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Structural characteristic of early Eocene extensional fault in Songkhla basin, Gulf of Thailand

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Abstract

The Songkhla Basin, located in the Gulf of Thailand, serves as a classic example of a Cenozoic rift basin. The basin spans approximately 75 km in a north-south direction and 30 km east-west. Its primary geometry is predominantly controlled by the main N-S to NNW-SSE, east-dipping boundary fault zone on the western side of the basin, forming an elongated half-graben under E-W extension since the Eocene. Many faults strike predominantly orthogonal to the extension direction. In this study, a set of E-W to WNW-ESE, north-dipping extensional faults is mapped based on 3D seismic data occurring in the early Eocene syn-rift strata. The younger, N-S striking normal faults either cut across or terminate against the older, basement-involved, E-W to WNW-ESE striking normal faults. The presence of both types of fault interactions in the Songkhla Basin suggests the possibility of multiple phases of non-coaxial extension during the Eocene. This study highlights the structural characteristics and 3D geometry of the early Eocene extensional faults and discusses their implications for the tectonic evolution of the Songkhla Basin.

Keywords: Songkhla Basin, Gulf of Thailand, Cenozoic rift basin, extensional fault

Introduction

The Songkhla Basin is a Cenozoic basin located in the southwestern Gulf of Thailand, 15 km offshore east of the town of Songkhla (Figure 1). It covers an area of approximately 2,500 km^2. The basin is an example of a predominantly orthogonal extended half-graben that developed in phases between the Eocene and the early Middle Miocene (Morley & Racey, 2011; Kaewkor et al., 2015; Rivas et al., 2016). The main controlling fault is the N-S to NNW-SSE trending fault that bounds the basin along its western margin (Phoosongsee & Morley, 2018). This fault is roughly parallel to the rift axis of Songkhla Basin and is responsible for the basin's asymmetric shape. Additionally, there are other fault trends in the basin, including N-S and rarely NE-SW trending faults. These faults are less prominent than the NNW-SSE trending fault but are still significant in controlling the basin's geometry and structural evolution (Kaewkor et al., 2015).

According to previous studies of basin evolution (Kartikasari, 2011; Paramita, 2012; Kaewkor et al., 2015; Phoosongsee & Morley, 2018), the Songkhla Basin has been interpreted as an extensional tectonic regime resulting from E-W extension during the Eocene to early Oligocene. The sediment is thicker along the western fault boundary and thinner towards the east. Inversion was dominant during the early

Miocene, and rapid thermal subsidence was the final phase of basin development.

