CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter is comprised of literature review of geology and petroleum geology in northeastern Thailand. The related knowledges are categorized into groups including general geology, stratigraphy, basin evalution, structural framework, petroleum provinces, petroleum prospect in Permian basin play, seismic interpretation of the Chonnabot prospect, subsurface structural map of the Permian play, petroleum geochemistry evaluation of Permian carbonate rock, carbonate reservoir characterization, and seal and trap rock characterization.

2.2 General geology

The northeastern region of Thailand is located between latitudes 14^{o} to 19^{o} North and longitudes 101^{o} to 106^{o} East, covering an area abount one third of the country or abount 200,000 square kilometers. The northern and eastern border is bounded by the Lao People's Democratic Republic (Laos) and the Mekong river. The southern part is connected to the Democratic Kamphuchea and the western part is bounded by certral and northern of Thailand.

The Khorat Plateau forms a part of the Indochina plate bounded by major Tertiary strike-slip faults. Althought several tectonic models indicate that the Khorat Plateau is largely underformed. It contains two fold belts; the N-S trending Loei-Phetchabun fold belt in the western area and NW-SE trending Phu Phan range in the

central part which divided the central plain in the northern Sakhon Nakhon basin, and the southern Khorat basin. General geology of the area and the sedimentary sequence consists of an initial rift sequence of Carboniferous to Triassic sediments and a sag sequence of Late Triassic to Cretaceous sediments that consisted of Khorat Group which is mainly sedimentary subsequence (Figure 2.1). The two sequences are separated by a regional erosive unconformity, known as the Indosinian unconformity, which represents the main collision of Indochina with its neighbours. The Khorat Plateau is the term in use for the area of outcrop of the post-Indosinian sequence. The structure of the bedding is gently tilted to the central part of the Khorat and Sakon Nakhon basins. The southern part of the Khorat Plateau is sporadically covered by the Quaternary.

Based on the drilled well data, the Khorat Group has been restricted to the Late Triassic to Early Cretaceous sediments. The underlying Late Triassic Huai Hin Lat and Kuchinarai Group and the overlying Early Cretaceous-Middle Eocene Mahasarakham and Phu Tok formatioms are excluded from the Khorat Group. In addition, an uppermost unit of the Late Tertiary called Tha Chang formation is represented in lithostratigraphy in the northeastern region of Thailand.

2.3 Stratigraphy

The lithostratigraphy of the Khorat Plateau is established (Figure 2.2) by the integration of the seismic stratigraphy, tectono-stratigraphy, well data, previous work, and tectonic history (Chantong, W., 2005). There are six tectono-stratigraphy units. Pre-Caledonian and Pre-Variscan Megasequences (Pre-Permian basement) are defined as Early to Late Carboniferous age. Pre-Indosinian I Megasequence is classified as

pre-rift Megasequence is Late Carboniferous to Late Permian age. Pre-Indosinian II Megasequence is classified as the syn-rift Megasequence and earliest post-rift Megasequence are Triassic age. Pre-Himalayan Megasequence is classified as post-rift Megasequence and post-inversion Megasequence are Late Triassic to Early Late Cretaceous age. Post-Himalayan Megasequence is Middle Miocene age. The new lithostratigraphy can be divided into two parts that the Pre-Khorat Group, and the Khorat Group. The Pre-Khorat Group has more complex structure than the Khorat Group. There are four orogenies in the Pre-Khorat Group. Normally Khorat Group is slightly folded and faulted.

2.3.1 Pre-Caledonian Megasequence (Pre-Permian basement)

The Pre-Caledonian Megasequence is consisted of the metamorphic basement which is clearly differentiated from the overly non-metamorphosed sequence. These rocks older than the Late Carboniferous are considered to be basement in the Loei-Phetchabun fold belt and the Khorat Plateau area.

