STRUCTURAL EVOLUTION USING SECTION RESTORATION, PHITSANULOK BASIN, CENTRAL THAILAND

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Abstract

The Phitsanulok basin, the largest Cenozoic rift basin in onshore Thailand, is composed of several sub-basins. Most of them are characterized by syn-rift and sag subsidence and distinguished by a limited post-rift unit. The integration of regional 2D seismic interpretation and structural restoration sections were used to define structural geometry variation, extension and subsidence history to improve the understanding of the structure evolution in the basin. The 2D restoration results in possibly six major stages of structural evolution in Phitsanulok basin using the ages referred in PTTEP, 2016: I) Early extension in Early-Oligocene? (>30Ma), II) High extension rate with high subsidence rate, indicates major rifting stage in Late-Oligocene (23 Ma), III) Low extension rate with low subsidence rate, indicates declined stage of rifting in Early-Miocene (18 Ma), IV) Low extension rate with high subsidence rate, indicates sagging process interference in Middle-Miocene (10 Ma), V) Gentle extension rate with gentle subsidence rate, indicates most late stage of rifting or early post-rift stage in late-Miocene (5 Ma), VI) Stable stage indicates Post-rift stage from 5 Ma until present day. The timing of rifting evolution reveals that there is a slightly different timing of events from that commonly applied. The major rifting comes earlier in the Late-Oligocene than Middle-Miocene and continued for a longer time until Late-Miocene. The inversion structure can be observed since Late-Oligocene. There is probably sagging process synchronous with rifting process since Middle-Miocene and most faulting is typically illustrated to die out around the base of Late-Miocene.

Keywords: Phitsanulok Basin, Structural Evolution, Section Restoration

1. Introduction

The Sirikit Oil Field is a major crude oil contributor in Thailand, located in the Phitsanulok Basin, approximately 400 km north of Bangkok. The Phitsanulok Basin also is the largest Cenozoic rift basins of onshore Thailand, occupying an area of about 6,000 square kilometers (km2) (Flint et al., 1988). The basin comprises a string of N-S Trending sub-basins (Morley et al., 2007). The northern half of the basin is bounded to the northwest by the east-dipping Western Boundary fault, while the Mae Ping fault and the Uttaradit fault respectively form the southwestern and northern basin margins.

The initial hydrocarbon discoveries were in 1981 and production started in 1983 by Thai Shell. Cumulative production over more than 30 years is approximately 500 MMBOE.

In order to find new resources in this brown field, the basin evolution, subsidence history, and structural evolution are essential for petroleum system analysis and identification of new play types.

Therefore, the key objectives of this study are:

• To understand the structural evolution and timing.

• Spatial variation in subsidence through deformation history, using balancing cross section and restoration to validate seismic interpretation. There are different published interpretations on the evolution of the Phitsanulok Basin. However, study of Phitsanulok Basin using modern structural restoration techniques has not been carried out. That is the reason for this study which will help to improve the understanding of the various structural components necessary to identify new play types and new potential prospects.

2. Tectonic Setting and Stratigraphy

The Phitsanulok basin is an extensional

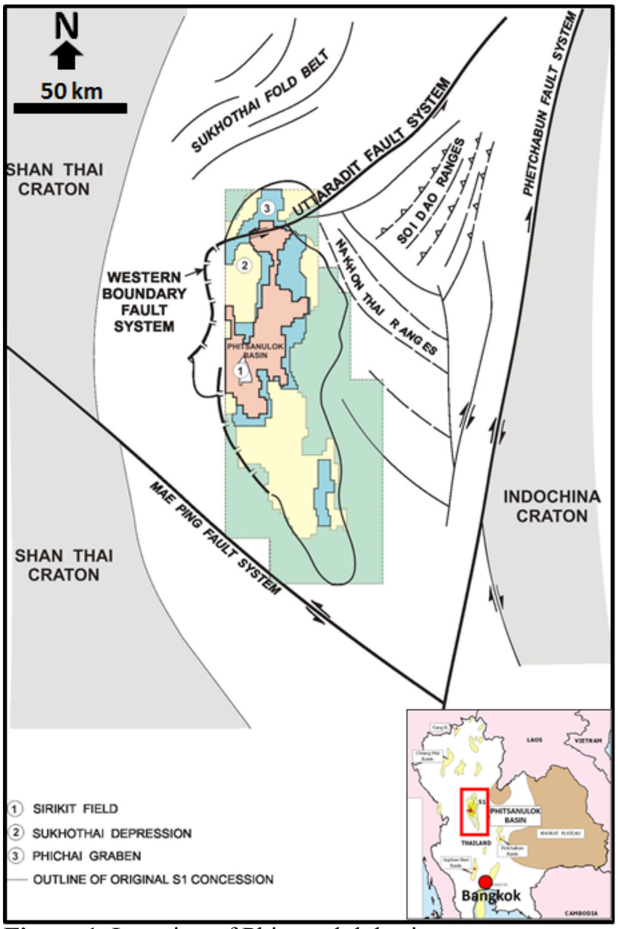

Figure 1. Location of Phitsanulok basin

basin which is situated in a triangular shaped zone defined by three regional strike slip faults systems: Uttaradit, Petchabun, and Mae Ping Faults. The opening of the basin has been related to the collision between the Indian Sub-continent and Eurasian Plate in Early Oligocene (PTTEP, 2009).

