Structural Style and Evolution of the Songkhla Basin, western Gulf of Thailand

Chanida Kaewkor[1,2,*] ,Ian M. Watkinson[2], and Peter Burgess[2]

[1]Department of Mineral Fuels, Bangkok, Thailand, chanida@dmf.go.th and Chanida.Kaewkor.2013@live.rhul.ac.uk
[2]Department of Earth Sciences, Royal Holloway University of London, Surrey, UK.

ABSTRACT

The Gulf of Thailand is part of a suite of Cenozoic basins within Sundaland, the continental core of SE Asia. The Songkhla Basin, in the southwestern gulf, demonstrates several properties that have previously been considered to be characteristic of these basins, such as: multiple distinct phases of extension and inversion, rapid post-rift subsidence, association with low-angle normal faults; and a Basin and Range-style. A large asymmetric half-graben, bounded by NNW-SSE-trending faults along its western edge, the Songkhla Basin is approximately 75 km long, 30 km wide, and is separated from other subbasins in the gulf by a N-S trending basement horst block, the Ko Kra ridge.

Two oil fields in the Songkhla Basin produce approximately 12,000 bbls/d, but the structural evolution of the basin remains relatively poorly known. This paper utilises 3 wells and 2,250 km^2 of 3D seismic from the Songkhla Basin to understand basin structure and evolution.

Structural elements in the Songkhla Basin include a major border fault, inversion-related compressional structures and inter-basinal faults. Sediments thicken to the west along growth fault surfaces. Most of the faults are east-dipping but some are antithetic. Three dominant sets of normal faults, trending NNW-SSE, N-S and rarely NE-SW are developed in this basin. The NNW-SSE faults bounds the basin and are sub-parallel to the rift axis of the Songkhla basin. Pre-Cenozoic basement fabrics are oriented broadly N-S, slightly oblique to the dominant Cenozoic fault orientation.

There are three major tectonostratigraphic packages in the Songkhla Basin:1) syn-rift, which can be divided into three sub-extensional packages and expressed as Eocene initial rifting I; Oligocene II; and the final rift stage Lower Miocene III;2) a period of positive inversion and deposition of post-rift package I; the inversion started from early Middle Miocene and was followed by post-rift thermal subsidence terminated by the Mid-Miocene Unconformity (MMU); 3)the last tectonostratigraphic package is post-rift II, that was deposited from the start of the Late Miocene to Recent.

Keywords: Songkhla Basin, structure, inversion, syn-rift

1. INTRODUCTION

Thailand's Cenozoic basins are located in the continental core of Southeast Asia known as Sundaland (e.g. Polachan et al. 1991; Hall 1997; Hall and Morley 2004) (Figure 1). While basins around the margin of Sundaland may be related to subduction (e.g. Andaman Sea), the basins in the continental interior, including the Gulf of Thailand (GoT), have been variously classified as transtensional pull apart basins (Polachan and Sattayarak 1989), major continental rifting basins (Charusiri and Pum-Im 2009), and intracratonic rift basins (e.g. Woolland and Haws 1976; Chinbunchorn et al. 1989; Morley 2015). However, it has been highlighted that there are key differences from other typical intracratonic rifts. Many of the basins exhibit multiple distinct phases of extension and inversion, very rapid post-rift subsidence, association with low-angle normal faults, widely diachronous initiation and cessation of rifting, low-displacement post-rift faults; and the basins are set within hot, thin crust similar to the Basin and Range province, but surrounded by active plate boundaries (Morley 2015).

The Gulf of Thailand is the biggest petroleum producing province in Thailand (Racey 2011; DMF Annual Report 2012). Therefore, this area has been extensively explored for hydrocarbons. Most exploration success has been in the eastern GoT, Pattani and North Malay basins. Basin ages and geometry are generally well established (Morley and Racey 2011). Nevertheless, the age of the oldest rift section is still unclear in both the western and eastern GoT basins (Charusiri and Pum-Im 2009; Morley and Racey 2011). Furthermore, the mechanisms of externsion and inversion throughout the basins are not well constrained.

Repeated inversion alternating with extension in the Gulf of Thailand (Morley, 2015) is very important for petroleum exploration because extensional phases create accommodation space for hydrocarbon reservoir rocks, whilst inversion–related fold closures provide the main hydrocarbon trap. Repeated alternation between these phases can create an array of petroleum plays.

The Songkhla Basin is 75 km long, 30 km wide, and lies 8 km offshore Songkhla (Figure 1). It is separated from other sub-basins to the east by a N-S trending basement horst block, the Ko Kra ridge (e.g. Polachan et al. 1991; Charusiri and Pum-Im 2009; Morley and Racey 2011). There are 2 producing oil fields that produce approximately 12,000 bbls/d (DMF production report of July 2015) in this basin. The main reservoirs are Lower Oligocene sandstone trapped in three-way dip closures against basin-bounding faults.

The aims of this paper are: 1) to demonstrate the structural styles and evolution of Songkhla basin, using 3D seismic interpretation. 2) To examine the mechanism of inversion.

*Corresponding author: Chanida.Kaewkor.2013@live.rhul.ac.uk

GEOINDO 2015, November 23-24, 2015

2. REGIONAL TECTONIC SETTING

Cenozoic basins in Thailand are failed rifts located within the continental crust of Sundaland (e.g. Polachan et al. 1991; Hall 1997; Hall and Morley 2004; Morley, 2015). Sundaland is the south-eastern promontory of Eurasia, and is comprised of continental fragments accreted since the Paleozoic (e.g. Metcalfe 2013). Sundaland is bordered by both active and old subduction zones and its Ceonzoic tectonics have been driven by the relative movement of surrounding major plates: the Indian, Australian and West Pacific Plates (e.g. Tapponnier et al. 1982; Hall 1997; Longley 1997; Polachan and Sattayarak 1998; Charusiri and Pum-Im 2009; Meesook and Saengsrichan 2011; Searle and Morley 2011; DMR 2014). During the Cenozoic as India moved north, Southeast Asian blocks were progressively extruded south-eastwards with clockwise rotation (e.g. Tapponnier et al. 1982; Packham 1993), and the angle of subduction below western Sundaland changed from perpendicular to oblique (Morley et al. 2001). Continuously increasing subduction obliquity probably accelerated dextral shear along the western margin of Sundaland, coupled with extrusion-related sinistral shear (Tapponnier et al. 1986; Morley et al. 2001; 2002) along the NW-trending strike-slip faults further east, for example Red River-Ailao Shan, Mae Ping, and Three-Pagoda faults (Lacassin et al. 1997; Charusiri and Pum-Im 2009) (figure 1). Linked to this setting apparently dominated by strike-slip, early models for the Cenozoic basins of Thailand proposed a prominent role for rigid blocks bounded by strike-slip faults in their evolution (e.g. Tapponnier et al. 1986; Polachan et al. 1991). More recent studies emphasise the role of pre-Cenozoic basement weaknesses, underlying hot, weak crust and the dynamically evolving plate boundaries and their far-field effects (e.g. Hall and Morley 2004; Morley et al. 2011; Hall 2011; Morley 2015).

