Deformation profile analysis of a deepwater toe-thrust structural trend – Implications on structural kinematics and sedimentary patterns

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Abstract: NW Sabah is dominated by numerous structural trends of tightly folded and thrusted Miocene to Pleistocene sediments forming the Sabah deepwater fold-thrust belt, resulting from the complex interaction between gravitational forces and compressional tectonics. The timing of structuration and deformation of most of the toe-thrust features is recorded by the Shallow-Regional Unconformity (SRU), which separates the pre- and post-kinematic phases of the structural development. A good understanding of the timing of the structural development is paramount in the analyses of sedimentary fairways and depositional patterns. The pre-kinematic phase is likely to result in an unconfined depositional setting, while structurally influence syn- and post-kinematic depositional phases tend to deflect turbidite sand fairways, and trap turbiditic sand in between ridges forming ponded turbidites. This study aims to provide further support for the semi-qualitative understanding of the various deformational episodes experienced in the "L-B-P" structural trend, from the oldest studied sequence, the Kinarut interval to the seabed, in a temporal and spatial framework. A quantitative analysis of the deformation profiles was conducted to observe the 3D structural evolution and its effect on the sedimentary patterns, supported by amplitude analysis and spectral decomposition mapping. The basic principal of line balance restoration is employed to unravel the deformation history of the "L-B-P" structures, with the fundamental assumption that a geological section will restore at any particular moment in time to an unstructured section according to the law of superposition and horizontality. Structures are examined by calculating the rate of shortening at different geological times over a number of line-sections. This quantitative analysis has shown that the structuration and deformation history of the "L-B-P" structures are varied along the structural trend. These variations in turn play a significant role in controlling sediment fairway distribution patterns and impact on the selection of exploration reservoir objectives.

Keywords: deformation, Miocene, NW Sabah, structural kinematics, toe-thrust

INTRODUCTION

This paper focuses on the structural geology and the deformation analysis of an anticlinal structural trend, the "L-B-P" Ridge, which resides in the deepwater setting of the NW Borneo fold-thrust belt offshore Sabah (Mohd Asraf Khamis *et al.*, 2017; Figure 1). The structures are complex with a genesis related to the gravitational collapse of the

up-dip delta and the associated down-dip compressional thin-skinned tectonics (Figure 2). The anticlines have a strong flexural element later in their history, which occurs as the faults become inefficient, with the structures eventually becoming translated and vergent to the northwest. The timing of structuration and deformation of most of the toe-thrust features is primarily reflected by the creation of the Shallow-



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Figure 2: A strike section across the investigated "L-B-P" structural trend with interpreted horizons annotated. Inset figures show diporientated snapshots of individual structure and a depth structural map of the three "L-B-P" features.

Regional Unconformity (SRU) around 8.5 Ma (Figure 3), which separates the pre- and post-kinematic phases. Hence, a sound knowledge on structural kinematics is important in predicting the reservoir fairway, and thereby influencing the choice for structural exploration targets in the study area. Major tectonic episodes, indicated by the pre-, syn- and post-kinematic phases are the key elements influencing the reservoir distributions, where post-kinematic play with stratigraphic pinch-out component remains unproven and a risky exploration target in the study area.

This study aims to provide further support for the semiquantitative understanding of the various deformational episodes experienced by the "L-B-P" structural trend, from the oldest interpretable interval, the Kinarut to the recent seabed (Figure 2). A quantitative analysis of the deformation profiles was conducted to observe the effect on the sedimentary patterns, by integration with amplitude analysis and spectral decomposition interpretation. The simplified chrono-stratigraphic scheme of the study area is shown in Figure 3, and a regional seismic illustration of the Sabah deepwater fold-thrust belt is shown in Figure 4.

STUDY OBJECTIVES

Mapping and predicting the effective sand fairways in deepwater Sabah is key to a successful hydrocarbon exploration effort in the area. Structural evolution of folds has a first order effect on reservoir sedimentation and hence, the study was conducted with the following objectives:

1. Unravel the structuration of the NW Borneo fold-thrust belt located within the study area, where a thorough



Figure 3: Chronostratigraphic scheme of the study area with the main stratigraphy column enclosed in dark-blue box (modified after Jong *et al.*, 2014a).

