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STRUCTURAL MODEL & SEDIMENTOLOGY ANALYSIS OF THE EX CARBONATE FIELD, CENTRAL LUCONIA PROVINCE, SARAWAK

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ABSTRACT

Central Luconia Province displays various structures in different parts of the basin attributed to extensional, strike-slip, and wrench tectonics. This affected the growth of the EX carbonate platform, the heterogeneity of carbonate facies, and lithological properties variations in the EX field. Such complexities restrict the understanding of the structures and sediments and may lead to well placement problems during a development stage. This research aims to study the carbonate growth of the EX field in accordance with the structural deformation and to analyse the field's sedimentology. Detailed research of the structures in the EX carbonate platform was done using seismic interpretation to determine the nature of the relationship between faults and carbonate formation. Concurrently, a comprehensive sedimentary analysis was conducted using core and thin section studies to interpret facies characterization and depositional environment. The spectral decomposition attribute was used to study the seismic response of the lithologies in this field by demonstrating the anomalies of the carbonate platform using frequencies ranging from 328 Hz to 356 Hz. This research contributed to the interpretation of individual faults and the generation of a conceptual growth and structural model based on a seismic, attribute, and structural interpretation. The anomalies were used to identify the EX carbonate body and features such as the rim of the build-up through the spectral decomposition attribute. The sedimentary analysis from the EX-4 well also improved facies distribution and depositional environment, ranging from a deeper lagoon to a reef environment. This research can be used as an input for further correlation studies of the Central Luconia basin at a regional scale.

Keywords: *carbonate platforms, tectonics, spectral decomposition, carbonate core*

INTRODUCTION

Location of Central Luconia

The Central Luconia province is an area that is characterized by Oligocene to Early Miocene shallow-marine clastic rocks with isolated carbonate build-ups. In contrast, the development of more carbonate build-ups was observed in the Middle to Late Miocene. About 200 carbonate structures were reportedly mapped on seismic by Sarawak Shell Berhad [1]. It is a geological province located in the Sarawak Basin. Baram Delta bounds it on the Eastern part as shown in Figure 1 and Rajang Delta on the Western part. This province is known to have a sizeable nutrient-rich water supply due to the opening of the South China Sea basin toward the southwest of the Sarawak shelf, which facilitated the formation of numerous carbonate platforms during the Middle to Late Miocene [2],[3]. This study is focusing on the EX field located in the southern part of Central Luconia. During the Early Middle Miocene, the rising sea level led to the influx of siliciclastic sediment, which resulted in the interfingering of the sediment with the EX carbonate banks [4]. Deteriorating growth conditions and prograding clastic caused an areal decrease of the platforms, which were finally burial by the coeval clastic sediment at the end of the Middle Miocene [5]. This comprehensive study contributes to the carbonate research of the EX field as not much has

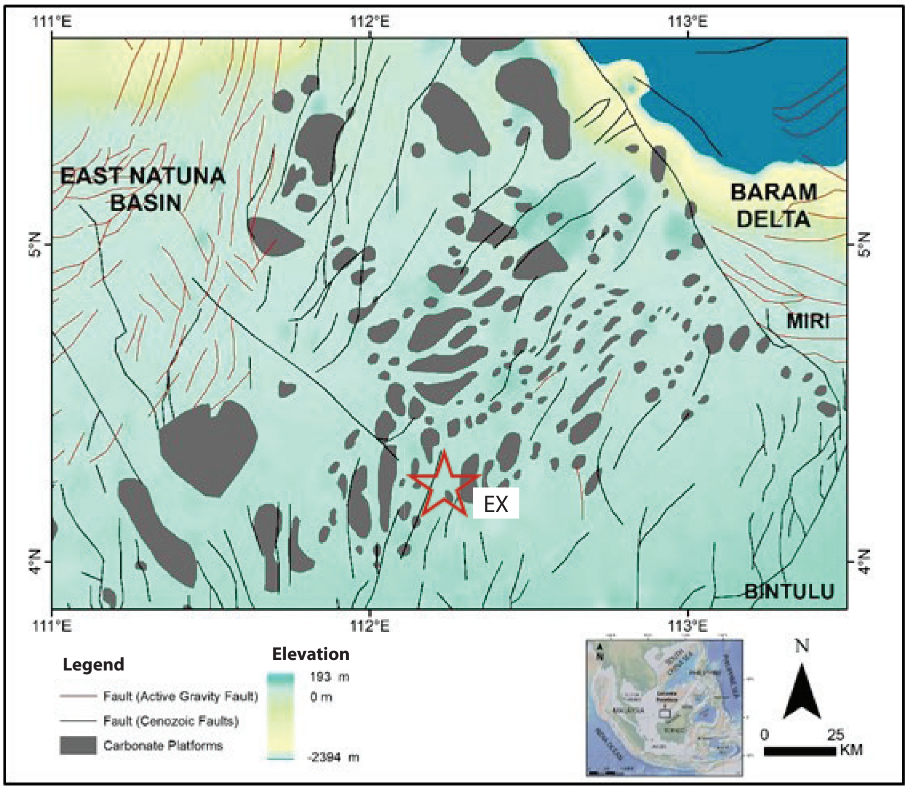

Figure 1 Location of the EX Field in Central Luconia Province modified after Ab Rahman et al. [6]

been published and much of the research is proprietary. The EX field also acts as an analog for the southern part of Central Luconia.

Furthermore, the study of the tectonic processes, geo-bodies, and sedimentology of this field may be correlated with the surrounding fields. This study contributes to the sedimentology, depositional environment, and structural interpretation of the EX field. It can be used as an input for further correlation studies at a regional scale.

Geological Settings of Central Luconia

Tectonic settings of Central Luconia Province have been associated with the formation of the Sarawak Basin. It has undergone Eocene extensional tectonics and subsidence in the north and compressional tectonics in the south. However, reefs started to develop in favorable areas such as the inner neritic environment in the Late Early Miocene as the tectonic events were slowing [7]. Carbonate deposition ceased due to prograding clastic materials from the nearby Baram deltas that increased the sediment load and the occurrence of significant sea-level falls [8]. From the Late Miocene until the present, clastic input continues to accumulate into the Central Luconia Platform, promoting gravitational tectonics within this province [7],[9]. According to Franke et al. [10], carbonate deposition was delayed in the Luconia Block due to the colliding and subsiding of the block beneath Borneo during the Late Oligocene. Zampetti et al. [11] stated that carbonate deposition in Central Luconia took place in the Late Early Miocene but more prolific in the Middle to Late Miocene. Regional cross-sections based on seismic exploration show that in the Early Miocene, faulting and folding were widespread and that deformation activity decreased during Late Miocene and Pliocene [8],[12].

