2.98 wt.% indicating fair to very good source rocks producing mainly type II and mixed type II-III kerogen as the dominant kerogen. These types can generate mainly gas and mixed oil and gas accumulations upon attaining thermal maturation level. Also, Rebab-1 shows fair to very good hydrocarbon-generating potentials. The vitrinite reflectance (Ro) and Tmax results showed that the analysed samples are generally plotted in the immature, mature, and post-mature stages of oil generation but still within the gas generation window. Overall, source rocks from Rebab-1 can be said to have attained maturity at the youngest during depositions of Cycle III to older than that, and faulting and folding serves as hydrocarbon trap systems, indicative of potential in having deeper hydrocarbon plays in Rebab-1 well.

Keywords: *Seismic stratigraphy, trap system, total organic carbon, source rock, hydrocarbon generating potentials, thermal maturity*

INTRODUCTION

The global demand for hydrocarbons is rising, which has prompted the exploration and production sector to look for new resources [1]. The new resources are, however, primarily found in deeper formations because prior explorations were typically focused on shallower formations. Every oil or gas play has a potentially mature source rock. A hydrocarbon play's potential depends on the basin's burial depth and petroleum source rock quality. According to Magoon and Beaumont [2], a source rock is a fine-grained organic-rich rock that can generate and discharge hydrocarbon when heated and pressured.

The Sarawak Basin has seven hydrocarbon-bearing geological provinces, including Central Luconia [3]. In offshore Sarawak, Central Luconia Province borders the compressive Balingian Province to the south and the Baram and West Luconia deltas to the east and west (Figure 1a). It is renowned for its extensive carbonate build-ups and has more than 50% of Malaysia's gas reserves and some oil rims [3]. Several studies in this Province identified four notable hydrocarbon plays in Central Luconia: Cycles IV/V/VI Carbonates, Cycles V/VI Post-Carbonate, Cycle II Carbonates, and Cycles I/II Pre-Carbonate Siliciclastic. Each play has at least an effective source rock [3]. Most of the previous works only focused on the shallower hydrocarbon plays (mainly Cycle IV/V) in the area [3]-[4] entrapped both structurally and strati-graphically. Cycle I/II play is unexplored, but pre-carbonate paleohighs, graben depocenters, tilted fault blocks, and stratigraphic traps are plausible traps [3]. Also, source rocks evaluation in Central Luconia has been based on assumptions due to its similarities to the Balingian Province [3],[5].

This study aims to determine the potential for the deep hydrocarbon play in the Rebab-1 well by re-assessing the various geological, geophysical, and geochemical data of Rebab-1.

The objectives are to:

1. interpret the structural and stratigraphic characteristics of seismic lines crossing the Rebab-1 well (b) characterised the organic matter richness, kerogen quality, thermal maturity, and hydrocarbon
2. characterised the organic matter richness, kerogen quality, thermal maturity, and hydrocarbon-generation potential of each stratigraphic cycle
3. integrate the basin history and geochemical analysis for Rebab-1 in finding the potential of deep hydrocarbon play.

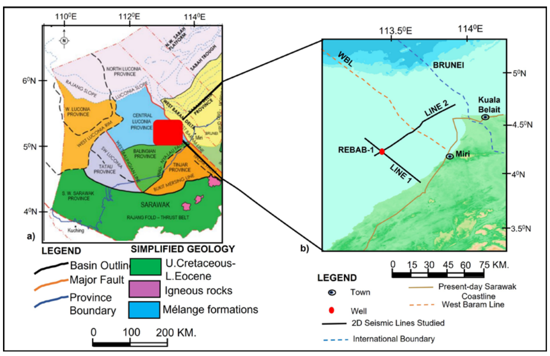


Figure 1 Location map showing (a) Central Luconia Province in Sarawak Basin and (b) Seismic lines crossing through Rebab-1 Well, adapted and modified from Jamaludin et al. [6]

Hence, the Rebab-1 well in Central Luconia Province, offshore Sarawak, Malaysia, was investigated for deeper hydrocarbon play potential. The location map showing the study area is shown in Figure 1.

GEOLOGICAL SETTINGS AND STRATIGRAPHY

The Central Luconia Province is an area of intense tectonic and structural evolution. The collision of the South China and Borneo plates formed it. Rifting, compression, and uplift have deformed the area [7]-[8]. These tectonic forces fractured and folded sedimentary rocks in Central Luconia, forming a succession of anticlines, synclines, and other faults that mainly terminate at Cycle IV (Figure 2).

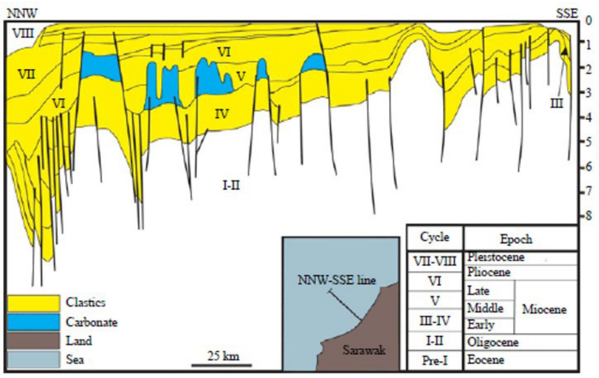


Figure 2 Central Luconia Structural sketch and carbonate build-ups [9]

These structures are important sites for hydrocarbon accumulations, with hydrocarbons trapped in both structural and stratigraphic traps [3]. These structures generally trend WSW-ENE, NNW-SSE, and SSW-NNE [9]-[10].

Central Luconia follows Sarawak's stratigraphic cycle concepts. Offshore Sarawak has eight stratigraphic cycles (Figure 3) from Oligocene to Recent [5],[9]. Cycle I-III sediments are coastal/marine siliciclastic sediments on the Rajang or Sarawak unconformity from the Late Oligocene to Early Miocene [9]–[12]. Cycle IV-V saw the build-up of carbonates across the province until the late Miocene, but Cycle VI-Present, derived from the Rajang Fold-Thrust Belt, witnessed a high input of marine siliciclastic sediments [3],[5]-[6],[9],[13].