The Phitsanulok Basin consists of seven sub-basins (PTTEP, 2016). The northern sub-basin is a large half-graben called Sukhothai Depression (I) bounded by the western boundary fault. South of the Sukhothai Depression, there is a number of smaller NW-SE trending sub-basins, namely Bung Chang (II), Dongchat (III), Bung Bon North (IV) and Bung Bon South (V). Further to the south, the Phitsanulok Basin is complexly structured by north-northwest trending faults in the Laharn graben (VI) and north-south trending faults in the Nong Bua sub-basin (VII).

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The basin filled with non-marine sediments up to 8 km which is divided into five units comprising an alluvial fan of Sarabop and Nong Bua formation, a lacustrine shale of Chum Saeng formation, a fluvio-deltaic of Lan Krabu formation and an alluvial plain of Pratu Tao and Yom formation. Chum Saeng formation is a main source rock and regional top seal. Lan Krabu formation is a main reservoir target whilst Pratu Tao, Yom and Sarabop are additional reservoir targets.

3. Methodology

This study is primarily based on regional (2D) seismic data from various surveys in 1980's for regional interpretation. The lines were selected based on seismic quality and covering important structure across sub-basins. The dataset consists of 13 regional composite 2D seismic profiles mainly in W-E orientation. Generally, the quality of the 2D surveys varies from moderate to poor depending on acquisition and initial processing technology of the time. The 3D seismic data is used to fill the gaps between 2D lines for accurate structural interpretation.

The three main steps methodology are seismic interpretation, geological cross-section and structural restoration.

4. Observations

In this study, the total of 13 composite seismic profiles were interpreted. Six of 13 profiles (Lines 2, 3, 6, 8, 10 and 13) were selected for structural restoration to illustrate the basin evolution from northern to southern area.

4.1 HORIZON INTERPRETATION

Five horizons were interpreted in this

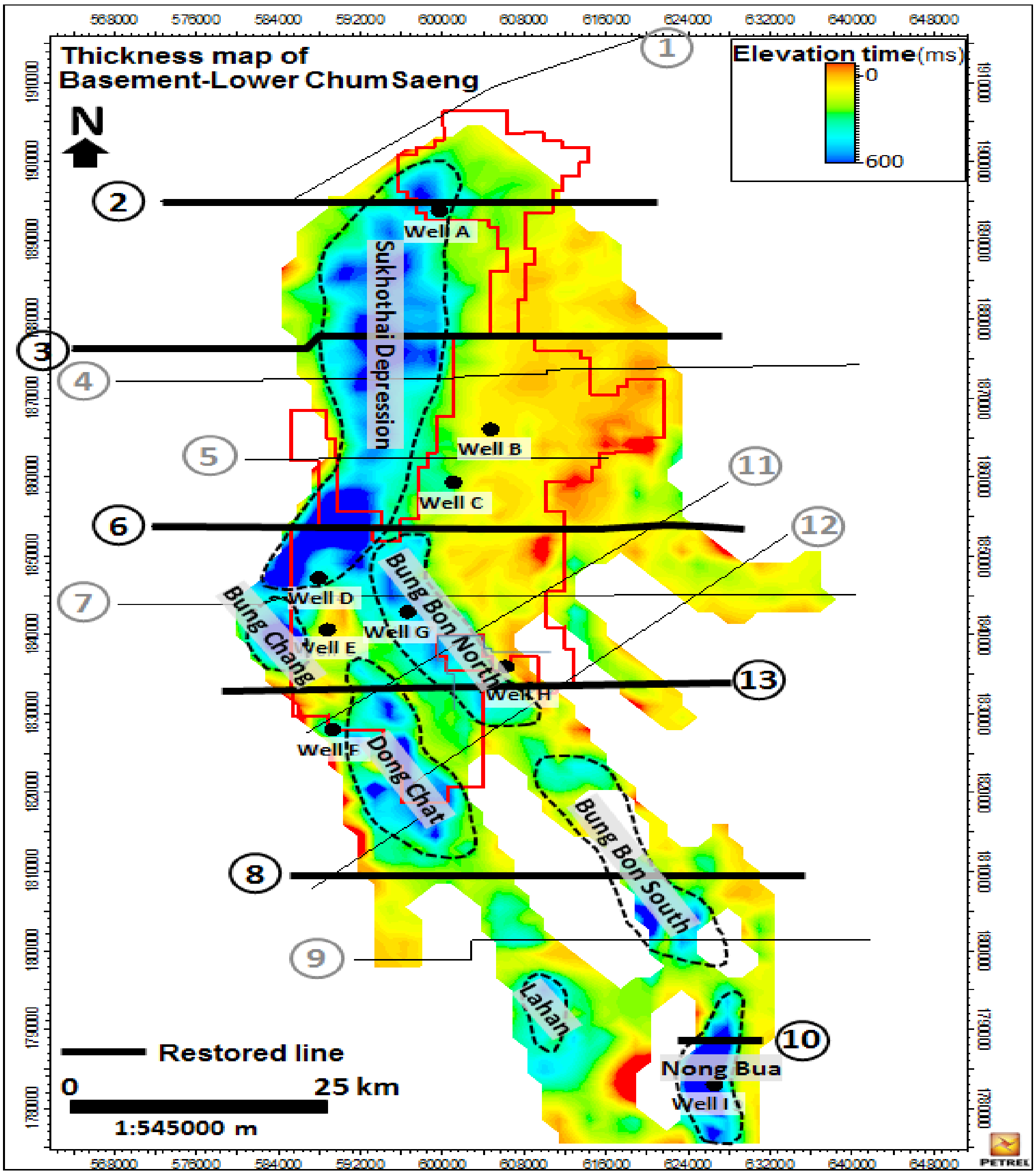


Figure 2. Regional composite 2D seismic line across the Phitsanulok basin.