Overview of the EX Field

The EX field is located in the southern part of Central Luconia. It comprises two carbonate build-ups of the Middle Miocene age, a southern steep-sided pinnacle type and a northern lower relief platform type separated by a saddle area [13]. The carbonate platforms are mainly from Cycle IV and V of Sarawak Basin. The carbonate growth is controlled by the change in sea level [3]. After the sea-level fall, a reflooding during the Early Middle Miocene re-established the smaller platform of the EX field. The sea-level rise then leads to the influx of siliciclastic sediment and forms the EX carbonate banks interfering with siliciclastic sediment known as stringers. Stringers are formed from an influx of carbonate sediment from a steep flank or the edge of a build-up into the surrounding shales, and they have limited thickness with poor reservoir quality. The drowning of platforms in the EX field was caused by poor growing conditions and clastic sediment at the end of the Middle Miocene [5].

METHODOLOGY

For the structural interpretation of the EX field, the methods used in this study include fault and seismic interpretation supported by seismic attribute and rose diagram analysis. Core description and thin sections were used for sedimentary analysis.

Core and Petrography Interpretation

The sedimentological interpretation using core and thin sections for the EX field was taken from the EX-4 well. The 269 m depth of core data with 20 cores were analysed to generate a detailed core description. The components that were examined during core analysis include lithology, grain size, texture, bioturbation, stylolite, porosity, diagenesis, and fossil content (Figure 2). The texture was classified based on Dunham [14], while the pore type was classified using Choquette and Pray [15]. The first step of the core description started with boundary identification based on the apparent changes in lithology, color, and grain size. A more detailed core description was carried out within each boundary with intervals ranging between 5 cm to 2 m. The core description was then compiled and digitised using WellCAD^{TM} Software for complete digital core analysis. Apart from that, 36 thin sections were analysed to identify the facies present (Figure 3) and the potential depositional environment by analysing the percentage of the distribution of pore type (Figure 4), lithology, texture, component, and matrix.

Seismic interpretation

Two horizons (Figure 5) which are the top of carbonate (TOC) and the base of carbonate (BOC), were picked for the interpretation of the carbonate build-up in the EX field using PaleoScan^{TM} software. The horizons were interpreted at every five inline in the time domain based on the amplitude and discontinuities of the reflections to produce a horizon map of the TOC (Figure 6). The EX-2 well data was used for the seismic-to-well tie process.

Fault Interpretation

Faults were picked and extracted from a seismic volume using PaleoScan^{TM} software (Figure 7). The interpretation was improved by viewing and editing the faults in the interpretation window. Faults were picked in the inline direction as well as other directions such as crossline and time slice. Some faults were merged and split using the merging/splitting tools available from the fault toolbar to improve the accuracy in interpreting subtle discontinuities observed on seismic data.

Seismic Attribute Analysis

Seismic attributes were applied to the interpretation window to boost and elevate the visibility of interesting features using PaleoScan^{TM} software. A 3D model grid was generated to produce a horizon stack between the TOC and the BOC. Few attributes were tested on the horizon stack, but only the spectral decomposition attribute was discussed as it showed the best representation of geological trends and anomalies (Figure 8).

Rose Diagram Analysis

The fault lineaments from the fault interpretation were classified into three chronological stages following the zonation schemes of the EX platform (Figure 9). They were represented in rose diagrams to visualize the significant trends in each period (Figure 10). The structural analysis of the study area was demonstrated by correlating each fault classification with major tectonic events in the region with respect to the fault and seismic interpretation.

RESULTS AND DISCUSSION

Sedimentary Interpretation

Based on the core description of the EX-4 well, three reservoir layers and two tight layers were identified (Figure 2). The reservoir layer is a layer that has high porosity and permeability to store and transmit fluids. The tight layers in the EX-4 well are characterized by a layer with a matrix permeability value of fewer than 0.1 millidarcys (mD) and a matrix porosity value of less than 10%, indicating a low reservoir quality. These tight layers result from the sea-level rise that deposited