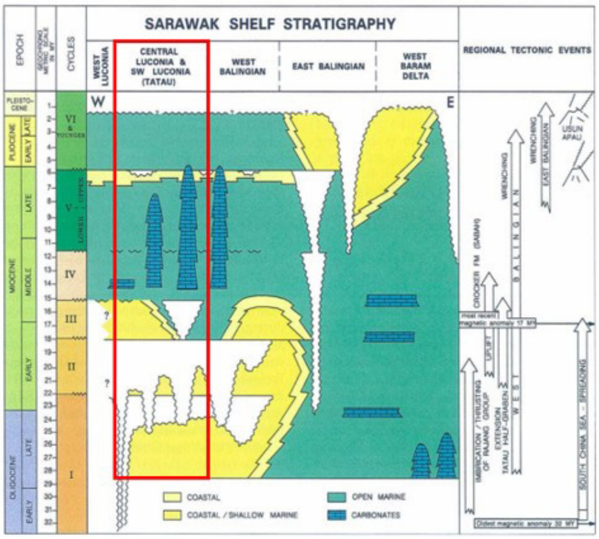


Figure 3 Geological map of the Sarawak Basin showing stratigraphy, major unconformities, sediment types, and regional tectonic events in Central Luconia Province [5]

SOURCE ROCKS QUALITY AND MATURITY

Central Luconia Province source rocks are mostly from Cycle I, II, and III deposits and share a similar depositional history with the Balingian Province [3],[14]. Cycle I generally have higher organic richness compared to those in the upper cycles. Source rocks here mainly contain type III kerogen, gas-prone materials, and minor type II at some places, which may generate oil [3]. Maturity is as crucial as source rock quality because it will not generate hydrocarbons without reaching the oil window. Cycle I and II were buried deeply enough to generate oil, whereas most of Cycle III and the younger strata were thermally immature for oil and gas generation [3],[5].

HYDROCARBON PLAYS

Four hydrocarbon play types have been identified in Central Luconia: Cycle IV/V/VI carbonates, Cycle I/II pre-Carbonate siliciclastic, post-carbonate V/VI siliciclastic, and cycle II carbonates. The most prolific cycle IV/V/VI carbonates have 24 TSCF of gas reserves in 17 build-ups [3]. Faulting in Cycle III facilitates hydrocarbon migration to carbonate reservoirs, whereas mid-cycle shales provide excellent seals to the reef play [3]-[4]. Cycle I/II play is unexplored, but pre-carbonate paleohighs, graben depocenters, tilted fault blocks, and stratigraphic traps are plausible. Structural or stratigraphic traps can seal deltaic and shelf sandstones and low-stand turbidites in Cycle V/VI post-carbonate plays. Porosity is high (34%) in these silty reservoirs. Rebab-1, Jintan Deep-1, G2.1, and G10.1 wells have been drilled in Cycle II carbonates; however, the porosity is unknown. These wells demonstrate that this play may be a hydrocarbon target, while cycle III shales seal them [3].

METHODOLOGY

The main goal of this study is to assess the potential of deeper reservoirs in Rebab-1. The data for this study was obtained from UTP in-house data at the Centre for Subsurface Imaging (CSI). The data include two 2-D seismic lines of 86.7 km and 59.8 km, respectively, well-log data and reports, vertical seismic profile data, and geochemical analysis data (TOC), rock eval pyrolysis, and thermal maturity). The workflow chart for this research is shown in Figure 4. The geochemical data were extracted from the Rebab-1 Well report of AGIP (Malaysia) Ltd. (July 1992). The methodology was divided mainly into two parts: geophysical analysis and bulk geochemical analysis. The results were subsequently integrated for the assessment of deeper hydrocarbon plays.

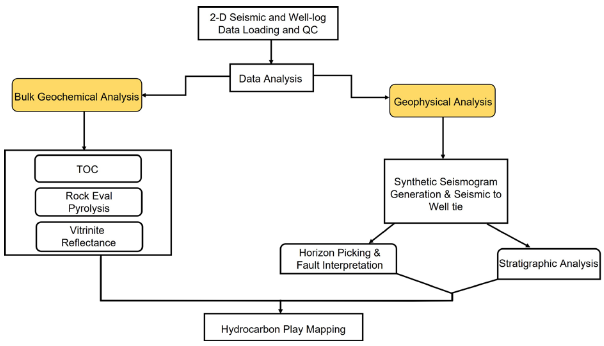


Figure 4 Flowchart of research methodology

Geophysical Analysis

Synthetic seismograms and well-seismic ties let geoscientists map the subsurface more accurately by correlating seismic and well data. Wavelet extraction produced synthetic seismic traces. Figure 5 shows the step-by-step process for generating synthetic seismic traces, starting with sonic log calibration with vertical seismic profile (VSP) data, then generating acoustic impedance from sonic and density logs, and finally calculating the reflection coefficient for each layer interval of different velocities. The reflection coefficient series over the entire area was convolved with an analytical Ricker, zero phase wavelet of 25 Hz frequency to generate a synthetic seismic trace.

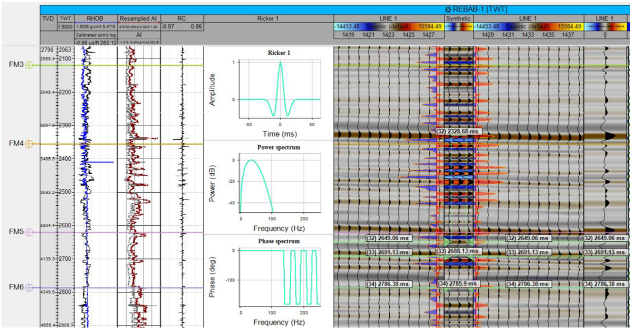


Figure 5 Steps in generating synthetic seismograms in Petrel for the seismic-to-well tie