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Figure 4: Top: a regional seismic section of Sabah deepwater fold-thrust belt with index map showing the line location. Bottom: a schematic illustration of structural evolution of an active margin fold-thrust belt (modified after Grant, 2005).





understanding of the structuration history, together with post-well success and failure analyses is paramount for further successful exploration,

- 2. Understand the primarily effect of the Shallow Regional Unconformity (SRU),
- 3. Analyse the structural evolution across three structures along "L-B-P" Ridge,
- 4. Identify the effect of pre-, syn- and post-kinematic mega-sequences of the deepwater sedimentary fairways and their depositional style, which play a critical role for reservoir distributions (Figure 5).

It is hoped that the outcome of this deformation analysis, along with integration of the well results and seismic attributes, can help to de-risk reservoir presence by predicting sand distribution patterns throughout these three structures and to establish the most prospective zone in term of maximum accommodation space for sediment accumulation in the study area.

REGIONAL GEOLOGY AND STRATIGRAPHY

The structural geology of the circum-Borneo fold-thrust belts, including the Sabah deepwater fold-thrust belt has been well-discussed by Hesse *et al.* (2010) and Jong *et al.* (2014b, 2015a & b), with a post-well sequence stratigraphic review of the study area summarised by Jong *et al.* (2016) highlighting the key challenge of sedimentary fairway mapping in the deepwater setting.

The NW Borneo margin is characterised by numerous NW-SE trending lineaments which control large scale, regional folds and faults. The West Baram Delta province lies on the key NW trending West Baram Line (WBL) and Tinjar Line (TL) (see Figure 1 inset map). These features are likely related to the Late Oligocene to Early Miocene sea floor spreading, which occurred in the South China Sea (Hall, 1997).

The study area is regionally located in the Sabah Basin, over a palaeo-subduction zone that has been a locus of major crustal shortening since the Middle Miocene. The basin started to develop during the Oligocene and is associated with the closing of the proto Rajang-Crocker Sea. Since the opening of the South China Sea at approximately 45 Ma, the two main tectonic events have been a Palaeogene rifting phase and a compressional phase from the Neogene to recent times (Hutchison, 1996, 2005).

During the Miocene, part of the Rajang-Crocker Range was uplifted and exposed onshore resulting in rapid erosion of the Sabah land massif, which led to a northwest progradation of regressive clastic deltaic deposits such as the Champion Delta/East Baram and the West Baram deltas (Kessler & Jong, 2015). Sediment input has greatly exceeded the accommodation space created along the narrow shelf. Consequently, shelf margin instability resulted in remobilisation of sands over the shelf edge through feeder canyons with regular episodes of massive slope failures, forming mega mass transport complex deposits (MTDs; Figure 6). The MTDs flowed over large areas of the basin and forged long-lived sediment fairways through which turbidites preferentially flowed, finally infilling topography generated by the regional MTD geometries (Figure 7). These



Figure 6: Depositional processes observed on present-day seafloor offshore Sabah (modified after Grecula *et al.*, 2008).

MTD intervals have been observed in all wells drilled in the study area with obvious chaotic seismic characteristics confirmed in both dip and image logs. There was also prolific turbidite deposition from Middle Miocene to Pliocene (Nanno zones - NN8 to NN12), and it was during this period that the target sandstone reservoirs were formed related to lowstand system tract deposits. Further sediment loading on the slope caused activation of a shale decollement at depth, which resulted in the outboard sedimentary section forming a belt of toe-thrust anticlines. These anticlines constitute major hydrocarbon traps throughout the Sabah Basin.

Our current interpretation of the study area suggests that the area has experienced a predominantly NW-SE oriented compression from the late Middle Miocene until the Late Pliocene (e.g., Hesse *et al.*, 2010). It is recognised that the compressional phase was induced by massive gravitational sliding of the whole shelfal sedimentary wedge to the northwest when the major uplift of Borneo occurred, resulting in the deposition of marginal marine to deepwater reservoirs. Along with the complicated motion of plate collision, the intrusion of Mount Kinabalu granodiorite pluton (8 Ma) in the Late Miocene added to the general instability of the NW Borneo region (Cottam *et al.*, 2013). This main deformation phase resulted in a rugose seabed profile providing depocentres for the Late Miocene deepwater slope turbidite packages.

