Cenozoic Tectonic Evolution of Major Sedimentary Basins in Central, Northern, and the Gulf of Thailand

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Abstract

In Thailand all major N-S trending Cenozoic basins are inferred to have developed in Late Eocene to early Oligocene as a result of the 'extrusion' tectonics of Southeast Asian block along the major NE-SW trending fault zones. These pull-apart basins in Thailand and nearby can be grouped based upon geomorphology, sequence stratigraphy, structural styles, geographical distribution, and geotectonic evolution into 6 segments viz. (1) isolated, basinal Northwest & West Segment, (2) intermontane faulted-bounded northern Segment, (3) large alluvial plain-dominated Central Segment, (4) basin-bearing plateau-type Northeastern Segment, (5) isolated, narrow intermontane Southern Segment, and (6) fault-bounded, largely subsided Gulf Segments. Individual segments can be divided into various sub-segments and several small basins.

Stratigraphic evolution of the deposition system of Thailand basins active during Early Tertiary, commenced with initial localized lacustrine and alluvial deposition in the Oligocene. Subsequent stratigraphy is dominated by sedimentation with significant hydrocarbon- and carbon-prone units, starting with fluvial and alluvial deposition in the lower unit (<100 to 2,500 m thick) in some basins and switched to transgressive fluvial and marginal marine deposition (<500 to 1,000 m thick) in the middle, and terminated by the overall regressive fluvial and alluvial deposition in the upper unit. The youngest sequence is dominated by alluvial and marginal marine sediments occurring in the Late Miocene to Pliocene.

Both ^{40}Ar - ^{39}Ar and K-Ar geochronological data together with fission - track dating information on rocks collected immediately at or close to these faults, indicate that the faults may have been reactivated episodically since very Late Cretaceous to Early Tertiary, and in turn given rise to several episodes of basin development.

Two major fault zones include NW -trending Three-Pagoda and Mae Ping Faults in the north and the conjugate, NE-trending Ranong and Klong Marui Faults in the South. The N-trending faults may have been developed in response to the principal strike-slip movement, and mostly they are normal with basement-involved listric and antithetic faults.

Four main tectonic episodes for major Cenozoic Basin development in Thailand are recognized. The first episode is the pull-apart and initial transtensional synrifting event (55 - 35) Ma) with the occurrence of rift sediments deposited by continental extension and mantle plume due to a change from continental margin to subduction for the interaction of India and Asia. This episode is marked at the end by the Middle Tertiary unconformity (MTU). The second episode is the quiescent thermal subsidence event (35 - 15 Ma) involving the significant transtensional component with rapidly basinal subsidence and widening by withdrawal of heat from the back-are region (the Gulf and the Andaman Sea) as well as widespread transpression and extensive delta progradation. Several basins were occupied by several fresh water lakes and marshes during that time, giving rise to carbon/hydrocarbon accumulation. The third episode is characterized by transpression wrenching event (15 - 10 Ma) due to the on-going dextral shear along the major NW-trending fault zones with subsequent basin inversion and folding resulting in a decrease and

more uniform subsidence rate and extensive basin highs with concomitant volcanism. The termination of this event is marked by the late Middle Miocene unconformity (MMU). The last episode is denoted by post-rifting event (10 Ma -Recent), thereby the entire region may have been tectonically adjusted. Onshore basins became inversed with terrestrial deposits covered whereas those in the Gulf were gradually and intermittently subsided with marine incursion without any significant hydrocarbon potentials.

Keywords: Cenozoic, Tectonic, Basins, Thailand

1. Introduction

It is at present widely accepted that the occurrence of all the Cenozoic basins in Thailand and perhaps all SE Asia (Fig. 1) has been controlled, to some extent, by the interaction of Australia-India, Burma, and the SE Asian plates (Packham, 1990, 1993; Peltzer and Tapponnier, 1988, Polachan and Sattayarak, 1998, McCabe et al., 1988, Bal et al., 1992, Bunopas and Vella, 1983, Pradittan and Dook, 1992, Market et al., 1997) since Early to Middle Tertiary.

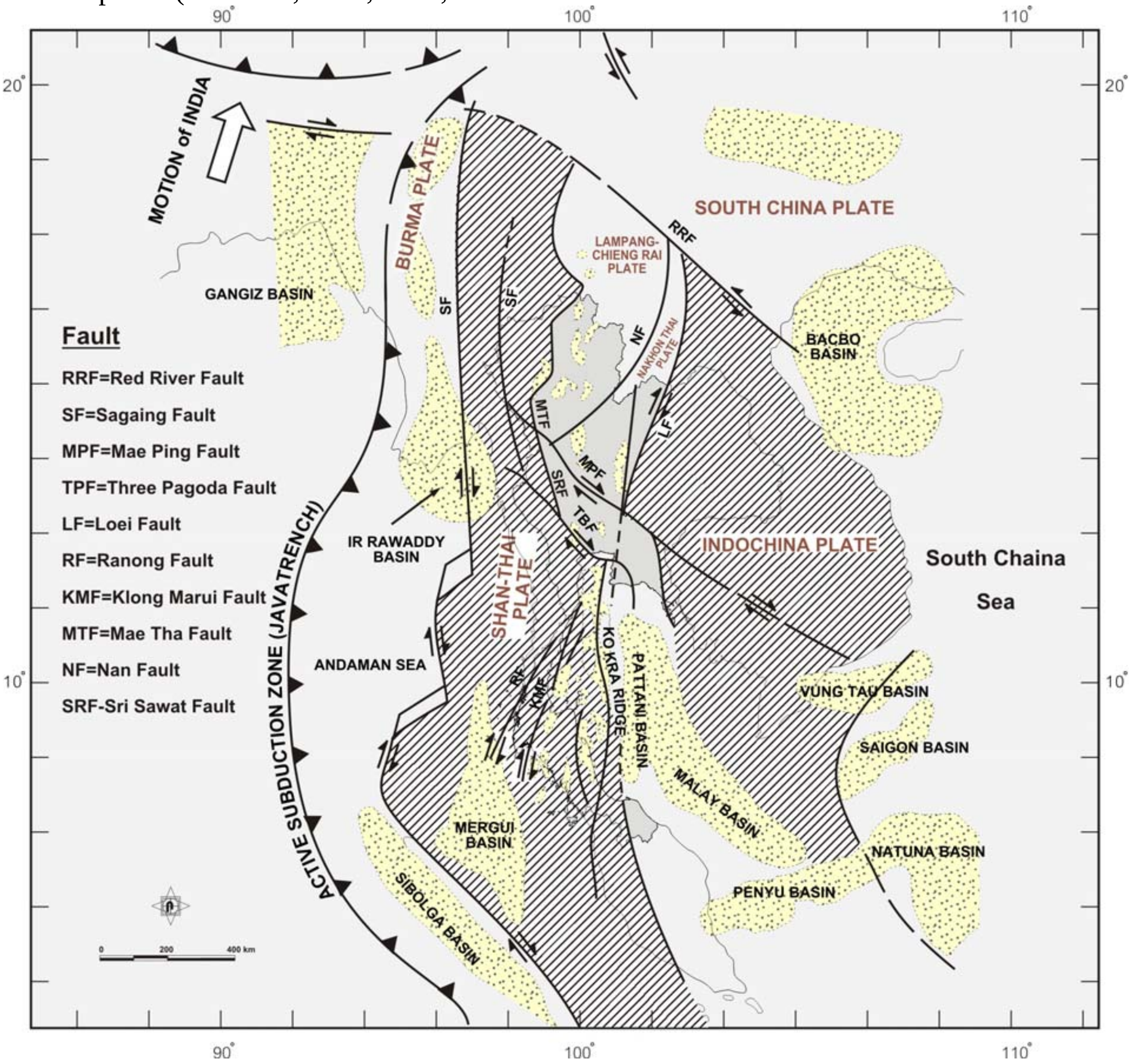

Figure 1: Major Cenozoic tectonic basins in SE Asia (modified from Hutchison, 1989, Bal et al., 1992).

Cenozoic deposits have been the focus of interest following 1981 discovery of the Sirikit Oilfield, central Thailand. Quite relatively little propriety information on subsurface geology was released during the main period of exploration. However, recently several reports and papers have been available to the public through conferences and scientific articles (e.g., Polachan and Sattayarak, 1989, Pradidtan et al., 1992, Remus et al., 1993, Markel et al., 1997, Morley, 2004, 2007, Morley et al., 2000, 2001, 2004, 2007a, b, c).