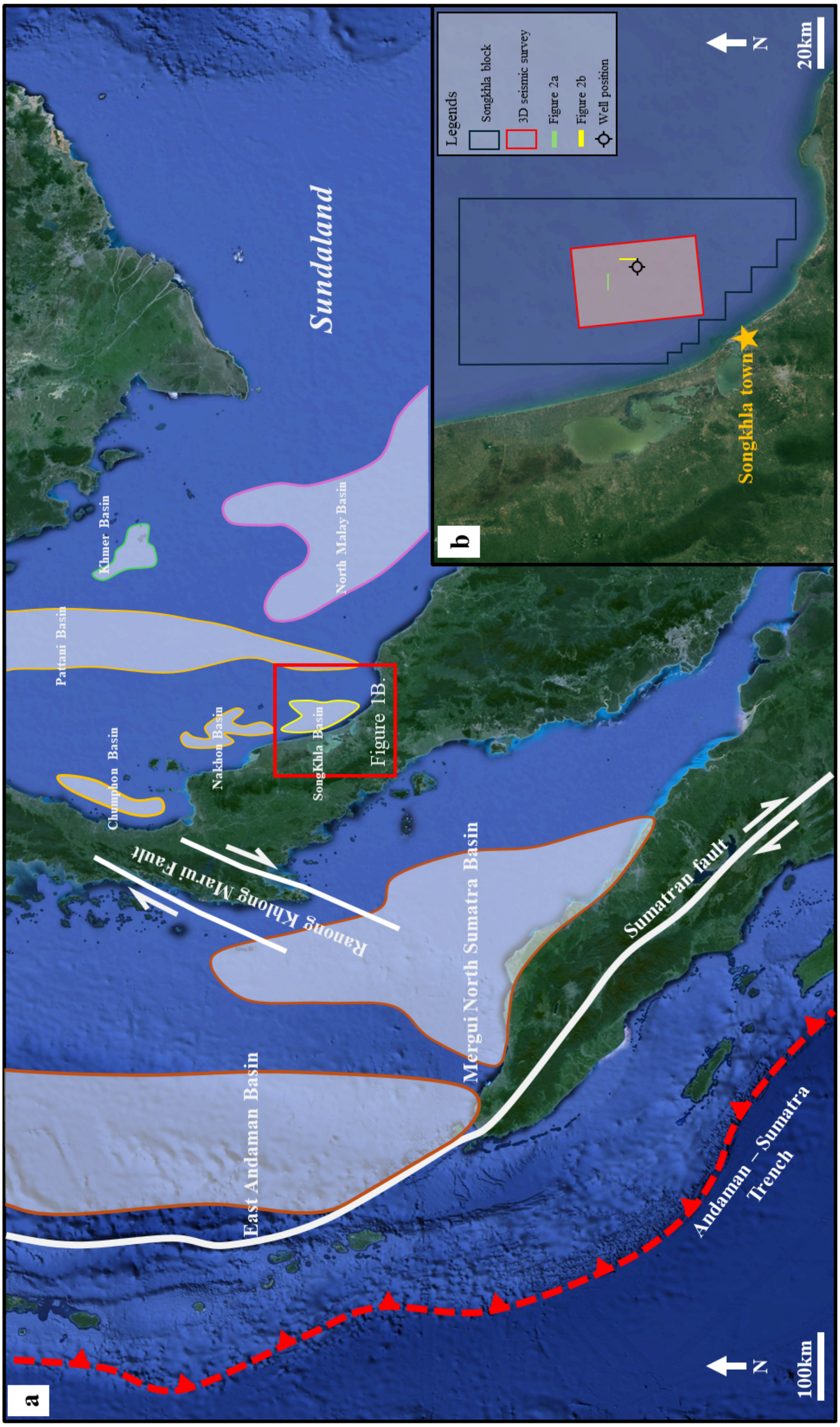

Figure 1. Satellite image showing (a) the petroleum basins province and tectonic features on SE Asia (modified from Morley, 2011), and (b) the Songkhla concession block with the location of 3D seismic reflection survey (modified from Phoosongsee & Morley, 2018).

However, upon investigation of the 3D seismic data in this study, we observed an additional fault set oriented sub-perpendicular to the main N-S to NNW-SSE, east-dipping boundary fault zone in the deeper section. This observation raises curiosity about whether the basin may have extended in an N-S distribution before undergoing a predominant E-W evolutionary phase. Early Paleogene N-S stretching is reported to be predominant in southern Sunda and occurs locally further north in the Gulf of Thailand (Sautter & Pubellier, 2022).

Therefore, this study focuses on the Eocene sequence of the Songkhla Basin to investigate the early rift faults using 3D seismic data and to define their structural characteristics. The results are presented with a discussion of the presence of these early rift faults, their tectonic evolution, and their relationship with other faults in the Songkhla Basin.

2. Seismic-stratigraphy and tectonic framework

The seismic stratigraphy in the Songkhla Basin, western Gulf of Thailand, is characterized by several distinct phases of extension and inversion (Figure 2; Korkaew, 2015; Phoosongsee & Morley, 2018). The basin is divided into three main phases: extension and inversion, which are separated by unconformities.

Eocene syn-rift I

This phase started in the Eocene and was marked by the deposition of fluvial-lacustrine sediments on the pre-Cenozoic rocks (referred to as basement). The initial rifting was characterized by the development of NNW-SSE trending normal faults, which bounded the basin and were roughly parallel to the rift axis. (Korkaew et al., 2015; Phoosongsee & Morley, 2018)

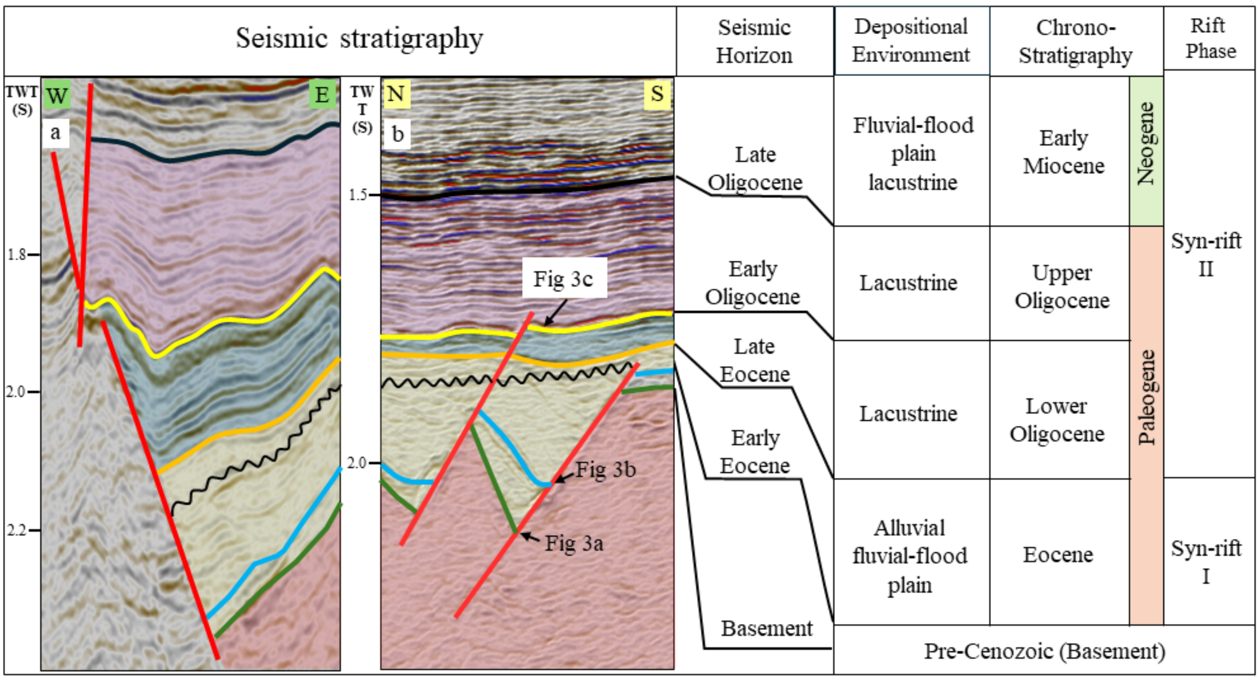

Figure 2. Paleogene-Early Neogene stratigraphy of the Songkhla Basin focuses on the rifting sequences (modified from Korkaew, 2015; Phoosongsee & Morley, 2018). Note: in seismic section (b), wedge-shaped geometry of the Eocene strata towards the north-dipping normal faults. See Figure 1b for line locations.