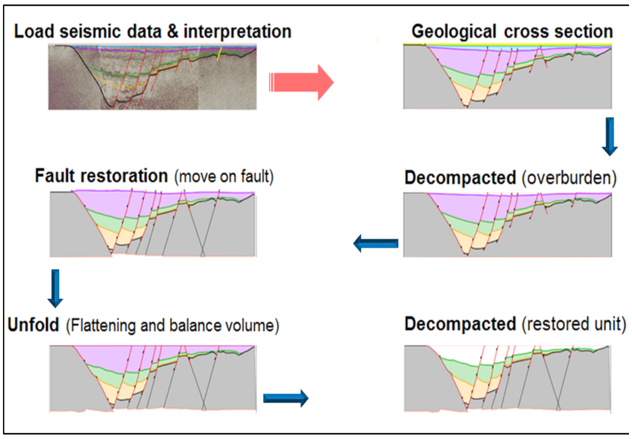


Figure 3. Simplified workflow of restoration method

study. Cross-sections with interpreted horizons are shown in Figures 4 and 5. Seismic characteristics of the horizons and units are provided in Tables 1-2.

Horizon	Symbol	Seismic Reflector	Amplitude	Acoustic Impedance	Continuity	Reflector Pattern
H01	—	Negative (Trough)	Weak	Decrease	Poor	Sub Parallel to Parallel
H02	—	Negative (Trough)	Weak	Decrease	Fair	Sub Parallel to Parallel
H03	—	Negative (Trough)	Strong	Decrease	Fair to Good	Sub Parallel
H04	—	Negative (Trough)	Strong	Decrease	Fair to Good	Sub Parallel
H05	—	Positive (peak)	Strong	Increase	Good	Chaotic

Table 1. Summary of interpreted horizons with characteristics

Unit	Top	Base	Symbol	Formation	Abbr.	Age
U1	H01 —	H02 —		Ping	Ping	Late-Miocene
U2	H02 —	H03 —		Pratu Tao	PTO	Middle-Micocene
U3	H03 —	H04 —		Upper Chum Saeng	UCS	Early-Micocene
U4	H04 —	H05 —		Lower Chum Saeng	LCS	Late-Oligocene
U5	H05 —		no colored	Crytalline Basement	Basement	Pre-Teriary

Table 2. Summary of interpreted horizons and units

4.2 STRUCTURAL INTERPRETATION

In general, the main structural style in Phitsanulok basin is conformable with typical rift basin systems which are characterized by half graben structures, tilted fault blocks, synthetic and antithetic faults. In some areas, the minority structures of inversion, and post rift unconformities also can be observed (Morley et al., 2007). The east dipping normal fault in the western part of the basin is interpreted as Low-angle boundary fault system (LABFS, < 30o dip) in the northern part and became High-angle boundary fault system HABFS, > 30o dip) in the southern part which are related to the last syn-rift stage in the basin (Morley, 2009). The border fault is characterized with large displacement in basement and observed as a growth fault during the depositional process as sediments are thickened toward the fault. The representative interpretation section from northern and southern area will be shown in this paper.