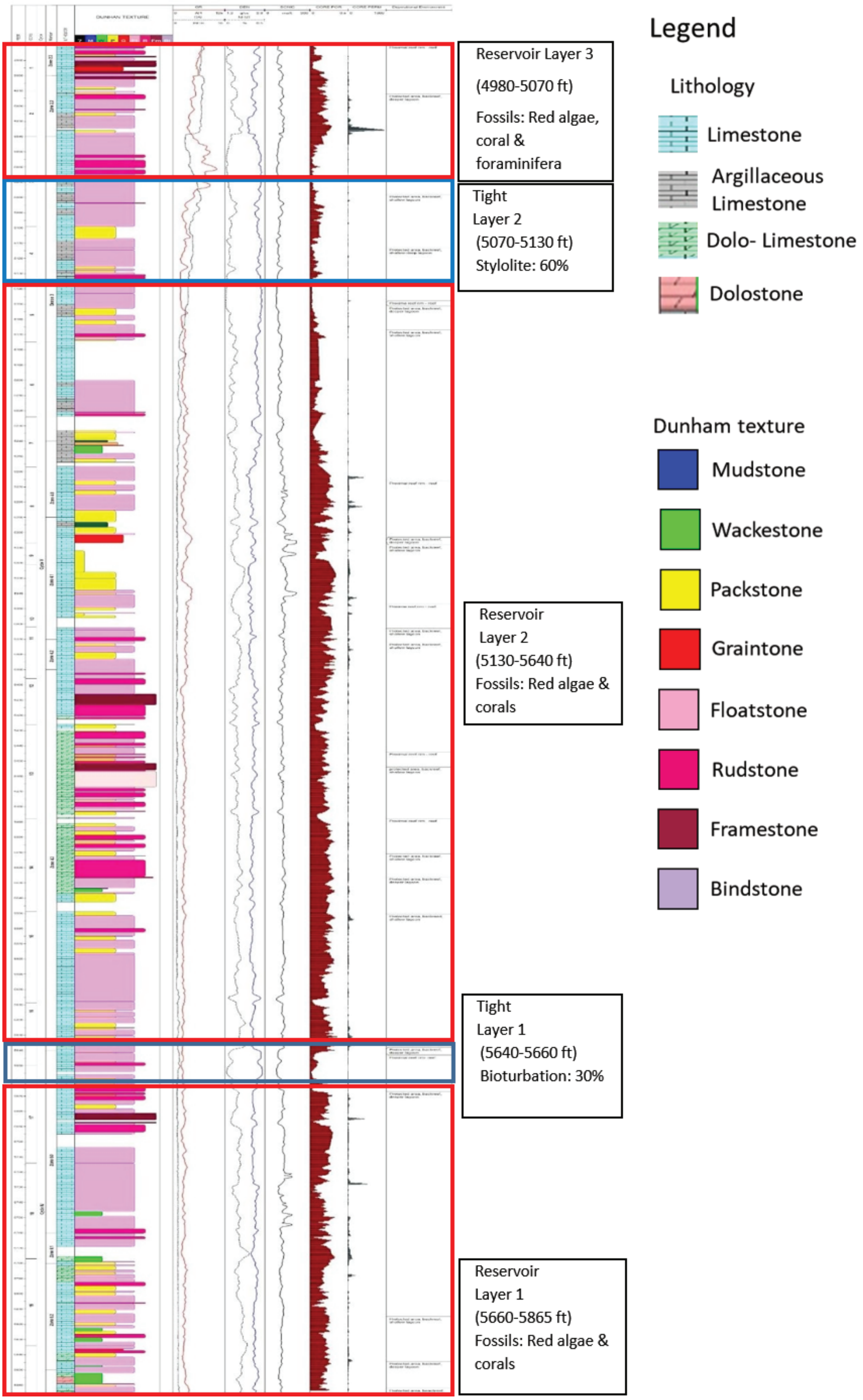

Figure 2 Core description of the EX-4 well, two tight layers, and three reservoir layers was identified

fine-grained sediments reducing the porosity and permeability [3]. The core and thin section analysis in terms of porosity range, fossil distribution, stylolite, and texture were used to classify the well data into five layers. The tight layers were classified as lower than 15% visual porosity value based on core interpretation validated by porosity log, presence of stylolite and texture related to a low energy environment (Figure 2).

Tight layer 1

Tight layer 1 is 20 ft in thickness. The lithology of tight layer 1 is limestone with a floatstone texture. The main fossil content is red algae. Based on the core description (Figure 2), there is evidence of bioturbation of 30% in this layer, indicating a low energy environment that deposits fine-grained sediments, creating a low porosity layer with less than 15% as per the reference from the porosity log. Based on Pomar [16], the interpreted depositional environment is from a deeper lagoon to a reef.

Tight layer 2

Tight layer 2 is 60 ft in thickness with a missing gap of 30 ft. The lithology of tight layer 2 is interbedded limestone with argillaceous limestone. Argillaceous limestone is characterized by a significant amount of clay present in the limestone, which explains the tight behavior of the layer. The texture is mainly floatstone with red algae as the main fossil content. High-frequency stylolite of 60% reflects the presence of fine-grained sediments that contributes to the porosity value of less than 15%, interpreted from the core description and porosity log (Figure 2). This layer was interpreted as a back reef, lagoon area rich in fine-grained sediment [16].

Reservoir layer 1

Reservoir layer 1 is 205 ft. The lithology in this layer is limestone with slight dolo-limestone and dolostone. The low gamma-ray value ranging between 20 to 30 API indicates that this layer has low clay content contributing to higher porosity (Figure 2). The texture ranges from packstone to framestone, and the minor presence of wackestone indicating an overall good porosity layer. The fossil content is mainly red algae and coral with average visual porosity of more than 25% with reference to the core description (Figure 2). The interpreted depositional environment for this layer ranges from a lagoon that consists of wackestone to a reef environment consisting of float-rudstone as given in Table 1.

Reservoir layer 2

Reservoir layer 2 is approximately 510 ft. The lithologies are mainly limestone and dolo-limestone with slight argillaceous limestone near the tight layer 2. Based on the core description (Figure 2), the texture in this layer is mainly packstone to floatstone with rudstone at the lower layer and slight wackestone near tight layer 2. Red algae and coral (Figure 2) are the main fossil content in this area, with observed visual porosity of more than 25% indicating a good porosity layer. This layer is interpreted to be located at a back reef to a reef environment where the energy level is medium to high (Table 1).

Reservoir layer 3

Reservoir layer 3 is about 90 ft. The lithology is mainly limestone with fine argillaceous limestone. Referring to Figure 2, the texture analysed from the core description in this area ranges from packstone to floatstone with some framestone on the top part of the layer, indicating a high porosity layer. The main fossil contents are red algae, coral, and foraminifera (Figure 2). The depositional environment for this layer is interpreted to be in a lagoon to a reef area [16].

Facies Identification

The petrographic analysis was carried out using 36 thin sections available from the EX-4. The analysis from thin sections is essential to give the interpretation on a microscopic scale, supporting the evaluation of the properties in macroscopic interpretation. The facies identified in the EX-4 well were classified into five microfacies. These microfacies are coral rud-framestone, algal wacke-floatstone, algal-foraminiferal float-rudstone, coral-algal rudstone, and skeletal pack-floatstone (Figure 3). The depositional environment of the five microfacies is ranging from the lagoon to the fore reef area. The primary porosity that was interpreted, based on visual porosity analysis for thin section (Figure 4) and core analysis with the reference from porosity logs in this well, is mouldic porosity about 25%, followed by vuggy by 15% and microporosity about 14%. All these microfacies are summarized in Table 1.

Table 1 Summary of the five microfacies interpreted in the EX-4 well

Microfacies	Component	Texture	Pore Type	Environment
MF-1 Coral rud-framestone	Coral, red algae, foraminifera	Rudstone to framestone	Vug, mouldic, intraparticle, microporosity	Proximal reef rim to reef
MF-2 Algal wacke-floatstone	Red algae, coral, and echinoid	Wackestone to floatstone	Vig, mouldic, intercrystalline	Protected area, back reef, deeper lagoonal environment
MF-3 Algal-foraminiferal float-rudstone	Red algae, foraminifera, echinoid, bivalve	Floatstone to rudstone	Vug, mouldic, intercrystalline	Protected area, back reef, shallow lagoon
MF-4 Coral-algal rudstone	Coral, red algae, foraminifera	Rudstone	Microporosity, mouldic, vug, interparticle	Proximal reef rim to reef
MF-5 Skeletal pack-floatstone	Coral, red algae, foraminifera, bivalve, skeletal debris	Packstone to floatstone	Interparticle, fracture, vug, mouldic	Protected area, back reef, shallow to a deep lagoon