Cenozoic basins in Thailand were first investigated by Lee (1923), and 5 basins were reported at that time. Brown et al. (1951) discovered 8 basins in the south and 6 basins in the north. Piyasin (1972) introduced the term Mae Moh Group with the type section of Tertiary stratigraphy within the Mae Moh areas, Lampang for applying to Cenozoic basins in adjoining areas. Suensilpong et al. (1979) introduced the "Krabi Group" for the stratigraphic sequences that occurred within Tertiary in Thailand and subdivided it into 2 formations, namely Mae Mo Formation and Li Formation. The first Tertiary stratigraphy based upon petroleum drilling information was made by Buravas (1973) for the Fang basin, northern Thailand (no. 1 in Fig. 2), and 6 formations were proposed, including Nam Pad (Paleocene), Li (Oligocene), Mae Mo (Miocene), Mae Sod (Pliocene), Fang (Pleistocene), and Chao Phraya (Recent). In southern peninsular of the Andaman coast, Garson et al. (1975) proposed the Krabi Group for the Cenozoic sedimentary strata occurring in that region. Subsequently, Gibling and Rattanasathien (1980), on the basis of grain-size distribution, subdivided Cenozoic sediments into 3 contrasting facies - coarse terrigeneous, fine terrigeneous, and fine terrigeneous/carbonate facies. The first compilation of the Cenozoic Basins in Thailand was performed by Chaudumrong et al. (1983).

The aims of this paper are to propose a new classification of basins in Thailand, to compile most recent data on stratigraphy, structure and geochronology related to major Cenozoic basins in Thailand, and to apply them to disclose the tectonic evolution of the basins.

2. Basin Category

In this paper, we select only the major Cenozoic Basins for explaining their tectonic evolution. Although Chaodumrong et al. (1983) reported up to 61 basins in Thailand, since then there was no such a systematic compilation like that. However two decades afterwards, more information has been gained through petroleum exploration and production. We therefore propose a new category of basin classification in Thailand (Fig. 2) based upon our analyses on structural styles, tectonic cvolution, geographic distribution, and morphology using our field, borehole, landsat image, aerial photographic, previously available investigations. Cenozoic basins in Thailand are simply categorized into 7 segments corresponding to the tectonic subdivision of Thailand proposed by Charusiri et al. (1998). These segments include Northern, Northwest-West, Central, Northeastern, Southern, Gulf, and Andaman segments. Among these, the basin-bearing plateau Northeastern Segment seems to be the one without prominent Tertiary strata and will not be mentioned in this study. To the east, a small Tertiary basin (Klaeng Basin, see Fig. 2) with thin coal seams and underclays has been recently discovered (Salyapongse, per. Com.)

Fig. 2 shows the distribution of these seven segments. It is figured out, based upon air-borne magnetic interpretation (Tulyatid and Charusiri, 1999), that the major basins in northern and central Thailand were situated within the terranes occupied mainly by paleo-oceanic crust. The Northeastern segments which limits only within the Indochina tectonic block can be subdivided into 2 major Pre-Cenozoic basins - a) Udon - Sakolnakhon Basin and b) Khorat - Udon Basin.

The Northwest -West Segment Comprises 3 main N- S trending, isolated basinal sub-segments including 1) Chiangmai, 2) Mae Hong Son, and 3) Karn - Prachuab Sub-segments. Among these, the Chiangmai sub-segment is the biggest sub-segment. The Chiangmai Sub-segment includes 4 major basins - a) Sarm Ngao, b) Li, c) Chiangmai, and d) Chiang Dao. The Mae Hong Son Sub-segments includes 10 small basins from north to south as a) Wiang Haeng, b) Pai, c) Muang Khong, d) Khun Yuam, e) Mae Chaem, f) Mae Sariang, g) Bo Luang, h) Ta Song Yang I) Mae sod, and j) Mae La Mao Basins. The Karn-Prachaub Segment is devided into 5 small and narrow basins namely a) Mae Chan Ta, b) Thong Phaphum, c) Sri Sawat, d) Nong Ya Plong, and e) Nong Plab Basins. Two last small basins are to some extent controlled by the Ranong Fault Zone. All the basins of the Northwest - West Segment are situated to the easternmost part of the Shan Thai block. Fang-Mae Tha, Srisawat and Ranong Fault Zones seem to control the western boundary of this basinal segment.

The intermontane basinal and fault - bounded Northern Segment, whose basins are located within the so-called Lampang - Chiang Rai tectonic block, is bounded to west and east by the Chiangmai and Nan sutures, respectively. The Northern Segment is further subdivided into 4 sub-segments, including 1) Lampang, 2) Chiang Rai, 3) Phrae, and 4) Nan Sub-segments. The Lampang sub-segments consists of 8 basins, including a) Fang, b) Phrao, c) Mae Saruai, d) Wiang Papao, e) Pan, f) Wang Nua, g) Lampang, and h) Mae Prick. The Chiang Rai Sub-segment comprises 7 basins, including a) Chiang Rai b) Payao c) Jae Hom - Jae Khon, d) Mae Teep, c) Mae Moh, and f) Wang Chin - Long Basins. The Phrae Sub-segment contains 5 basins, namely a) Chiang Khong, b) Chiang Kharn, c) Pong, d) Chiang Muan, and e) Phrae Basins. The Nan Sub-segment is composed of 4 basins, including a) Pua, b) Nan, c) Na Noi, and d) Fak Tha basins. All the basins of the Northern segment seem to be controlled by faults, some of which are regarded to be tectonically active at present (Charusiri et al., 2000). The Nan Sub-segment is likely to be controlled by Pua and Nan Faults. The Phrae Sub-segment is constrained by Phrae and Uttaradit Faults. The Lampang Sub-segment is somewhat assigned by Nam Mae Lao Fault. According to Polachan (1988) and Polachan andSattayarak (1989), these faults are collectively called Northern Thailand Fault Zone.

In central Thailand, the Central Segment, the large alluvial - dominated plain, consists of three sub-segments, namely Upper Chao Praya, Lower Chao Praya, and Phetchaboon Sub-segments and is bounded to the north by the Nan Fault, the west by the Sri Sawat Fault, the south by the Three-Pagoda Fault and the east by the Phetchabun Fault. The Upper Chao Praya Sub-segment comprises 4 large basins including a) Pitsanulok, b) Nong Bua, c) Lad Yao, and d) Nakhon Sawan Basin, the former being the largest. The basins are considered herein to be the southern extension of the Nakhon Thai block. The Lower Chao Praya Sub-segment is limited to the north by the Mae Ping fault. Four other basins constitute this sub-segment, i.e., a) Ayuthaya, b) Suphanburi, c) Kampang Saen, and d) Thonburi. Shape of the segment is delineated by the Mae Ping (Morley et al., 2007c) and Kham Pang Saen Fault Zones. The Phetchabun Sub-segment forms almost 300 km long and narrow intermontaine basin lying in the N-S trend and chiefly comprises one isolated basin called Nong Pai - Petchaboon Basin. The basin is principally controlled by the Petchaboon Fault Zone.

In southern Thailand, about a dozen of small, isolated, and narrow intermontane basins constitute the upper and Lower Peninsular sub-segments. Only 8 basins are recognized, namely a) Kian Sa, b) Sin Pun, c) Krabi, d) Huai Yod, e) Kan Tang, f) Sadao, g) Betong, and h) Sabayoi Basins. These eight basins were developed within the NE-trending Surat - Krabi and the NNE-trending Pattani Fault Zones.

In the Gulf of Thailand, we subdivide the Gulf Segment into 2 major sub-segments including Western Gulf and Eastern Gulf Sub-segments, separated from each other by Ko Kra Ridge. This ridge perhaps extends to the south and joins the Pattani Fault. The Western Sub-segment includes 9 graben - type basins - Sakorn, Paknam, Hua Hin, Northwest, Western, Kra, Chumporn, Nakhon Srithammarat, and Songkhla Basins. The Eastern Sub-segment consists of 2 major basins, namely Pattani and Malay basins and one smaller basin -the Khmer Basin. In the Andaman Sea only the Mergui Sub-segment (or Basin) belongs to Thailand.