3. STRATIGRAPHY IN THE GULF OF THAILAND

Cenozoic sedimentary rocks are not well exposed onshore peninsular Thailand, and are best known from subsurface data acquired during hydrocarbon exploration. Hydrocarbons have been extensively explored in the GoT for over 40 years, particularly in the east. In contrast, there has been little detailed study of the western GoT basins (Table 1). Subsurface data reveal, for example, overall basin age and geometry, which are generally well established (Morley and Racey 2011). However, the oldest rift sediments remain unclear due to the lack of deep well penetration. Offshore pre-Cenozoic? basement rocks are also poorly identified.

3.1 Pre-Cenozoic Section

The Pre-Cenozoic section offshore in the GoT is poorly

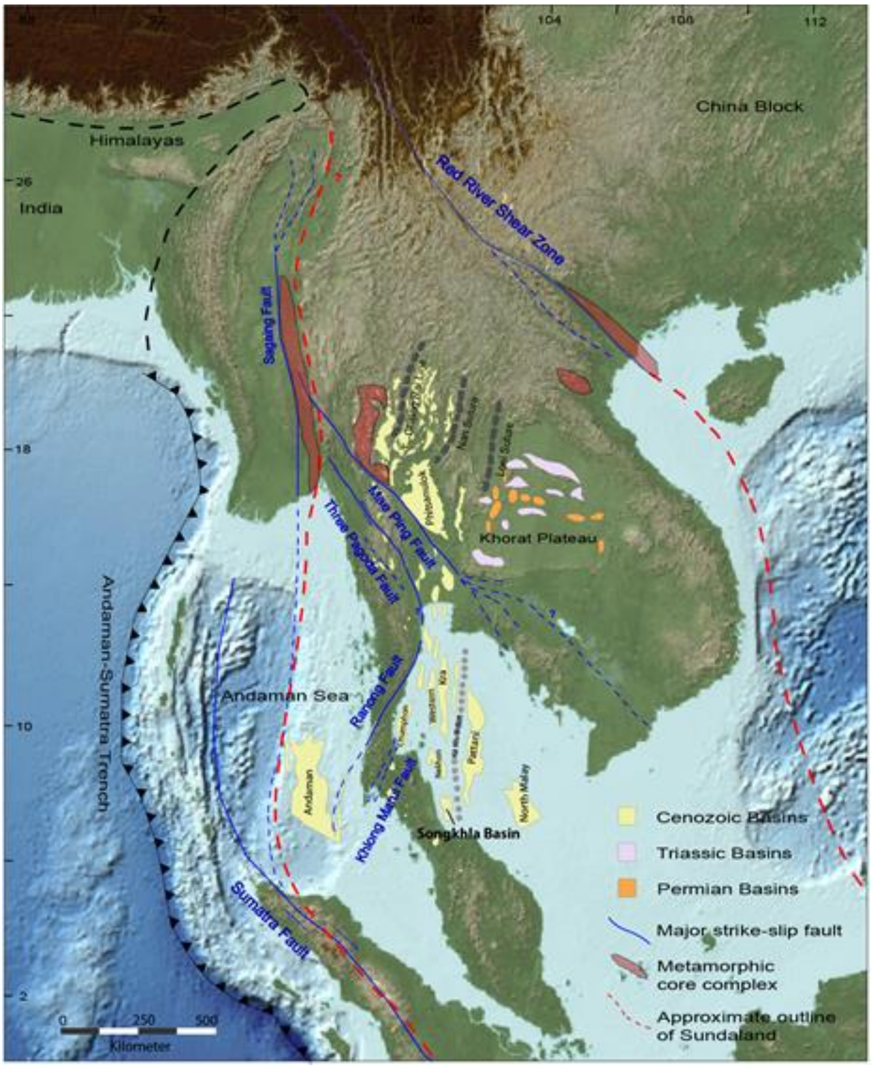

Figure 1 Study area and regional tectonic setting.

Table 1 A summary of Cenozoic stratigraphy and major tectonic in the Gult of Thailand (combined after Charusiri and Pum-Im, 2009 and DMR 2014)

Gulf of Thailand										
Age	Woodland and Haw, 1976					Lian and Bradley, 1986			Chinbunchorn et al., 1989	
	cycle	Northern GoT		Southern GoT		rock unit	lithology	environment	tectonic event	environment
		lithology	envi.	lithology	envi.					
Quaternary Pliocene Late Miocene	3 transgression	sandy, muddy and coal	restricted marine, floodplain	muddy,sandy, mudstone intercalation with coal and sandstone	floodplain, mangrove and restricted marine	4	muddy intercalated with sandstone and coal with some dolomite	floodplain, mangrove and restricted marine	post rift	fluvial floodplain and delta plain with marine sediments
Mid Miocene	2 regression	sandy, muddy, mudstone, limestone, and calcareous	fluvial floodplaindelta plain and mangrove	sandstone shale and coal	fluvial floodplain, delta, floodplain, mangrove and	3	varicolour mudstone and organic sandstone-coal-shale, thin bedded coal	fdelta fore front, salt lake and delta	rift	alluvial and lacustrine
Early Miocene						2				
Oligocene?	1 regression	sandstone and conglomerate	alluvial plain	sandstone siltstone mudstone and shale	along river and fluvial floodplain	1	varicolour shale intercalated with sandstone	floodplain and lacustrine		

Gulf of Thailand							Thailand Cenozoic Basin	
Age	Polachan et al., 1991				Unocal (Thailand)		Charusiri and Pum-Im, 2009	
	rock unit	lithology		environment	rock unit	environment	Age	Tectonic Episode
		west	east					
Quaternary Pliocene	4	mud, mudstone, and varicolour sandstone	mud, mudstone and gray sandstone	fluvial floodplain, mangrove and delta plain with marine	5	delta, marine	Recent to Lower Miocene	post-rifting
Late Miocene							Late Middle Miocene	transpression wrenching
Mid Miocene	3	shale, varicoloured mudstone, some sandstone, limestone and coal; organic shale, thin bedded coal and		fluvial floodplain, and delta, salt lake and restricted marine	4 3	alluvial, fluvial floodplain, salt lake and restricted	Middle Miocene	quietscent thermal subsequent
Early Miocene	2				2		Early to Middle Miocene	initial transtensional synrifting
Oligocene?	1	varicoloured shale and sandstone		alluvial floodplain and lacustrine	1	lacustrine	Early Eocene to Late Oligocene	pre-rifting, pull-apart and uplifting

documented due to the lack well penetrations and/or paleontological control (Morley and Racey 2011). In contrast, the Palaeozoic and Mesozoic section onshore has been studied in detail and is reasonably well understood (Barber, et al. 2011; Morley and Racey 2011). The late-Palaeozoic section is a passive margin sequence of clastics, (Kaeng Krachan Group), and platform carbonates, (Ratburi Formation) (Ridd et al. 2011). Onshore, in peninsular Thailand, this section is overlain by a Jurassic to Early Cretaceous section that begins with marginal marine deposits that pass upwards into a massive sequence of continental clastic sediments (Meesook and Saengsrichan 2011).