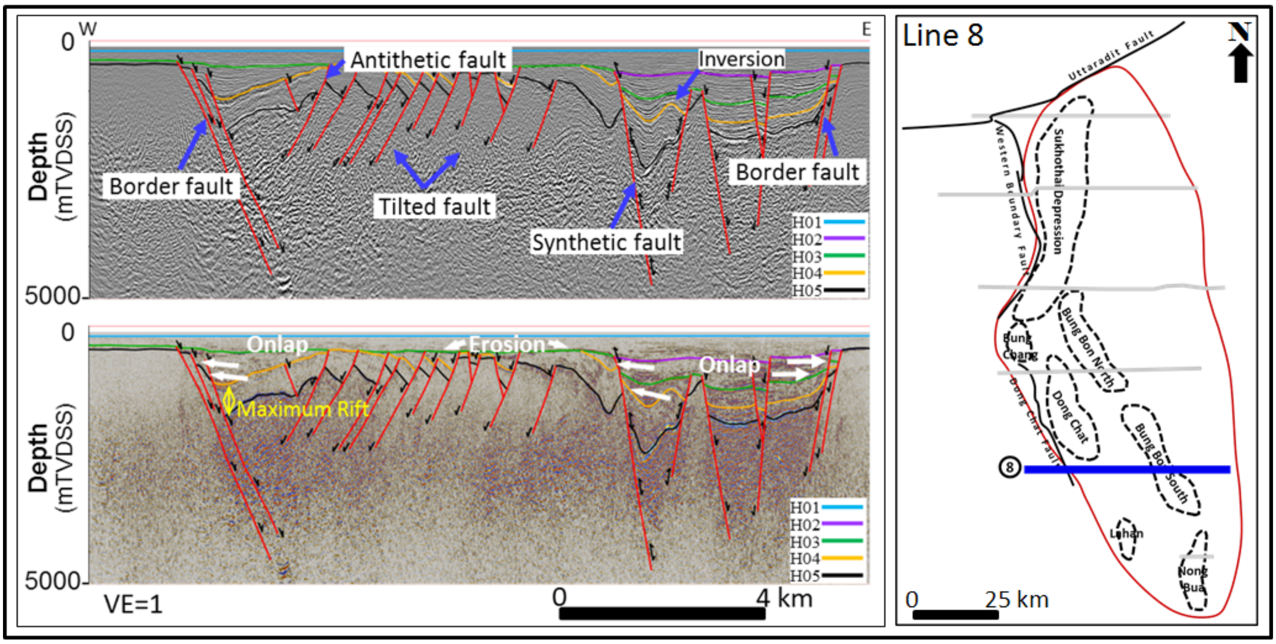


Figure 4. Seismic interpretation of Line 2

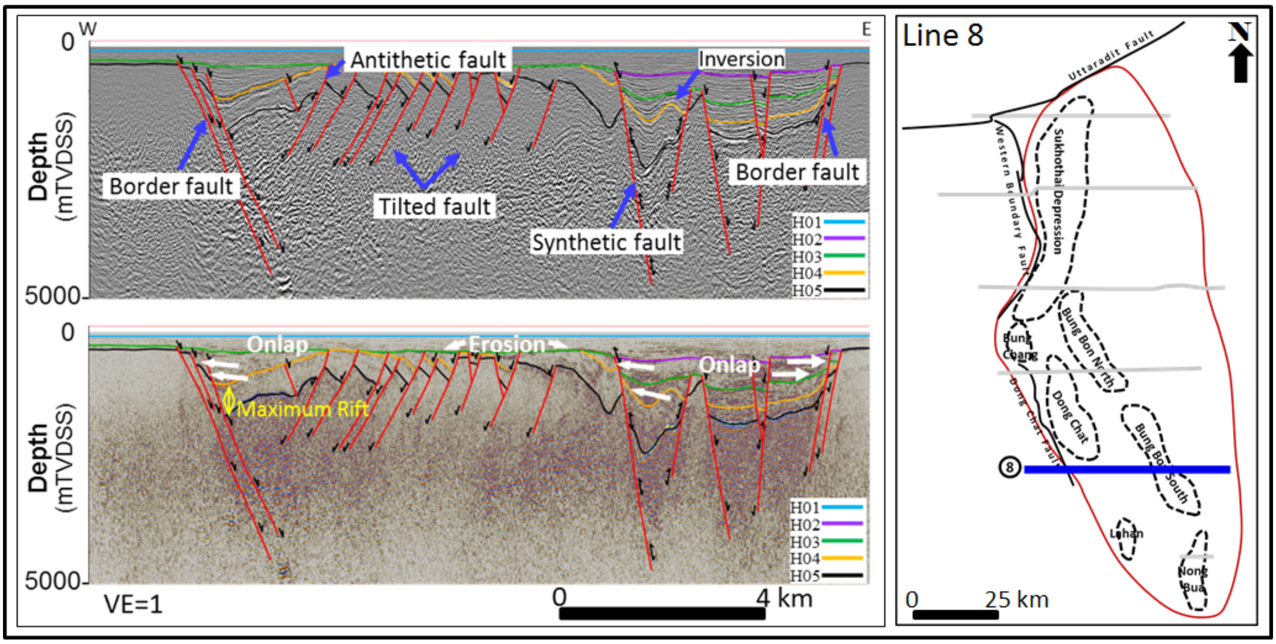


Figure 5. Seismic interpretation of Line 8

4.3 STRUCTURAL RECONSTRUCTION

The representative restored section from northern and southern area will be shown in this paper, while the result of other sections will be mentioned in the discussion. The following section describes the structural restoration results.

Line 2 (Northern area)

The structural restoration shows that the basin began to form as the Pre-Tertiary basement was faulted due to extension (Figure 6a). The area developed as a half graben during the Late Oligocene bounded to the west by the east-dipping normal fault and a west-dipping antithetic fault. The Late Oligocene sediment (Lower Chum Seang Fm.) thickens towards the hanging walls of the active normal faults forming a growth fault characteristic of syn-rift sequences (Figure 6b). During the restoration process, elongation of Lower Chum Seang unit is about 13.75% (4.9 km).

The sedimentary deposition continued widespread across the area of syn-rift section up to Early Miocene time (Figure 6c). During this time, the west border fault activity appears to have grown and the antithetic fault also developed. The sedimentary unit (Upper Chum Seang Fm.) shows thickening to the western border fault. The elongation shows extension from Late Oligocene time of 7.55 % (3.1 km). The first signs of thermal sag are observed during this time. This sagging stage results in the Upper Chum Seang unit being thicker in the center than in the western and eastern edge of the basin. During this period there are both the effects of asymmetrical rifting and sagging processes.