Oligocene syn-rift II

The Oligocene phase includes the continuation of extensional tectonics, with the deposition of thick syn-rift packages. The faults during this phase were also NNW-SSE trending but with a slightly different orientation compared to the Eocene phase.

Lower Miocene syn-rift II

The Lower Miocene phase marked the final stage of extensional tectonics in the Songkhla Basin. This phase was characterized by the deposition of thick syn-rift packages and the development of growth faults that thicken towards the fault.

Middle Miocene post-rift I

This phase includes a shift from extensional to compressional tectonics, resulting in the reactivation of basin-bounding rift faults as reverse faults, hangingwall anticlines, and basin uplift. The inversion was most pronounced in the western part of the basin (Korkaew et al., 2015; Phoosongsee & Morley, 2018).

Upper Miocene to Recent

The final phase of the Songkhla Basin's evolution was characterized by post-rift subsidence, with the deposition of thick clastic sediment packages. This phase marks the cessation of extensional tectonics and the onset of sag subsidence.

3. Data and methodology

3.1 3D seismic data

Songkhla 3D seismic volume is used in this project. The survey area is aligned NNW-SSE, covering an area of approximately 700 km2 along the western margin to the deep basin of Songkhla Basin and extending down to 4.0 seconds in depth. The seismic volume was realized (32-bit to 16-bit) to optimize seismic processing during interpretation with the bin size 12.5 x 12.5 m. The data quality is fair to poor in complex structures and deeper sections, particularly below the Early Oligocene syn-rift strata, possibly from the structural complexity and challenging conditions for data acquisition and processing from survey companies. In this study, the poor seismic reflectors were improved using Petrel's auto gain control (AGC) and structural smoothing volume processing, enhanced low amplitude sections, and increased signal-to-noise ratio for structural interpretation.

3.2 Seismic Horizon Interpretation

Seismic interpretation and visualization were conducted using Petrel software, focusing on the mapping of key horizons, including the basement, Early Eocene, and Early Oligocene, to determine significant geological events in the Early Paleogene due to their significant structural characteristics. Seismic horizons were interpreted at intervals of every 50 inlines and 50 crosslines, with a line spacing of 12.5 meters, resulting in a grid spacing of 625 x 625 meters.

3.3 Attribute extraction and structural interpretation

Seismic Variance was mainly used on the interpreted horizons. This was used to investigate fault segmentation in depth. Attribute extraction was carried out and overlain in Petrel to highlight structural discontinuities.

Fault interpretation was made in the 3D data by faults across multiple mapped horizons. 3D fault segments were interpreted on inline and crossline. Additionally, faults that are not distinctly observable in both inline and crossline sections are interpreted using arbitrary line cross-sections.

3.4 Data limitation

Only a few borehole data are available for this study. The 3D seismic interpretation of stratigraphic units is referenced from previous studies (Korkaew et al., 2015; Phoosongsee & Morley, 2018). The horizontal extent of the structural interpretation is limited by the 3D seismic survey due to the lack of regional 2D seismic lines.

4. Results

Structural maps of the basement (Figure 3a) and Early Eocene (Figure 3b) horizons illustrate two distinct trends of normal faults: N-S to NNW-SSE and E-W to WNW-ESE. The former trend includes the western boundary fault and its antithetic faults. The latter trend mostly occurs within the Eocene strata and is not present in the early Oligocene structural map (Figure 3c). The structural characteristics of these extensional faults are described below.

4.1 N-S to NNW-SSE striking normal faults

In the map view (Figure 3b), the faults in the western region predominantly strike N-S to NNW-SSE, with some segments curving NE-SW, all of them have developed in the same phase, resulting from the extension and pre-existing structures influenced. The main western boundary fault, which controls the basin, dips towards the east. Synthetic and some antithetic faults are distributed from the eastern side to the center of the basin. These faults fault range in length from 5,000 to 15,000 meters, shorter than the main western boundary fault.

In the eastern part of the basin, normal faults predominantly strike NNW-SSE. Compared to the western faults, the eastern faults exhibit gentler dip angles and greater rotation, and some faults exhibit a curved NW-SE pattern along their tips (Figure 3a)

As shown in the cross-section (Figure 5a), the faults can be classified as planar normal faults characterized by linear features cut through the reflectors. The main N-S to NNW-SSE, the east-dipping boundary fault zone, is basemen involved. The stratigraphic units affected by these faults include the Middle Miocene, Oligocene, and Eocene and extend down to the pre-Cenozoic basement. The upper stratigraphic units, from the Miocene to the Top Oligocene, experience minimal displacement faults, with displacements ranging from 100 to 500 ms.