Therefore, the entire structural and stratigraphic framework established onshore has been used as a guide to the Pre-Cenozoic section in the GoT (figure 2). Achalabhuti (1981) proposed that the overall structure and basement configuration of the GoT area is grossly similar to the onshore structural trend of Thai-Malay Peninsula. The Narathiwat, Ko Kra Ridge, and the Samui Shelf are offshore prominent, northward plunging basement highs or horsts intruded by Cretaceous(?) granite. This section is unconformably overlain by Cenozoic sedimentary rocks.

3.2 Cenozoic Section

Cenozoic rift basins in Thailand share some similarities in origin, timing, sedimentary environments, and basin structural styles (e.g. Charusiri and Pum-Im 2009; Racey 2011, Morley and Racey 2011). Those basins contain major deposits of petroleum, coal and oil shale (e.g. Racey 2011; DMR 2014).

The entire Cenozoic rift basin system of the GoT is dominantly or entirely filled by continental deposits.. It is only in the post-rift phase that marine incursions become a feature of the GoT basins (e.g. Morley and Racey 2011; Shoup et al. 2012). The age of the top syn-rift section in the GoT varies across the area from Middle Oligocene in the east to Early Miocene in the northwest (Shoup et al. 2012). In the GoT, the oldest section from palynology appears to be Oligocene (Charusiri and Pum-Im 2009). Unpublished results from one well in the GoT demonstrated that the earliest rift stage was at least of Late Eocene age (Morley and Racey 2011). However, no specific dating of the strata has been done, so this inference needs to be confirmed by other evidence.

The Cenozoic sedimentary section in the GOT comprises a Paleogene fluvio-lacustrine syn-rift section that is overlain by a post-rift Neogene section that is predominantly alluvial in character (Racey 2011, Morley and Racey 2011). The transition from syn-rift to post-rift subsidence occurred in the eastern GoT in the Late Oligocene–Early Miocene and was marked by widespread lacustrine shales (Morley and Racey 2011). The Miocene post-rift comprises broad sag subsidence and progradation of marginal marine, deltaic/paralic facies across the gulf (e.g. Achalabhuti 1976, 1978; Wollands & Haw 1976; Leo 1997; Morley and Racey 2011). Huge sediment supply to the GoT during the Miocene–Recent (particularly the Early–Mid-Miocene) contributed to the thick post-rift section in the Pattani Basin (Jardine 1997; Morley & Westaway 2006; Morley and Racey 2011).

4. DATA AND METHODOLOGY

The Songkhla Basin dataset was provided by the Department of Mineral Fuels (DMF). It consists of 2,250 full fold km^2 of 3D seismic and 3 wells. 3D seismic data was acquired by WesternGeco on behalf of CEC Limited in 2012 (12.5 m line spacing). The survey was processed using a pre-stack time migration sequence in 2013.

The first step was to tie the wells to seismic, in order to tie depth domain to time domain using check shot data. Vertical seismic profiles were interpreted to identify key structure types and horizons mapped. Seven regional horizons were picked, at stratigraphic levels identified by well ties; 1 Pre-Cenozoic, 2 Eocene, 3 Lower Oligocene, 4, Upper Oligocene, 5 Lower Miocene, 6 Middle Miocene, and 7 Sea Bed.

The interpretation of each seismic horizon was initially made on every 20 seismic lines in both dip and strike directions. The rest of the horizon between the grid was automatically interpreted using Petrel software. After a reasonable interpretation was attained, a 3D grid surface was created based on the seismic-time.

5. INTERPRETATION RESULTS

The Songkhla basin is separated from the Pattani Basin by the Ko Kra ridge. The basin is a large half graben, with the controlling fault system along its western edge and the dominant structures in the basin are all related to variably inverted extensional faults.

5.1 Stratigraphy of the Songkhla basin

The age of initiation of Cenozoic extensional faulting in the Songkhla Basin is not known because the full sedimentary fill has not been penetrated. However, the oldest sediments encountered have been dated as Eocene, (Figure 2) which would make the Songkhla Basin one of the first Cenozoic basins to develop in this area. Dating of the oldest sedimentary fill was obtained from the Benjarong-1 well where clays from a core in the syn-rift sequence gave an age Early-Middle Eocene (Premier Oil, 1996), figure 2.

5.1.1 Pre-Cenozoic

The underlying basement is thought to vary considerably both below the basin and on the surrounding structural highs. To the west, seismic lines clearly show several well-bedded sedimentary packages below the unconformity Cenozoic section (figure 3). Although they have not been drilled, by analogy with onshore data these packages are likely to be clastics of various ages from Paleozoic to Mesozoic. Further to the east, and underlying the basin bounding fault, the basement sediments have been penetrated by some wells. They consist of Late Cretaceous interbedded red claystones and sandstones.

In contrast, the Pre-Cenozoic section of the eastern part of the basin is thought to be composed largely of granite, possibly with some preserved remnants of the Permian Rat Buri Group carbonates.

5.1.2 Eocene (Early to Middle)

Based on the company well report this section has been confirmed as Early-Middle Eocene by K-Ar Age dating (Premier Oil unpublished Final Well report 1996). This horizon overlies the Base Cenozoic pre-rift and has thicker sediments along major fault, as the pre-rift sequence had been tilted and created accommodation space for the sediments, thus theses sediments are classed as syn-rift. The sediment is deposited only in the depocentre and does not cover all the area. Sedimentology were described from well suggested that there are two sedimentary facies; fluvial channel facies and overbank facies. Fluvial channel facies comprises of conglomeratic sandstones, clast supported conglomerates, cross bedded medium sandstones. Overbank facies comprises of mottled sandstones, siltstones and mudstones, laminated and bioturbated fine sandstones. Seismic show dim to bright laterally discontinuous reflectors along the major faults may be represent erosional surfaces within fluvial facies. Therefore, integrated all data this section can be interpreted as fluvial and alluvial dominated environments.