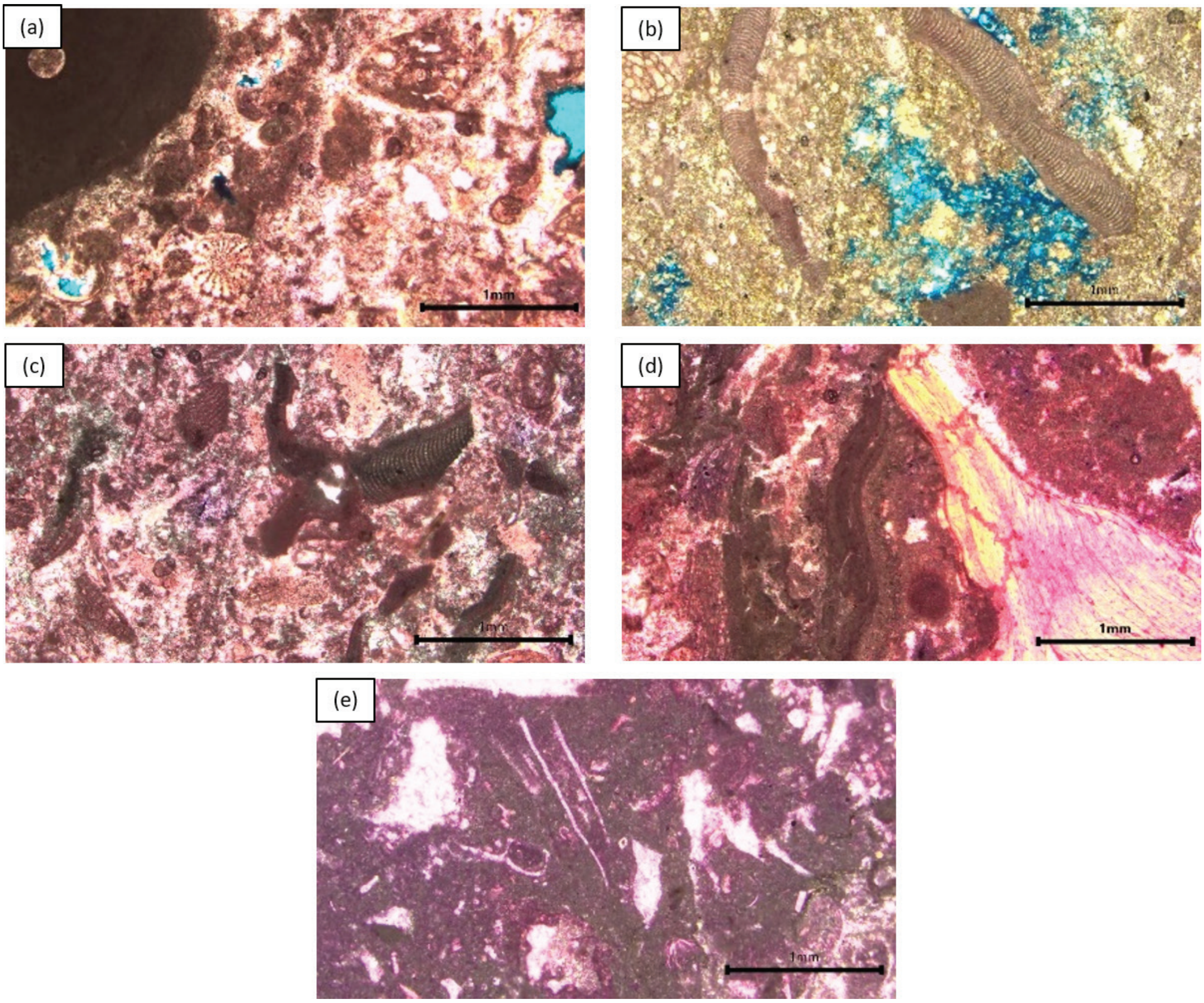

Figure 3 Five microfacies (MF) distinguished in the EX-4 well. (a) MF-1 coral rud-framestone, (b) MF-2 algal wacke-floatstone, (c) MF-3 algal-foraminiferal float-rudstone, (d) MF-4 coral-algal rudstone, (e) MF-5 skeletal pack-floatstone