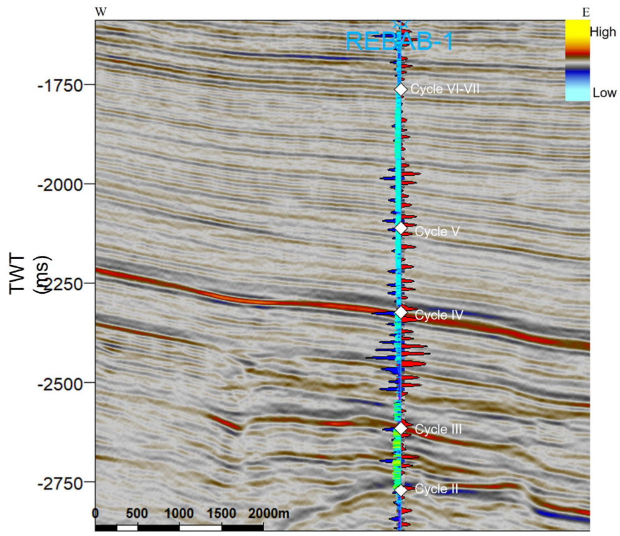


Figure 6 Seismic to well tie, with gamma-ray log overlayed, confirming the change in lithology

Horizon picking, fault, and stratigraphic interpretations followed seismic-well-tie. Horizons were tracked manually and/or automatically from the two 2-D lines using seismic reflected amplitudes, phase, and continuity. The horizon discontinuity was used to identify the presence of a fault, and matching these horizons across fault zones was applied to map out the faults in the seismic data. Both horizon and fault were interpreted until the maximum resolution limit was reached. Seismic stratigraphic interpretations were carried out by dividing the sequences based on lateral terminations caused by strata changes; these are onlap, downlap, toplap, and truncations, and classified into seismic facies based on reflection amplitude and configuration, frequency, and horizon continuities.

Bulk Geochemical Analysis

The organic richness was determined by plotting TOC values against depth and comparing them with the standards based on the observations of Peter and Cassa [15]. The TOC value from 0.5wt.% and above is fair to generate hydrocarbon. Samples with TOC <0.5% are removed for further analysis because they are considered poor in generating hydrocarbon. Each zone's kerogen type was established by cross-plotting HI versus OI and HI vs S2/S2. The kerogen type, deposition environment, and hydrocarbon potential were compared to Peter and Cassa [15] and Tissot and Welte [16]. TOC versus S2 and TOC versus GP were plotted and compared to conventional standards [17] to estimate generation potential. Rebab-1's thermal maturity was assessed using vitrinite reflectance, Tmax, SCI, and TAI. The plots of Ro versus depth and Tmax versus depth were used with the SCI and TAI values to identify immature, mature, and post-mature hydrocarbons and compare them to the standards of Peter and Cassa [15] and Waples [18].

RESULTS

Seismic Horizons and Fault Interpretations

The horizon interpretation was based on good continuity of seismic reflector after applying several seismic attributes techniques. Upon conducting the reflector picking, two seismic attributes were applied: structural smoothening and Trace AGC. Based on integrated seismic and well-log interpretations, seven horizons were identified and interpreted by tying them across areas of displacements. These horizons correspond to the eight sedimentation cycles per Sarawak's stratigraphic cycles. The horizons selected corresponded to the well tops and were based on the reflectors' positive reflectivity, amplitude, continuity, and resolution limit. Although some of the horizons picked have low amplitudes, they are continuous and may suggest a gradual change in lithological facies (Figure 7a).

The study discovered faults using seismic reflection discontinuity. Structural smoothening and Trace AGC features increase seismic event continuity, eliminate unwanted noise in seismic data, and improve fault visualisation and viewing. The faults are major and minor. Figure 7a illustrates the major faults offset from Cycle V to Cycle I (Early - Late Miocene), displacing strata vertically. Some younger thrust faults affected cycles VII-VIII and occasionally cycle VI (Figure 7b) sediments. Synthetic and antithetic normal faults are related to minor faults in this region.

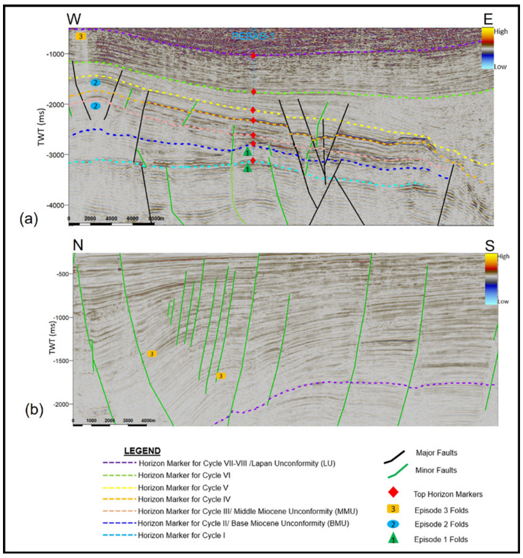


Figure 7 These figures show the horizon markers and structural features of Rebab-1 (a) Line 1 (b) Line 2, after applying Structural Smoothening and Trace AGC attributes to improve reflection continuity, terminations, and visualisation

Seismic Stratigraphic Interpretations

Cosine phase seismic properties optimised bedding layer terminations and improved stratigraphic sequences as they were deposited. Based on major seismic facies analysis parameters (seismic reflection configuration, amplitude, continuity, and frequency), the seismic stratigraphic mega-sequences were divided into four groups (Figure 8a and b). Cycle II-V, Cycle VI-Cycle VI (base), and top of Cycle VII-Present. Hummocky and varied amplitude reflections distinguish the Pre-Cycle I-Cycle I sediments from the upper Cycle II-V sequence. Cycle II-V has seismic features parallel to sub-parallel and mounded for limestone, moderate to very strong amplitude reflections, and high frequency. Cycle VI has basinward converging, prograding clinoforms (complex sigmoid to oblique), low amplitude reflections, low to medium frequency, onlaps, downlap, and complex-top lapping boundaries. Cycle VII-Present has sheet, parallel, smooth, continuous, and medium to strong amplitude reflections. The stratigraphic mega-sequences for seismic lines 1 and 2 that cross Rebab-1 Well are shown in Figures 8a and 8b, respectively. The detailed seismic facies analysis of each mega-sequence is presented in the subsections below.