The Na Mo Group of Middle Silurian is the oldest metamorphic basement, exposed in the Loei provivnce on the northwestern margin of the Khorat Plateau. The low-grade metamorphic rocks of the upper greenschist facies are consisted of phylite, chlorite and pelitic schist, metatuff, and quartzite.

2.3.2 Pre-Variscan Megasequence (Pre-Permian basement)

The Pre-Variscan Megasequence is consisted of Pak Chom Group which underlies the Variscan unconformity. The Varican Orogeny is dated stratigraphically as the Early to Middle Carboniferous. These rocks older than the Late Carboniferous are considered to be basement in the Loei-Phetchabun fold belt and the Khorat Plateau area.

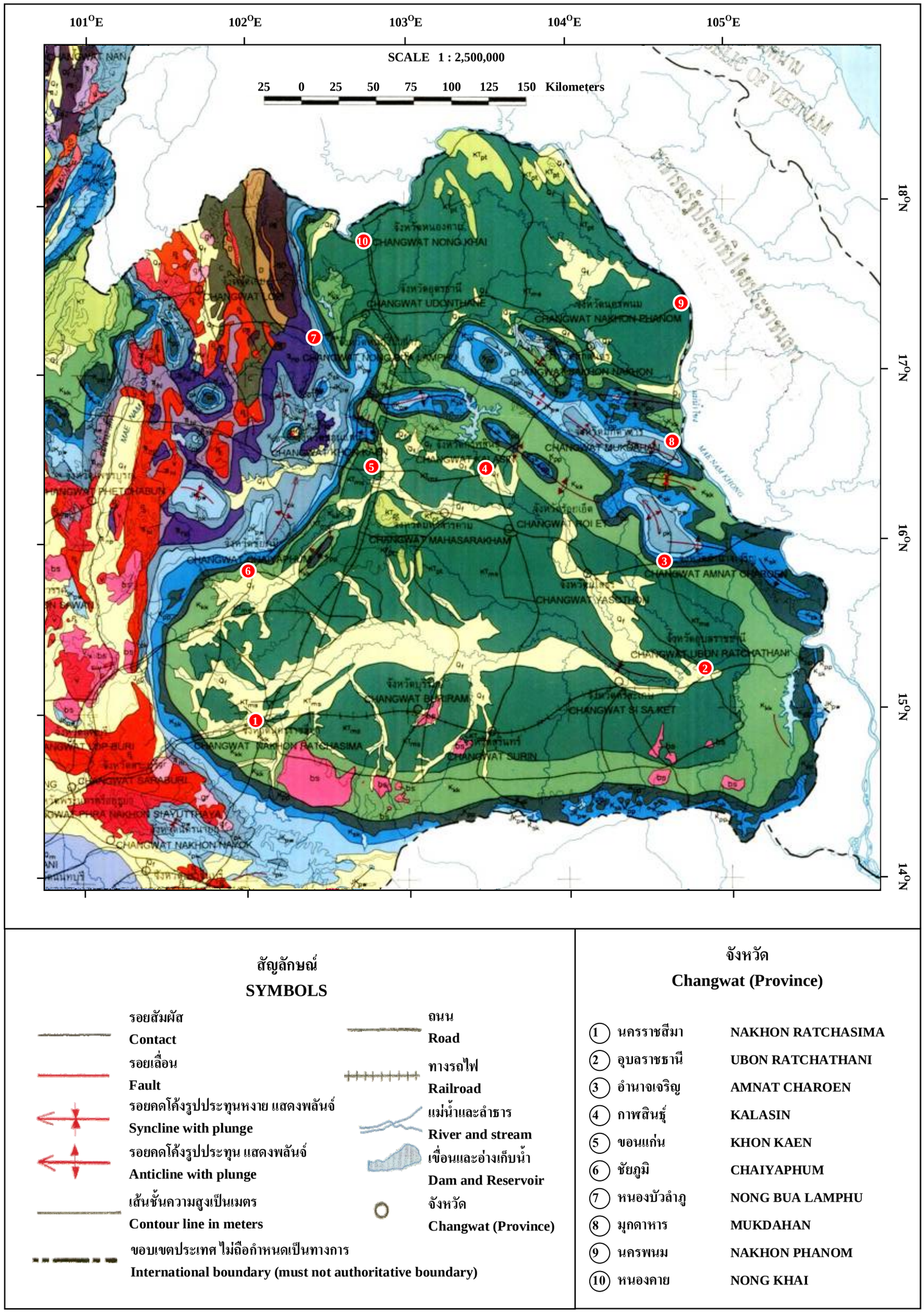


Figure 2.1 The general geological map in the northeastern region of Thailand (Modified from Department of Mineral Resources, 1999).