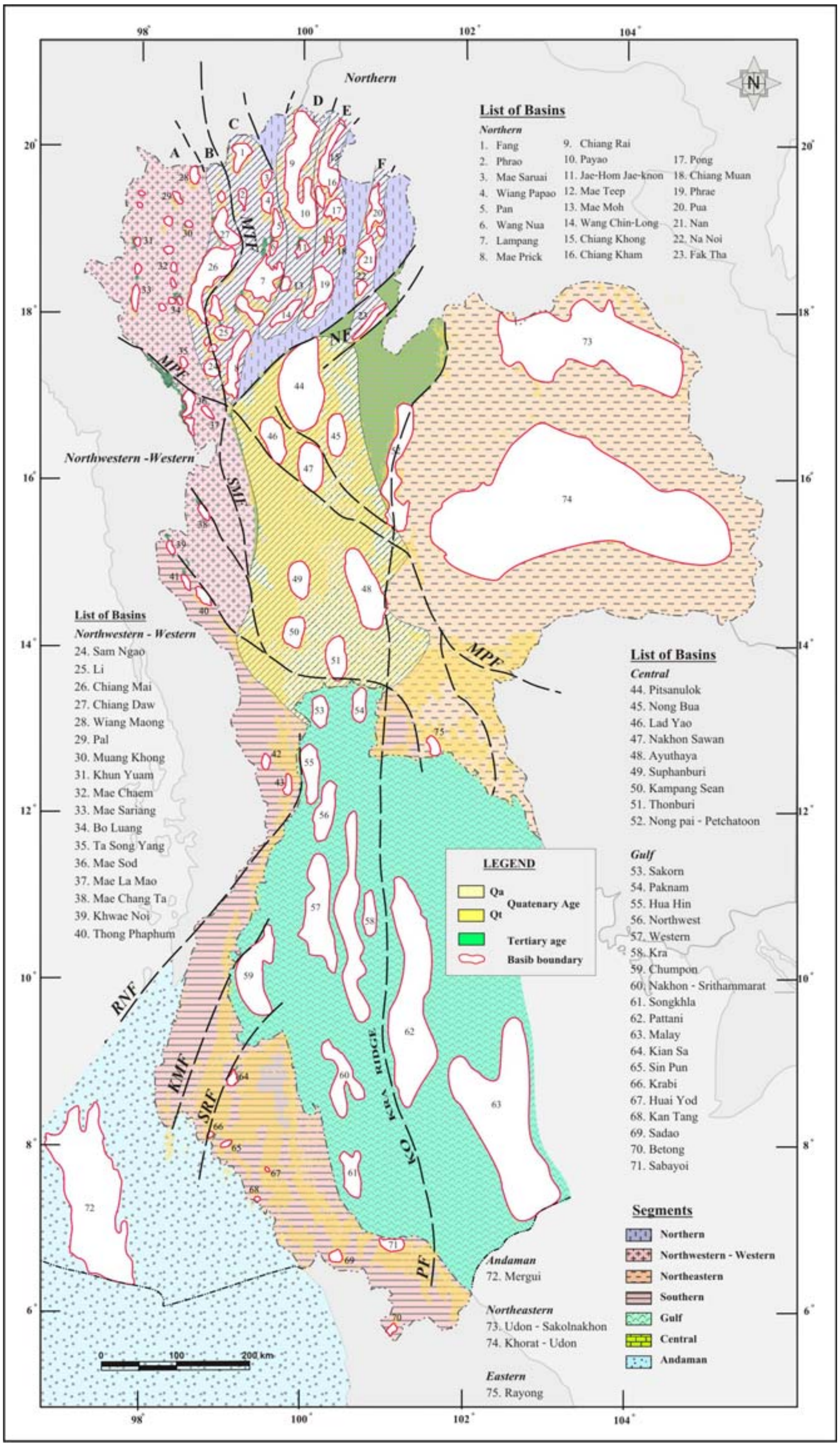

Figure 2: Distribution of Cenozoic basins with associated and significant fault systems in Thailand. (MPF = Mae Ping Fault, TPF = Three – Pagoda Fault, NF = Nan Fault, RNF = Ranong Fault, KMF = Klong Marui Fault, SWF = Sri Sawat Fault, MTF = Mae Tha Fault). Insert map – major tectonic subdivision in Thailand (Charusiri et al., 2000a).

3. Regional Stratigraphy

In our study, emphasis is placed on the major basins which are regarded as representatives of the sub-segments. They are the Fang and the Mae Moh Basins of the Northern, the Phitsanulok Basin for the Upper Chao Praya, the Suphanburi Basin for the Lower Chao Praya, the Chumporn Basin for the Western Gulf, and the Pattani Basin for the Eastern – Gulf Sub-segments.

Tertiary sedimentation throughout the entire SE Asia displays a well – defined series of transgression and regression cycles (Beddos, 1980, Wollands and Haw, 1976, Pradittan et al., 1992, Pradittan and Dook, 1992). The first cycle which is a Paleogene transgressive cycle (Eocene to Oligocene) is represented by lacustrine / marine clastics deposited over pre- Tertiary rocks. A second cycle is a major transgressive cycle (Early Miocene to Late Middle Miocene) and characterized by Late Miocene fluvio-lacustrine sediments. A third cycle was dominated by Miocene regression, overlapped subsequently by Early Pliocene transgression, and terminated by Pleistocene to Quaternary regression. However, in Thailand marine clastics "sensu stricto" are much less developed than those of the lacustrine environment. It seems recognized that at the end of each cycle in Thailand and perhaps SE Asia (see Packham, 1993) is marked by the major unconformity remarkably corresponds to a period of regional tectonic activity.

Stratigraphy of the Chumporn basin (Pradittan et al., 1992) is marked by the occurrence of at least 1,000 m thick, Middle to Late Paleogene red brown claystones with few thinly bedded sandstones in the middle parts. The sequence is interpreted to indicate flood plains with marginal lacustrine conditions. The middle sequence consists chiefly of 600 m – thick gray claystone with thin interlayers of thinly bedded lignites in the upper part and red brown sandstones of coarsening upward facies in the lower. These sediments are considered to have deposited in the lacustrine and lacustrine deltaic environment. The upper sequence is dominated by Miocene multi-colored claystones/sandstones with intercalated lignite seams and sandstones/conglomerates with dominated coarsening – upward facies in the lower part. These sediments are inferred to have deposited in flood plains of the lower part and fluviatiles for the upper. The uppermost sequence comprises predominantly up to 200 m-thick varicolored to grey claystone and occasionally sandstone. Coastal plains to inner neritic environments are suggested for the environment of deposition.

For the Eastern Gulf Sub-segment, its stratigraphy is denoted by the Pattani Basin, the largest basin in the Gulf (see Fig. 1), by which geologic settings were earlier described (Lian and Bradley, 1986, Pradittan et al., 1992, Lockhart et al., 1997). Five Sequences were recognized by seismic reflection and drill-hole data (Jardine, 1997). The Late Oligocene reddish brown claystone and siltstone with the thickness of 650 m are predominated in Sequence 1. Very coarse- to fine – grained sandstone and argillaceous are dominant in the lower part and multiple unconformities are very characteristic (Lockhart et al., 1997(. The depositional environments are inferred to be lacustrine and alluvial – fan wedges and fluvial – plain channel deposits for the Sequence 1. Sequence 2 of 300 – 1,200 m-thick referred to as the Lower Redbeds, includes Lower Miocene variegated, dark brown to reddish brown claystone and grey to clear, fine- to coarse – grained sandstone with occasional lignite seams and lenses. These sediments are considered to have formed as fluvial point-bar and channel deposits in the northern and central Pattani Basin (Jardine, 1997) and as upper intertidal, fluvial, and lower deltaic plains in the southern basin (Lockhart et al., 1997). Sequence 3, which may have occurred during early Middle Miocene, is referred as Upper Grey bed with the average thickness of 500 m. The sequence comprises light to brownish grey claystone, mudstone with interbeds of sandstone, argillite and coal seams. The sequence is considered to have occurred in coastal plain, mangrove, swamp marginal marine, and upper intertidal to subtidal lagoonal environments. Sequence 4 is characterized by the 900 m-thick Upper Redbeds of Late Middle to Upper Miocene. This sequence comprises predominantly of fine- to coarse grained sandstone and varicolored claystones (Pradittan et al., 1992). Grey claystone and lignite lenses are quite dominant locally. However, the unit is discontinuous, particularly in the southernmost basin (Lockhart et al., 1997). The sequence is inferred to have deposited as point – bar and channel – filled deposits in the fluvial – flood plain environment. Sequence 5, the youngest unit, is predominated by 1,200-1,800 m-thick, unconsolidated grey claystones with extensive coals and shle in the lower part. Fine- to medium – grained sandstones and limestones are locally present. The sequence deposited initially in the deltaic plain to marginal marine (outer littoral to sublittoral) environment and culminated in a further shift towards normal marine, neritic condition during Upper Miocene to Recent.

The Phitsanulok Basin is the largest and representative basin of the Upper Chao Praya Sub-segment, whose stratigraphy has been subdivided by Bal et al. (1992) into 8 lithostratigraphic units constituting the so-called Phitsanulok Group (Oligocene to Recent) with the diachronous nature of many formations (Makel et al., 1997, Morley et al., 2007a, b). The oldest sequence is dominated by alluvial – fan and fan – delta clastics of the Sarabob Formation with the thickness varying from less than 500 m up to more than 2,500 m. The Sarabob Formation may have formed successively during Late Oligocene to early Miocene and lateral – facies change to Nong Bua Formation (up to 2,000 m thick) which displayed proto-lacustrine and lacustrine environment in the middle basin. The Sarabob Formation also exhibits lateral – facies change with the fan – delta clastics of Khom Formation in the northern basin and is sometimes overlain by this clastic unit to the east. The Khom Formation has the thickness not more than 1,000 m. The forth and fifth formations are Early to Middle Miocene open – lacustrine Chumsaeng Formation (up to 1,000 m) in the south and fluvio – deltaic Lankrabu Formation (~ 700 m thick) in the central and eastern parts of the basin, respectively. The former becomes lateral – facies change with the latter in the N-S section and seems to be overlying the latter in the E-W section (see Fig. 6). The so-called “Lake Phitsanulok” which is a large (1,000 – 4,000 km^2), fresh-water, quiet (15-50 m deep) lake (Makel et al., 1997) dominated by these kinds of clastic sedimentation. The Chumsaeng Formation is composed of uniform, organic-rich, dark grey claystone. The sixth and seventh formations are the Middle to Late Miocene clastic units of the deltaic-plain Pratutao (200 – 400 m thick) and alluvial plain (meandering dominant) Yom Formation (200 – 600 m thick), respectively. These clastic units are considered to have deposited in the braided- and meandering –river environment. The eighth unit is the Late Miocene to Recent Ping Formation which overlies Yom Formation in the east-west section and shows lateral – facies change with the Ping Formation in the N-S section. The Yom Formation is composed almost entirely of unconsolidated clastic sediments interpreted to have deposited in the alluvial fan and braided plain environment.