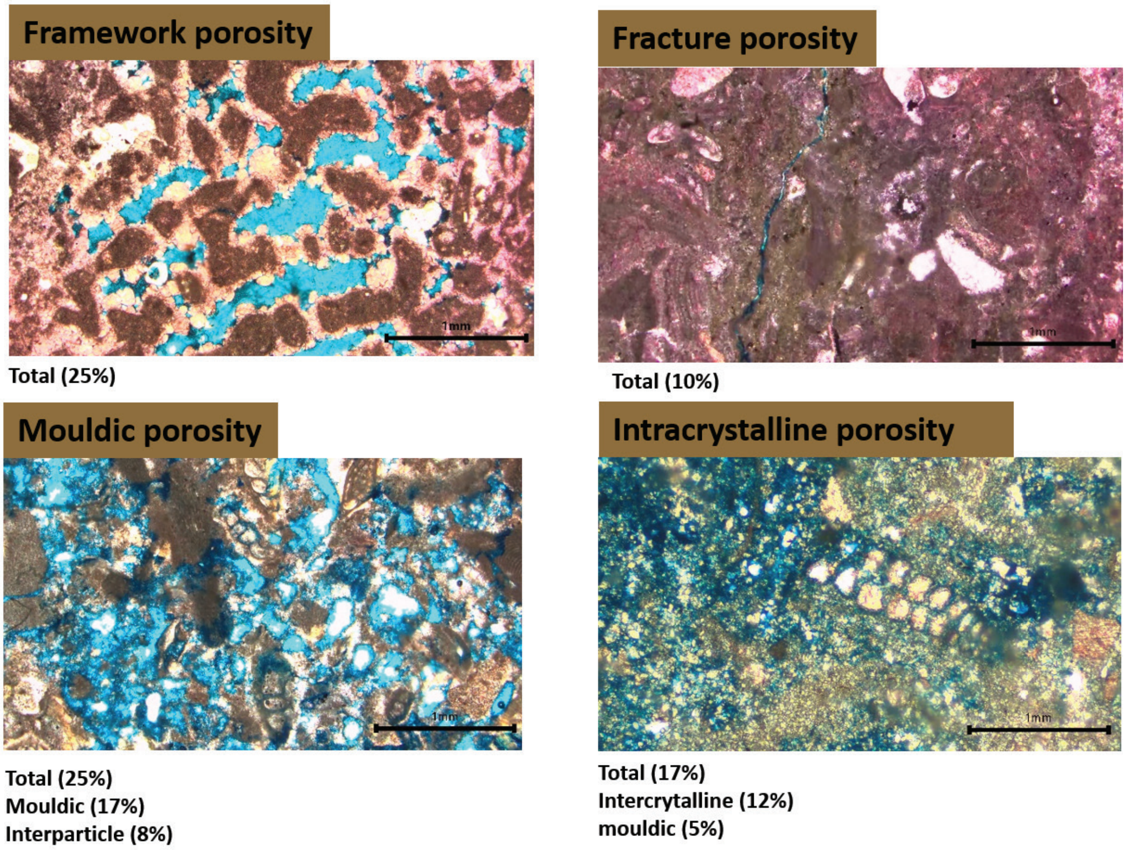

Figure 4 Quantitative analysis of porosity distribution in the EX-4 well

Seismic Interpretation

EX carbonate platform is related to a lateral carbonate progradation and as a saddle area between two build-ups. The location of the windward margin has been observed through the seismic attribute map on the top of the carbonate map (Figure 6).

Three stratigraphic seismic units were labeled as A, B, and C (Figure 5) based on reflection configurations, continuity, and amplitude. The reflection configurations were identified to observe the depositional surface present within the layer. Unit A has a subparallel to mounded and a slight chaotic reflection configuration, while Unit B has a mounded to chaotic reflection configuration. Unit C represents parallel configurations that are mainly present in the overlying clastic sediment. While Unit C has continuous reflections, Unit A and B have semi-continuous to discontinuous reflections. Furthermore, the high amplitude is visible at the top of Unit B near the TOC. Unit A is interpreted to be mainly Cycle IV, while Unit B is interpreted to be Cycle V.

Fault Interpretation

Twenty-four faults were interpreted from the seismic section for the structural interpretation. The dip angle of most faults ranged from 23˚ to 39˚ with dip direction ranging from 53˚ to 97˚ and 211˚ to 280˚. The southwest area of the EX carbonate build-up is highly faulted (Figure 7).

Generally, the faults in the EX field have a general NNW-SSE trend; however, they are classified into three chronological stages (Figure 10), which will be discussed in the structural interpretation section. The faults are mainly interpreted as extensional or normal faults, and the platform itself is observed to have grown on the elevated blocks, thus producing an asymmetrical platform.

Seismic Attribute Analysis

The application of seismic attributes highlights the carbonate geomorphology, which is distinguishable due to the seismic characteristics of density, velocity, amplitude, frequency, and continuity that vary from surrounding clastic sediments.

