Relationship between syn-depositional faulting and carbonate growth in Central Luconia Province, Malaysia

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Abstract: Using 3D seismic and well data, detailed seismic interpretation has been conducted on two carbonate Platforms EX and FY located in the Central Luconia Province, Malaysia. The results provide an insight to understand the relationship of faulting with syn-depositional carbonate growth. Five geo-seismic units were interpreted from the Late Oligocene to present day sedimentation in the basin. Structural interpretation of both platforms shows that almost all the faults in the deeper part of the platforms are normal listric faults that resulted from the final rifting stage of the South China Sea. Small-scale, steep normal faults within the carbonate units behave relatively as syn-depositional faults that became the base and template for the reefs to grow as these faults created conjugate and branching faults systems. Apart from becoming templates for the reefs to grow, these syn-depositional faulting events had also interrupted the growth of reefs especially those that were located at the platform margin. Slight movement of the branching faults induced sub-marine landslide to create reefs collapse. The establishment of relationship between faulting and carbonate growth in Central Luconia Province might be useful for revisiting mature hydrocarbon reservoirs.

Keywords: Central Luconia Province, South China Sea, seismic interpretation, fault, carbonate

INTRODUCTION

Successful carbonate deposition requires a combination of several environmental factors such as suitable structural template, sufficient water depth, salinity and enough nutrient supply. This was the case in the Central Luconia Province in offshore Malaysia during the Miocene where extensive carbonate reefs deposited on tilted horst blocks at the time when the sea floor remained at a shallow depths for a long time (period of tectonic stability) (Franke et al., 2014). Research focusing on the sedimentology of the carbonate platforms in the Central Luconia Province had begun with the first publication by Epting (1980) and Doust (1981). They had suggested that the development of the carbonate platforms in the Central Luconia were essentially unaffected by tectonic deformations, and only governed by eustatic sea level changes. However, improved seismic imaging in the Central Luconia's subsurface shows that faulting and folding were widespread, throughout Miocene to Pliocene. Thus, apart from eustatic sea level and nutrient supply, significant tectonic activity also played a role in the development of the carbonate platforms in this area.

To investigate the relationship between the growth of carbonate platforms and structural effects, two reference platforms, EX and FY located in the southeastern part of this province, were studied using 3D seismic volume and well data. Recognition of the relationship between syndepositional faulting and growth history of the carbonate platforms is the key to increase hydrocarbon production in this basin. This study aims to establish the relationship between structural framework within carbonate platforms and its growth in response to syn-depositional tectonics.

GEOLOGICAL SETTING

The Central Luconia Province (Figure 1a) is a relatively broad and stable structural block at present (Zampetti *et al.*, 2004a) covering an area of 240km x 240km (Vahrenkamp, 2004) in offshore Sarawak and has become the target for many prolific oil and gas exploration since 1968. It has undergone Eocene extensional tectonics and subsidence in the north and compressional tectonics in the south. To date, more than 200 drowned carbonate platforms ranging in size from a few km² to more than 200km² across have been seismically mapped (Ali and Abolins, 1999) with 55 fields proven to contain commercial quantities of hydrocarbon, particularly gas (Ali, 1995; Pierson *et al.*, 2010).

In the Late Early Miocene, when the tectonic activities were slowing down, reefs started to flourish where favourable conditions prevailed. Reefs had become more prolific throughout the Early Middle Miocene to Late Middle Miocene. The carbonate reefs were interpreted to be deposited in the inner neritic environment. Influence of prograding clastic materials from the nearby Baram deltas and increase of sediment load from the NW Borneo Wedge and major sea level falls had subsequently stopped the carbonate deposition. Clastic deposits continued to prograde into the Central Luconia Platform since the Late Miocene until today, and promoted gravitational tectonics within this province.

Compared to the other basins in the South China Sea, there was a delay in carbonate deposition at Central Luconia (Franke *et al.*, 2014) because the Luconia Block was still colliding and subsiding beneath Borneo during the Late Oligocene, whereas the other parts of South China Sea had



Figure 1: (A) Location of Central Luconia Province in the bigger South China Sea, highlighting the carbonate Platform EX and FY used in this research. (B) Top carbonate map of Platform EX and FY with "No data zone" labelled in between the two platforms. "No data zone" represents the area without seismic data (not provided for this research).

settled in their rifting processes. Carbonate deposition in the Central Luconia took place in the Late Early Miocene but become more prolific in the Middle to Late Miocene (Zampetti *et al.*, 2004a,b).