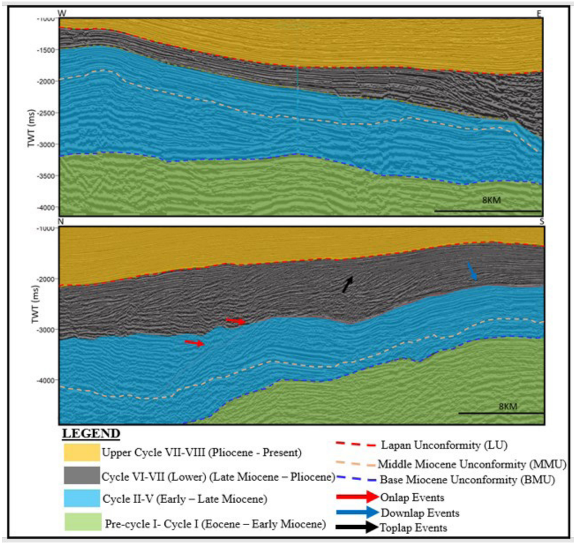


Figure 8 Stratigraphic Sequences of Rebab-1 for (a) Line 1 (b) Line 2 after application of Cosine phase seismic attribute

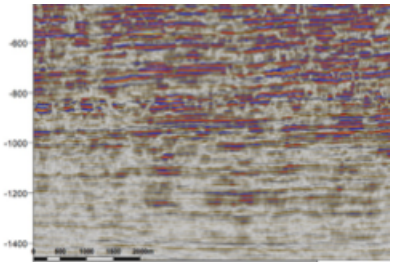
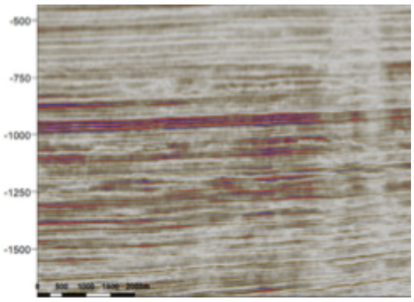
Upper Cycle VII-Cycle VIII (Present) Sequence

This sequence shows low-frequency data with continuous, moderate to strong amplitude, laminated, and parallel seismic facies that characterised the seismic responses captured between Cycles VII and VIII (Table 1). The uppermost layers of this unit are characterised by strong amplitude and low-frequency reflectors, while the lower part shows a lower amplitude reflector. The seismic facies are parallel and laminated, indicating sand interbeds with shale; this suggests uniform deposition rates on a uniformly subsiding shelf.

Cycle VI - Lower Cycle VII Sequence

This sequence is characterised by prograding clinoforms and the beginning of high input of siliciclastic sediments into the basin, marking the end of the carbonate build-ups. It is a deposit of the coastal plain and open marine in the deeper part. It has a wedge shape that increases in thickness towards the basin floor in the northwest region (Figure 7a) and thinning landward (southeast region).

Table 1 Seismic features of Upper Cycle VII-VIII (Present) Sequence sediments

Cycle/Age	**Line** Note: Vertical Scale in TWT (ms)	**Seismic Features** (a) reflection configuration (b) amplitude (c) frequency (d) continuity & appearance
VIII- Upper part of VII (Pliocene – Present)	 1)  2)	a) Sheet, Parallel b) Medium to strong reflection c) Low to medium d) Continuous and Smooth **Lithologies** 1. Mainly sandstone- Medium-grained sandstone grading (to fine-very fine sands) downhole 2. Occasionally interbedding with shaly sandstone and calcareous sandstone (From the Report)

Cycle VII is delineated from Cycle VI by the Lapan Unconformity (Figures 6 and 7). It has configuration styles of basinward convergent, prograding clinoforms of complex sigmoid oblique, with hummocky configuration occasionally occurring in some parts of the sequence package. Low amplitude and low to medium frequency reflections also characterised this sequence. Topset reflections and segments of oblique configuration with toplap terminations set the upper limit, whereas downlap surfaces and onlapping on carbonate build-up edges set the base limit (Table 2).

Cycle II - V Sequence

The Base Miocene Unconformity (BMU) marks the boundary between Cycle II and the lower sequences. They are Early-Middle Miocene shallow marine carbonate deposits. Cycle II sediments have smooth, parallel, continuous, very strong amplitude, and high-frequency reflectors (Table 3), indicating carbonate build-ups with shale and shaly sandstone interbeds. Cycle III is distinct from Cycle II in shape, significant amplitude reflections, and frequency. It has sediments with a hummocky form at certain points, parallel-sub-parallel towards the south, with strong amplitude and low-frequency reflectors, indicating shale intercalations with carbonate materials.

The Middle Miocene Unconformity (MMU), a period of widespread carbonate build-ups, separates Cycle IV and V from Cycle III. They are generally parallel, continuous, extremely strong amplitude, low-frequency reflectors (Table 3). The carbonate build-ups are still in the catch-up phase, and the carbonate production rate outpaced the influx of sediments into the basin. The reflection amplitude becomes weaker going up to cycle V, which indicates the onset of an influx of siliciclastic materials into the basin. Seismic evidence can be seen in the quick amplitude fluctuations at the top of the limestone build-ups (Table 3). Carbonate build-ups are more prevalent and thicker towards the deeper marine realm as siliciclastic materials dominate the upper part.