อายุ AGE	หินชั้นและหินแปร SEDIMENTARY AND METAMORPHIC ROCK
ควอเทอร์นารี QUATERNARY	Q_f ตะกอนธารน้ำพา ที่ราบน้ำท่วม ที่ราบน้ำพา ตะพักลำน้ำและเศษหินเชิงเขา Fluvial deposits: flood plain, alluvium, terrace and colluvium. Q_m ตะกอนชายฝั่งทะเล หาดทราย ป่าชายเลน ที่ลุ่มชื้นแฉะ และลากูน Coastal deposits: beach, mangrove swamp, marsh and lagoon.
เทอร์เชียรี TERTIARY	T กลุ่มหินแม่เมาะและกลุ่มหินกระบี่ หินกึ่งแข็งตัว หินแข็ง ชั้นถ่านหิน Mae Moh Group and Krabi Group: semiconsolidated, consolidated rocks and coal beds. KT หินทราย หินทรายแป้ง หินเกลือ หินกรวดมนและยิปซัม Sandstone, siltstone, claystone, conglomerate and gypsum. KT_{pt} หมวดหินภูทอก หินทราย หินทรายแป้งและหินเกลือ Phu Thok Formation: sandstone, siltstone and claystone. KT_{ms} หมวดหินมหาสารคาม หินทรายแป้ง หินเกลือ หินทราย เกลือหิน และยิปซัม Maha Sarakham Formation: siltstone, claystone, sandstone, rock salt and gypsum.
ครีเทเชียส CRETACEOUS	K_{kk} หมวดหินโคกกรวด หินทรายแป้ง หินทราย หินเกลือ และหินกรวดมน Khok Kruat Formation: siltstone, sandstone, claystone, and conglomerate. K_p หมวดหินพูพาน หินทรายแสงชั้นเฉียงระดับ หินทรายแป้ง และหินกรวดมน Phu Phan Formation: sandstone, cross-bedded, siltstone and conglomeratic sandstone. K_{pp} หมวดหินภูพาน หินทรายแสงชั้นเฉียงระดับ หินทรายแป้ง และหินกรวดมน Phu Phan Formation: sandstone, cross-bedded, siltstone and conglomeratic sandstone. K หินทราย และหินโคลน Sandstone and mudstone. K_{sk} หมวดหินเสาขัว หินทรายแป้ง และหินทราย Sao Khua Formation: siltstone and sandstone. JK_{pw} หมวดหินพระวิหาร หินทราย แสงชั้นเฉียงระดับ หินทรายแป้ง และหินเกลือ Phra Wihan Formation: sandstone, cross-bedded, siltstone and claystone. JK หินทรายอาร์โคส, หินกรวดมน และหินดินดาน Arkosic sandstone, conglomerate and shale. JK_l หมวดหินลำทับ หินทรายอาร์โคส และลิทิก หินโคลน หินทรายแป้ง มีรอยชั้นเฉียงระดับ หินกรวดมน และหินทราย Lam Thap Formation: Arkosic and lithic sandstone, mudstone, siltstone, cross-bedded, conglomerate and sandstone.
จูแรสซิก JURASSIC	J หินกรวดมน หินทราย หินดินดาน และหินโคลน Conglomerate, sandstone, shale and mudstone. J_{pk} หมวดหินภูกระดึง หินทรายแป้ง หินทราย หินเกลือ และหินกรวดมน Phu Kradung Formation: siltstone, claystone, sandstone and conglomerate. J_{um} กลุ่มหินอุ้มผาง หินโคลน หินทรายแป้ง หินทราย และหินปูน Umpang Group: mudstone, siltstone, sandstone, and limestone. J_k หมวดหินคลองมืน หินปูน หินดินดาน และหินทรายแป้ง Khlong Min Formation: limestone, shale and siltstone. TR_{np} หมวดหินน้ำพอง หินทราย หินทรายแป้ง หินเกลือ และหินกรวดมน Nam Phong Formation: sandstone, siltstone, claystone and conglomerate.