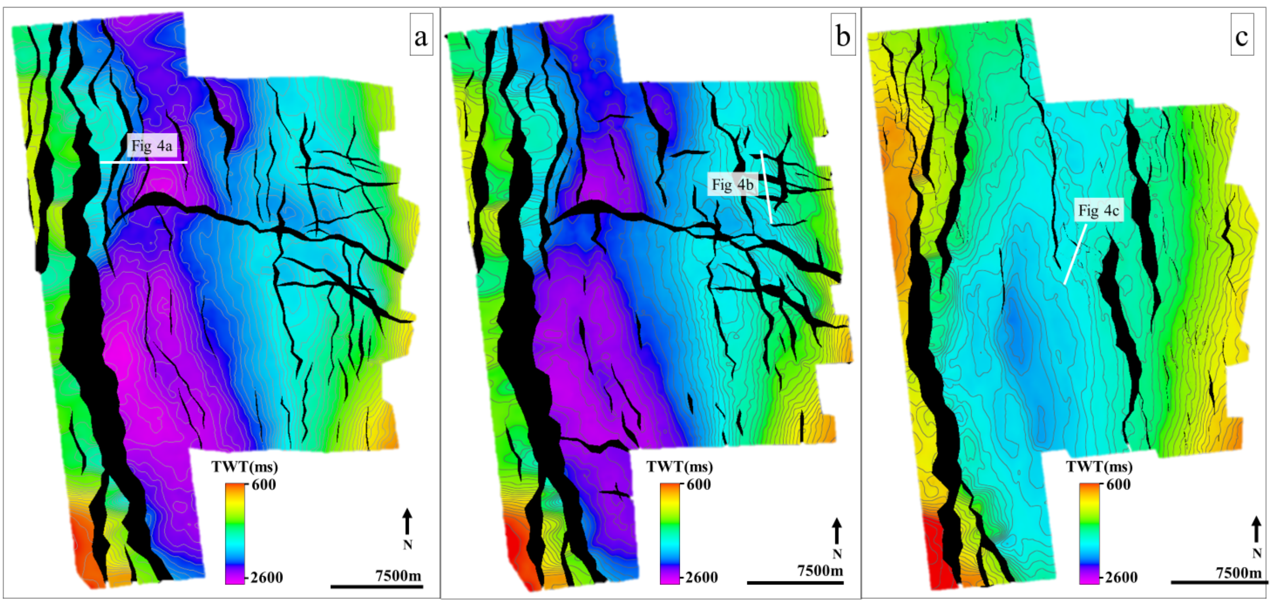

Figure 3. Time structural map of (a) basement, (b) Early Eocene, and (c) Early Oligocene. Note: In (a) and (b) maps, some of the younger, N-S striking normal faults cut across the older, E-W to WNW-ESE striking normal faults, whereas others terminate against the older, E-W to WNW-ESE striking normal faults.