Table 2 Seismic features of Cycle VI-VII (Lower) Sequence sediments

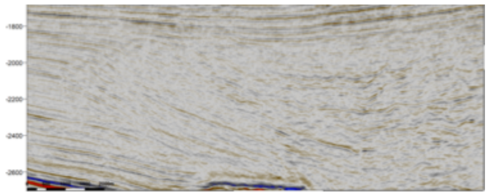
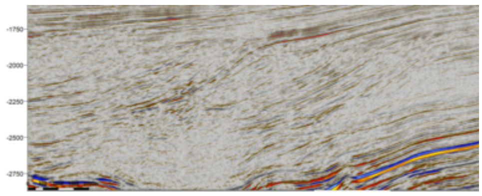
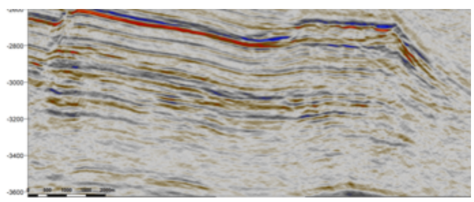
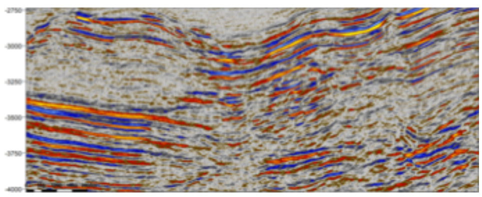
Cycle/Age	**Line** Note: Vertical Scale in TWT (ms)	**Seismic Features** (a) reflection configuration (b) amplitude (c) frequency (d) continuity & appearance
VI - Lower part of VII (Late Miocene – Pliocene)	(1)  2) 	a) Basinward convergent, Prograding clinoforms (complex sigmoid oblique) b) Low to high reflections c) Low to High d) Discontinuous and **Lithologies** Mainly shale, with shale and sandstone intercalations and a few calcareous shales (From the Report)

Table 3 Seismic Features of Cycle II- V Sequence sediments

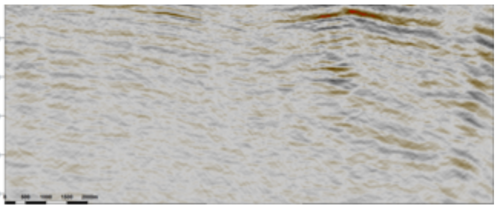
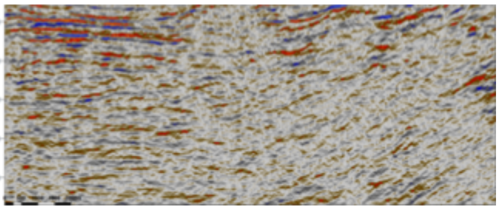
Cycle/Age	**Line** **Note: Vertical Scale in TWT (ms)**	**Seismic Features** (a) reflection configuration (b) amplitude (c) frequency (d) continuity & appearance
II-V (Early – Late Miocene)	(1)  2) 	a) Parallel to Sub-parallel, mounded for limestone (cycle IV & V), and poor amplitude in gas-affected zones. b) Moderate to very strong reflections c) Moderate to High d) Stratiform and acoustic blanking at some places due to gas effect **Lithologies** 1. Mainly Limestone in Cycle II, III, & IV 2. Shaly Limestone intercalating with shaly sandstone in Cycle V 3. Cycle II predominantly shaly limestone with a thin bed of organic-rich shale at 4560 m 4. (From the Report

Pre-cycle I- Cycle I Sequence

Well drilling did not reach Cycle I and Pre-Cycle I layers, but seismic reflection amplitude and continuity indicated the top of Cycle I at 5,250 m. This study does not cover the Base Oligocene Unconformity (BOU), which separates the Cycle I sediments from the Pre-Cycle I strata deposited in the Eocene.

The Pre-Cycle I sequence has a hummocky configuration, variable amplitude reflections, medium to high frequency, decreased seismic amplitude and more chaotic features towards the NW. The sediments become thinner and more chaotic towards the NW (towards the ocean floor/rifting points) and show high reflections at some spots, indicating carbonate intercalations (Table 4). Cycle I sediments exhibit sub-parallel, sometimes hummocky shapes, moderate amplitude and moderate frequency reflectors, and high amplitude and high-frequency reflections in some spots. The high-amplitude, high-frequency reflectors, possibly carbonate interbeds, are surrounded by low-amplitude sediments (Table 4), usually shale or mud-rich source rocks.

Table 4 Seismic features of Pre-cycle I- Cycle I Sequence sediments

Cycle/Age	**Line** **Note: Vertical Scale in TWT (ms)**	**Seismic Features** (a) reflection configuration (b) amplitude (c) frequency (d) continuity & appearance
Pre-Cycle I-I (Oligocene - Early Miocene)	(1)  2) 	a) Hummocky, sub-parallel-wavy b) Variable reflections c) Low to Medium d) Discontinuous and acoustic blanking at some places due to gas effect **Lithologies** 1. The top of cycle I is predominantly shaly limestone. 2. Sandstone interbed with shale (Based on seismic features)

Bulk Geochemical Analysis

The variables that have been assessed here are the organic richness, kerogen type, thermal maturity (vitrinite reflectance (Ro), thermal alteration index (TAI), and spore colour index (SCI). These were achieved by analysing total organic carbon (TOC), pyrolysis, and organic petrographic results.

Total Organic Carbon (TOC) Contents

The cross plot of TOC value vs depth zoned based on cycle nomenclature was shown (Figure 9). Cycle VI sediments had TOC values of 0.84-1.21 wt% (average 1.06 wt%), indicating a good source rock. Figure 9 reveals that sediments between 650-1150 m (Cycle VII) and below 3660 m (Cycle IV down to Cycle II) depth exhibit poor TOC values (<0.5wt.%), with occasional fair and a rare, very good thin layer at 4560 m having 2.92 wt.%. The zones with higher TOC values were identified to compose mainly of shale, shaly limestone, and calcareous shale, while zones with extremely low TOC values can be found in an area predominantly composed of limestone, shaly limestone, and sandy limestone at the upper part of the well.