ไทรแอสซิก TRIASSIC	TR_{cb} หมวดหินชัยบุรี หินปูน หินโดโลไมต์ และหินเชิร์ต Chaiburi Formation: limestone, dolomite and chert. TR_{hl} หมวดหินห้วยหินลาด หินดินดาน หินโคลน หินทรายแป้ง หินเกรย์แวก หินปูน หินปูนกรวดมนฐาน และหินภูเขาไฟกรวดมน Huai Hin Lat Formation: shale, mudstone, siltstone, graywacke, limestone, basal limestone conglomerate and local volcanic conglomerate. TRJ หินกรวดมน หินอาร์โคส หินทรายแป้ง หินดินดาน และหินโคลน Conglomerate, arenite, siltstone, shale and mudstone. TR_l กลุ่มหินลำปาง หินโคลน หินปูน หินทราย หินทรายแป้ง และหินกรวดมน Lampang Group: mudstone, limestone, sandstone, siltstone and conglomerate. TR หินกรวดมนฐาน หินดินดาน หินทราย หินเชิร์ต และหินปูน Basal conglomerage, shale, sandstone, chert and limestone.
เพอร์เมียน PERMIAN	P_{rb} กลุ่มหินราชบุรี หินปูน หินปูนเนื้อโดโลไมต์ หินเชิร์ต และหินโดโลไมต์ Ratburi Group: limestone, dolomitic limestone, chert and dolomite. PT หินทราย หินปูน หินทัฟฟ์เนื้อไรโอไลต์ถึงเนื้อแอนดีไซต์ ถูกแปรสภาพ หินดินดาน หินปูนถูกแปรสภาพ และ หินชิร์ต Sandstone, limestone, metarhyolitic to metaandesitic-tuffs, shale, metalimestone and chert. P_s กลุ่มหินสระบุรี หินปูน หินเชิร์ต หินบะซอลต์ หินอัลตรามาฟิก และหินเซอร์เพนทิไนต์ Saraburi Group: limestone, chert, basalt, ultramafic and serpentinite.
คาร์บอนิเฟอรัส CARBONIFEROUS	C หินกรวดมน หินทราย หินดินดาน หินชนวน หินเชิร์ต และหินปูน Conglomerate, sandstone, shale, slate, chert and limestone. CP หินทราย หินปูน หินดินดาน และหินเชิร์ต Sandstone, limestone, shale and chert. CP_{kk} กลุ่มหินแก่งกระจาน หินทรายและหินกลุมเป็นกรวด หินดินดาน หินทราย หินทรายแป้ง หินโคลน และหินเชิร์ต Kaeng Krachan Group: pebbly sandstone, pebbly mudstone, shale, sandstone, siltstone, mudstone and chert.
ดิโวเนียน DEVONIAN	D หินเชิร์ต หินดินดาน หินปูน และหินทัฟฟ์ Chert, shale, limestone and tuff. DC หินเชิร์ตถูกแปรสภาพ หินทัฟฟ์ถูกแปรสภาพ หินอ่อน หินปูน-ถูกแปรสภาพ หินภูเขาไฟและหินกึ่งภูเขาไฟถูกแปรสภาพ Metachert, metatuff, marble, metalimestone, metavolcanics and metasubvolcanics. SDC กลุ่มหินทองผาภูมิ หินหินดานเนื้อปูน หินดินดาน หินเชิร์ต หินทรายแป้ง และหินปูน Thong Pha Phum Group: calcareous shale, shale, chert, siltstone, and limestone.
ไซลูเรียน SILURIAN	SD หินฟิลไลต์ หินฟิลไลต์เนื้อคาร์บอน และหินฟิลไลต์เนื้อควอรตซ์ Phyllite, carbonaceous phyllite and quartzitic phyllite.
ออร์โดวิเชียน ORDOVICIAN	O กลุ่มหินทุ่งสง หินปูนเนื้อดิน หินปูน หินปูนเนื้อโดโลไมต์ หินอ่อน และหินดินดาน Thung Song Group: Argillaceous limestone, limestone,dolomitic limestone,marble and shale. ϵO หินอ่อน และหินควอรตซ์ ไมกา ชีสต์ Marble, and quartz-mica-schist.
แคมเบรียน CAMBRIAN	ϵ_t กลุ่มหินตะรุเตา หินทราย หินควอร์ตไซต์ หินดินดาน และหินกรวดมน Tarutao Group: sandstone, quartzite, shale, and conglomerate. ϵ หินควอร์ตไซต์ หินออร์โทควอร์ตไซต์ หินทราย และหินดินดาน Quartzite, orthoquartzite, sandstone and shale.
พรีแคมเบรียน PRE-CAMBRIAN	PE หินไนส์ลานสาง หินไนส์ หินชีสต์ หินแอมฟิโบไลต์ชีสต์ หินควอร์ตไซต์ หินแกลก์-ซิลิเกต หินอ่อน และหินไบโอไทต์มาร์เบิล Lansang gneiss: gneiss, schist, amphibolite-schist, quartzite, calc-silicate, marble and biotite marble.