DATA AND METHODOLOGY

The data which include 3D seismic and well data of Platforms EX and FY (Figure 1b) were made available by the Petroleum Management Unit (PMU), Petronas and Shell Sarawak Berhad. The seismic volume used for this research is a filtered, scaled and migrated seismic volume. The inline interval was 25m with crossline interval of 12.5m (grid size = $25m \times 12.5m$), with 245 inlines and 1124 crosslines for Platform FY, and 272 inlines and 492 crosslines for Platform EX.

Interpretation of seismic data began with creation of a synthetic seismogram. Moderate to good correlations between synthetic and seismic data were achieved through seismic to well tie analysis. Horizons for seismic interpretations were selected according to the obvious reflectors correlated from the seismic to well tie process. Since the available wells only penetrate up to the depth of 2280 m (to the base of carbonate layers), interpretation on the deeper horizons were only based on the continuity of the seismic reflectors, as observed on several seismic attributes. Maps for each of the horizons were created and overlaid with fault surfaces.

The internal geometries of the seismic reflections within Platforms EX and FY were also used to understand and interpret the environment of deposition for each carbonate unit. In this study, the geometries of seismic reflections were identified and interpreted for the purpose of understanding the features seen on each interpreted sequence. Sequence stratigraphy (i.e.: on-lap, top-lap and down-lap) was not applied in this study. Three seismic geometries were identified in Platforms EX and FY (Figure 3).

RESULTS AND DISCUSSIONS Horizons and Geo-Seismic Units

Eleven horizons (H1-H11) have been interpreted in this study, with five geo-seismic units, labelled as Geo-Seismic Unit 1 to 5 (Figure 2). These units were interpreted based on a combination of continuity of amplitude displayed on seismic data, well data (to the extent of its last penetrated depth) and gathering of information from the available literatures. The horizons were interpreted within a geoseismic framework and tied to the biostratigraphic markers that correspond to time intervals from recent to 15.97 Ma (Early Middle Miocene). Biostratigraphic markers for the deeper horizons were not available for Platform FY and EX. Well F6 from nearby platform within the Central Luconia Province, together with the other deeper wells from Balingan Province and North Luconia Province were incorporated to interpret the lithology of the deeper horizons.

Horizons were interpreted from the sea bottom, labelled as Sea Bottom (SB), followed by Horizon 1 (H1) to Horizon 11 (H11) in the deepest part of the seismic section. Horizon 11 to Horizon 7 have the same seismic pattern, and are grouped as Geo-Seismic Unit 1 (GSU 1). The top of Horizon 7 to Horizon 5 shows the same seismic characteristics and are grouped as Geo-Seismic Unit 2 (GSU 2). Geo-Seismic Unit 3 (GSU 3) consists of the carbonate units interpreted from Horizon 5 to Horizon 3. Geo-Seismic Unit 4 (GSU 4) is grouped from the top of Horizon 3 to Horizon 2. The final interpreted Geo-Seismic Unit 5 (GSU 5) is bounded between Horizon 2 to the sea bottom (SB). The main internal geometry within each geo-seismic units interpreted in this study is shown in Figure 3.

Well Logs Interpretations

Gamma Ray Logs for Well EX-2, EX-3, FY-2 and FY-6 have been used in interpreting the lithology for Platform EX and FY (Figure 4). Regrettably, Gamma Ray Logs are

Fault Class	Criteria	Platform EX	Platform FY
А	Displaced all geo-seismic units except Geo-Seismic Unit 5. Displacement in Geo-Seismic Unit 4 is small compare to the older units. Associated with conjugate faults in the NE of Platform FY.	Not available for interpretation	10 faults
В	Fault(s) that displaced Geo-Seismic Units 1 to 3.	14 faults	15 faults
С	Fault(s) that do not displace Geo-Seismic Units 3, 4 and 5. The displacement(s) are only visible in Geo-Seismic Unit1 and 2.	Not available for interpretation	6 faults
D	Earlier fault(s) that only displaced Geo-Seismic Unit 1. Difficult to image in seismic but might be related with rifting fault.	Not available for interpretation	5 faults

Table 1: Faults classes in Platforms EX and FY.