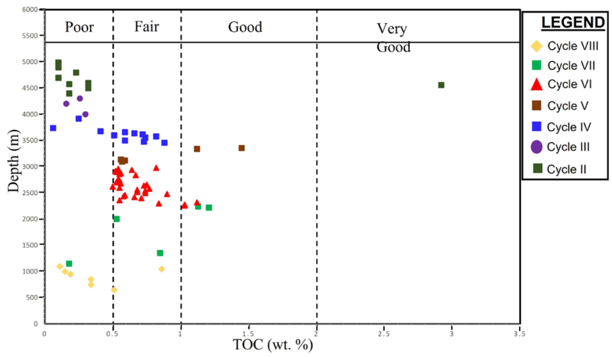


Figure 9 Plot of Depth versus TOC showing the organic richness of the source rock in Rebab-1

Kerogen Quality

The plots of HI versus OI (Figure 10a) and HI versus S2/S3 (Figure 10b) show that Cycle VIII (Late Pliocene to Present) exhibits HI values between 55-86 mg HC/g, high OI values, and S2/S3 values between 0.12-0.40. Based on these findings, Cycle VIII can produce type III kerogen. The Pliocene Cycle VII contains HI values of 85-227 mg HC/g rock, low OI values, and 1.74-9.52 S2/S3 values, indicating type III and mixed type II/III kerogen. Cycle VI, further in the Late Miocene, contains 97-388 mg HC/g rock HI values, generally low OI values, and S2/S3 values between 1.13-23.00, indicating type III and II kerogen, with most plots in the region of mixed type II/III.

Cycle V (Late–Middle Miocene) contains HI values between 54-337 mg HC/g rock, relatively low OI values, and S2/S3 values between 0.90-13.79, charting in type III and II kerogen range. Cycle IV, deposited during the Middle Miocene, includes HI values of 54-337 mg HC/g rock, low OI values, and 0.89-6.67 S2/S3 values. Type III and IV kerogen are plotted here. Cycle II sediments were deposited in the Early Miocene, and a small layer at 4560m depth had 504 mg HC/g rock, very low OI (23 mg HC/g rock), and 32.28 S2/S3 values, indicating type II kerogen.

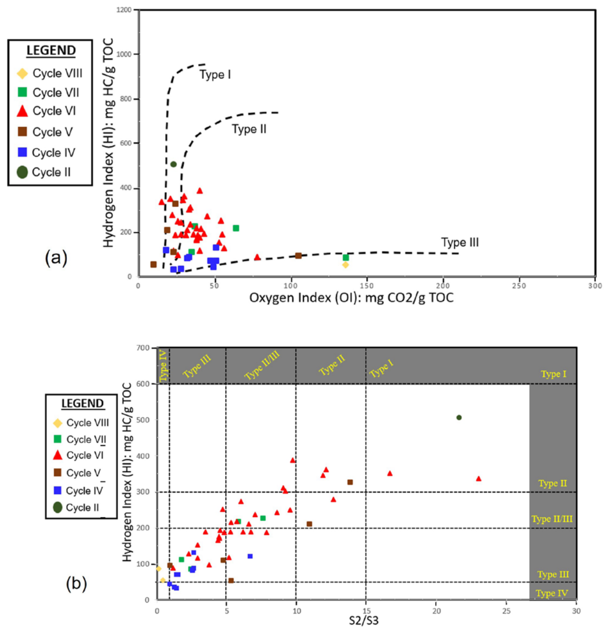


Figure 10 Plots of (a) HI versus OI, modified from the van Krevelen diagram, and (b) HI versus S2/S3 illustrating the kerogen quality (Type) of Rebab-1

Hydrocarbon Generating Potentials

According to Peter and Cassa [15] and Abd-Allah [17], Rebab-1 source rock has low to very good producing potential with S2 values of 0.31-14.72 mg/g rock and GP values of 0.30-32.28. However, most sections have S2 values below 2.5 mg/g rock, between 2.5-5.0 mg/g rock, GP value <2, and few within 2-5 mg/g rock, indicating that the source rocks have largely poor to fair hydrocarbon producing potentials (Figures 11a and 11b).

Cycle VIII and IV have S2 values between 0.44-0.47 and 0.26-0.80 mg HC/g rock and GP values between 0.30-0.35 and 0.30-0.91 mg/g rock, respectively (Figures 11a and 11b). This is comprehended with poor hydrocarbon-generating potential for this cycle of sediments. Cycle V, VI, and VII have S2 values ranging from 0.53-1.93, 0.44-3.16, and 0.59-2.62 mg/g rock and GP values ranging between 0.67-3.55, 0.47-4.17, and 0.67-3.01 mg/g rock respectively, indicating a poor to fair hydrocarbon generating potentials for these sections. The deepest cycle reached by Rebab-1, Cycle II, has a thin layer at 4560 m depth, with 14.72 and 32.28 mg/g rock S2 and GP values, respectively, suggesting that this section has excellent hydrocarbon generating potentials. However, the availability of this section is just 20 meters thick.

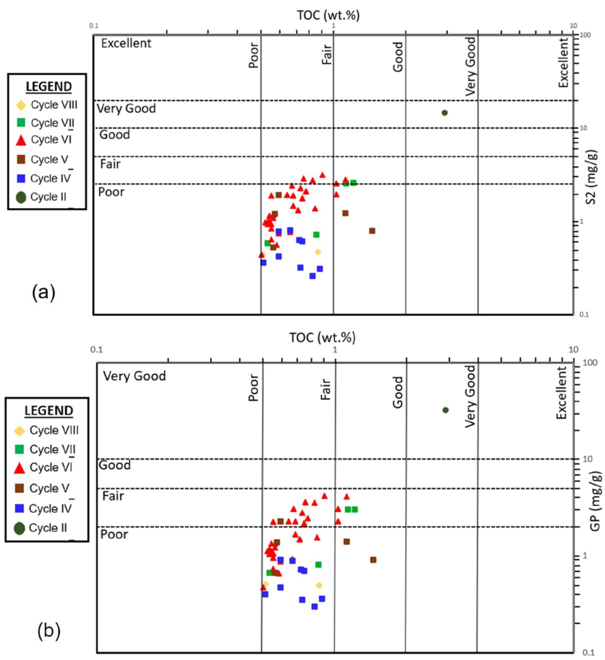


Figure 11 Plots of (a) S2 vs TOC (b) GP vs TOC indicating expected hydrocarbon types and quality of the source rocks in Rebab-1