In contrast, in some areas north of the study area, where mobile shale thicknesses are greater, continued regional compressive deformation and associated shale mobilisation has led to a prolific intrusion of the Late Miocene reservoir sequence by mobile shale diapirs. This forms a very different structural province compared to the other toe-thrusts in the study area. The difference in structural style has developed as a result of timing and intensity of deformation and a thinner pre-kinematic section. As a consequence of these differences, minor shale or mud diapirism in the southern part of the study area is present in the overburden but is far less prevalent than in areas further to the north.



Figure 7: Analogue for basin fill process in offshore Sabah illustrating the genetic link between MTD's and turbidite sands (after Posamantier & Walker, 2006 and Algar *et al.*, 2011).

The prominent Deep Regional Unconformity (DRU) occurs between regional stratigraphic Stages I-III (deep marine sedimentation) and Stage IV (progradational shelf/ slope deposition) (Levell, 1987). Meanwhile the SRU separates Stages IVC and IVD sequences (and the Kamunsu and Pink fans). It is noted that the Stage IV deposits are correlatable to the series of submarine fan complexes in the deepwater setting; namely the Yellow, Pink, Kamunsu, Kinarut and Kebabangan fans (Figure 3).

METHODOLOGY

Similar to the study conducted by Jong *et al.* (2014b) and Mohd Asraf Khamis *et al.* (2017), deformation profile analysis was assessed to evaluate the tectonic history and structural development of the "L-B-P" Ridge. The fundamental key behind the line balance restoration is that by assuming that a geological section will restore at any particular moment in time to its original position during sedimentation, in accordance with Steno's law of original horizontality (e.g., Levin, 2009, p. 15). Multiple cross-sections were selected for each individual structural anticline. The folded representative line lengths (6 key horizons – Lingan, Yellow, Pink, Kamunsu, Kinarut and Kebabangan; see Figure 3) were measured and compared with the cross-sectional length. The input was then used to calculate the rate of shorting (ROS) at different geological times, using biostratigraphy as a temporal framework (Table 1), with Figures 8 and 9 summarising the deformation profiling methodology.

The ROS is used here as a proxy for the rate of growth and is calculated by measuring the full length of the folded horizon and comparing it with the current day line length. Then shorting is simply calculated:

Line shortening (m) = Folded length (m) - Present-day cross-section length (m)

The rate of shortening can then be calculated based on the temporal data and is calculated:

Horizon	Ма	Epoch	Biostratigraphic nanno zones
Lingan	5.0	Late Late-Miocene	NN12
Yellow	6.1	Late Late-Miocene	NN11C
Pink	7.2	Mid Late-Miocene	NN11B-11A
Kamunsu	8.7	Mid Late-Miocene	NN10A
Kinarut	9.5	Early Late-Miocene	NN9D-9C
Kebabangan	10	Early Late-Miocene	NN9B-9A, NN8

Table1: Seismic horizon, temporal framework, and cycle nomenclature used for deformation profiling.



Figure 8: Summary of deformation profiling methodology. Multiple line-sections at regular spacing with interpreted key horizons covering the "L-B-P" structures from SW to NE were used for the analysis to calculate the rate of shortening (ROS) for establishing the growth history of the investigated structures.

Rate of Shortening (m/Ma) = Line shortening (m) / Time period (Ma)

However, it is important to note that the methodology may be affected by seismic interpretation uncertainty with depth, in addition to the complexity of the structures making the line-length measurements difficult and sometime subjective for the older sections. The calculated results are



Figure 9: Deformation profile analysis across (a) "L" structure, (b) "B" structure, and (c) "P" structure, showing variations in timing of individual structure growth history. The histograms summarise the timing of deformation at various intervals with the tallest bar indicating the time of maximum growth of the investigated structure. Locations of line-sections selected for average rate of shortening (ROS) calculation are annotated in the index maps.

therefore used semi-qualitatively to infer the deformation history of the investigated structures.