In the Lower Chao Praya Sub-segment, we regard the Suphanburi Basin to represent the sub-segment. O’Leary and Hill (1989) subdivided the Suphanburi stratigraphy into 2 major formations, namely the T1 unit (50 – 150 m thick) overlying the pre – Tertiary rocks, and the younger T2 unit (40 – 80 m thick) which is overlain by the so – called Tertiary – Quaternary sediments. The T1 unit is inferred to have deposited in the lacustrine environment whereas the T2 unit is of the fluviatile – dominated environment. Lawwongngam and Philp (1993) reported that significant thickness of fine – grained lacustrine sediments are more predominated to the west of the basin.

To the north, the stratigraphy of the Northern Segment is represented herein by that of the Mae Moh Basin belonging to the Chiang Rai Sub-segment. Three formations (Corsiri and Crouch, 1985) are recognized, namely Huai King, Na Kham, and Huai Luang Formations constituting the so-called Mae Moh Group

(Charusiri et al., 1997). Huai King Formation, the oldest unit, is composed of the 300 m-thick, fine to coarse – grained clastics deposited within the fluvial environment during Early Miocene (- Late Oligocene?). The depositional environment of the Formation is characterized by alluvial fans at the beginning stage and swamps and flood plain with channel bar in the subsequent main stage (Evans and Jitapunkul, 1992, Morley and Wonganan, 2000). The overlying unit, the Na Kham Formation, is lignite – bearing sequence and comprises 3 members: the lowest member (Member III) including monotonous, ceramic-used, underburden type claystones with the lignite seam at the lower contact and in the middle part, the middle member (Member II) containing the productive lignite seams with the silty claystone interburden containing thin gastropod and calcareous beds, and the upper member (Member I) composed of silty claystone with intercalated subeconomic coal seams in the middle part. The sediments of this formation are considered to have deposited in the Miocene fresh-water lacustrine in the tropical semi – arid region. The youngest formation is the Huai Luang Formation (or Redbeds) with the thickness of 100 – 150 m and unconformably high over the Nakham Formation. The formation is characterized by Pleio – Pleistocene reddish brown to yellowish brown, siltstone to mudstone with some intercalations yellowish sandstone. The sediments are thought to have found in the channel and flood plain deposits. Geochemical studies by Charusiri et al. (2001) show that sediments from the basin were mainly derived from the Triassic clastic and Permo-Triassic volcanic rocks to the east.

The northernmost basin of the Lampang Sub-segment regarded as a representative of petroleum – bearing basins in northern Thailand is Fang Basin. Sethakul (1993) divided the Fang oil – bearing folded sequences into 2 formations in an ascending order as Mae Sod and Mae Fang Formations. The latter is dominated by the 50 – 90 m thick, semi – consolidated varieagated arkosic sanstone of fluviatile environment. The former is composed largely of the 700 m – thick alternated sequences of shale, claystone, and fine – grained sandstone. The upper sequence is characterized by the sequence of 300 m – thick, monotonous, gray shale, which possibly acts as the essential seal / cap rocks. The Mae Sod Formation is interpreted herein to indicate the fluvial – lacustrine environment.

4. Structural Setting

In SE Asia, Cenozoic structural tectonics has been principally caused by the interaction of Indo-Australian and Eurasian Plates. The former separated from Gondwana northwards during late Cretaceous and eventually collided with the latter in the Eocene time. As India continued penetration to the north, SE Asian block was gradually pushed out southeastwards with progressively clockwise rotation (Packham, 1993), and angle of subduction changing from perpendicular to oblique (Morley et al., 2001). Progressively increase in oblique subduction probably accelerated dextral shear mechanism of formation based upon the extrusion or escape tectonic model (Tapponnier et al., 1986, Morley et al., 2001, 2002) along the NW-trending strike – slip faults, viz., Three-Pagoda, Mae Ping, and Red River Faults.

Many of the basins shown in Figs. 1 and 2 appear to lie at or immediately close to the intersection of three major strike-slip faults, namely NE – SW, NW – SE, and N – S trending faults. These faults have been proved by satellite - borne image interpretation (see Charusiri et al., 1997), air – borne geophysical data (Tulyatid and Charusiri, 1999), and seismic data (ASCOPE, 1974, and Polachan and Sattayarak, 1989, Remus et al., 1993) to extend into the Cenozoic basins of Thailand and nearby. However, their senses of movement have been poorly described and still in argument. Both dextral and sinistral movements along the fault planes have been reported by several geoscientists (Bunopas and Vella, 1983, Polachan and Sattayarak, 1989, Morley, 2007, Morley et al., 2007b). Pre-Triassic structural elements in Thailand both on – shore and off –

shore display the regional strike in the N – S trend (Morley, 2004). These structural grains are likely to be present in almost all of the major basins (Morley et al., 2004). Particular important are the so – called the Western Boundary fault system (Bal et al., 1993, Makel et al., 1997), the almost N – trending faults, which have taken up the movement and basin extension as normal fault, and the Phetchabun Fault which is also the N – S running dextral wrench fault, system with the total displacement of about 50 km (Makel et al., 1997).

Apart from the faults, another structural feature is the appearance of several basement highs in various basins. Particularly interest are those of the Phitsanulok basin where the oilfields are located above or closely related to pre- Tertiary basement – high (<2,000 m below the surface). Such basement highs have formed the positive feature almost throughout the basinal development. The onlaps of sediments onto the highs, the different thickness of sedimentary successions over the highs, and the contrast depth at which the highs are found, provides good evidences.

McCabe et al. (1987) described dextral movement of the NW – trending Three – Pagoda Fault during the Neogene time whereas Polachan (1988) and Polachan and Sattayarak (1989) suggested dextral movement of the NW – trending faults and sinistral movement of the NE – trending conjugate fault, both of which have probably occurred during the Oligocene. We infer the hypothesis proposed very recently by Charusiri et al. (1999) that these fault systems are pre – existing basement faults and may have exhibited the senses of movement prior to Cretaceous (Charusiri et al., 1993) in the opposite way as they have shown in the post – Cretaceous (Fig. 3). Some of the faults act as the basin limit (e.g. Phitsanulok Basin, Makel et al., 1997; Chumphon Basin, Pradidtan and Dook, 1992). Besides the boundary faults, numerous N-trending normal faults both listric and basement involved are also reported (Pradidtan and Dook, 1992, Makel et al., 1997). Movements of the listric faults were obviously penecontemporaneous with Tertiary sedimentation. Antithetic faults are well-recognized, and the basement-involved faults appear low – angle and more planar. Several faults appear to cease at the Late Middle Miocene, with a few showing reactivation till recent (Pradidtan and Dook, 1992). The throw of these faults are much less than that of the major boundary faults. In addition, seismic sections reveal that in some basins (e.g. Pattani and Kra Basins) the faults with essential strike – slip components and negative flower structures appear to be present. We infer that the combination of normal and strike – slip components may have created such densely faulted and intricated structures. Fig. 3 shows the orientation of ellipsoids prior to and after Cretaceous. Therefore, the NW – trending strike – slip faults, e.g. Three Pagoda Faults, may have the senistral movement in the pre – Cretaceous, the latter being shown by the offset of up to 100 km (Bal et al., 1993), and both may have the dextral movement and developed the duplex structure in the Cretaceous - Paleogene time (Morley, 2004). On the contrary, for the senses of NE –trending (e.g. Ranong – Klong Marui, Uttaradit) fault movement, the faults may have shown the dextral movement prior to Cretaceous and exhibited the senistral one ofter Cretaceous. We also consider that during the period of changing fault movement, extension tectonic regime may have exerted more than transtensional one. It is also visualized in Fig. 4 that some of N – trending faults may have been developed originally as thrust faults before Cretaceous. Perhaps, these N – trending faults and thrusts may have either become the sedimentary provenance or the zone of weakness, a preparatory depocenter during Cenozoic time.