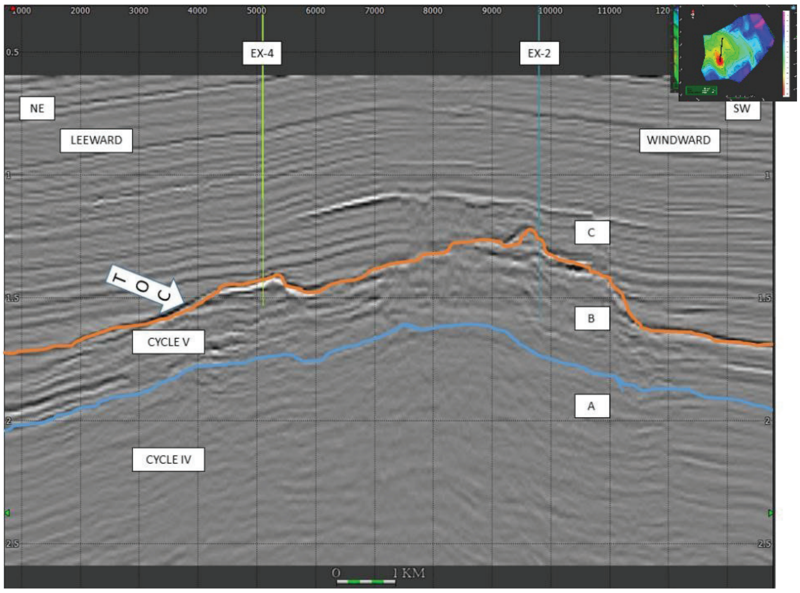

Figure 5 Horizon and seismic unit interpretation of the EX carbonate platform

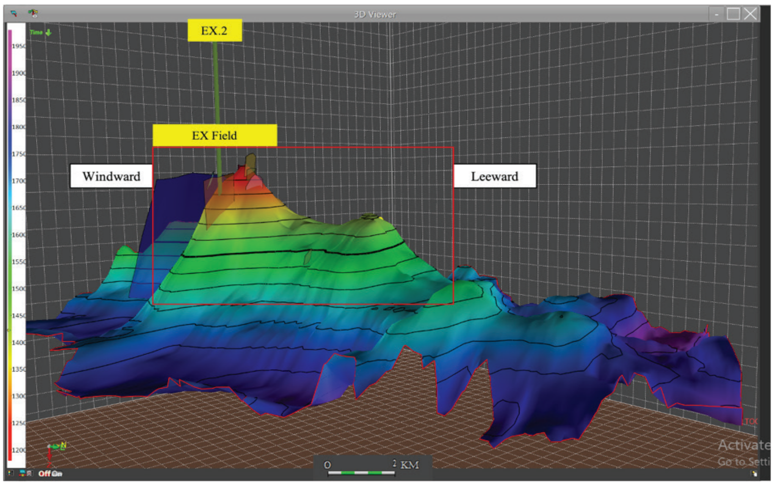

Figure 6 3D view of the TOC horizon

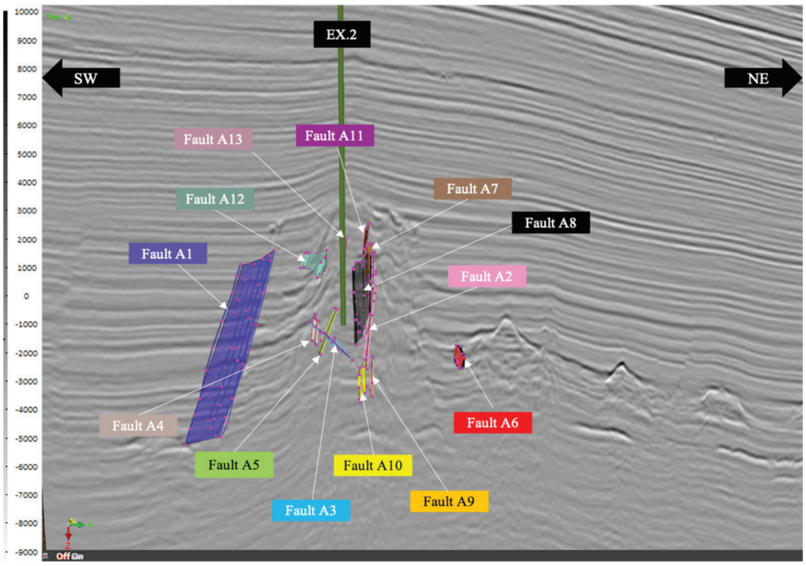

Figure 7 Fault interpretation of the EX carbonate platform

Unique carbonate characteristics are distinguishable using seismic attributes, but gas and diagenesis processes have affected the amplitude strength in some areas. Attenuation of amplitude can be observed on the southern part of the carbonate platform due to the effects of diagenesis. Spectral decomposition has been applied to the carbonate body to observe anomalies. The technique was applied to highlight the stratigraphic features [17]. Figure 8 shows a strong amplitude anomaly with a frequency range of 328 Hz to 356 Hz, which best represents the carbonate build-up from its base to its top. The brighter-colored area, which represents the carbonate body, is an anomaly compared to the dull-colored surrounding. The anomaly reflects sediments with low density and high porosity that characterizes carbonate sediments. Moreover, the whitish ring-like anomaly depicts the rim of the carbonate build-up. Spectral decomposition also enhances the fault features as the thin lines that can be easily detected on the map.

From this seismic attribute analysis, spectral decomposition enhanced the seismic image of the EX field, facilitating the interpretation of carbonate build-ups. The anomalies associated with the carbonate platform were best shown with the high frequencies. The horizontal profile illustrates the spatial arrangement of carbonate distribution that aids in delineating the formation difference.

Structural Interpretation

In this analysis, the faults are classified into three chronological stages: pre-depositional faults, syn-depositional faults, and post-depositional faults based on seismic units (Figure 5) and the respective zones of the platform (Figure 9). The zonation scheme is in accordance with the core description of the EX-4 well (Figure 2). The three reservoir layers and the two tight layers from the sedimentary interpretation (Figure 2) are part of the three zones and the two dense layers, respectively (Figure 9).

Rose diagrams were created based on these classifications (pre, syn, and post) to represent the fault trends during their respective period. Analysing the faults is significant as the faulting within the carbonate platform could influence the growth of carbonates attributed to the platform edges that coincide with the fault systems [7].

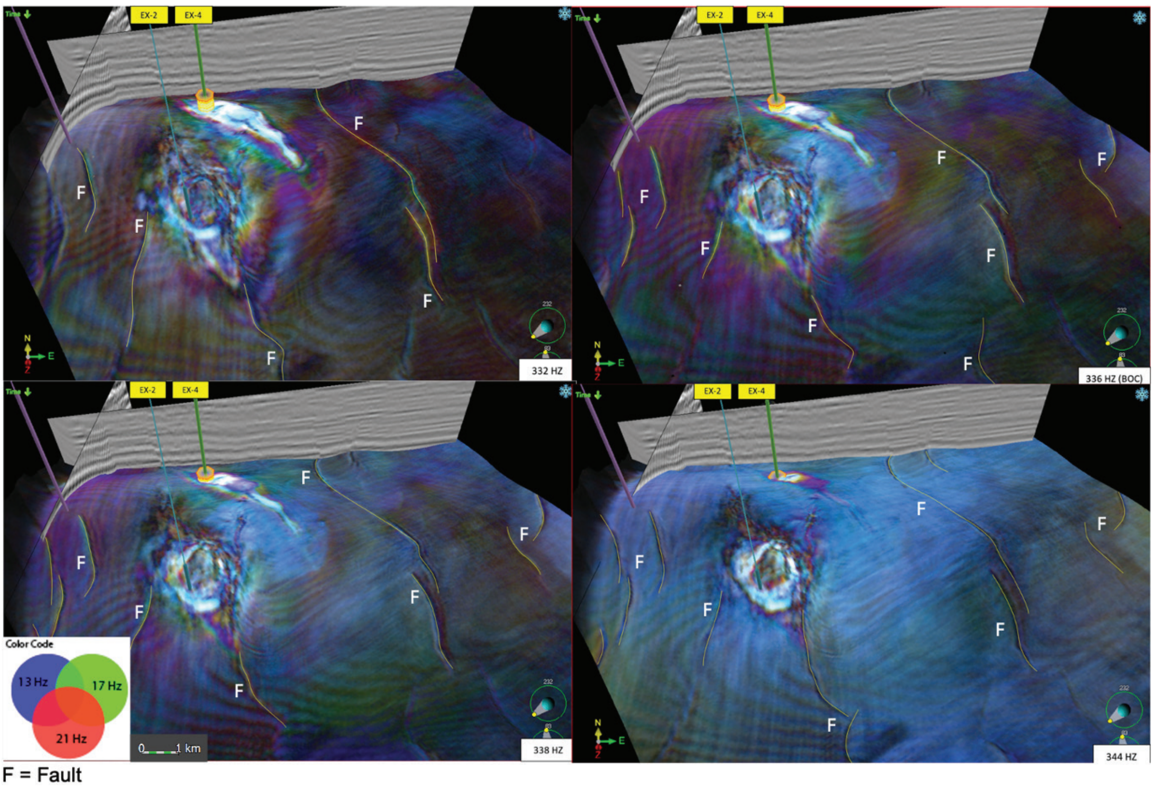

Figure 8 The growth of carbonate build-up from base to top illustrated with a range of 332-344 Hz

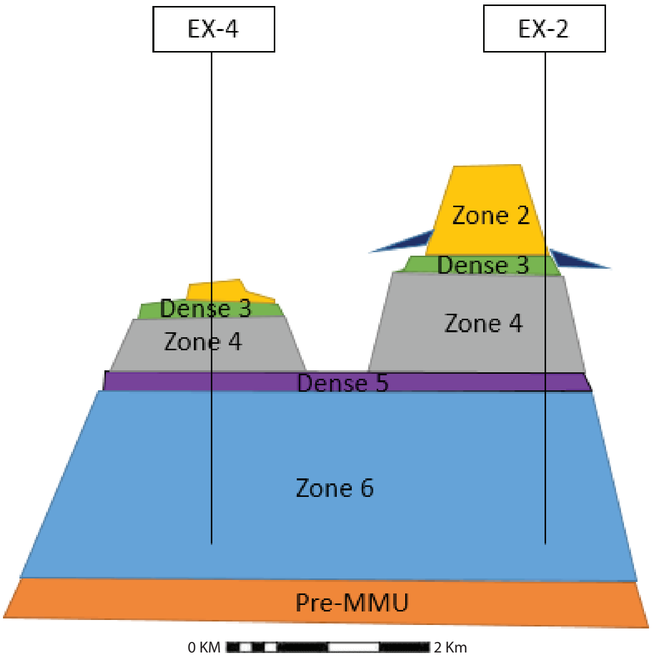

Figure 9 Schematic diagram showing the zonation schemes in the EX platform, modified after an unpublished report