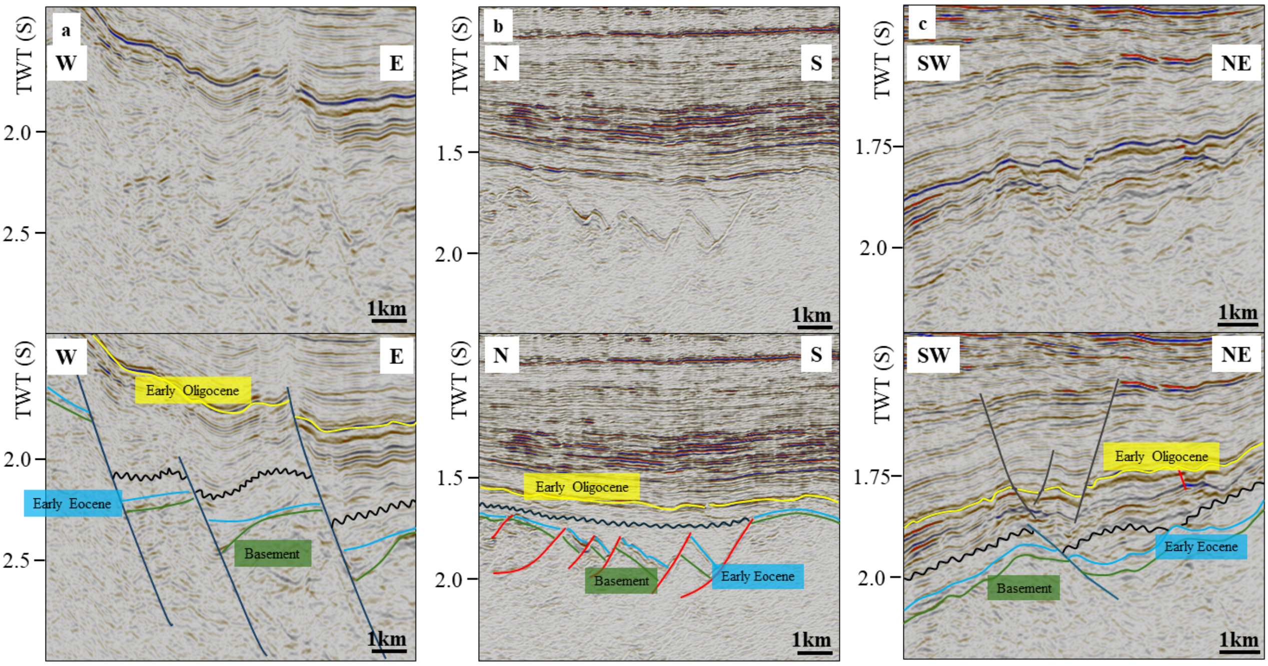

Figure 4. (a) E-W seismic section with interpretation of (a) east-dipping extensional faults (blue lines) near the western margin of the Songkhla Basin. (b) N-S seismic section with the interpretation of north-dipping extensional faults (red lines) in the Eocene sequence. (c) NNE-SSW seismic section with the interpretation of extensional faults (black lines) and graben formed in the overlapping zone of the syn-rift II sequence. See Figure 3 for line locations.

In contrast, the lower stratigraphic units, from the Top Oligocene down to the basement, exhibit greater displacement, ranging from 500 to 1,000 ms.

4.2 E-W to WNW-ESE striking normal faults

This fault set is characterized by predominantly linear features with slight curvature, oriented E-W to WNW-ESE, and ranging in length from 1,800 to 18,500 meters (Figures 3a and 3b). All faults dip northward and are primarily clustered in the eastern part of the 3D survey, where the basement level is relatively high. Their fault tips do not show a curve of bend toward the other fault set. Only one significant fault cuts across the basin, as shown in Figures 3a and 3b. This fault separates the elongated depocenter along the western margin of the basin. These early rift faults are not present on the Early Oligocene horizon map (Figure 3c).

In cross-section (Figure 4b), a half-graben geometry in the Eocene syn-rift I sequence is formed by tilted synthetic north-dipping faults. However, the spatial distribution of this syn-rift sequence associated with the E-W to WNW-ESE striking faults remains unclear due to the interruption of the N-S to NNW-SSE striking faults, which also formed local depocenters (Figure 3a and 3b). The lower tips of the E-W to WNW-ESE striking faults cut into the basement. The upper tips die out within the syn-rift sequence or terminate at the Eocene unconformity, indicating that the effective N-S extension ceased at the end of the Eocene. The intersection at a high angle between these two fault sets is further discussed below.

5. Discussion

5.1 Fault interactions

Our 3D seismic interpretation shows that, particularly to the east of the 3D survey, some of the younger N-S striking normal faults cut across the older E-W to WNW-ESE striking normal faults, whereas others terminate against the older, E-W to WNW-ESE striking normal faults (Figures 3a and 3b).

Figure 5 presents 3D views of the fault model, showing fault interactions compared with the experimental sandbox model. The younger faults in the eastern part of the 3D seismic survey area tend to curve more towards NW-SE in the same direction as the older faults as they approach the older fault zone. This curving is a result of the pre-existing fabric. In contrast, faults located further from the older fault zone generally strike N-S, aligned with the E-W extension. The presence of both types of fault interactions in the Songkhla Basin is likely to occur with multiple phases of non-coaxial extension (see Henza et al., 2010, for an experimental study).