Source Rock Maturation

This was interpreted based on the guidelines of Peter and Cassa [15] and Waples [18]. The Ro value increases linearly with depth, but uplifting events cause a break. The sediments are immature from the top to 336 m, with Ro values below 0.6%. At 3460 m, oil generation (Ro >0.6%) begins. At 4560 m, Ro exceeds 1.30%, making this zone post-mature for oil generation yet within gas-generation window (Figure 12a). Also supported by the Tmax plot against depth (Figure 12b), the Recent – Middle Miocene strata are immature, sediments from the Middle Miocene to the Early

Miocene are early mature. At the same time, those older than that are mature to post-mature for oil formation. The sediments deposited during the Middle Miocene to the Present comprising cycle V-VIII including the uppermost part of cycle IV (0-3360 m), have Ro values between 0.30-0.59% (Figure 12a) and Tmax values between 365-443°C (Figure 12b), generally less than 435°C with occasional Tmax values greater than 435°C, indicating that they are immature. Middle Miocene to Early Miocene (top of cycle II - the lower part of cycle IV) have 0.60-0.69% Ro and Tmax values between 435-450°C, indicating an early-peak mature stage. Cycle II's Early Miocene sediments exhibit a 1.38% Ro value and 438°C Tmax, showing it is post-mature for oil generation but within a gas generation. PI, TAI, and SCI values from 0.06 to 0.54, <1 to >2, and 2.0 - >7.5 support this maturity stage.

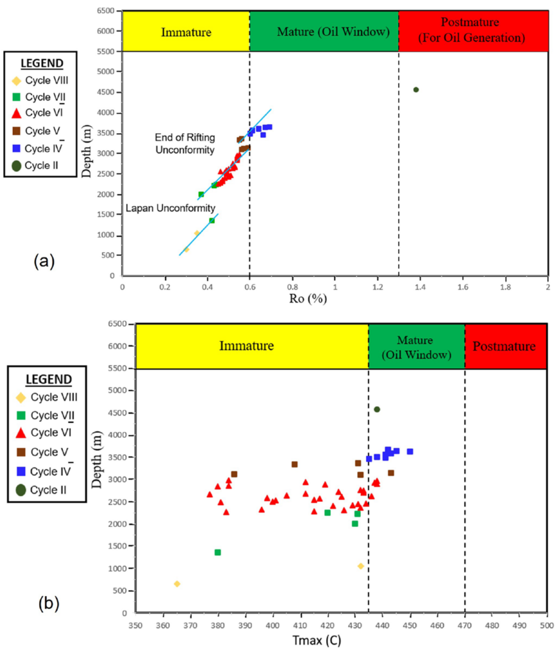


Figure 12 Plots of (a) Depth vs Vitrinite Reflectance (Ro) and (b) Depth vs Tmax showing thermal maturity levels of the analysed rock samples of Rebab-1

The sediments deposited during the Middle Miocene to the Present comprising cycle V-VIII including the uppermost part of cycle IV (0-3360 m), have Ro values between 0.30-0.59% (Figure 12a) and Tmax values between 365-443°C (Figure 12b), generally less than 435°C with occasional Tmax values greater than 435°C, indicating that they are immature. Middle Miocene to Early Miocene (top of cycle II - the lower part of cycle IV) have 0.60-0.69% Ro and Tmax values between 435-450°C, indicating an early-peak mature stage. Cycle II's Early Miocene sediments exhibit a 1.38% Ro value and 438°C Tmax, showing it is post-mature for oil generation but within a gas generation. PI, TAI, and SCI values from 0.06 to 0.54, <1 to >2, and 2.0 - >7.5 support this maturity stage.

Hydrocarbon Play Types

Three hydrocarbon play types (fault-bounded closure, anticlinal, and low-relief gentle anticlines) were identified at differing stratigraphic cycles based on interpretations of seismic data (Figure 13). The interpretations of 2D seismic data corroborate the presence of trap systems, which are supported by the regional tectonics of the area Mat-Zin [8] and Madon [10]. The fault and compressional anticlinal systems provided the hydrocarbon trap system, with fault planes functioning as hydrocarbon migration paths.

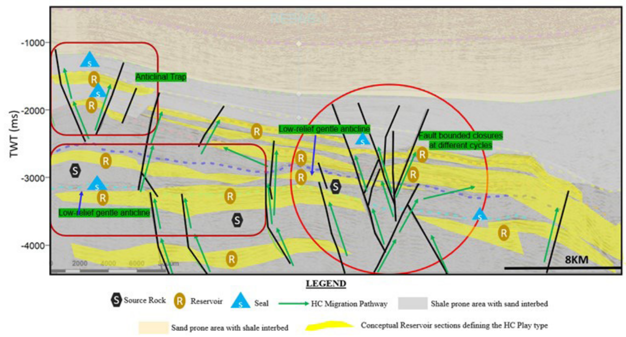


Figure 13 The various types of Hydrocarbons Plays in the Rebab-1

DISCUSSIONS

Using two 2D seismic lines, well logs, and bulk geochemical data, we evaluated the Rebab-1 well potential for hydrocarbon play as well as the quality and maturity of the source rock. Two forms of hydrocarbon occurrences were mapped within the II-VIII cycles (Figure 13). The integrated hydrocarbon plays evaluation was achieved by integrating source rock evaluations and seismic data interpretations. Interpretation of the seismic data and overlay of the gamma-ray logs indicate that clastic sediments dominate the upper section of the Rebab-1 well and that carbonates with alternation of shale predominate at depth in the well (Table 5).

Source Rock Evaluation

In several works carried out in Central Luconia, the source rocks were not evaluated, but only assumptions were

made about their quality and degree of maturity [3],[14]. The findings of this study suggest that carbonate deposits and a lack of organic matter input in the early Miocene contribute to a low organic matter content in the source rocks of Cycle III. The targeted cycle II with high TOC, HI, and GP indicates that the source rock is very good and derived mainly from plankton, spores, pollen, leaf and stem cuticles of terrestrial plants, and some contributions from algae, indicating that oil and gas will be produced at optimal temperature and high temperature, respectively. Due to the shallow burial of sediments and uplift during the closing of the South China Sea (SCS), source rocks younger than the IV cycle are immature [3],[5]. Therefore, the source rock of Cycle II is very good and mature, indicating that gas has been generated. This study is limited to the Rebab-1 well, but geochemical analyses of additional wells can be performed to evaluate the quality and maturity of the source rocks in Central Luconia. Furthermore, vitrinite reflectance and Tmax may be considered adequate, but conventional methods of evaluating the thermal maturity of the source rock. However, there is a lack of sufficient vitrinite material, and sometimes interference from lipids can occur, as well as some other uncertainties that are not accounted for in these methods.
Therefore, a more robust Surface-enhanced Raman spectroscopy (SERS) method can be used to improve the fundamental structural changes of the kerogen and the aromatic saturation shift during the thermal maturation process.