A west-dipping normal fault continued to develop as an antithetic fault in Middle Miocene (Figure 6d). Subsequent extension in the Middle Miocene resulted in an elongation of 9.52% (4.2 km) from Early Miocene. The west border fault continued to be active as a growth fault resulting in sedimentation thicker than on the eastern edge in the syn-rift section. Thermal sag continued during this time since there is thickening of sediments in the basin center with distinct geometry of convergent beds in the western and eastern edges of the basin. This is the result of subsidence in the synclinal areas increasing accommodation space for the deposition of thick Middle Miocene sediment (Pratu Tao Fm.). During this time there is a combined effect of rifting and sagging stages.

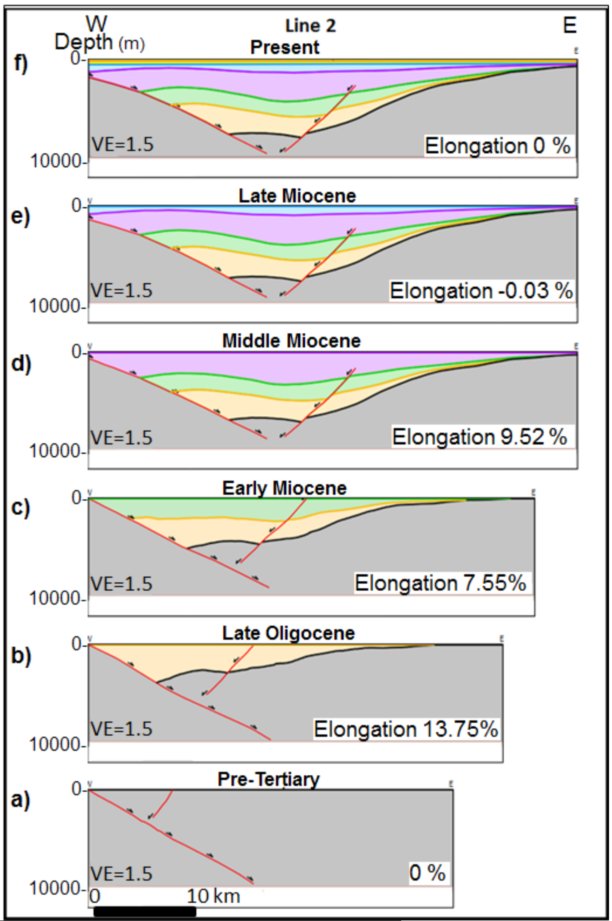
Activity on this antithetic fault continued in Middle Miocene and ceased before the Late Miocene deposit (Ping Fm.) (Figure 6e). It seem to be the late stage of extension as elongation remains unchanged in this period. Sagging process probably continued during this time, marked by the Ping unit deposition in the small synclinal troughs of the basins with thickening in the center of basin. Most sagging effects ceased within this period. A number of small shortenings of 0.03% (0.02 km) indicates that the extension was subdued after the deposition of Mid Miocene. Therefore the top of H01 is interpreted as the base of post-rifting on the blue line.

In the Pliocene to the Present-day, no faulting was observed during the restoration process. Most faulting, including the west border fault, ceased by the Middle Miocene. This is indicated by top Ping unit (H01) which is the start of consistent stratigraphic thickness of post rift section along the area as shown in yellow color with no change of elongation number (Figure 6f).

Structural restoration shows the basin at the top of the crystalline basement, prior to deformation with line length of about 35.82 km. The maximum extension can be observed during Late Oligocene. Total strain elongation from Pre-Tertiary to present is 12.2 km (33.9 %) indicating that the Sukhothai Depression was dominant by extensional forces.

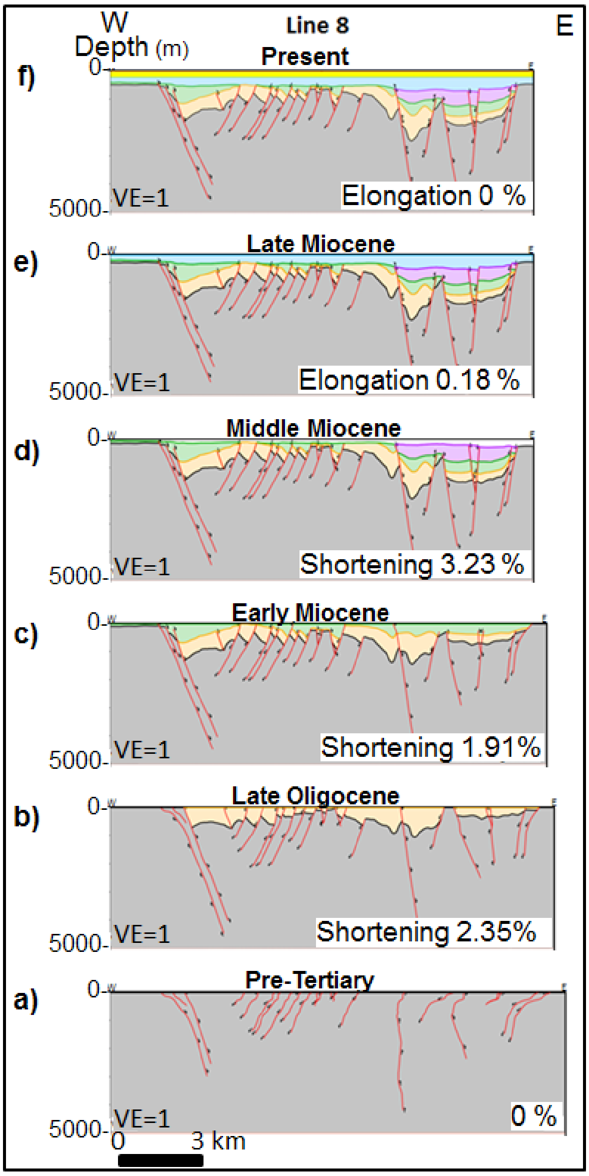
Line 8 (Southern area)