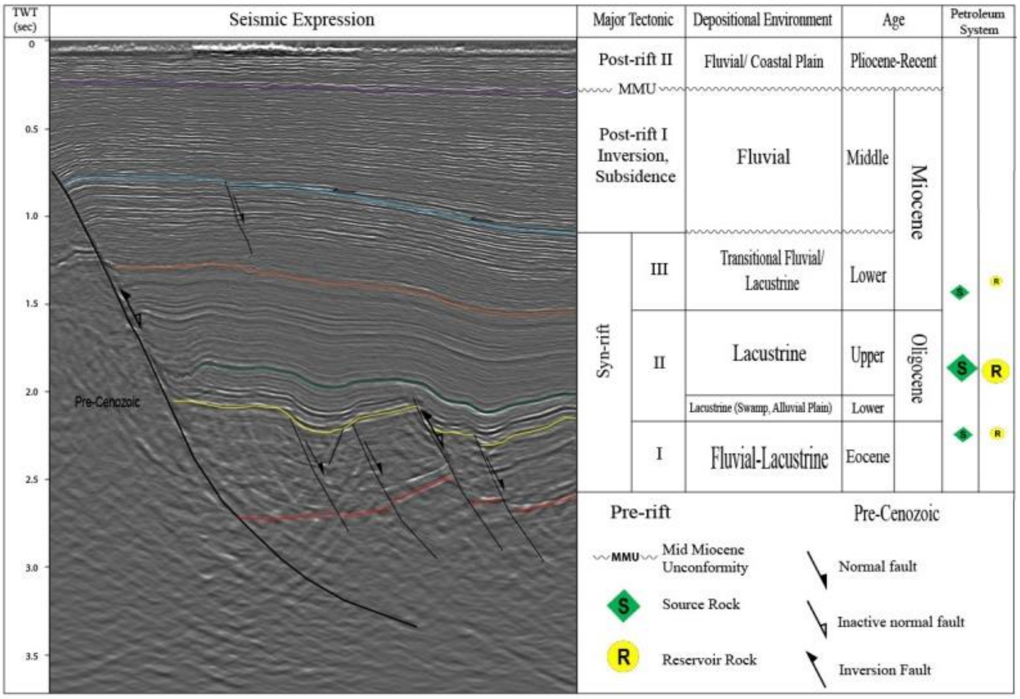

Figure 2 Stratigraphy of the Songkhla basin.

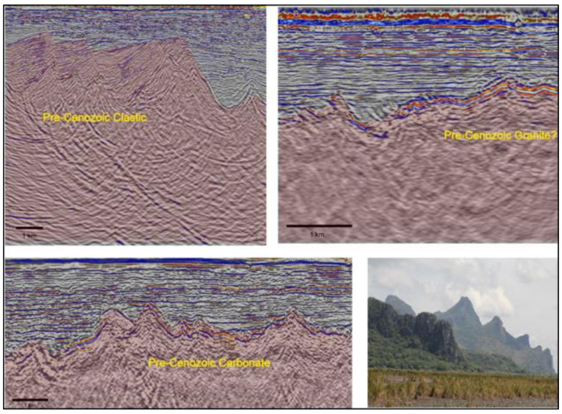

Figure 3 The seismic features indicated Pre-Cenozoic sedimentary section.

5.1.3 Lower Oligocene

The top Lower Oligocene consists of a thin sedimentary package across the whole Songkhla Basin, and is characterized by strong continuous, parallel to sub-parallel seismic reflectors. The section is less strongly faulted than deeper sections. Significant fault throws in this horizon can only be seen in the western part of the area along major east-dipping faults. The lower Oligocene section consists largely of lacustrine deposits, including thick, organic-rich shales with excellent oil source potential (Premier Oil unpublished Final Well report 1996).

5.1.4 Upper Oligocene

The upper Oligocene section extends across the basin, and is overlain by younger growth packages related to secondary fault systems. This section characterize by wavy, continuous reflection, moderate amplitude. The sediment in this sequence is composed predominantly of grey, non-organic lacustrine shales. Well penetrations have encountered relatively few, thin sandstones. Thus, the relatively thick, uniform shale sequence of this section could be a regional seal to the lower Oligocene and Eocene hydrocarbon systems.

5.1.5 Lower Miocene

Lower Miocene sediment had expanded outside the half-graben. The lower section has low amplitude, discontinuous reflection. While the seismic characters in the upper part show high amplitude, sub-continuous and erosional surface channel. This can be interpreted as a gradual transition from a dominantly lacustrine environment to fluvial environment.

5.1.6 Middle Miocene to Recent

The Middle Miocene horizon cut by some minor normal faults likely caused by differential compaction. The reflector of this package is good quality, and represents a prominent Middle Miocene unconformity that extends across the entire basin. The sediments were deposited over the whole study area above this unconformity. This unconformity was penetrated in the well, and marks the change from fluvial deposition below to shallow marine, coastal plain deposition above (Premier Oil unpublished Final Well report 1996).

5.2 Structural Style of Songkhla Basin

The main observed geological structures in seismic interpretation were locally listric normal growth faults that may detach in the basement, extension fault blocks and inversion structures. The majority of faults dip eastward with north-south orientation (Figures 4a and 4b). The growth faults of the basin are also east-dipping faults with strike sub-parallel to north-south basement high (e.g. Ko Kra ridge) in the area. These growth faults were recognized by syn-tectonic strata which thicken towards the fault.

The pre-Cenozoic section is dominated by large tilted fault blocks, with a deeply eroded upper angular unconformity. The most obvious pre-Cenozoic fault trend is a series of E-W trending normal faults. Seismic sections of the central part of the depocentre show positive inversionstructures. This inversion may be evidence of a switching in tectonic mode from extension to compression or changing paleo-stress direction. The fault block geometry is domino style and fault blocks appear as rotated slabs in cross section.
The other observed features are syn-depositional detached normal fault assemblages. Generally, this structural style comprises of both synthetic and antithetic faults. These detached normal fault assemblages can be seen similarly in the whole area but in the northern part, these are steeper and structure more developed as compared to the south.

In term of fault orientations three sets of normal faults, trending NNW-SSE, N-S and rarely NE SW are developed in the basin. The NNW-SSE faults bounds the basin and are roughly parallel to the rift axis of the Songkhla basin. The pre-Cenozoic fabrics oriented in more or less N-S while the Cenozoic faults normally in NNW-SSE direction.

5.3 Basin Evolution

The interpretation results indicated that there are several major phases of tectonic activities. The initial basin forming was due to tectonic extension (resulting in earliest syn-rift sediment deposition) which can be divided into three sub-rift packages separated by unconformities, after this, positive inversion was dominant, resulting in reactivation of basin-bounding rift faults as reverse fault, hangingwall anticlines and basin uplift. A final phase of post-rift subsidence is most pronounced over the syn-rift depocentre.

5.3.1 Syn-rift Episode (Eocene-Lower Miocene)

The initial syn-rift starting from Early to Middle Eocene (syn-rift I), was followed by Oligocene and Lower Miocene, syn-rift II and III, each separated by minor unconformities. The syn-rift packages were classified based on 1) top lapping of overlying sequences, 2) the unconformity or discordance between the upper and lower section, 3) the sediment thickening towards the bounding fault, 4) sedimentary facies changes and 5) overall wedge shape geometry of the package (Figure 5).
On seismic reflection data, the syn-rift section shows a clear half-graben style, with predominantly NNW-SSE trending master faults.

5.3.2 Inversion, Post-Rift I and Subsidence Episode (Middle Miocene)

Inversion of the syn-rift section in this basin is very important in terms of petroleum systems, particularly in the lower Oligocene section (Figure 4, 6, and 7).

The positive inversion was dominant, resulting in reactivation of basin-bounding rift faults as reverse fault, hangingwall anticlines and basin uplift. Apart from basin bounding faults, the Eocene to Lower Oligocene faults show minor inversion-related structures, particularly in the middle area but only in the Lower Oligocene section (Figure 4, 6, and 7).