หินอัคนี IGNEOUS ROCKS	อายุ AGE
gy หินกีเซอไรต์ **Geyserite**	ควอเทอร์นารี **QUATERNARY**
bs หินบะซอลต์ **Basalt**	ควอเทอร์นารี-เทอร์เชียรี **QUATERNARY-TERTIARY**
gr หินแกรนิต และหินแกรโนไดออไรต์ **Granite and granodiorite**	ครีเทเชียสถึงคาร์บอนิเฟอรัส **CRETACEOUS TO CARBONIFEROUS**
m หินมิกมาไทต์ หินแกรนิต หินไนส์ หินชีสต์ หินควอร์ตไซต์ และหินทราย **Migmatite, granite, gneiss, schist, quartzite and sandstone**	ไทรแอสซิก **TRIASSIC**
v หินไรโอไลต์ หินแอนดีไซต์ และหินทัฟฟ์ **Rhyolite, andesite, and tuff**	ครีเทเชียสถึงเพอร์เมียน **CRETACEOUS TO PERMIAN**
u หินไพรอกซีไนต์ หินเซอร์เพนทิไนต์ และหินฮอร์นเบลนไดต์ **Pyroxenite, serpentinite, and hornblendite**	ไทรแอสซิกถึงเพอร์เมียน **TRIASSIC TO PERMIAN**
b หินอัคนีชนิดเบส หินควอรตซ์แกบโบร **Basic igneous rocks: quartz-gabbro**	คาร์บอนิเฟอรัส **CARBONIFEROUS**

Figure 2.1 The general geological map in the northeastern region of Thailand (Modified from Department of Mineral Resources, 1999) (Cont.).