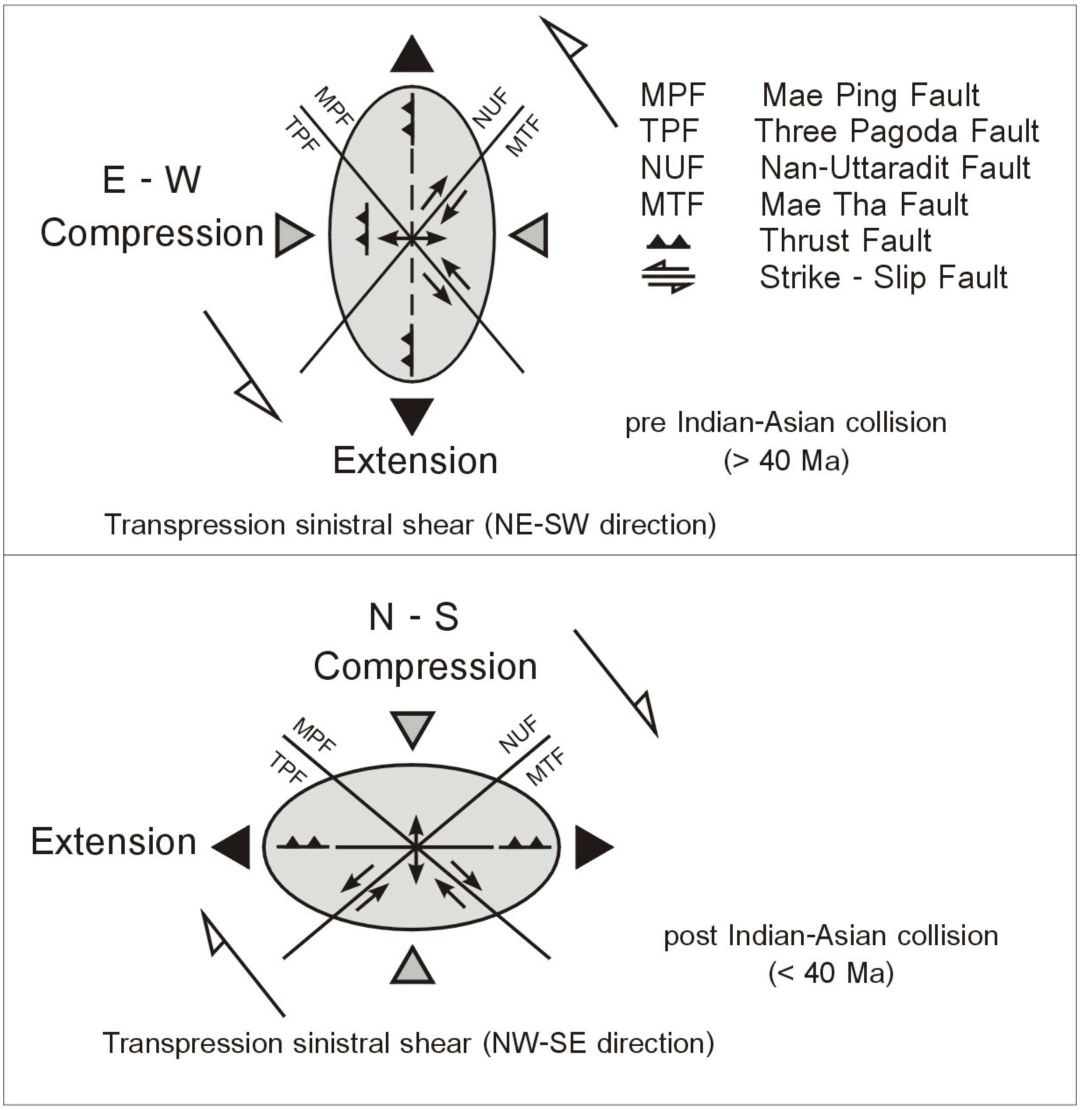

Figure 3: Strain ellipsoids showing the development of major fault zones in Thailand (modified from Charusiri et al., 2000a) (a) prior to Late Cretaceous (b) after Late Cretaceous

Based upon seismic stratigraphy, faulting is thought by most authors (e.g. Makel, 1997, Packham, 1993, Jardine, 1987, Morley and Westaway, 2006) to have been continuous throughout basin development, however, the amount of faulting after the Late Middle Miocene unconformity is less than that before it. The faults are mainly basement-involved listric and frequently with antithetic branches.

5. GEOCHRONOLOGICAL SYNTHESIS

There is somewhat difficulty in dating the sequences in these groups of basins in Thailand. This is probably due to the almost absence of marine sediments. The formations are dated palynologically and perhaps, unfortunately, apart form the problem in correlating the non – marine strata with those of the marine sediments. Correlations seem to be better in the Malay and Natuna Basins (Pacham, 1993), but the published accounts do not present a clear picture of the correlation with Thailand. Therefore, interpretation of the early history of basin formation has been performed further by the absence of avaliable information on the deeper structures of Cenozoic basins in Thailand, to neither which drill – holes were penetrated nor which seismic signals were accessed.

The oldest Tertiary rocks penetrated in the Gulf of Thailand to date are regarded to be of Late Oligocene age. However, seismic data indicate that the oldest undrilled strata have been known to be present in the deepest parts of the area on – shore. Eocene macrofossils have been recorded from the onshore Krabi Basin (see fig. 1, and Ducrocq et al., 1993). Although based upon palynological result reported very recently by Songtham and Watanasak (1999), Early Miocene is considered for the deposition of the Krabi Basin. Quantitative biostratigraphic analysis is also approached (Highton et al., 1997) to constrain the age of basin formation. The faunas and palynofloral assemblages are of low diversity and logn range in Thailand basins (Packham, 1993). This perhaps leads Alderson et al. (1994) to assign an age of Pleiocene for the latest phase of deposition in the Gulf of Thailand whereas Jardine (1997) prefers Upper Miocene time for that depositional phase. So there is certainly an unsolved problem relating to the age of basin formation. However, playnological and micro-paleontological analyses indicate that the onset of basin formation may have occurred during Early Miocene (Alderson et al., 1994).

Isotope age – dating approach can also provide the significant and reliable data pertaining to the age of basin formation. The result from apatite fission – track geochronological analysis of a metatonalite cored in the Phitsanulok basin suggests the the Tertiary sediment fill is likely to be limited within 44 Ma (Legenre et al., 1988). This age information seems to correspond with the fission – track dating results reports earlier by Putthapiban (1984) for apatite, sphene and zircon separated from granites in Phuket region of the Andaman coast. These dates were interpreted by Charusiri et al. (2000) to represent the tectonothermal uplift of the region caused by the reactivation of NE – trending Klogn Marui fault (Fig. 4). Older and younger dates than that are those of fission – track results which were reported by Putthapiban (op. Cit.) to be about 50 – 55 Ma and those of ^{40}Ar/^{38}Ar results on several rocks close to the Klong Marui and the nearby faults by Charusiri et al. (1993) to be about 15-35 Ma, respectively. These older dates were considered to point to the tectonothermal overprints caused by reactivation of the similar fault movement which in turn have caused the Sn – W – REE mineralization (Charusiri et al., 1993). The fission – track age data from the granites of the same region (Putthapibban, op. Cit.) also yield the young dates (30 – 35 Ma) probably indicating the similar fault movement. These above – mentioned age ranges are essential since they presumably confirm the more regional-scale tectonic uplift and adjustment as shown in Fig. 4.

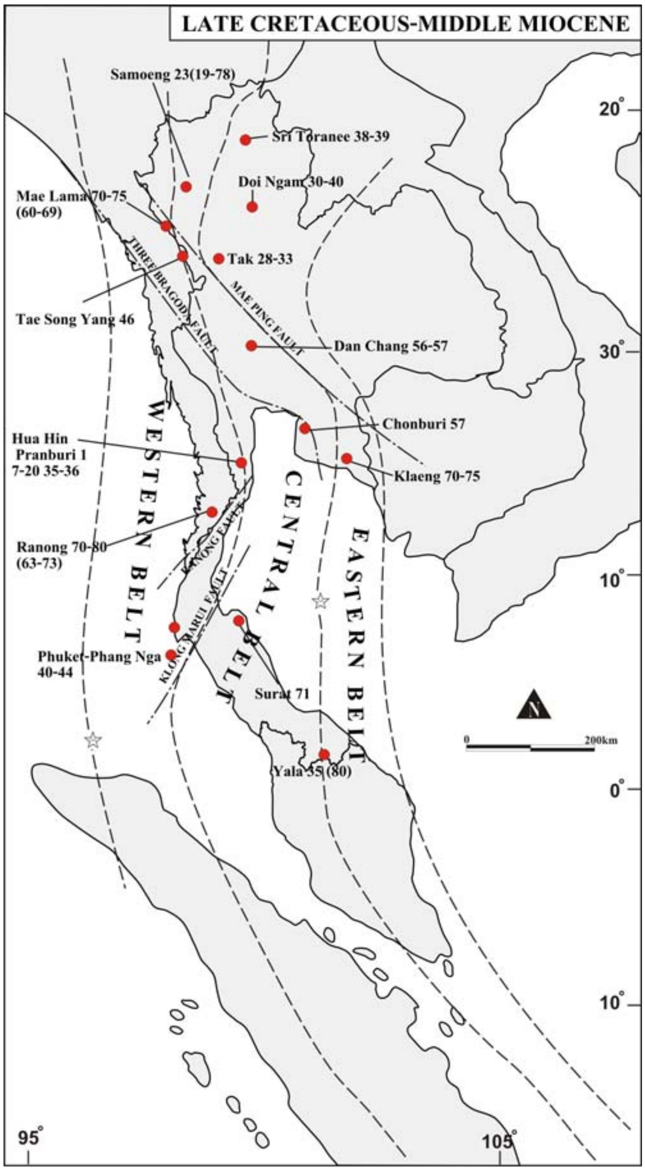

Figure 4: Granite belts in Thailand, 40Ar/39Ar age dating data (Charusiri et al., 1991) and previous K – Ar mineral age data (bracketed) of