RESULTS AND FINDINGS

"L" structure

The "L" structure is an elongated toe-thrust anticline with a simple 4-way closure from the Lingan to the Kinarut intervals with well over 30km² of closure (Figure 10). The anticline has no obvious present-day seafloor expression and represents the lowest top seal risk among the toe-thrust structures in the study area. To date, 4 wells have been drilled to appraise the "L" structure. Only L-1ST1 well discovered mainly gas, while the other 3 wells found oil primarily in Kamunsu and Kinarut reservoirs (assumed as no detailed biostratigraphic investigation were conducted in these wells).

Figures 11 and 12 summarise the deformation analysis over the "L" structure:

- Zero structuration is identified across the "L" structure during the Kinarut time (9.5Ma). As such no obvious anticlinal seabed topography would be present allowing for maximum accommodation space to develop for the incoming sediments. Hence, it is interpreted as a prekinematic phase.
- 2. Structuration began within the Kamunsu time (8.7Ma), when the thrust fault started to propagate, forming minor seabed topography. Ample accommodation space is still expected over the central and northeast area of the "L" structure. Therefore, this period is interpreted as early syn-kinematic.
- 3. Structuration continues throughout the Pink time (7.2 Ma) and reaches maximum deformation during the Yellow time (6.1Ma). The "L" structure is likely a distinctive bathymetric high at this time. The incoming sedimentation



Figure 10: Depth structure map of the study area at Top Kamunsu level (8.7 Ma), with the investigated "L-B-P" Ridge located in the middle trend with growing structures at this time.



Figure 11: Structural profile across the "L-B-P" structural trend from Kinarut interval to seabed with no or minimum growth during the Kinarut time (9.5 Ma, pre-kinematic phase), and active growth took place from Kamunsu (8.7 Ma) to Lingan (5.0 Ma) times (syn-kinematic phase).



Figure 12: Average rate of shortening (ROS) and cumulative shortening over "L" structure with peak growth observed during the Yellow time (6.1 Ma).

would have been constrained by the topographic relief and would have resulted in the fairways either avoiding the topographic high and/or sediment thinning across the structure. This time period is indicative of syn-kinematic deposition.

4. While sedimentation is believed to continue, deformation decreases during Lingan time (5Ma). This period marks the end of syn-kinematic phase.

5. Zero to minimal structuration is seen in the recent and therefore it can be interpreted as a post-kinematic phase.

"B" structure

It is an elongate toe-thrust anticline formed by continued regional compressive deformation and associated shale mobilisation at depth. It encompasses an area of 30 to 40 km² depending on reservoir level (Figure 10). The reservoir targets at "B" are Late Miocene deepwater turbidite packages formed from initially unconfined (pre-kinematic) turbidite deposition (Kebabangan and Kinarut fans) to later, subconfined (syn-kinematic) turbidite deposition (Kamunsu and Pink fans).

Figures 11 and 13 summarise the deformation analysis over the "B" structure:

- 1. Zero structuration is apparent across the "B" structure during the Kinarut time (9.5Ma) and therefore this formation is interpreted as a pre-kinematic phase. Unconfined and widespread sheet fans might be expected.
- 2. During the Kamunsu time (8.7Ma), moderate deformation is observed on the northeastern part of the structure trend, where the thrust fault started to propagate. Along strike, the central "B" structure shows minor deformation, while in



Figure 13: Average rate of shortening (ROS) and cumulative shortening over "B" structure with peak growth observed during the Lingan time (5.0 Ma).

the southwest, the "L" structure suggests moderate deformation. This results in an early syn-kinematic phase for the structure with sedimentation becoming more confined towards the Late Kamunsu time (8.7 Ma).