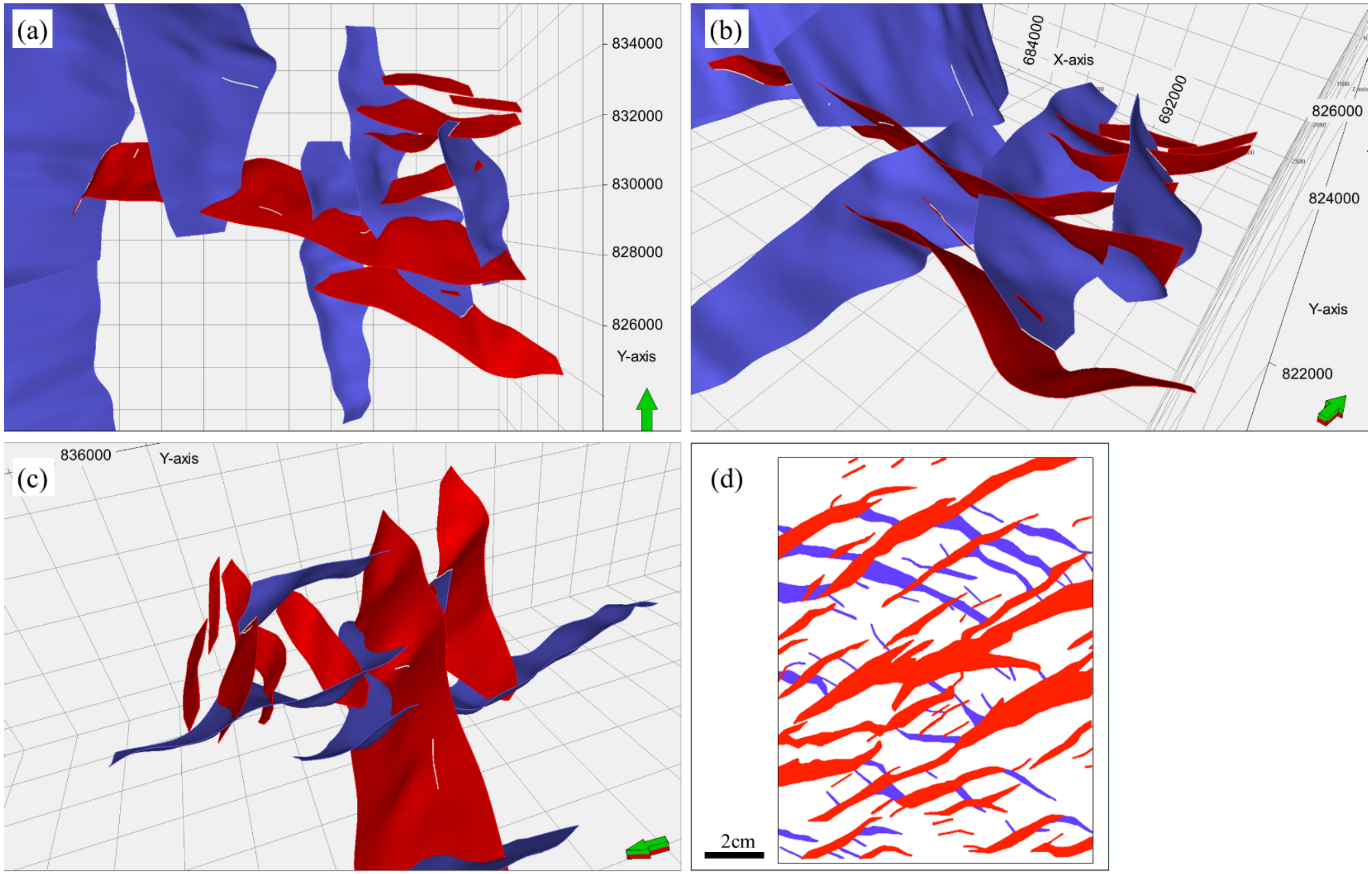

Figure 5. 3D fault model in the Songkhla Basin showing intersections between N-S striking fault (blue) and E-W striking fault (red). (a) looking above of 3D fault model, (b) looking NW of 3D fault model, (c) looking E of 3D fault model Compared with (d) Experimental sandbox model (modified from Henza et al. 2020). In (d) the red polygons represent the faults developed in the first stage of development, while the blue polygons represent the second stage of development in the different direction. The fault interactions and curved faults observed in the experimental model can be compared to the 3D fault model in the Songkhla Basin, which exhibits similar features.