rocks collected close to the major fault systems. (MPF = Mae Ping Fault, TPF = Three Pagoda Fault, RNF = Ranong Fault, KMF = Klong Marui Fault, NF = Nan Fault, MSF = Mae Sarieng Faukt, and PTF = Pattani Fault).

The occurrence of 70 – 80 Ma, somewhat mineralized, S – type granites in Mae Sariang and Ranong areas (Fig. 4) may have pointed to the east – directed subduction / collision of Burma block beneath Shan – Thai block. Paleomagnetic studies for Shan – Thai rocks (Bunopas and Vella, 1983, Charusiri et al., 2000), suggest small declination and inclination during Mesozoic, implying that the Shan – Thai block remains at the same position after Jurassic. In this case the contact boundary between Shan – Thai and Burma blocks, which is shown by the Sagiang Fault, probably aligned in the N – S direction since Jurassic. Therefore, based upon the geological and geochronological syntheses, during the end of Cretaceous, the Burma block may have abut obliquely against the Shan – Thai plate in the approximate N – S direction, and the Sagaing fault may have shown the dextral slip movement during Early Tertiary onwards.

6. Basin Development

All the results described and synthesized above may be adequate for determining and deciphering, based upon tectonic syntheses, the formation and development of the major Cenozoic basins in Thailand. As specified earlier, major sites of basin development were within the Paleotethian oceanic crust in northern and central regions of Thailand. In response to subsequent tectonic regimes whereby interaction of India and Asia subduction and continental collision was triggered, thinner oceanic crust of Nakhon thai and Lampang-Chiang Rai terranes with minor and thin Middle to Late Paleozoic marine sedimentary covers, were therefore became the weaker zones than the thicker Shan-Thai and Indochina continental terranes. Consequently, this perhaps may have caused the mantle plume by convection currents.

Four phases of basinal development are recognized herein and interpreted based upon the plate – tectonic regime including: (1) pull-apart and syn – rifting; (2) quiescent thermal subsidence; (3) transpressional wrenching; and (4) post – rifting episodes. Cenozoic basins in Thailand are classified as intracratonic rift basins by Woolland and Haws (1976), Chinbunchorn et al. (1989) and as transitional pull apart basins by Polachan and Sattayarak (1989) and O'Leary and Hill (1989), and as major continental rifting basins (this paper).

Pull-apart and Synrifting Episode (~55 Ma to 35 Ma)

The first episode of basin formation commences with the onset of transtensional rifting in which predominantly N – NNW trending extensional troughs were formed, probably reflecting grains of underlying basements. The onset of this episode is difficult to date since the initial rift sediments deposited, e.g. Huai King Formation of Mae Moh Basin, Nong Bua and Sarabob Formations of the Phisanulok Basin, and Sequence I of the Pattani Basin were mostly fluvial and non – marine lacustrine. The change in tectonic style from passive continental margin to subduction convergent margin for the interaction of India – Asia may have occurred during 55 Ma (early Eocene) as evidence by reactivation of the NE – trending fault. The crustal pure extension associated with oceanic rifting in Andaman Sea (see Packham, 1993) and the continental rifting in the Gulf of Thailand (this paper), would have resulted in extensive crustal thinning. Such situation may have increased the heat-flow, leading to subsequent mild regional up lift (~40 Ma) and degradation in the Oligocene (~30 Ma) (see also Fig. 4). The densely faulted margins in several Thailand basins advocates the appearance of high heat flow (Burri, 1989). The pattern of basin development is one of the initial extension with deposition restricted to trough axes followed by propressive onlap onto adjacent highs, as regional subsidence happened, presumably due to continued extension and possibly subsequent thermal contraction. Simultaneously, the terrestrial, alluvial fan and fan – delta sediments deposited earlier (Cretaceous to Eocene) may have been folded and accreted to the basement. As a result of this tectonic episode, localized sub – basin (e.g., Pattani and Phitsanulok Basins) forming graben- and half graben – type basins of Late Eocene to Late Oligocene time, may have been created. This perhaps leads to the occurrence of Mid – Tertiary Unconformity (MTU) as clearly observed by seismic data (see Jardine, 1997). This unconformity is more clearly observed almost all basins onshore and offshore. Volcanic activity in some basins (e.g. Phetchabun Basin, Remus et al., 1993) may have also been reported, giving rise to structural inversion and denudation at the end of Oligocene.

Quiescent Thermal Subsidence Episode (~35 to 15 Ma)

This episode possibly commenced in the Late Oligocene when pure extension in the basin decreased and a transtensional tectonic component gained in importance. Tremendous sedimentation, starting immediately before the beginning of the Miocene and continuing to Middle Miocene, rapidly became basin widespread. This began with fluvio – deltaic sediments (e.g. Lan Krabu Formation of the Phisanulok Basin, and Upper Greybed Sequence 3 of the Pattani Basin) and open – lacustrine sediments (e.g. Chumsaeng Formation of the Pattani Basin, and Na Kham Formation of the Mae Moh Basin). Regional transgression alternated with extensive delta progradation result in the aerial extensive transgressive / regressive cycle.

We propose that extension of the basin was triggered by thermal contraction presumably resulting from withdrawal of heat from the back – arc region for both the Andaman Sea and the Gulf of Thailand by mantle plume (or hot – spot). The absence of deformation structure and the strengthening of the lithosphere by cooling perhaps resulted in the tectonic strain, forming the widening of the basin by extensive strike – slip movement. The thinning of the continental crust due to high heat flow results in the rapid basinal subsidence with the sedimentation rate reaching up to 1 m per 1,000 yrs (Bal et al. 1992), and the advent of lake highstands replacing lowstands may have developed onwards. Graben – to half – graben – type fault system developed in response to the rapid extension and deepening. The strike – slip movement are supported geochronologically by the dated fault materials using $^{40}Ar/^{39}Ar$ techniques (Charusiri et al., 1991, see also Fig. 4). Onshore, the region has variable heat – flow values that attain up to 105 mW/m^2 in some areas (Thienprasert and Raksasakulwong, 1984) probably suggesting the continuation of extensional tectonics. This has been accompanied by basaltic and alternated rhyolitic vulcanism, as evidenced at the Lam Narai volcanic field, central Thailand. This volcanic activity is claimed as a bimodal suite occurring in the high heat – flow region (see also McCabe et al., 1988). The series of episodic felsic – mafic extrusives were dated using $^{40}Ar/^{39}Ar$ whole – rock method to be ca. 24 to 7 Ma from SSW to NNE direction (Charusiri, 1999 b), implying mantle plumes or hot spots.

Transpressional Wrenching Episode (~15 to 10 Ma)

The on-going dextral shear eventually produced a change in tectonic style, becoming transpressional in the late Middle Miocene, leading to folding and inversion of Thailand basin in the very late Neogene. The time fairly corresponds to the inception of Burma plate to part of SE Asian Block and the advent of Andaman sea floor spreading (Packham, 1993). The Tertiary sediments of the Fang Basin may have been folded during this episode. In the northern Phitsanulok Basin, compression continued, extension ceased, and overthrusts developed, particularly in the NE part of the basin. To the south of the Phisanulok Basin, extension continued and as a result the anti-clockwise rotation occurred and was compensated by dextral movement along the NW – trending Mae Pin Fault.

The evidence of this episode is marked by the Mid – Miocene to early Late Miocene unconformity (MMU) which is observed from geophysical signals both in the Gulf (Pradidtan and Dook, 1982) and the central part of Thailand (Bidston and Daniels, 1992) better than that of the north (see also Makel et al., 1997). In some north – central Thailand basins, as Phisanulok basin, the change in transtensional to transpression styles resulted in the decreased and more uniform subsidence rate than previously experienced. In response to this change, dominant depositional environment switched from meandering fluvial (Yom Formation) to alluvial fan / braided plain (Ping formation) system. In the Gulf, transpression may have caused the marked uplift or basement highs, and extensive regression with widespread erosion may have been developed apart from the subsidence negative or basin inversion. Further development of the complex, densely faulted graben systems form the main structural traps of hydrocarbons in the basin.