Figure 2: Seismic cross-section of Line AA' showing five geo-seismic units (Geo-Seismic Units (GSU) 1-5) and saddle area (no seismic data zone) between Platform EX and Platform FY. Both platforms have been directly affected by normal faults.

not available from top to bottom of the wells. Most of the logs and cores are tight within a depth of 1700m to 3300m. All available wells are exploration wells, thus they only penetrate to either the top of carbonate or inter-carbonate section within Geo-Seismic Unit 3 of our interpreted data. None of these wells penetrate into the deeper Geo-Seismic Units 2 and 1. The lithological interpretation of Platform EX based on Well EX-2 and EX-3 was made methods by Gartner et al. (2004) and Zampetti et al. (2004b). In Platform EX, some limestone breccias have been observed especially towards the edge of the platform (Figure 5). Three limestone breccias intervals with a minimum thickness of 1m were recognized at the top of core in Well EX-3 (Gartner et al., 2004). Based on gamma ray logs plotted in Figure 4, gamma ray values ranging from 50 to 80API are common within limestone intervals, indicating the existence of shales within the carbonate intervals (contaminated carbonate). Clean limestones have gamma ray values of 10-30 API. Lithological interpretation of Platform FY remains confidential within industrial companies.

Structural Interpretation

Faulting affects the whole area covered by the entire 3D seismic survey for both Platforms EX and FY. Structural interpretation was mainly based on the observable offset of seismic reflectors in the reflectivity data or lineaments observed in the variance (coherence) volume. A total of 50 faults has been interpreted within Platform EX and FY (Table 1). These faults are mainly planar in nature within Geo-Seismic Unit 3 and turn into listric shape in the deeper seismic units. Most faults died out in the Geo-Seismic Unit 3 but some continues to displace Geo-Seismic Unit 4. No major faults were observed within Geo-Seismic Unit 5, except for small-scale localised fractures. Observation of seismic data between Platform EX and FY shows that, there is potential for normal faulting in the saddle area that separated these two platforms (no data zone in Figure 2). All faults are normal faults, generally oriented N-S and NE-SW which seems to govern the north-south elongation of platforms in the south eastern part this province.

Fault Classes

Faults have been classified into few classes, based on the units they displaced. The fault classes are summarized in Table 1.

Platform EX

Platform EX grew on a few small scale domino system fault blocks. These faults are interpreted to be related to the last rifting stage of the South China Sea. Throughout carbonate growth in Platform EX from Middle to Late Miocene, small scale normal faults are observed. Some of them were active during carbonate deposition, promoting platform collapse especially in the Eastern and Western



Figure 3: Seismic geometry based on seismic reflection pattern on Platform EX and Platform FY.

flank of Platform EX (Gartner *et al.*, 2004; Zampetti *et al.*, 2004a,b). The majority of the faults are closely spaced, steeply dipping with dipping angles ranging from 40° - 70° with dominant fault system strikes from 015° - 040° and 040° - 070° (Figure 6).

Fourteen faults have been interpreted within Platform EX, and they are concentrated in the eastern and western margins of the platform. Structure interpretation in Platform EX is only limited to the carbonate section of Geo-Seismic Unit 3 reasonably due to the small size of the provided seismic data, hence all the faults in this platform falls in Class B Fault. Velocity pull-up effects were taken into account when doing interpretation as extremely high velocity had passed through the carbonate build-ups of Platform EX and resulted in fold-look-a-like structure underneath the carbonate build-up.

Faulting and fractures within this carbonate platform had somehow created an outline for the platform as they showed straight segments where the platform edge coincides with the faults or are guided by the fracture systems. Multiple sliding events had been interpreted to be responsible for submarine landslide in Platform EX. Zampetti *et al.* (2004a,b) had classified patchy, chaotic and hummocky seismic geometry to describe slide deposits on the eastern and western flanks of Platform EX. Slide scars were represented as sharp discontinuities forming crescentshaped embayments associated with seismic chaotic bodies of slide deposits.



Figure 4: Lithological interpretation based on core interpretation and gamma ray for Well EX2, EX3, FY2 and FY6.



Figure 5: Wells EX2 and EX3 in Platform EX. (A) The wells location on the surface timeslice. (B) Crossline 1, showing Well EX3 penetrates to the depth of approximately 1960m. (C) Inline 2, showing Well EX2 penetrates to the depth of approximately 2090m. (D) Core images of limestone breccia in the upper part of Well EX3, consist of grainstone, packstone and wackestone (modified after Gartner *et al.*, 2004). (E) Core images of argilaceous limestone at the base of Well EX2. Exact depth is unknown. (modified after Warrlich *et al.*, 2010). (F) Core sample showing dolo-mudstone in core of EX3. Exact depth is unknown (modified after Warrlich *et al.*, 2010). (G) Thin section from Well EX2 showing foraminifera with platy corals in lime-mudstone. Exact depth is unknown (modified after Gartner *et al.*, 2004).