The inversion was focused along the western margin fault. The vertical seismic profile clearly shows sediment onlapping onto Lower Miocene section (syn-inversion), indicating that the inversion probably started from early Middle Miocene. Moreover, seismic profiles clearly show the unconformity at the top of the fold. The hangingwall segments were uplift and caused the fault-related fold structure, the top surface was eroded. The fold related inversion structure in this area appear different feature. The Upper Oligocene to Lower Miocene part shows less significant deformation, with gentle but widespread folds. However, the Lower Oligocene section manifests high deformation, tight folds particularly along the western margin, and more patchy anticlinal distribution. The inversion probably ended around mid-Middle Miocene, marked by the Mid-Miocene Unconformity (MMU), then the post-rift sediment I was deposited across the whole area. It clearly shows the subsidence or sagging in the middle part of Middle Miocene section.

5.3.3 Post-Rift II (Middle Miocene to Recent)

This episode commenced when extension and inversion in the basin ceased, as no growth faults are associated with the thick post-rift package. Clastic sedimentation, starting immediately before the beginning of the Miocene, rapidly became widespread across the basin. This package began with fluvial– coastal plain sediments.

6. DISCUSSION

Rifting has been considered to have begun earlier (?Eocene–Oligocene) and ended earlier (Late Oligocene) in the eastern GoT, compared to many basins in the western GoT, such as the Songkhla Basin, where the rifting was considered to be Late Oligocene–Middle Miocene (Morley and Racey 2011)**.** However, this paper proposes that extension in the Songkhla basin began by at least the Middle Eocene, a result confirmed by the company well K-Ar age dating.

Petroleum has been extensively explored in the eastern GoT, where Pattani and North Malay basins are located, it is reflects that basic difference in the Cenozoic geology from the western GoT. The Songkhla Basin is separated from the Pattani Basin by the Ko Kra Ridge – a palaeo-topographic high that means the basins have a discrete general geology and stratigraphy. However, there are fundamental differences for example; 1) basement

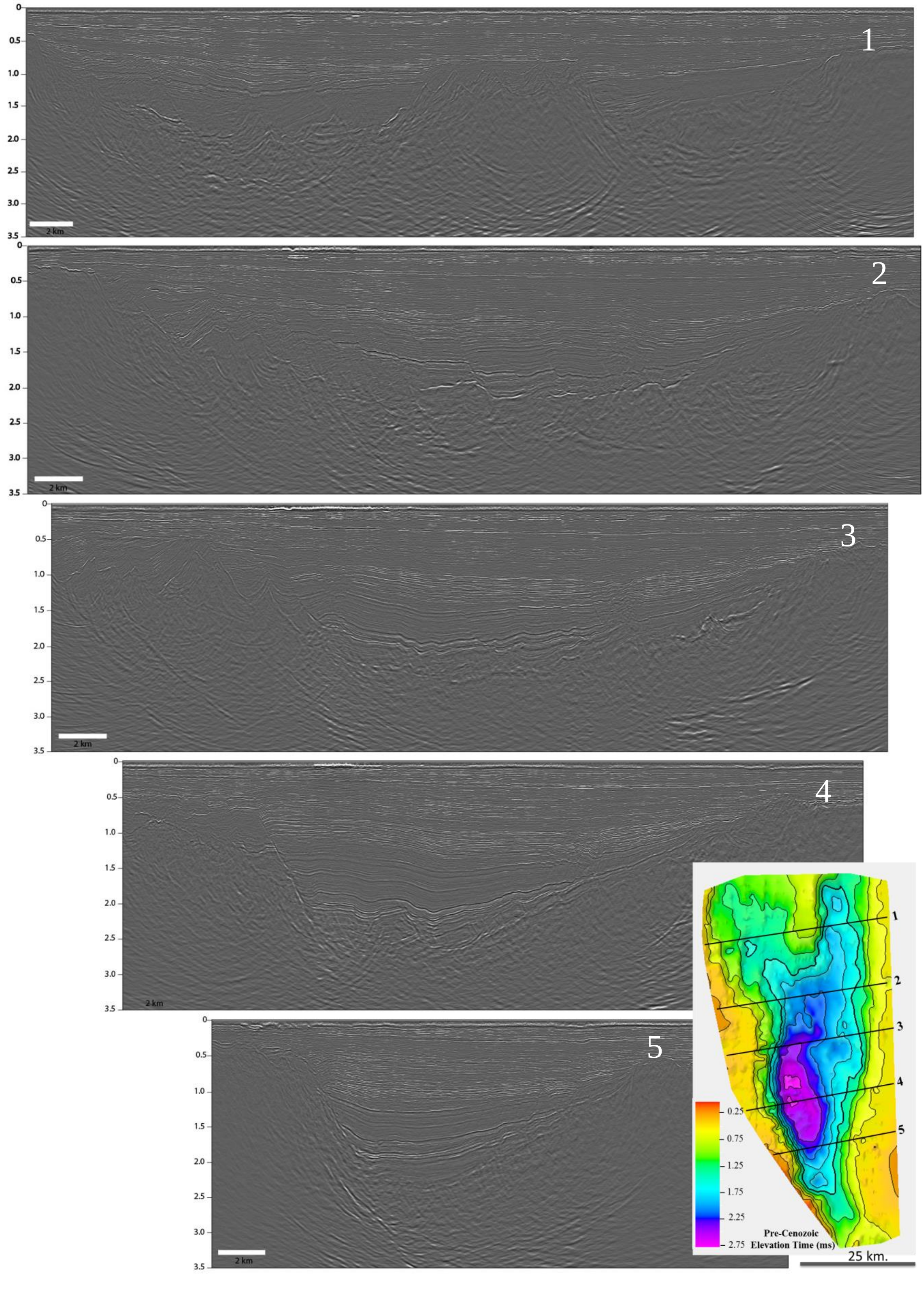

Figure 4a The original seismic profile from the northern to the southern area (VE=3)