$^{40}Ar/^{39}Ar$ age data from the granites/gneissic rocks in Hua Hin area, south central Thailand, may indicate the tectonothermal overprint of reactivation of movement along the so-called Hua Hin fault (Charusiri et al., 1991). The K-Ar dating result of a laccolith extruded in the Petchabun basin yielding a date of 11.6 Ma confirms the igneous associated with Middle to Late Miocene tectonothermal event. All the age data lead us to infer that the Ko Kra Ridge and other relevant basin highs in the Gulf may have developed significantly at this time, although dating data imply that they may have formed earlier than that. The evidence of older ages of igneous activities is supported by the occurrence of dolerite and diabase sills found at the base of the oldest sequence and K – Ar dates of Early to Middle Miocene mafic rocks (Remus et al., 1993). This strongly proves that Ko Kra Ridge which may have formed gradually and successively since Early Miocene, extends to the north, and perhaps corresponds to the uplift of the Khorat maga – basin. This leads to the readjustment of the crust south of the Khorat, and as a result deeper and larger basins may have developed for the Eastern – Gulf Sub-segment comparing to those of the Western – Gulf Sub-segment, the latter being narrower and shallower.

Post – rifting Episode (~10 Ma to Present)

After the extensive transpressive episode, the overall region may have been adjusted. In the Gulf and central Thailand, basins were subsided without significant tilting or rotating, giving rise to transgression and deposition of predominant marginal marine deposit in the Upper Miocene. The subsidence rate in those basins decreased with time. To accommodate with the south, basins in northern Thailand became negatively subsided (basin – inversed). As a result, the entire region are regionally uplifted and deposition environments were dominated by fluvial / alluvial systems. The Huai Luang Formation and other uppermost units in several basins in northern Thailand are dominated by red clastic unit and may have formed in this episode.

Basaltic extrusion whose age range falls within this episode is evident from 40Ar/39Ar dating approach. The extension is regarded herein to have occurred in the continental-rifting environment. The existence of the basalt extrusion is quite unique. Fig. 5 displays the distribution of Cenozoic alkaline basalt in mainland SE Asia. It is visualized that their age distribution pattern may have been controlled by regional tectonics. When the ages of these basalts are plotted, it is obvious that they show the older age – to – the south pattern (Fig. 5). Another word, the active extension continued northwards until late Miocene time. Similar scenario was proposed by Takami and Honza (1991) who claimed, from the age distribution pattern of the marginal basin in the West Pacific region, that there is a tendency the marginal basin becoming younger outward. Although detailed tectonics of eruption remained unsolved at present, we tentatively believe that these alkaline – rich basalts may be related to the northward migration over an underlying hot spot. Packham (1993) made an interesting point that rifting phase of basin tectonism in western Southeast Asia seems to occur from the south to the north. The situation corresponds very well with the older – to – the south pattern and the local scale Lam Narai volcanic field (Charusiri et al., 1999) in central Thailand, implying that the basins may have beendeveloped in the south prior to the north.

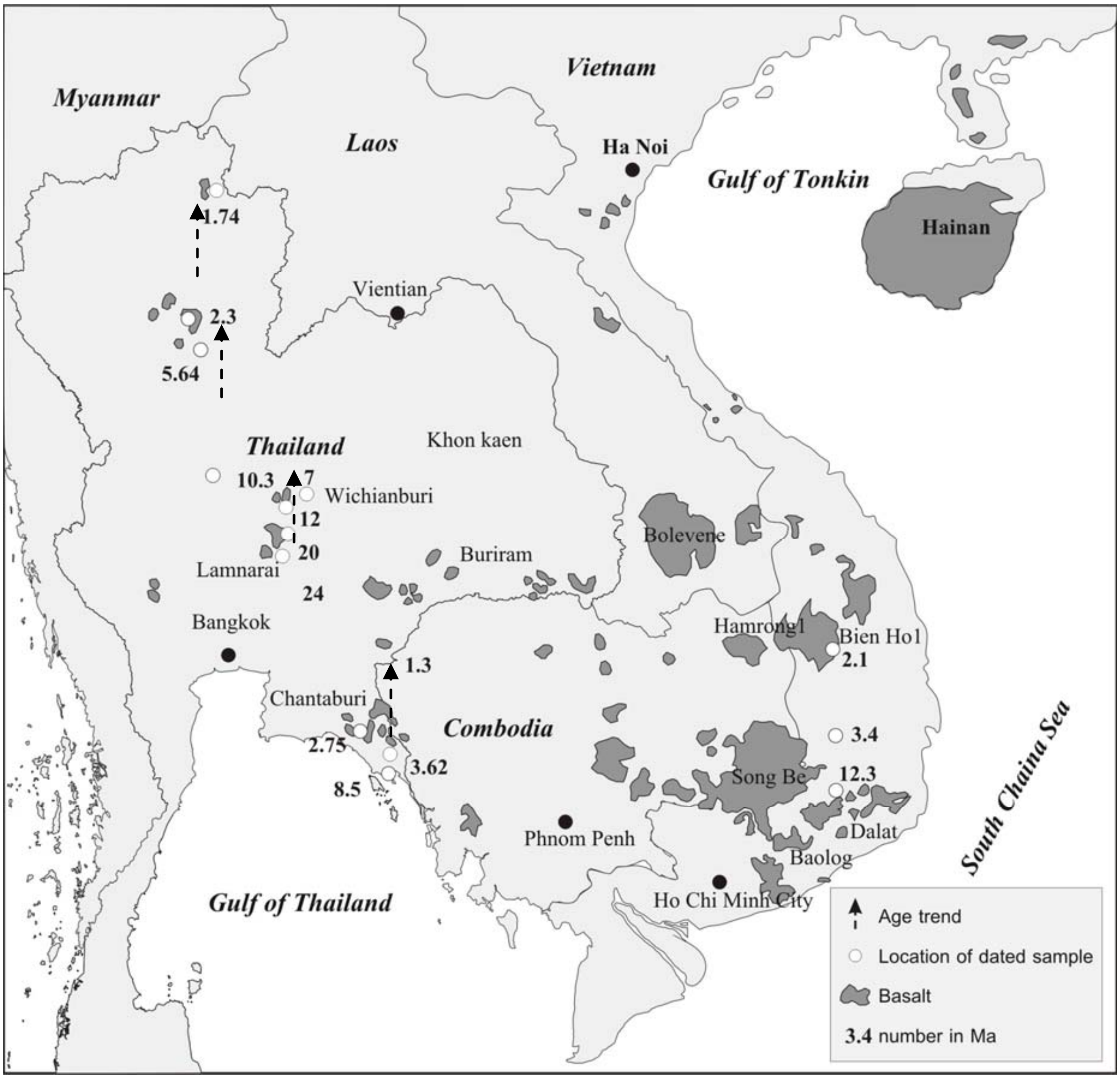

Figure 5: Distribution of Cenozoic volcanics in mainland SE Asia with the younger – to – the – north geochronological pattern.

The quite high present-day heat flow in the Gulf and the hot spring distribution on – shore particularly in the north imply the occurrence of on – going tectonics. We also infer that the sinking of Bang Khun Thien coastal area and the uplift of eastern and western coastal zones along the Gulf of Thailand may have related to present-day tectonics. The summary of tectonic evolution and potentials of the Cenozoic basins in Thailand is shown in Table 2.

7. Conclusions

Major sedimentary basins of on – land (max. 4,000 m-thick) and the Gulf (max. 7,000 m-thick) have been developed in response to the N to NNE pushing of India towards Asia. The ca. 80 Ma reactivation of the major NE- and

NW- trending strike-slip faults, regarded as the predecessor of the basin development, was triggered by the prolonged interaction of Burma block with the mainland SE Asian mega-plate.

Subsequently, due to the change in direction of plate interaction from E-W to N-S, the significant modification in tectonic from transpression to transtensional regimes occurred and accounted for the initiation of major basins in Thailand (see Table 1). The 45-55 Ma India collision may have exerted a stop for reactivation of fault movement. Moreover, because of the ongoing collision, these major faults may have changed their movement directions during 35 Ma and became the right lateral movement for the NW – trending and left lateral movement for the NE – trending.

Later on a successive South China anti-clockwise rotation and a commence of tectonic extrusion of SE Asian continental block, southeastward between Red River and Mae Ping – Three Pagoda Faults, may have developed the rift – generating tensional pull apart, and N-S trending fault bounded basins. Results from the $^{40}Ar/^{39}Ar$ geochronological data, geological setting and petrophysical analysis have indicated that the oldest strata of the basin is younger to the north, implying that the basins may have been developed in southern Thailand prior to northern. The sediment influxes, which were derived from the denudation of exposed mega-landmass, may have taken place and resulted as an extensive syn-rifted fluviolacustrine deposition. This rifting phase might be ceased at about 25 Ma, by the same time the short period of the relative sea-level fall took place. These eventually generated the regional Mid-Tertiary unconformity. Duing 15-25 Ma, the basins continued to subside and concurrently the marine transgression took place, from the south.