Platform FY

Faulting in Platform FY is relatively more pervasive compared to faulting in Platform EX. Most of the faults cut through the carbonate platform. Some of the fault(s) were initiated earlier before the carbonate started to deposit on this platform and continued to move slowly during deposition of carbonate, making a syn-depositional faulting event. Sets of conjugate faults can be seen at the edge of Platform FY (in NE of the platform). In the northern part of Platform FY, the faults are oriented in ENE-SW direction while in the southern part, the faults are oriented about N-S direction (Figure 7a). The dip angles of these faults are ranging from 40°-80°. Different fault directions within Platform FY might be indicative of a localised strike-slip fault in this area with an approximately N-S oriented basement fault, promoting E-W extension.

Conjugate faults in Platform FY have similar dips of approximately 30°-40°, oriented NE-SW and NW-SE. A detailed inspection within Geo-Seismic Unit 3 carbonate shown that Fault Class B and C develop various numbers of conjugate fault systems, crossing each other and developed X-patterns within the carbonate unit(s). Some of the faults Bulletin of the Geological Society of Malaysia, Volume 60, December 2014

failed to create conjugate systems and later changed into distributed branching faults, creating positions of mini horsts and graben patterns within Geo-Seismic Unit 3 that become the templates for the reefs to grow. These branching conjugate normal faults within the carbonate units were tilted and rotated and provided changes in the environment of deposition from reef build-up to lagoonal facies. This is proven by fossil assemblages such as corals, corraline algae, echinoderms and operculina found in Well FY-6. The fossil assemblages represent shallow open marine close to reef slope as the possible environment of deposition in Platform FY (Figure 8).

CONCLUSION

Detailed seismic interpretation of Platforms EX and FY in the Central Luconia Province has shown well defined carbonate build-ups that had been affected by syndepositional faulting during their growth. Both Platforms EX and FY have five geo-seismic units (1-5). The older geo-seismic units 1 and 2 are dominated with older listric normal faults. Their displacements in each of the geo-seismic units are small (to seismic scale), suggesting that these faults S.N. FATHIYAH JAMALUDIN, MANUEL PUBELLIER & DAVID MENIER



Figure 6: Faulting in Platform EX. Interpreted faults on the section (cross-section K-K') and horizontal (coherence (variance)) slice at time 1515ms. The faults are dipping 40°-70°. Faulting stopped during the final stage of carbonate deposition and hardly affected the clastic layers of Geo-Seismic Unit 4 above the platform. Coherence (variance) slice shows that the top carbonate (green contour) is bounded by faults on both flanks.

Figure 7: Fault trends in Platform FY. (A) Faults are dominated by two sets. Set 1: Oriented in N-S direction (red colour) and Set 2: Oriented in ENE-WSW direction (green colour). (B) Fault trends as observed in the cross-sections UU' and YY'.



Figure 8: Environmental changes from lagoon (back reef) to reef flat/front, observed in seismic data of Platform FY. The changes in environment of deposition were due to template provided by the branching conjugate faults system in carbonate units of Platform FY.

Bulletin of the Geological Society of Malaysia, Volume 60, December 2014

formed during or just after the final rifting stage of the South China Sea. Some of the older listric faults continue to move during deposition of Geo-Seismic Unit 3 that is the main carbonate depositional unit in Platforms EX and FY. Slight movement within the carbonate depositional unit had either encouraged the reefs to grow on the topographic highs such as at the tip of a faulted block, or promoted sub-marine landslides as what we observed in the flanks of Platform EX. In general, syn-depositional faulting within carbonate platforms in the Central Luconia Province had provided templates for the reefs to find suitable bases for them to grow during Miocene time. However, at the same time, syn-depositional faulting during carbonate deposition had led to reef collapse together with other environmental factors such as storm and wind directions. In conclusion, the branching conjugate normal faults and older listric faults in the carbonate deposits might serve as potential hydrocarbon traps and migration paths within the carbonate reservoirs in the Central Luconia Province, which can be useful for exploration revisits.

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