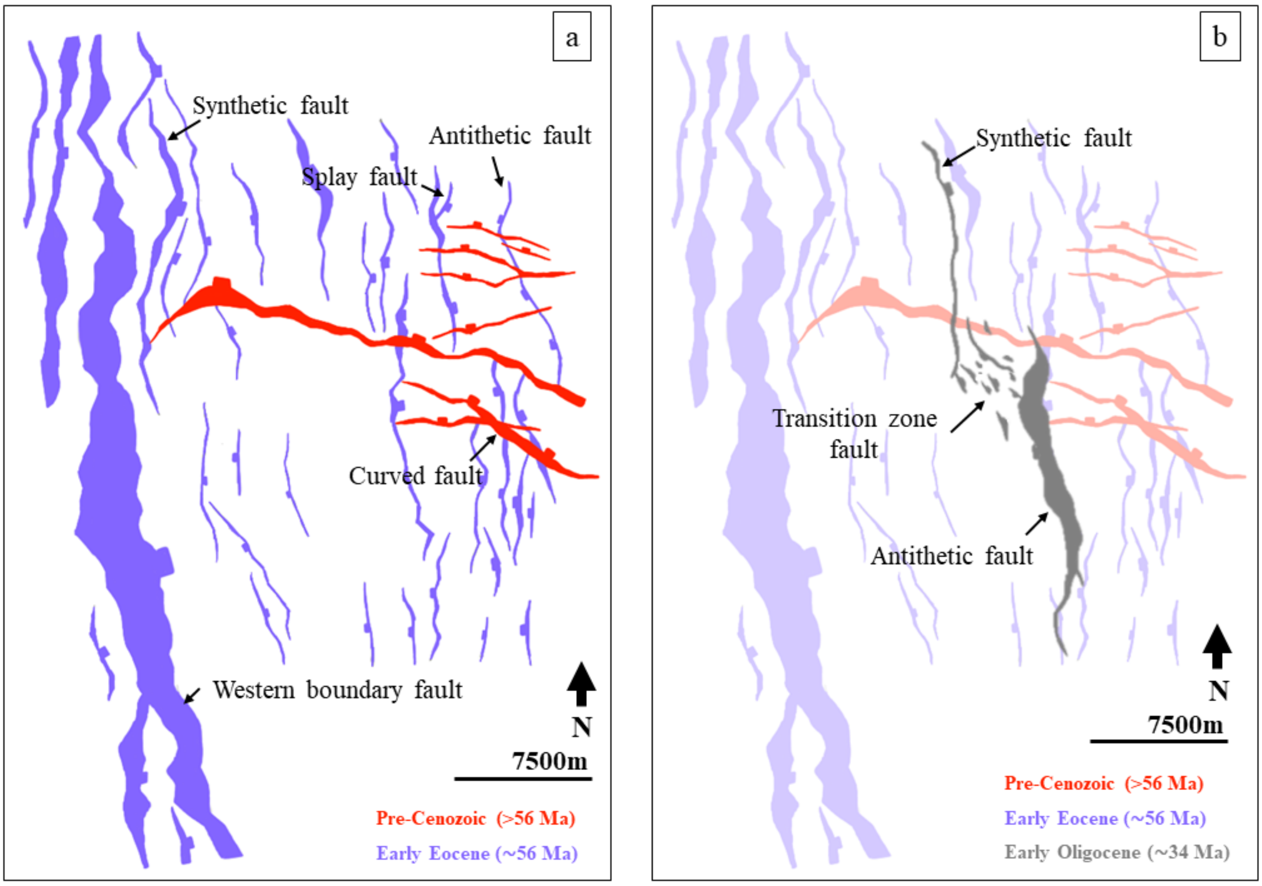

Figure 6. Maps showing (a) extensional faults in the Eocene strata and (b) in the early Oligocene. Red polygons represent older, E-W to WNW-ESE normal faults. Blue polygons represent the western boundary faults and the younger N-S to NNW-SSE normal faults. Grey polygons represent those faults developed later during the Early Oligocene.

A basin in Thailand that exhibits similar evolutionary characteristics is the Chumphon Basin (Figure 1). This basin is characterized by a set of sigmoid low-angle normal faults affecting the uppermost sedimentary rocks of the Khao Phanom ductile core, which are crosscut by a later set of brittle fractures. The basin underwent N-S extension in the Paleogene, which reactivated the Late Cretaceous structures. This extension is thought to have been triggered by the change in migration direction of the Indian plate in the Late Paleogene (~45 Ma; Sautter B et al., 2017).

A similar case is observed in the Java Basin, Indonesia, which experienced the N-S extension before the E-W extension. This event occurred just after the Late Cretaceous period, with most of the syn-rift section deposited during the Oligocene. The syn-rift section is characterized by a transition from continental shales to thick deltaic marine sandy sequences from the middle to late Oligocene (Sautter & Pubellier, 2022).

However, the Nakhon Basin, located between the Songkhla Basin and Chumphon Basin (Figure 1), has a different basin orientation due to the Western boundary fault in the NW-SE direction and the effects of pre-existing structure, causing the orientation of The Basin to be different from other basins in the western Gulf of Thailand. In addition, the Nakhon Basin is probably to have an initial stage of development later (Late Eocene? / Oligocene - Recent), resulting in no N-S extension found in the basin. (Bangpa et al., 2020)

5.2 Pre-existing structures influence

The previous N-S compressional axis associated with the sutures (e.g., Bentong Raub Suture Zone; Sautter et al., 2017) in the Southern Malay Peninsula is expected to extend northward and form pre-existing structures in the Songkhla Basin. This N-S striking pre-existing structure likely controls the boundary faults and basin geometry of the Cenozoic rift basins in the southwestern part of the Gulf of Thailand. Reactivation of these structures under an E-W extension creates orthogonally extended half grabens (e.g., the Chumphon, Nakhon, Songkhla, and South Pattani Basins).

An outcrop study by Sautter et al. (2017) provides evidence that the E-W to NW-SW structural trends are secondary between sutures in the Southern Malay Peninsula, including southern Thailand. We suspect that these secondary pre-existing structures in the Songkhla Basin control the initiation of the early rift faults during a short N-S extension in the Early Eocene. The development of the E-W to WNW-ESE normal faults is localized and may be confined between the basin boundary faults. At this time, the western boundary faults may have activated as obliquely slip normal faults. We do not observe features associated with strike-slip faults in the Songkhla Basin.

Following this, the E-W extension occurred, introducing NNW-SSE trending faults that began to control the basin. This led to the opening of the basin and the formation of a depocenter along the NNW-SSE faults. However, due to the influence of the pre-existing E-W structures, the depocenter in the northern section is offset across the E-W-striking fault (Figure 3a).

The older, E-W-striking normal faults also affect the orientation and pattern of the younger normal faults in the eastern part of the basin. These N-S trending normal faults tend to curve more towards NW-SE above older faults. (Figure 5). In the Early Oligocene stratigraphic unit, some faults in the eastern part of the basin show fault tip rotation towards each other within the transition zone, resulting in the formation of fault linkages. These fault linkages trend NW-SE, influenced by the pre-existing fabric.

5.3 Tectonic evolution relationship

According to Sautter and Pubellier (2022), during the Paleogene period, SE Asia experienced stretching in the N-S direction. This stretching is attributed to the extensional tectonic regime that occurred perpendicular to the margin. This extension is characterized by block faulting, dykes, and parallel extensional joints. Interestingly, the direction of the opening is perpendicular to the former sutures, which were formed during the Indosinian Orogeny.

The N-S direction of stretching during the Paleogene period is a result of the relaxation of the thickened crust that developed during the Late Mesozoic (Sautter & Pubellier, 2022). This relaxation led to the formation of large crustal tilted blocks, which were bounded by low-angle normal faults that captured most of the clastics derived from the formerly uplifted magmatic arc. These faults are frequently continent-dipping (counter-regional) and often reactivate former thrust faults and plutons boundaries on the edges of the Mesozoic magmatic arc.