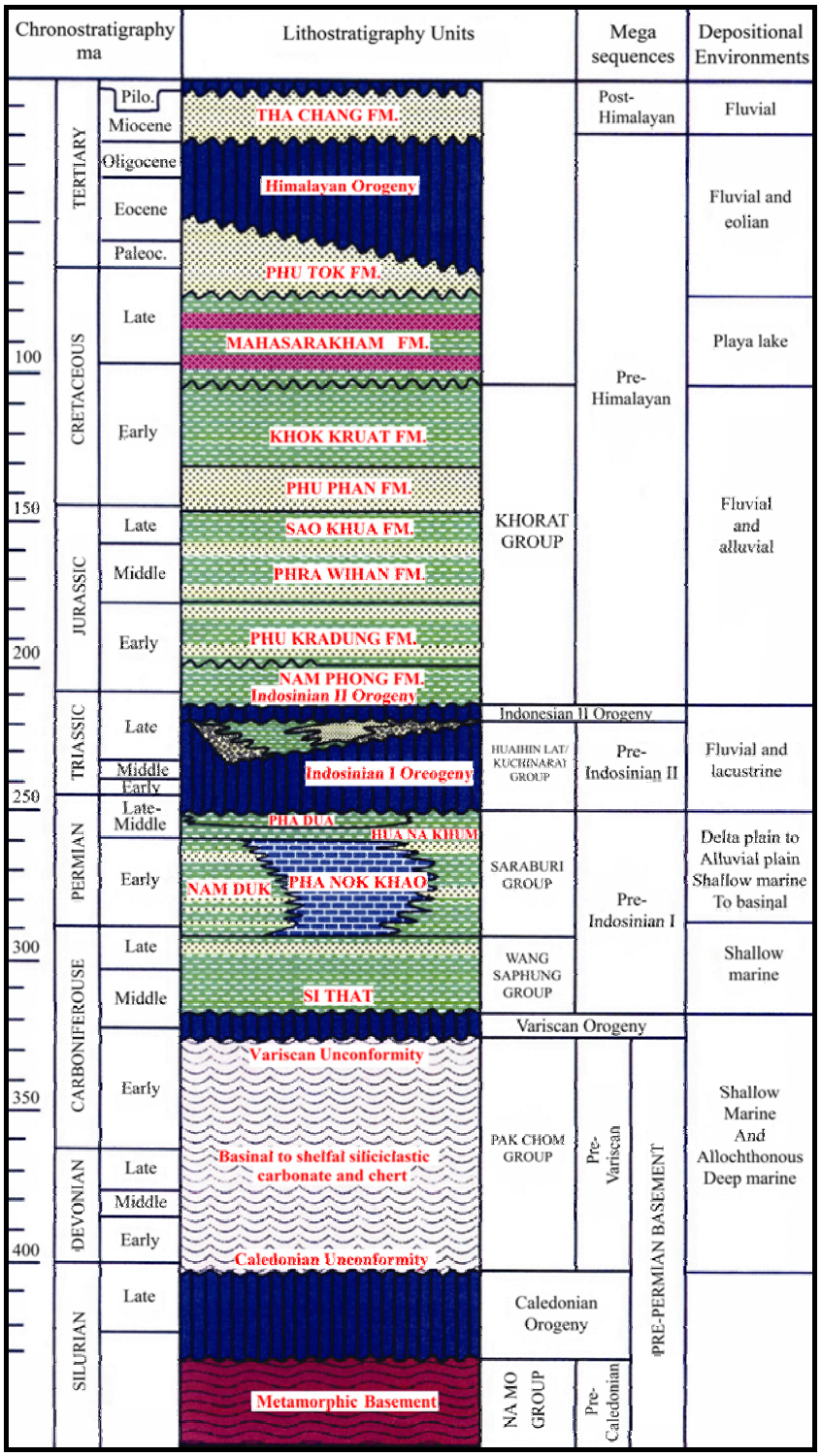


Figure 2.2 Lithostratigraphy in the northeastern region of Thailand and related to tectonic events (Modified from Sattayarak, N., 2005 and Chantong, W., 2005).