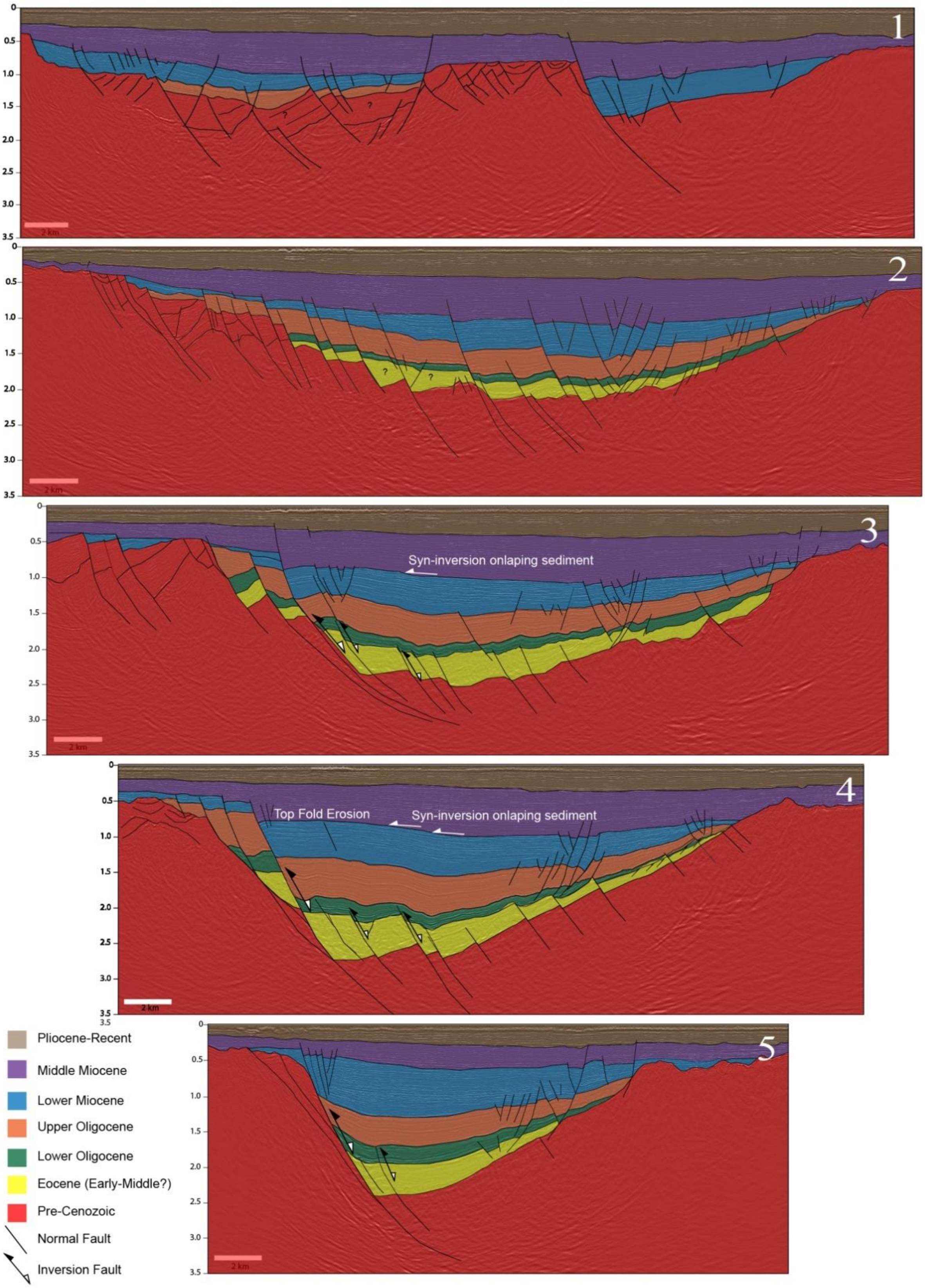

Figure 4b The seismic interpretation of Figure 4a. Cross-section showing basin geometry and structural development. The main observed geological structures were growth faults, extension fault blocks, inversion structures and detached normal fault assemblages. The majority of faults dip eastward with north-south orientation. These faults were recognized by syn-tectonic strata which thicken towards the fault. The pre-Cenozoic section is dominated by large E-W trending of tilted fault blocks, with a deeply eroded upper angular unconformity. Along the central part of the depocentre show positive inversion-related structures. The fault block geometry is domino style and fault blocks appear as rotated slabs in cross section. The syn-depositional detached normal fault assemblages can be observed as both synthetic and antithetic faults which can be seen similarly in the whole area but in the northern part, these are steeper and structure more developed as compared to the south.

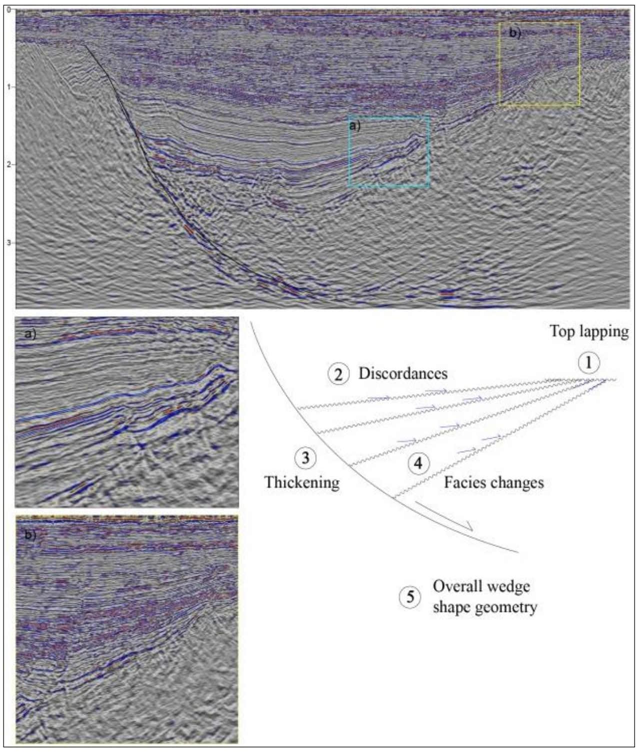

Figure 5 A simple model explaning criteria used to establish the case for a syn-rift succession. Five main criteria were classified as 1) Top lapping, 2) Discordances or unconformity, 3) Sediment thickening toward the major fault, 4) Sedimentary facies changes, and 5) Overall wedge shape geometry.

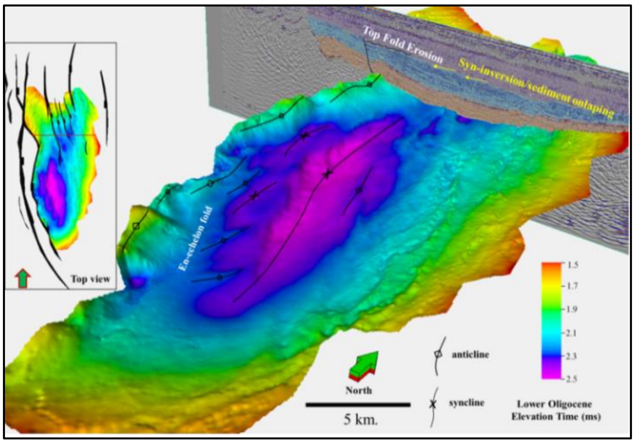

Figure 6 Lower Oligocene time elevation map. The folding structures were highlight. The inversion occurred along western margin fault and some from Eocene to Lower Oligocene fault in the middle part. The vertical seismic profile clearly shows the onlap sediment onto Lower Miocene section (syn-inversion) and clearly shows the erosion at the top of the fold. The inversion of Lower Oligocene show patchy fold but high magnitude.

structure; 2) early Miocene sediment in the Songkhla basin is much shallower structural level than the Pattani basin; 3) the main petroleum system in the Songkhla Basin is in the lower Oligocene, while the lower to middle Miocene sections host major petroleum systems in the Pattani basin.