During 10-15 Ma, a grand readjustment of the adjoined mega-plate took place, and the intensive tectonic uplift of tectonic block in southern Thailand gave rise to the new sequence stratigraphy, especially in the Gulf. This eventually generated the regional Mid-Miocene unconformity, as detected by seismic reflection and well logging data. Basin subsidence may have developed slsewhere afterwards, and as a consequence, the magma-involved, N-trending Ko Kra ridge may have formed almost following the edge of the Khorat plateau. Rather high heat flow is likely to account for the significant petroleum generation and accumulation in the Gulf of Thailand. The major basins in the Gulf became inundated due to extensive marine trangression. Marine-prone sedimentation may have caused the widespread development of clastic sediments of the Chao Phraya Group, unrelated to any petroleum genesis.

Acknowledges

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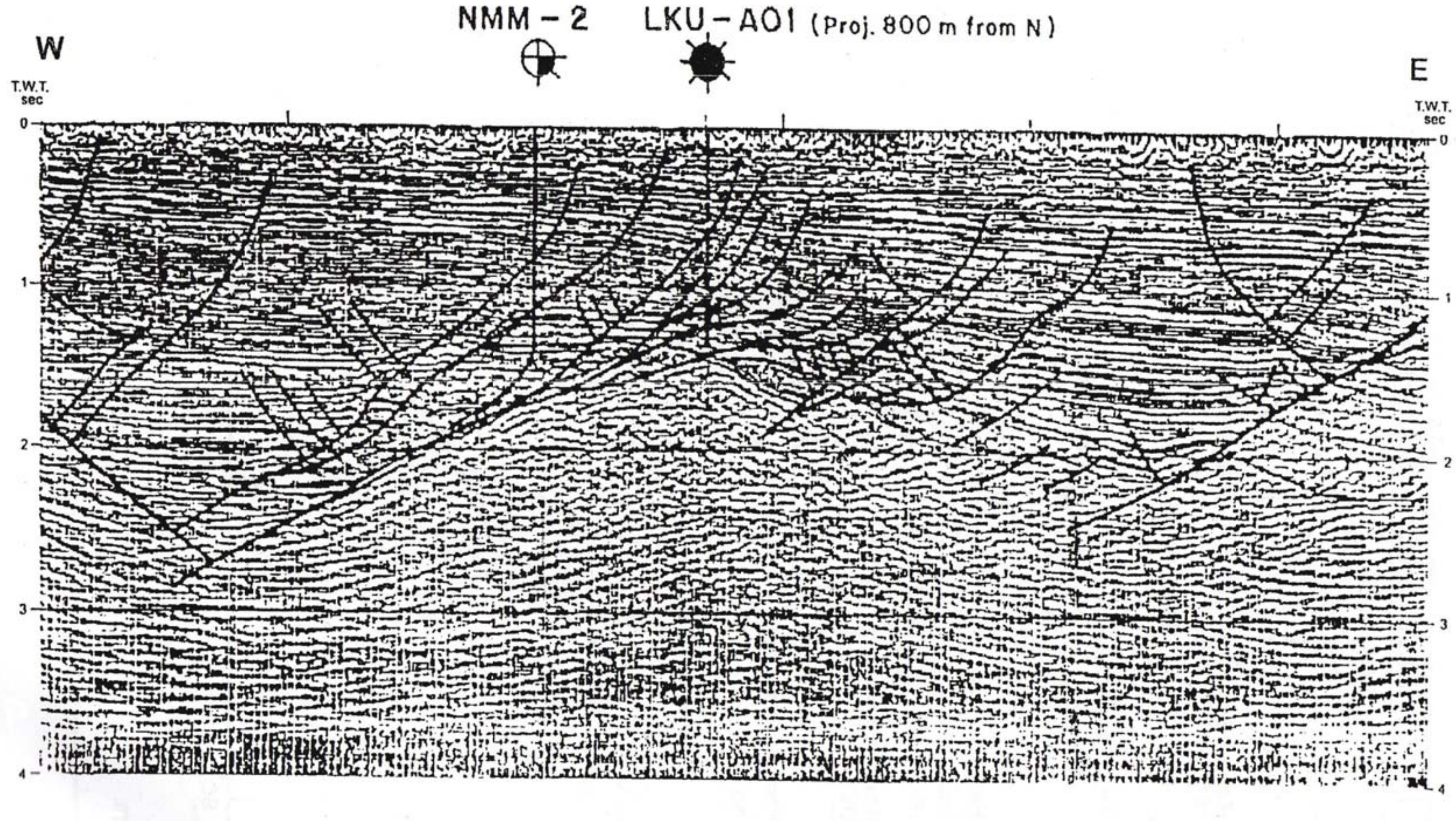

Figure 6: Seismic section in the E-W direction along the Pitsanulok basin of the Upper Chao Praya Sub-segment showing the graben and half graben fault system (Bal et al., 1992).

Table 1: A summary of some major basin development in Thailand during Cenozoic time.

	Age	Tectonic Episode	Northwestern	Northern		Central		Gulf	
			Mae Sod	Fang	Mae Moh	Suphan	Pitsanulok	Chumpon	Pattani
MMU	Recent to Lower Miocene	Post-rifting	Unconsolidated gravel, sand silt, of alluvial, channel fills	Fine to coarse clastics, of fluviatile deposit	Redbed clastics of sand and silt, deposited in the channel and flood plain	Unconsolidated sand, silt and gravel, of alluvial and fluvial deposits	Varigated to grey brown Sandstone and siltstone of meandering fluvialto alluvial fan and braid plain	Varigated-grey claystone with acc. Sandstone of coastalplain to inner neritic	Grey claystne with some some sandstone and limestone, of deltaic plain to marginal marine
Neogene	Late middle Miocene	Transpression wrenching	Shale with mud and oil shale, of fluvolacustrine deposit	Fine clastics, of lacustrine environment	Clay with lignite seams, of lacustrine origin	Fluviatile-dominted environment with sand and some shale	Grey to varigated sandstone with some clay/silt, of braided and meandering with delta.	Varicoloured claystone/sandstone with lignite of flood plain to fluviatile environment	Upper Redbeds withsome grey beds and sandstone, of flood plains with point bar
	Middle Miocene	Quietscent Thermal Subsequent	Shale to sandy shale and marlstone turbidite rocks, of deeper water enviroment		Lignite seams with intercalated clay, of mrsh and fresh-water lustrine	Lacustrine-dominated clastics, of lacustrine deposit	Grey claystone with somesandstone ans conglomerate, of open, shallow, fresh water lacustrine delta and deltaic plain	Grey claystone with lignites and brown sandstone of lacustrineand lacustrin deltainc environment	Upper grey bed of upper intertidal and coastal plain/lagoon Lower redbeds of fluvial point – bar and channel sands with intertidal and deltaic plain
	Early to Middle Miocene	Initial Transtensional Synrifting	Marlstone with mudstone interbedded with some oil shale, of lacustrine – dominted facies		Clay with lignite seam, of swamp and lacustrine deposition		Alluvial-fan and fan-delta clastics with protolacustrine to floodplain	Red brown clays with sandstone of flood plain with marginal lacustrine	Varigated clastics of lacustrine, allvial-fan deposits
Paleogene	Early Eocene to Late Oligocene	Pre-rifting, pull-apart and uplifting	Redbed and grayish green sands, of fluviatile deposit		Sandstone with siltstone and conglomerate of alluvial fan with subsequent flood plain				
References		This paper	Thanomsap (1991)	Settakul (1993)	This paper	O'Leary & Hill (1989)	Makel et al. (1997)	Pradidtan & Dook (1992)	Pradidtan et al. (1992)

Table 2: Summary of Cenozoic evolution and potentials of sedimentary basins in Thailand.

Age (in Ma)	Nature of basin	Sediment Type and Potential	Cause	Tectonic Milieu
10 to Recent	Onshore & Gulf basins	Terrestrial to Marine ***(No hydrocarbon potential)***	Structural Inversion	Tectonic adjustment
~~ ***Middle Miocene Unconformity***~~~~~~~~~~~~~~~~~~~				
15 to 10	Transpression Wrenching	Paralic to lake and non-marine	Dextral shear in NW faults	Decrease in subsidence
35 to 15	Transtensional	Fresh water lakes and marshes **(Hydrocarbon potential)**	Withdrawal of heat from back arc regions	Quiescent thermal subsidence
~~***Middle Tertiary Unconformity*** ~~~~~~~~~~~~~~~~~~				
55 to 35	Pull-apart & Transtensional	Rift - related	Mantle plume	Subsidence

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