Since the initiation of carbonate growth occurred before the Mid-Miocene Unconformity or pre-MMU (Figure 9), it is proven to be a transition from Cycle III to Cycle IV [18]. Two faults were interpreted and represented in the rose diagram that shows the NNE-SSW trending fault system (Figure 10a). These interpreted normal faults could have occurred due to gravitational tectonics [9] and subsidence resulting from the movement of the older Baram fault zone [7] or due to the extensional deformation of the Sarawak margin during the Early Miocene indicating the end of Cycle III, causing displacements attributed to the final rifting of the South China Sea [10].

One of the pre-depositional faults that occurred pre-MMU is interpreted to have reactivated, creating a displacement between the southern and northern platform that developed into a saddle. The reactivation of the fault is potentially due to the gravitational loading during the gravity tectonic events throughout Late Miocene to Pliocene when more sediments were transported to the sea from the land [8] that induced

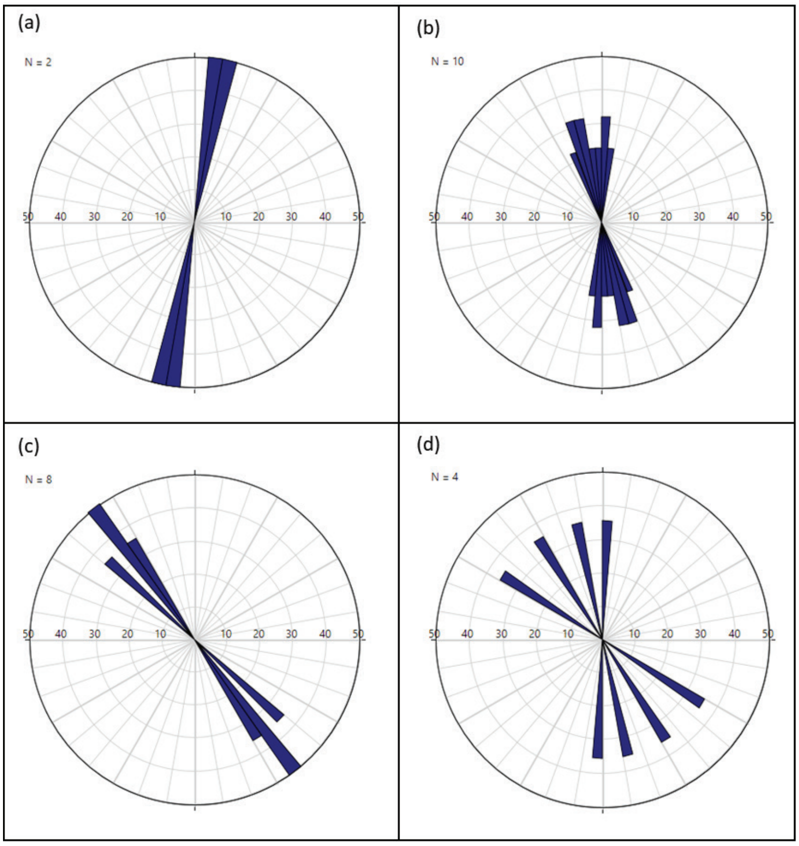

Figure 10 Rose diagrams of the interpreted faults from the seismic section. (a) Pre-depositional NNE-SSW faults, (b) Syn-depositional N-S to NNW-SSE faults, (c) Syn-depositional NW-SE faults, (d) Post-depositional WNW-ESE to NW-SE to NNW to SSE to N-S faults

compaction on the EX platform and the sediments beneath it.

The syn-depositional faults occurring from Cycle IV to Cycle V (zone 6 to zone 4) (Figure 9) showed two trends ranging from N-S to NNW-SSE (Figure 10b) and NW-SE faulting (Figure 10c). Deposition of Cycle IV and younger sequences ended with periods of compressional wrench deformation. Hence by the start of Cycle V occurrence, fault blocks were uplifted where higher relief reefs were growing on these features. Small scale normal faults have been observed throughout the seismic section crossline of the EX platform, especially on the southern pinnacle, with the interpreted age of Middle to Late Miocene (Figure 7). Since the southern pinnacle is broader than the northern pinnacle, the syn-depositional faults could have provided templates for the reefs to find suitable bases for them to grow during the Miocene age.

The post-depositional faults occurring after zone 2 of Cycle V showed a more comprehensive series of trends, ranging from WNW-ESE to NW-SE to NNW to SSE to N-S (Figure 10d). Most of the faults that affect the carbonate platform are collapsed structures on the edges that could be seen on the southern pinnacle (Figure 7).

Commonly, fault lineaments are analysed to understand the regional stress direction by interpreting rose diagrams, in which dominant sets (higher occurrence) are used to identify the primary stress ($\sigma1$). Based on the rose diagrams (Figure 10), the interpreted primary stress ($\sigma1$) is in the NNE-SSW direction in the pre-depositional fault sets and the NW-SE direction syn-depositional fault sets. In post-depositional faults, it is difficult to determine the primary stress as the trend varies significantly without any dominant fault sets.

Conceptual growth and structural model for the EX platform

The EX field carbonate platform is divided into five zones: Zone 6, Dense 5, Zone 4, Dense 3, and Zone 2 (Figure 9). Zone 6 is expected to be during the deposition of Cycle IV in the Middle Miocene (Figure 9). Based on the results from the seismic interpretation, the platform grew on an irregular deposition template as the southern part of the platform is slightly elevated compared to the northern part of the platform. A fault is observed between the two pinnacles of the EX platform in zone 6 (Figure 11) that eventually settled into a saddle.