- 3. The "B" structure continues to develop during the Pink (7.2Ma) and Yellow times (6.1Ma). The anticlinal structure is likely to form a topographic high on the seafloor. Resultant sedimentation would have either avoided the bathymetric highs and/or sediment thinning would be present across the structure. This period marks the syn-kinematic phase.
- 4. Deformation reached a maximum during the Lingan time (5Ma). The anticlinal structure would form a distinctive feature on the seafloor causing the incoming sediments (of Lingan Fan) to be highly affected by the structural high, resulting in sediment thinning across the structure. This late stage deformation causes sediment instability on the structural crest and induces slumping and erosion. Fault amalgamation also occurs via fault tip growth into one through going structure.
- 5. Zero to minimal structuration is seen in the recent interval and therefore it can be interpreted as a post-kinematic phase.

"P" structure

The "P" structure is located along strike from "B" to the northeast and forms the last anticline in the "L-B-P" Ridge. The "P" structure is an elongated SW-NE 4-way dip closure (Figure 10). The seismic is of poor quality over parts of this prospect, especially at the structural crest due to the presence of significant gas clouds. The presence of gas clouds affects the amplitude anomalies impeding the detailed attribute extraction and analysis at the prospective levels.

Figures 11 and 14 summarise the deformation analysis on the "P" structure:

- Very minor structuration is identified in the Kinarut time (9.5Ma). This subtle deformation can be considered the transition from pre-kinematic into syn-kinematic episodes.
- 2. The structure continues to grow fairly consistently throughout the Kamunsu time (8.7Ma). This is likely to



Figure 14: Average rate of shortening (ROS) and cumulative shortening over "P" structure with peak growth culminating in the Lingan time (5.0 Ma).

form further seafloor expression. Sedimentation would be constrained by the structural high, which would result in sediment fairways avoiding the "bumps" and/ or sediment thinning across the structure. This period is part of the syn-kinematic phase.

- During the Pink time (7.2Ma), structure "P" has 3. developed significantly on its southwestern fault segment, therefore providing potentially more accommodation space in the central to northeastern areas. The deformation decreases during the Yellow time (6.1Ma) and reaches its maximum deformation during the Lingan time (5Ma). The southwestern area consistently records higher deformation rates in comparison to the rest of the structure. This part of the anticline would therefore have possibly been more apparent on the seafloor, thus having more effect on the incoming sediment. This variation along strike can be seen on the seismic image as a tighter folding. The observation is indicative of continued syn-kinematic deformation.
- 4. Zero to minimal structuration is seen in the recent and therefore it can be interpreted as a post-kinematic phase.

DISCUSSION

The "L-B-P" structural trend has experienced a NW-SE oriented compression from Early Miocene until the Pliocene. Variations in the kinematic growth for each structure were identified and it is clear that structural growth varies along strike (Figure 15); where (1) the "P" structure formed earlier compared to the "B" and "L" structures, and (2) maximum deformation occurred during Yellow time (6.1 Ma) for "L" structure, and at the Lingan time (5Ma) for the "B" and "P" structures. The significant effect of late stage deformation (higher stress regime) can be seen by a substantial shortening in the "B" and "P" structures during this Lingan time (5Ma), probably induced by compression associated with massive gravitational sliding of the whole shelfal sedimentary wedge to the northwest. In addition, the formation of steeply dipping forelimbs on the "B" and "P" structures result in the triggering of erosive slumping at these locations driven by the anticlinal fold geometry,

as can be seen on seismic sections (Figure 2). Regionally, the late stage deformation might be also associated with the Late Miocene compressional tectonicism experienced along the NW Borneo margin (Hutchison, 1996 & 2005; Kessler & Jong, 2015 & 2016), with local uplift resulting in Horizon II erosional event around 5.6 Ma (Figure 3),



Figure 15: Kinematic deformation history through time of the three investigated structures as derived from the average rate of shortening (ROS) calculations summarise in Figures 12 to 14.

and major sedimentary input into the Sabah Basin during the period of Lingan Fan deposition.

One of the key inputs in determining possible sand fairways is to generate attribute maps and integrate those maps with other G&G data in order to highlight the most prospective areas in term of reservoir presence. Since only limited information on rock physics or seismic inversion is available outside of JX Nippon operated block, basic seismic attributes were generated to delineate and identify potential sand fairways over the study area. Some of these attributes indicate deepwater channel and fan features, which are therefore considered as potential reservoirs.