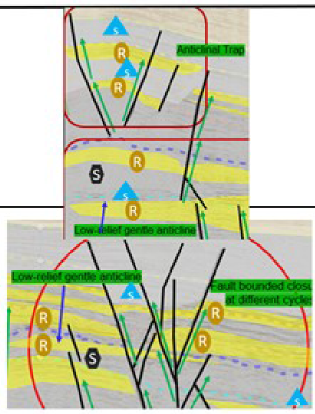
Hydrocarbon Plays

The faulting and folding in the studied area suggest that rifting and compressional deformation episodes affected Rebab-1 [7]-[8]. We found that cycles I–V were mainly influenced by rifting events during the opening of the SCS, with little influence from compressions. The younger cycles, VI–VII, were influenced by simultaneous rifting and compression tectonics, giving rise to fold-thrust faults. Since Cycle I/ II has not yet been sufficiently explored [3]-[4], we have limited ourselves to investigating the hydrocarbon deposits of Cycle II. The faults provided an excellent migration path for the hydrocarbon. Alternating limestone and shale lithologies and graben-titled fault blocks are excellent trap systems for the II cycle and older cycles, while shale lithologies in the mid-cycle seal them. The source rock presented in Cycle II is organically rich, matured, and generates hydrocarbon, while the carbonate lithology provided a good reservoir for the generated hydrocarbon.

Overall, the Cycle II petroleum system is effective, and hydrocarbons have accumulated in the trench fracture system.

Table 5 Integrated assessment for deeper section hydrocarbon plays

Cycle and Age	Depth (m)	Lithology	GR (gAPI) -10 130	Bio-stratigraphic Zonation	Source Rock Evaluation (a) Richness (b) Quality (c) HGP (d) Maturity	Hydrocarbon Trap based on Seismic Interpretations (Referring to Fig. 12)
Cycle VIII Early Pliocene - Recent	800, 1000			NN21- NN12	(a) Poor (b) Type III (c) Poor (d) Immature	
Cycle VII Late Miocene - Early Pliocene	1200, 1400, 1600, 1800, 2000, 2200			NN15 - NN10 (Lower Part) and N14 -Younger	(a) Poor to good (b) Type III (c) Poor (d) Immature	
Cycle VI Middle - Late Miocene	2400, 2600, 2800			NN10 - NN8; N14 - N9 and Upper Tf (Tf3)	(a) Fair to good (b) Type III & mixed II/III (c) Poor to Fair (d) Immature	
Cycle V Middle Miocene	3000, 3200, 3400			NN8 - NN6; N9 - N8N9 and Upper Tf (Tf3) - Lower Tf (Tf1-2)	(a) Fair to good (b) Type III with occasional type II (c) Poor to Fair (d) Immature	
Cycle IV Early - Middle Miocene	3600, 3800			NN6 - NN4; N8 and Lower Tf (Tf1-2)	(a) Fair (b) Type III-IV (c) Poor (d) Early mature	
Cycle III Early Miocene	4000, 4200			NN4; N8 & Older and Lower Tf - Upper Te (Te 5)	(a) Poor (b) Not Determined (c) Poor (d) Not Determined	
Cycle II Early Miocene & Older	4400, 4600, 4800, 5000			N8 & Older and Upper Te (Te 5) and Older	(a) Generally Poor to very good (b) Majority unknown with Type II at 4560 m (c) Poor to Very Good (d) Mature	



LEGEND
Sandstone/Limestone; Shaly Sandstone; Limestone; Shaly Limestone; Very Dark Shaly Limestone
Sandstone; Limestone/Shale; Shale/Sandstone; Shale; HGP Hydrocarbon Generating Potential

CONCLUSIONS

Interpretation of two seismic lines showed that the area of Rebab-1 has been influenced by extensional and compressional tectonics having structures predominantly trending to NE-SE and NE-SW direction. These are possible traps for hydrocarbon accumulations in Cycle II and III at 3980 to 4991 m depth. Four seismic stratigraphic mega-sequences were identified, comprising eight sedimentation cycles of varying characteristics. Cycle II-V predominantly comprises carbonate lithology, while the upper cycles are more siliciclastic sediments derived from the Rajang Thrust Belt and the Baram Delta (Borneo inland).

The sediments' organic matter (TOC) values indicate poor to very good organic matter richness. Type III and the mixture of type II-II kerogen is determined to dominate the rocks in Rebab-1. This indicates that source materials mainly have higher plants, planktons, spores, and little contribution from algae deposited in the terrestrial geological environment, which is capable of generating mainly gas and a mixture of oil and gas. The values of hydrocarbon generated during pyrolysis (S2) and generating potentials (GP) indicate that only a few sections of the intervals studied have good potential for hydrocarbon generation, with the majority falling in the range of poor to fair generating potentials.

The values of vitrinite reflectance and other thermal maturity parameters recorded indicated that potential source rocks in the area can be categorised as immature, mature, and post-mature for oil generation but still within the gas generation window. Considering all the above, it can be concluded that hydrocarbon has been generated (at 3460 m depth during the Middle Miocene), which caused blanking of acoustic impedance of some lithologies as observed in the seismic data. However, the volume generated may not be significant enough for commercial purposes considering the thickness of the potential source rock that is considered good and matured. Cycle II can be said to contain accumulated hydrocarbons. Further investigation is required for the deeper part of the sediments (Cycle I and II), as the data available for these sections is very limited. An appraisal well for Rebab-1 may be sufficient in confirming the potential of deep reservoirs within Cycle I and II sediments in this field.

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