The structural restoration shows that the Bung Bon South basin began to form as the Pre-Tertiary basement was faulted due to extension (Figure 7a). The area developed as a half graben during the Late Oligocene bounded to the west by the east-dipping normal fault and a series of west-dipping antithetic tilted faults. The Late Oligocene sediment (Lower Chum Seang Fm.) thickens towards their respective



Unit	Top	Symbol	Formation
U1	H01		Ping
U2	H02		Pratu Tao
U3	H03		Upper Chum Saeng
U4	H04		Lower Chum Saeng
U5	H05	no colored	Crytalline Basement

Figure 6. Structural restoration of Line 2



Unit	Top	Symbol	Formation
U1	H01		Ping
U2	H02		Pratu Tao
U3	H03		Upper Chum Saeng
U4	H04		Lower Chum Saeng
U5	H05	no colored	Crytalline Basement

Figure 7. Structural restoration of Line 8

hanging walls of active normal faults forming a growth fault characteristic of syn-rift sequences (Figure 7b). During the restoration process, an erosion surface in the center of section indicates compressional during the Late Oligocene time. The elongation of Lower Chum Seang unit is about -2.35% (0.38 km). The sedimentary deposition continued widespread across the area of syn-rift section up to Early-Miocene time (Figure 7c). During this time, the west border fault activity appears to be growth and a series of synthetic faults also developed. The sedimentary unit (Upper Chum Seang Fm.) shows thickening to the western border fault and an erosion surface is observed in the center of section that indicates compressional has begun.

The elongation deviated from Late Oligocene time with -1.91% (0.3 km). During this period, there are both the effects of rifting and compression events. The elongation of Lower Chum Seang unit is about -1.91% (0.3 km).

Compressional event continued to develop in Middle Miocene (Figure 7d). Subsequently more erosion in the center of section resulted in an elongation of -3.23% (0.5

km) from Early Miocene. However, a small half graben appeared on the eastern side since there are thickening sediments of Middle Miocene deposit in the syn-rift section. It indicates a combined effect of compression and rifting processes.

Activity on the series of antithetic faults in the eastern part of the basin continued in Middle Miocene and ceased in the Late Miocene deposit (Ping Fm.) (Figure 7e). It seem to be the late stage of extension with minimal observed elongation change in this period. Sagging process probably continued during this time, marked by the Ping unit deposition in the small synclinal troughs of the basins with thickening in the eastern basin. Most sagging effects ceased within this period. A number of small elongation of 0.18% (0.03km) indicates that the extension is subdued after the deposition of Mid Miocene. Therefore the top of H01 is interpreted as the base of post-rifting on the blue line.

In the Pliocene to the Present-day, no faulting was observed during the restoration process. Most faulting including the west border fault ceased by the Middle Miocene. This is indicated by top Ping unit (H01) which began with a consistent stratigraphic thickness of post rift section along the area as show in yellow color with no change of elongation number (Figure 7f).

Structural restoration shows the basin at the top of the crystalline basement, prior to deformation with line length of about 16.21 km. The maximum extension can be observed during Early Miocene. Total strain elongation from Pre-Tertiary to present is -1.2 km (-7.2 %) indicating that the Bung Bon South sub-basin was dominant by the compressional forces.

5. Discussions

5.1 STRUCTURAL EVOLUTION OF THE PHITSANULOK BASIN

Based on structural restoration results the Phitsanulok basin formed when the Pre-Tertiary basement began to deform during Oligocene (30Ma). This timing is matched to the documented regional Indian – Eurasian collision tectonic event (Hall, 2012 and Pubellier and Morley, 2014). As the plot in figure 8a is an Extension History plotted between total line length measured from basin wide in each age (Y-axial) and Age (Ma) (X-axial), the high slope indicates increasing rate of line length, gentle slope indicates less increasing rate of line length, and flat slope indicates almost little to no extension of line length in the period of time. While the plot in figure 8b is showing a Subsidence History plotted between the maximum basin depth calculated in each age (Y-axial) and Age (Ma) (X-axial). This study will use these two plots together to illustrate both the vertical and lateral deformation of subsidence related to extension events in the same time. This study shows evidence of the maximum extension in concordance with the maximum subsidence in Late Oligocene (23Ma) (Figure 8a and 8b). The plot in figure 8a is showing slope increasing while the figure 8b showing high subsidence rate during 30 – 23 Ma indicating major rifting stage this time. Only the line 8 is showing shortening since 23 Ma which indicates the sub-basin had to be rifted before Late Oligocene (>30 Ma) and become inverted later on. This inversion possibly aligning with the regional tectonic of dextral strike-slip reactivation in Mae Ping and Three-Pagodas Faults during Late Oligocene (25 Ma) (2016 PTTEP Internal Study-Basin Geology and Tectonics of Southeast Asia), There is also in Morley et al., 2000 mention about unusual inversion structures that occur in Central and Northern Thailand that relate to 4-5 inversion events in the Late Oligocene – Miocene based on outcrop observation.