To enhance the understanding of the sedimentary patterns, spectral decomposition analysis was performed (Figure 16), which can help to reveal the geology that is present, but often hidden within the seismic signal. This can create meaningful geological images and delineate the sedimentary features such as reservoir fairways, by outputting a number of band-pass and amplitude response (magnitude) volumes generated at discrete frequencies bands chosen by the interpreter (these generally support the simple attribute extractions, such as RMS amplitude).

From the attribute analysis (both spectral decomposition and simple attributes), a clear first order correlation between the sediment fairways and structural development can be inferred. It is clear that the identified sedimentary fairways are in agreement with the findings of structural deformation analysis, which was carried out independently. Areas identified as pre-kinematic show broad unconfined fan geometries which cover the yet-to-form structures; while during times of syn-kinematic deformation the sedimentary fairways flow around the structures or through them, as



Figure 16: Deformation history of "L-B-P" structural trend through Kinarut (bottom) and Pink (top) intervals, overlaid on spectral decomposition maps illustrating the effect on the sedimentary distribution patterns.

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confined channel fan complexes before the smaller lobe fans form in the synclinal areas (Figure 16). This first order effect between deformation and sedimentation therefore has major implications for reservoir quality and effectiveness.

As a comparison, it is noted that the same observations were also documented by Totake *et al.* (2017), and the deepwater fold-thrust belt in offshore NW Borneo exhibits a range of structural styles that vary along strike. Along their axes, anticlines vary from gentle open structures to tight fold, which also can clearly be seen in "L-B-P" structural trend (Figure 2). Another notable finding from this study is the possibility that the main toe-thrust is being produced by the amalgamation of two or more elements of thrust-faults, with linkage failure between the toe-thrusts formed individual structures along strike.

CONCLUSIONS AND RECOMMENDATION FOR FURTHER STUDY

All three structures along the "L-B-P" Ridge experienced a NW-SE oriented compression from the Early Miocene until the Pliocene (~15Ma to 4Ma). The semi quantitative deformation study has shown that the structuration and deformation history of the ridge varied along strike (Figure 17). The variations are most likely resulted from additional influence of area-specific controlling factors including large-scale lithological inhomogeneity, variable surface slopes, irregular topography of the basement below the fold-thrust system, lateral variations in sediment input and storage, and the presence of gas hydrates in the subsurface (Hesse *et al.*, 2010). These variations are in agreement with isopach maps generated by seismic interpretation. The outcomes play a significant role on understanding sediment fairway distribution patterns and the subsequent impact on the selection of exploration reservoir objectives. It is also noted that the structures were well-developed at the latest by the Yellow time (6.1Ma), which is favourable considering that the timing of hydrocarbon generation is modelled to occur during and post the Yellow time (6.1 Ma), and thus, providing a favourable timing for hydrocarbon entrapment and accumulation in "L-B-P" structural trend (Figure 18).



Figure 17: A map view summary of deformation history of "L-B-P" structural trend through time.



Figure 18: Peak oil and gas generation in the study area took place after the toethrust structures were well-developed, thereby providing a favourable timing for HC trapping and oil/gas accumulations (after Jong *et al.*, 2014a).

With the aid of attribute and spectral decomposition maps, a depositional system model can be developed to better understand the deepwater fan behavior in relation to the structuration.

The current study suggests that a clear first order correlation between the sediment fairways and structural development can be inferred in Sabah deepwater foldthrust belt. The combined techniques of attribute mapping for fairway identification and deformation profiling for establishing growth history can be applied to predict intervals with better reservoir development in exploration structures. While the deformation profiling of the "L-B-P" Ridge has revealed different growth histories of the investigated structures, thereby providing a critical piece of information for predicting sedimentary fairway distributions, on a wider scale it is recommended that the same analysis is to be performed on both the inboard and outboard structural trends next to the "L-B-P" Ridge in the vicinity of the study area for a better understanding of regional reservoir potential. In addition, it will be interesting to observe from a more regional viewpoint, the effect of the regional stress regime (e.g., Hesse et al., 2010), on the formation of the toe-thrusts and distributing patterns of the sediments affected by these growth structures in this Sabah deepwater area, which currently remains a focus area for hydrocarbon exploration and development.

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