Dense 5 is a dense or tight layer due to either a flooding event or the platform's exposure. This layer acts as baffles or conduits. This layer is interpreted to be in the transgressive basal unit of Cycle V in the Late Miocene. The main carbonate build-up in Cycle V is seen in zone 4, where the carbonate grew as two isolated pinnacles (Figure 11). The deposition is accompanied by many syn-depositional faults that acted as a base for the reefs to grow (Figure 7). Dense 3 was deposited during the transgressive cap unit of Cycle V. The pinnacles continued to grow as isolated pinnacles in Zone 2 but were short-lived in the northern part but continued to prosper in the southern part of the platform till it drowned. Since there were more faults accumulated in the southern pinnacle, the relationship of reef growth and faults intercepting the build-ups is now proven, based on the evidence seen on seismic data (Figure 7). According to the interpreted stress directions from the rose diagram (Figure 10b, 10c), the deformation indicates an extension event might have taken place in the NW-SE direction.

By the end of Cycle V, at the end of the Late Miocene, clastic sediments filled the basin (Figure 11). The deposition environment of the northern part of the platform is interpreted mainly in the back reef to a lagoon environment based on the microfacies (Table. 1), core, and well logs (Figure 2) data. In contrast, the platform's peak in the southern part is inferred to have been deposited in a reef environment. According to the unpublished report, the stringers in the southern part of the platform are a mixture of reef and reef debris with clastic substrates. Hence a reef environment is proven, where the environment subsequently progrades into a fore-reef environment.

CONCLUSION

Central Luconia Province has undergone a series of extensive tectonism. However, there are insufficient analyses of the impact of tectonic events on the EX carbonate structures and limited published work

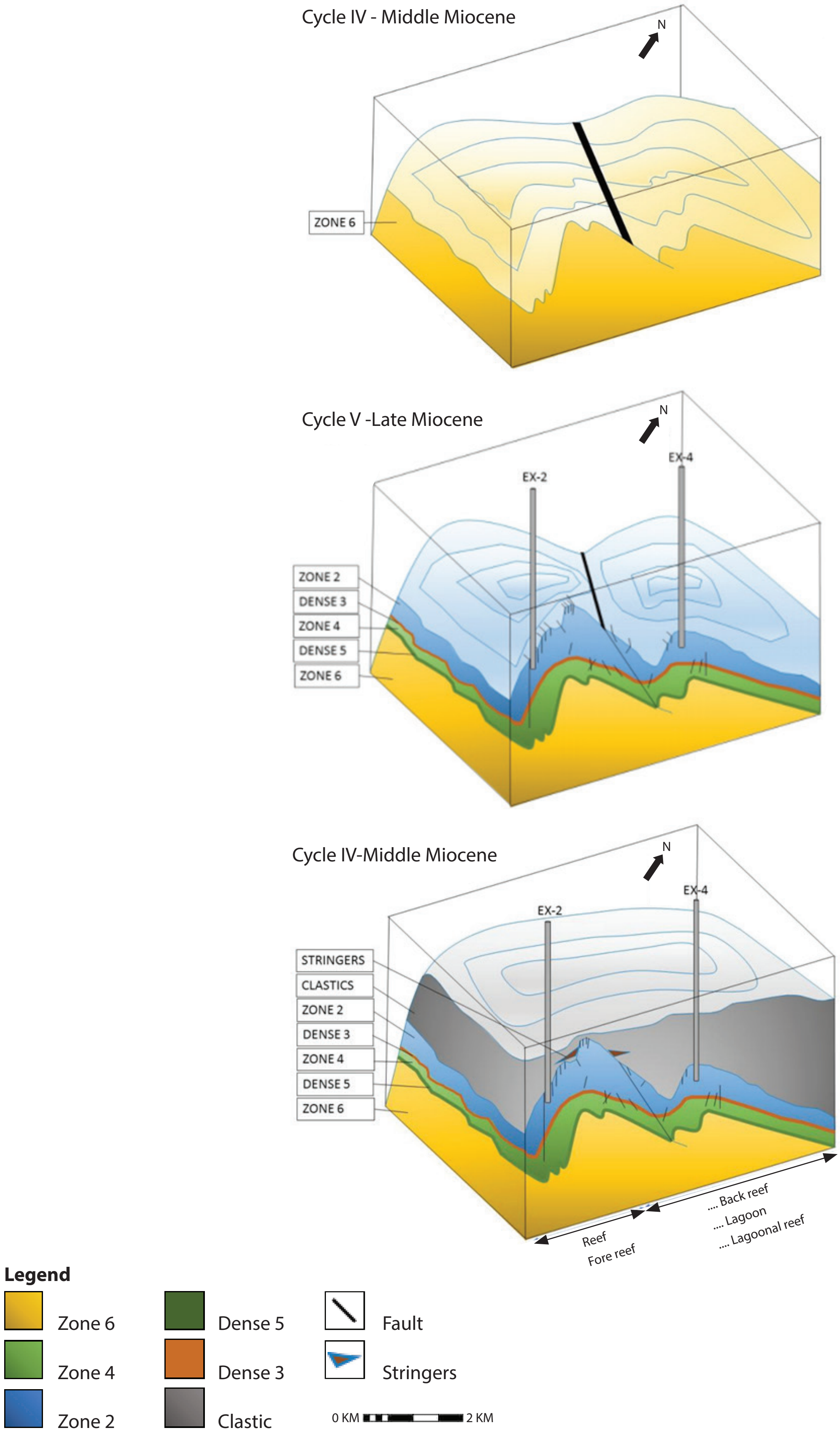

Figure 11 Growth and structural model of the EX platform by stages (Cycles IV-V)

on the sedimentology of the EX field. Based on the research results:

1. The structure in the EX field is interpreted as a carbonate build-up with two pinnacles. However, it is observed that the base of the carbonate platform is tilted towards the southwest due to the carbonate reefs that have grown on the uplifted blocks. The southern part of the EX carbonate build-up is highly faulted; hence, the faults could have been used as a base for the reefs to seek favorable conditions to grow. The primary stress ($\sigma1$) differs for each fault sets based on their chronological stages. However, the maximum stress is difficult to be determined in the post-depositional fault set due to the lack of high occurring faults in the same direction.
2. From the seismic attribute analysis, spectral decomposition with the frequency range of 328 Hz to 356 Hz has validated the EX carbonate build-up by highlighting the anomalies. The carbonate rim is delineated from the surrounding area of the map by the whitish ring-like features.
3. Through the sedimentary analysis, there are five microfacies identified from the EX-4 well, and each of the facies represents a different depositional environment depending on the texture and fossil content. The depositional environment for the northern platform is ranging from the lagoon to the fore reef area. The EX-4 well was also classified into five layers consisting of three reservoir layers and two tight layers based on core analysis represented in the zonation scheme of the growth and structural model of the EX field.

These structural and sedimentology interpretations can be used for correlation studies for other southern platforms in the Central Luconia Province.

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