The extension continued with a low rate (low slope in fig 8a) and also with low subsidence rate until Early Miocene (18Ma). This probably indicates the declined stage of rifting. During Early to Middle Miocene (18 – 10 Ma), Sukhothai sub-basin still continued extension (Line 2,3 and 6) with a high subsidence rate again, while the Dong Chat, Bung Bon, and Nong Bua sub-basins (Line 13 and 10) are showing less extension (gentle slope in fig 8a) with some subsidence rate increase. This indicates that there might have be an interruption of the major sagging process during this time. During Middle to Late Miocene

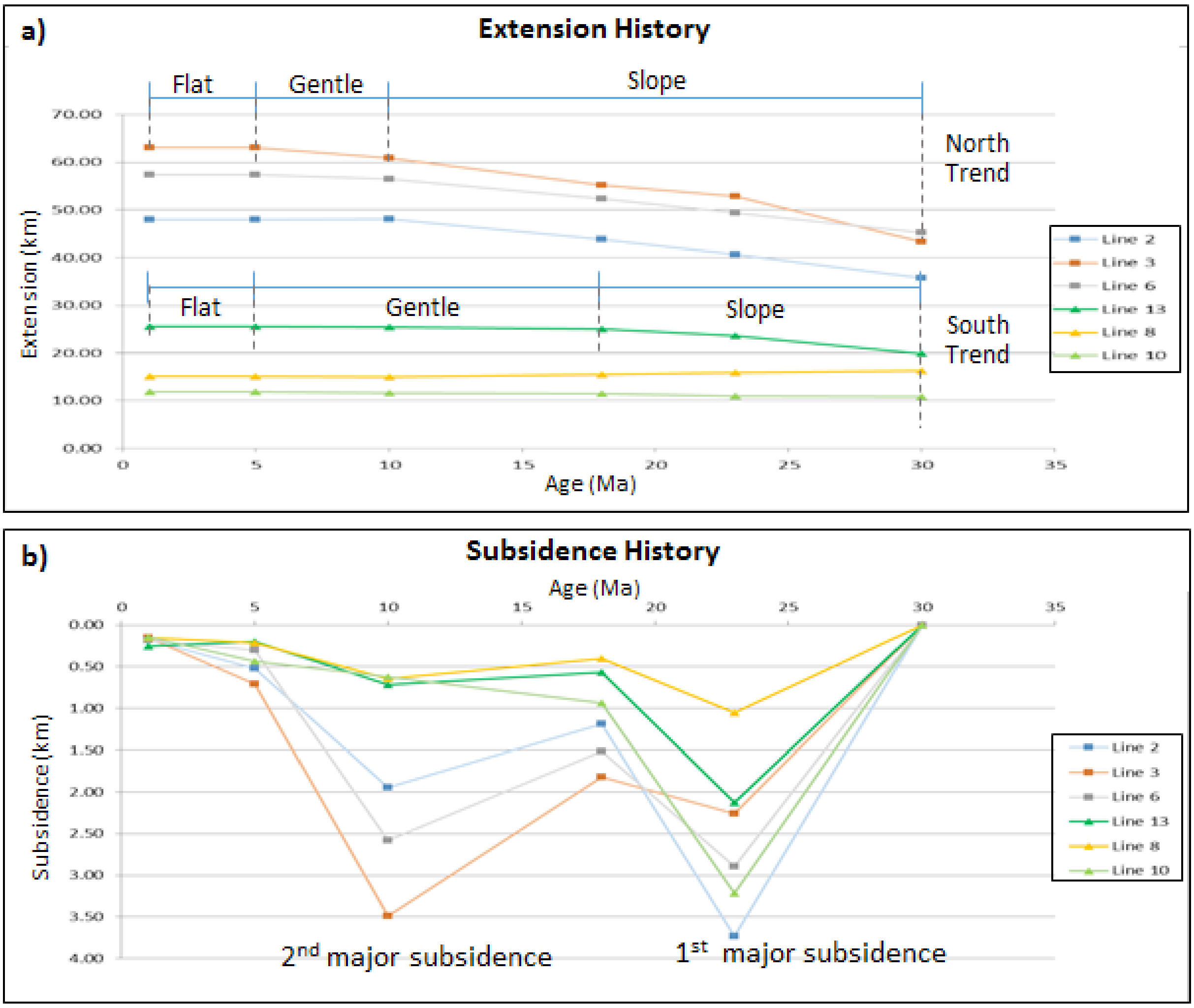


Figure 8. The extension and subsidence history along Phitsanulok's sub-basins through time (a) Extension history and (b) Subsidence history

(10 – 5 Ma), the extension slope was quite stable and the subsidence rate significantly decreased indicating the late stage of extension and rifting that became stable until present day. In summary, there are possibly 6 major stages of basin evolution in Phitsanulok sub-basin compiling with Morley et al., 2015 in Table 3 as below: I. Early extension in Early Oligocene? (>30Ma) is indicated by shortening section from line8. II. High extension rate with high subsidence rate, indicates major rifting stage in Late Oligocene (23 Ma),