The main reservoir in the Songkhla basin is the Lower Oligocene sandstone that is trapped in three-way dip closures against basin-bounding faults. These closures are related to the Lower Miocene inversion. Inversion-related deformation of the upper part of syn-rift sediment (Upper Oligocene to Lower Miocene) is widespread and almost consistent across the whole basin and is expressed by gentle anticlines. Inversion in the lower section (Lower Oligocene) is minimal and localized, expressed by appear widely distributed anticlinal folds but with smaller interlimb angles. The inversion occurred during early Middle Miocene along the western margin fault and also the Eocene to Lower Oligocene faults show evidence of minor reactivation, particularly in the middle area. Reactivation structures are discontinuous, suggesting that movement on the deeper faults was not connected or was soft-linked to those in the upper sedimentary section. Further study should focus on structural analysis in this area. The time of inversion is indicated by onlap of sediments onto the Lower Miocene section (syn-inversion). This timing matches the timing of transpression during of the Cenozoic , as proposed by Charusiri and Pum-Im 2009.

The lower Oligocene section consists largely of lacustrine deposits, including thick, organic-rich shales. Hydrocarbons were expulsed at this time, and perhaps resultant high pore pressures localised inversion-related deformation. Thus, this section has more mobility and deformation. Therefore, the main factor causing inversion is a regional transpression event. The magnitude of deformation depends on lithology and local structures, including source rock maturation.

7. CONCLUSION

The Songkhla Basin is a large asymmetric half-graben, bounded by NNW-SSE-trending faults along its western edge and is separated from other sub-basins in the gulf by a N-S trending basement horst block, the Ko Kra ridge.
Structural elements in the basin include a major border fault, inversion-related compressional structures and inter-basinal faults. Sediments thicken to the west along growth fault surfaces. Most of the faults are east dipping but some are antithetic. The fault orientation has three sets of normal faults, trending NNW-SSE, N-S and rarely NE SW developed in this basin. The NNW-SSE faults bounds the basin and are roughly parallel to rift axis of the Songkhla basin. The pre-Cenozoic fabrics oriented in more or less N-S while the Cenozoic faults normally in NNW-SSE direction.

The interpretation results indicated that there are several major phases of tectonic activities. The initial basin forming was due to tectonic extension, after this, positive inversion was dominant. A final phase of post-rift subsidence is most pronounced over the syn-rift depocentre.

The syn-rift phase can be divided into three sub-extensional package separated by unconformities and expressed as Eocene initial rifting I; Oligocene II; and Lower Miocene III the final rift stage. A period of positive inversion and post-rift I during Middle Miocene.

The last tectonic event is post-rift II that start from upper Miocene to Recent.

The inversion occurred along western margin fault, resulting in reactivation of basin-bounding rift faults as reverse fault, hangingwall anticlines and basin uplift. It start from early Middle Miocene end around mid-Middle Miocene

8. ACKNOWLEDGMENTS

I grateful acknowledge the Department of Mineral Fuels (DMF) for research funding and data providing, and also CEC Limited for data permission. I would like to express my sincere thanks to Department of Earth Sciences, Royal Holloway University of London.

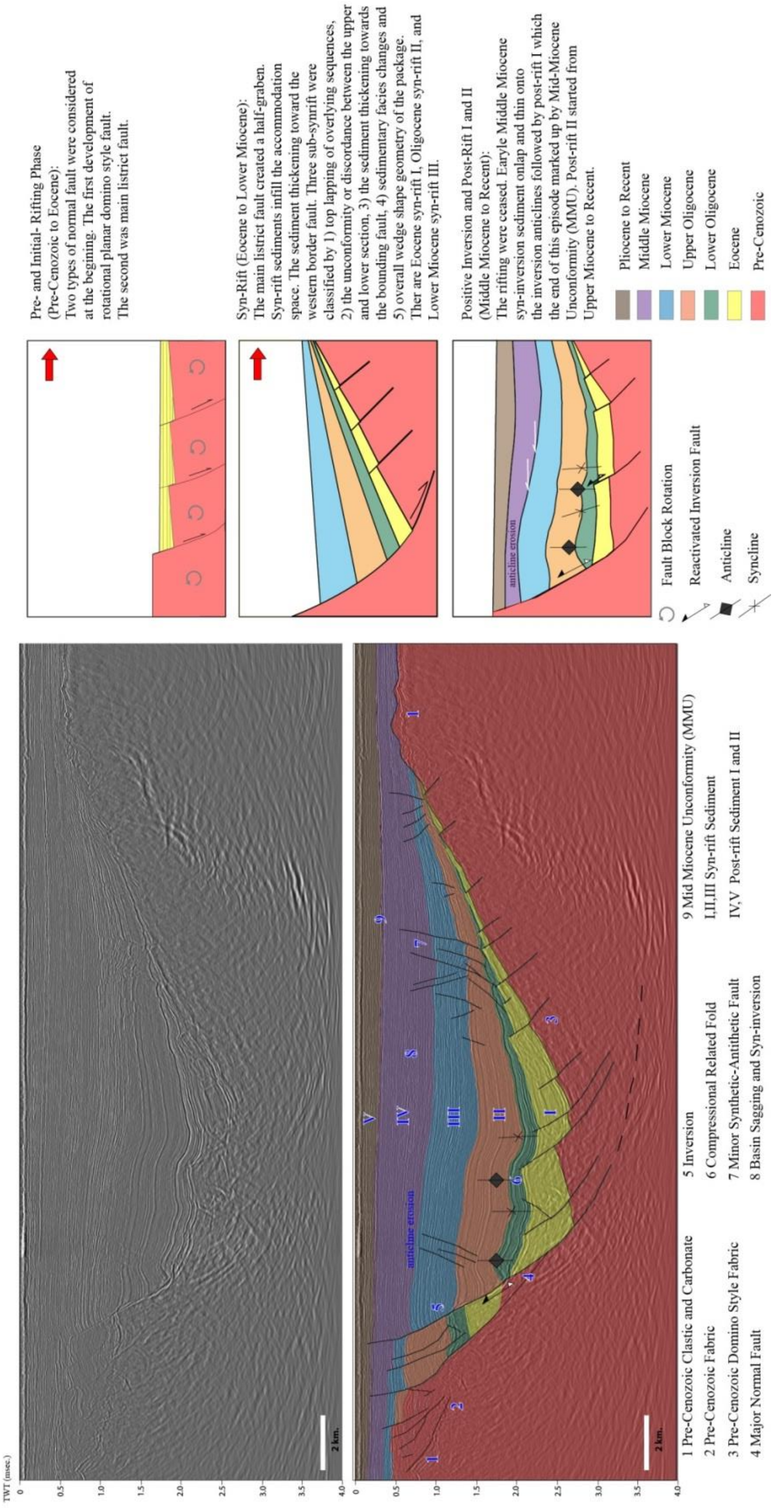

Figure 7 A summary of structural styles and evolution of the Songkhla basin

9. REFERENCES

Chantong, W., Burrett, C., and Songtham, W., 2014, Geology of the Gulf of Thailand and the Andaman: In Geology of Thailand. Department of Mineral Resources, 243-262

Charusiri, P., and Pum-Im, S., 2009, Cenozoic Tectonic Evolution of Major Sedimentary Basins in Central, Northern, and the Gulf of Thailand, BEST, v. 2, p. 40-62.