According to Sautter et al. (2017), the WNW-ESE extension in the Malay Peninsula during the Paleogene period was characterized by a series of tectonic processes that led to the formation of rifted basins and the development of normal faults. The evidence for this extension includes structural features. The presence of N-S to NNE-SSW stretching lineation in metasediments and top-to-the-south shear in migmatites indicates a Maastrichtian tectonic event, which was followed by a period of WNW-ESE extension.

Another piece of evidence is the quartz dykes filling conjugate sets of fractures in granite plutons, indicating a regional E-W shortening followed by a period of WNW-ESE extension. These dykes are seen at the edges of granitic bodies throughout Malaysia and Thailand (Sautter et al., 2017).

In another study, it was found that during the Paleogene, the Gulf of Thailand region was within a domain of transpressional or inversion-related folds. Areas experiencing extension were located only in the Southeast China Sea or northern Sundaland, with extension occurring in the N-S to NW-SE direction (Morley & Wang, 2023). This suggests that future discussions or studies could investigate whether the E-W trending faults identified in the 3D seismic survey originated from N-S extension due to the relaxation of thickened crust or resulted from Paleogene transpressional forces.

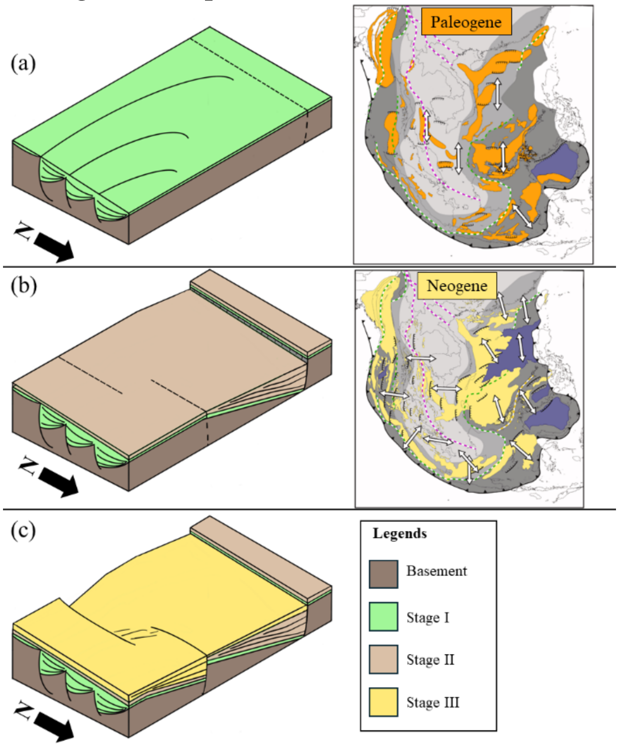

Figure 7. Simplified cartoon model reconstruction of the Basin. (a) First stage of rifting and map of distribution of the basins during the Paleogene with stretching directions represented with arrows, (b) Second stage of rifting and distribution of basins during the Neogene with stretching directions represented with arrows (modified from Sautter & Pubellier, 2022), (c) Third stage of rifting with the same direction of stage II.

The structural evolution model of the Songkhla Basin based on 3D seismic interpretation is compared with the tectonic maps from Sautter & Pubellier (2022), which primarily considers the basin to be within an extension domain (Figure 7). During the early stages of basin formation in the Early Eocene, it was controlled by N-S extension until the Late Eocene when fault development ceased. Subsequently, the basin prominently developed under the E-W extension. The basin continued to extend, leading to the development of ramps and a transition zone, with faults evolving under the control of pre-existing older fault fabrics.

6. Conclusion

The Songkhla Basin in the Gulf of Thailand is a classic example of a Cenozoic rift basin characterized by a complex tectonic evolution. This study presents the structural characteristics and 3D geometry of early Eocene extensional faults in the basin, which are crucial for understanding the basin's tectonic history.

The main findings of this study include the identification of two distinct sets of normal faults: N-S to NNW-SSE striking faults and E-W to WNW-ESE striking faults. The former set includes the western boundary fault and its antithetic faults, which are planar normal faults that are basement-involved and exhibit greater displacement in the lower stratigraphic units. The latter set occurs within the Eocene strata and is characterized by E-W to WNW-ESE striking faults with northward dipping. These linear faults form a half-graben geometry, and they do not extend into the Early Oligocene horizon.

The study concludes that the Songkhla Basin has undergone a complex tectonic evolution, with multiple phases of extension and inversion. The younger, N-S striking normal faults either cut across or terminate against the older, E-W to WNW-ESE striking normal faults, suggesting multiple phases of non-coaxial extension during the Eocene. This interaction between the two fault sets is likely due to the influence of pre-existing structures, such as the N-S striking sutures in the Southern Malay Peninsula, which may have controlled the basin's boundary faults and geometry.

The Early Eocene extensional faults played a significant role in shaping the basin's geometry and structural evolution, and their interactions with other faults are crucial for understanding the basin's tectonic history. The presence of both types of fault interactions in the Songkhla Basin suggests the possibility of multiple phases of non-coaxial extension during the Eocene, which is supported by the experimental study of Henza et al. (2010).

7. Acknowledgement

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