III. Low extension rate with low subsidence rate, indicates declined stage of rifting in Early Miocene (18 Ma),

IV. Low extension rate with high subsidence rate, indicates sagging process interference in Middle Miocene (10 Ma),

V. Gentle extension rate with gentle subsidence rate, indicates most ending stage of rifting or early post-rift stage in late Miocene (5 Ma),

VI. Stable stage indicates Post-rift stage from 5 Ma until present day.

According to Morley et al. (2001) the structural evolution of the Phitsanulok Basin began with the Oligocene extension, which reached its climax in the Middle Miocene. Extension continued to the Late Miocene when structural inversion took place. new evidence of structural restoration suggests that the major rifting occurred earlier in Late Oligocene rather than in Middle Miocene. There are probably sagging process interference with the However,

Age		Tectonic events of Phitsanulok basin	
		Morley et al., 2015	**This Study**
Quaternary	**<5**	Plio-Pleistocene post-rift Inversion	Post-rift
Late Miocene	**5**	Minor extension Inversion	End Extension, Late Sagging
Middle Miocene	**10**	Extension, Inversion	Late Extension, Sagging, Local inversion
Early Miocene	**18**	Extension	Extension, Early Sagging, Local inversion
Late Oligocene	**23**		Major Extension, Local inversion
Early Oligocene	**>30**		Early Extension

* age reference (PTTEP,2016)

Table 3. The summary of the Tertiary structural events of Phitsanulok Basin.

new rifting process. The rifting process continued for a longer time until Late Miocene, and inversion can be observed since Late Oligocene. For the Phitsanulok basin evolution, the sub-basins had stopped extension progressively in a southern to northern direction. The northern basin has formed a larger geometry than the south and becomes the highest depositional accumulation area compared to the surrounding sub-basins.

5.2 IMPLICATION TO PETROLEUM SYSTEM

As stated previously, the Phitsanulok Basin is composed of several sub-basins. Most of them are characterized by syn-rift and sag subsidence and distinguished by a limited post-rift unit. All discoveries and production areas in the basin are located in the northern part. No discoveries exist in southern part around Bung Bon South and Nong Bua sub-basins.

Based on restoration results, the northern part of the basin comprises a major half-graben and several sub-basins, bound by a large east-dipping low angle normal fault to the west. The deepest part of the basin, termed the Sukhothai Depression, is located near the west fault. The basin is characterized by syn-rift subsidence and a pronounced sag subsidence without erosion and unconformity evidence. An extensive distribution of volcanism activity in northern part, as represented in 1988 Thai shell – Hydrocarbon Habitat in Phitsanulok Basin, is indicative of the second major subsidence. It is synchronous with volcanism in Middle to Late Miocene (17 – 9 Ma) in the northern sub-basins of Sukhothai Depression, Dong Chat, Bung Bon North, and Bung Chang. The location and timing of the flows of these igneous rocks coincide with the location and timing of maximum fault displacement in Sukhothai depression (Morley, 2009). The second major subsidence has implications that the basins were connected by lateral linkage and deeper geometry development associated with high heat flows in the crust. This is important for the maturation of source rocks and petroleum generation of the northern sub-basins.

The southern part of the basin is composed of a few rift basins; Bung Bon South and Nong Bua that display different structures and subsidence histories. The Nong Bua, which is representative of the southern sub-basins, is controlled by a high angle normal fault. It experienced limited subsidence and did not develop lateral growth with the adjacent basin (small isolate basin). As implied by the erosion and shortening in Line 8 of this study and 2D seismic interpretation of inversion in Nong Bua basin (Morley, 2007), the basin underwent uplift and erosion prior to the reduced second major subsidence. There was no volcanism activity (?) (Thai Shell, 1988), which should be disadvantageous for the maturation of source rocks and absence of regional top seal.

6. Conclusions

The section restoration method can provide important information as the section is structurally restored to a pre-deformed state. This can provide new ideas on the observed structure, insights into the geometry, extension and subsidence history in spatial variation and timing which is the essential information to enhance the understanding of basin and structural evolution analysis. However the application and type of analysis changes according to the available data, scales and study purposes.

The balancing and restoration technique can help ensure that the seismic interpretation is realistic and admissible and provide support for strain estimates, for example by determining the amount of extension or shortening along a cross-section by comparing undeformed and the deformed states.

Phitsanulok Basin is composed of several sub-basins. Most of them are characterized by syn-rift and sag subsidence and distinguished by a limited post-rift unit. The northern part of the basin comprises a major half-graben and several sub-basins, bound by a large east-dipping low angle normal fault to the west. The southern part of the basin is composed of a few rift basins that display different structures and subsidence complexes controlled and bounded by a high angle normal fault. Faulting and syn-rift growth continued until very recently in the basin's history. Most faulting is typically illustrated to die out around the base of Ping Formation (Late Miocene). The evidence for inversion and truncation surface can be found in the southern part of basin. There are very typical structural styles developed in the extensional basin.

Basin evolution resulting from section restoration is slightly different from previous published studies in terms of timing of rifting evolution. The major rifting occurred earlier in the Late Oligocene than Middle Miocene and continued for longer time until Late Miocene. The inversion structure can be observed since Late Oligocene. There is probably sagging process synchronous with rifting process since Middle Miocene and most faulting is typically illustrated to die out around the base of Late Miocene.

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