Hall, R., 1996. Reconstructing Cenozoic SE Asia. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of SE Asia. Geological Society of London Special Publication, v.106, p.153-184.

Hall, R., 1997: Cenozoic plate tectonic reconstructions of SE Asia; in Fraser, A.J., Matthews, S.J., and Murphy, R.W. (eds.), Petroleum Geology of Southeast Asia, Geological Society Special Publication No. 126, 11-23.

Hall, R. & Morley, C. K. 2004. Sundaland Basins. In: Clift, P., Wang, P., Kuhnt, W. & Hayes, D. (eds) Continental–Ocean Interactions within East Asian Marginal Seas. AGU Special Publications, 149, 55–87.

Hall, R., 2002, Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations, Journal of Asian Earth Sciences, v.20, p.353-432

Jardine, E., 1997, Dual petroleum systems governing the prolific Pattani Basin, offshore Thailand, In: Dheeradilok, P., Hinthong, C., Chaodumrong, P., Putthapiban, P., Tansathien, W., Utha-aroon, C., Sattayarak, T., and Techawan, S. (eds.), The International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific, Bangkok, Thailand, p.525-534.

Longley, I.M., 1997, The tectonostratigraphic evolution of SE Asia; in Fraser, A.J., Matthews, S.J., and Murphy, R.W. (eds.), Petroleum Geology of Southeast Asia, Geological Society Special Publication No. 126, 311-339.

Matthews, S.J., Fraser, A.J., Lowe, S., Todd, S.P., and Peel, F.J., 1997: Structure, stratigraphy and petroleum geology of the SE Nam Con Son Basin, offshore Vietnam; in Fraser, A.J., Matthews, S.J., and Murphy, R.W. (eds.), Petroleum Geology of Southeast Asia, Geological Society Special Publication No. 126, 89-106

Meesuk, A., and Saengsrichan, W., 2011, Jurassic: The Geology of Thailand, In: Ridd, M.F., Barber, A. J., and Crow. M. J., The Geological Society London, 151-168.

Metcalfe, I., 2011. Tectonic framework and Phanerozoic evolution of Sundaland, Gondwana Research, v.19, p.3–21

Metcalfe, I., 2013, Gondwana dispersion and Asian accretion: Tectonic and palaeogeographic evolution of eastern Tethys, Journal of Earth Sciences. V. 66, p. 1-33

Morley, C.K., 2001, Combined escape tectonics and subduction rollback arc extension: a model for the evolution of Tertiary Basin in Thailand, Malaysia and Lao, The Geological Society London, v.158, p. 461-474

Morley, C.K., 2002. A tectonic model for the Tertiary evolution of strike-slip faults and rift basins in SE Asia, Tectonophysics, v.347, p.189–215.

Morley, C.K., 2013, Development of the Khao Khwang Fold and Thrust Belt: Implications for the geodynamic setting of Thailand and Cambodia during the Indosinian Orogeny, Journal of Asian Earth Sciences, v.62, p.705-719

Morley, C.K., 2014, The widespread occurrence of low-angle normal faults in a rift setting: Review of examples from Thailand, and implications for their origin and evolution, Earth Sciences Review, v.133, p.18-42

Morley, C.K., 2015, Five anomalous structural aspects of rift basins in Thailand and their impact on petroleum systems, Geological Society, London, Special Publications, 421

Morley, C. K. and Westaway , R. 2006. Subsidence in the super-deep Pattani and Malay basins of Southeast Asia: a coupled model incorporating lowercrustal flow in response to post-rift sediment loading. Basin Research, 18, 51-84.

Morley, C.K., Charusiri, P., and Watkinson, I. M., 2011, Structural Geology of Thailand during the Cenozoic: The Geology of Thailand, In: Ridd, M.F., Barber, A. J., and Crow. M. J., The Geological Society London, 273-334.

Morley, C. K. & Racey, A., 2011, Tertiary stratigraphy, In: Ridd, M. F., Barber, A. J. & Crow, M. J. (eds) The Geology of Thailand. Geological Society, London, 223–271.

Packham, G.H., 1993. Plate tectonics and the development of sedimentary basins of the dextral regime in western Southeast Asia. Journal of Southeast Asian Earth Sciences, v.8, nos. 1-4, 497-451.

Polachan, S., Pradidtan, S., Tongtaow, C., Janmaha, S., Intarawijitr, K., and Sangsuwan, C., 1991: Development of Cenozoic basins in Thailand; Marine and Petroleum Geology, 8, 84-97.

Polachan, S. and Sattayarak, N., 1989. Strike-slip tectonics and the development of Tertiary basins in Thailand. In Proceedings on the International Symposium on Intermontane Basins, Chiang Mai University, Chiang Mai, 343-353

Pradidtan, S., and Dook, R., 1992, Petroleum Geology of the Northern Part of the Gulf of Thailand, In: Piancharoen, C. (ed), National Conference on "Geologic Resources of Thailand: Potential for Future Development", Department of Mineral Resources,17-24 November 1 992, Bangkok, Thailand, 235-245.

Premier Oil Pacific Ltd, 1996, Benjarong-1, Unpublished Final Well Report, DMF

Racey, A., 2011, Petroleum Geology: The Geology of Thailand, In: Ridd, M.F., Barber, A. J., and Crow. M. J., The Geological Society London, 351-392.

Ridd, M.F., 2012, The role of strike-slip faults in the displacement of the Palaeotethys suture zone in Southeast Thailand, Journal of Asian Earth Sciences, v.51, p.63-84

Searle, M. P. and Morley, C. K., 2011, Tectonic and thermal evolution of Thailand in the regional context of SE Asia. In: Ridd, M. F., Barber, A. J. & Crow, M. J. (eds) The Geology of Thailand. Geological Society, London, 539–571.

Shoup, R., C., Morley, R., J., Swiecicki, T., and Clark, S., 2012, Tectono-stratigraphic Framework and Tertiary Paleogeography of Southeast Asia: Gulf of Thailand to South Vietnam Shelf, abstract for oral presentation in AAPG International Conference and Exhibition, Singapore, September 16-19, 2012,

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., and Cobbold, P., 1982: Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine; Geology, 10, 611-616.

Tapponnier, P., Peltzer, G., and Armijo, R., 1986: On the mechanics of the collision between India and Asia; in Coward, M.P., and Ries, A.C. (eds.), Collision Tectonics, Geological Society Special Publication No. 19, 115-157.

Woolands, M. A. and Haw, D., 1976. Tertiary stratigraphy and sedimentation in the Gulf of Thailand. In Proceedings of the SEAPEX Offshore SE Asia Conference, Southeast Asia Petroleum Exploration society, Singapore, 1-22

DMF annual report 2012, Department of Mineral Fuels http://www.dmf.go.th/resources/annualReport/annual/en/annualReport_en_2012.pdf

DMF Monthly Production Report (July 2015) http://www.dmf.go.th/service/monthlyReport.php?m=7&y=2015&ln=en