The Pak Chom Group of Late Silurian to Early Carboniferous mainly is consisted of shallow marine sediments of limestone, greywacke, shale, conglomerate, and tuff. However, radiolarian chert of deep sea facies is also recorded in the sequence, suggested allochthonous content. The Pak Chom Group unconformably overlies the Na Mo Group.

2.3.3 Pre-Indosinian I Megasequence

The Pre-Indosinian I Megasequence unconformably is ovelies the Pre-Varisan Megasequence. It is below the Indosinian I unconformity which is dated as Late Carboniferous to Late Permian. It is divided into Si That Group and Saraburi Group in ascending order.

The Si That Group

The Si That Group is defined as the pre-rift megasequence. This formation is found only in the subsurface data (underneath the Phu Phan range). The group is consisted of sediments in shallow marine depositional environment (E-Sarn sea) which are deposited during the Late Carboniferous to Late Permian. The Si That Group can be divided into three formations: Si That, Dong Mun, and Lam Pao formations.

Si That formation is defined as the Late Carboniferous to Early Permian. This rock unit has been informally named the Lower Clastics and is consisted of grey to dark grey shale interbedded with limestone, dolomite, and siltstone with some conglomerate in the lower part of the formation.

Dong Mun formation is defefined as Early to Middle Permian. This rock unit is consisted of the carbonate rock which mudstone, and dolomite. The

limestones are pale yellow, brown, and moderate hard. The dolomire is light grey to dark grey, and moderate hard.

Lam Pao formation is defined as Late Permian. This rock unit is consisted of interbedded siltstone, claystone, and limestone. Silstones are grey to dark grey, moderate hard, and argillaceous. The claystones show light grey. The limestone types are mudstone and wackstone, brown, medium grey, dark grey, hard, and calcareous.

The Saraburi Group

The Saraburi Group is defined as the pre-rift megasequence. The group is consisted of sediments of shallow to deep marine depositional environment (Nam Duk sea) which are deposited during the Early to Early Late Permian. This group is widely outcrop along the western edge of the Khorat Plateau, extended from Loei, Petchabun to Saraburi province. The carbonate sequence is consisted mainly of limestone, dolomite, and clastic sediment of shale, sandstone, and siltstone, which represent sediment which deposited in different environment ranging from delta plain, shelf platform, and to deep basin. The Saraburi Group can be divided into three formations as follows;

Nam Duk formation is defined as the Early to Middle Permian. This rock unit is consisted of pelagic shale, grey to black sandstone, yellowish brown, fine grained, limestone, lense and bedded limestone with a minor amount of chert. The rock sequence represents a deep-sea basin depositional environment and grades upward into the shallow marine platform of Hua Na Kham formation.

Pha Nok Khao formation is defined as the Early to Middle Permian. These outcrops are wildly distributed in Saraburi and Nakhon Ratchasima provinces.

This rock unit is consisted of predominantly white to dark grey massive limestone with minor beds of dark shale, chert, siltstone and fine-grained sandstone, and dolomite. The rock sequence represent the depositional environment in the intertidal and tidal flat, fore reef to back reef, and lagoonal.

Hua Na Kham formation is defined as the Late Permian. The outcrops found in the northern edge of the Khorat Plateau near Laos border in Loei province. This rock unit is clastic conformably overlies the Pha Nok Khao formation and has been informally named the Upper Clastics. The Upper Clastics are consisted of light grey to grey shale, siltstone, conglomeratic sandstone, and sandstone with minor beds of limestone. The fossils including fusulinid in limestone suggested that the sedimentary sequence of formation is depositied in a shallow platform marginal marine environment.

2.3.4 Pre-Indosinian II Megasequence

The Pre-Indosinian II Megasequence unconformably is ovelies the Pre-Varisan or Pre-Indosinian I Megasequences. The Khorat Group of the Pre-Himalayan Megasequence overlies it unconformably. It is divided into Kuchinarai Group and Huai Hin Lat Group.

The Kuchinarai Group

The Kuchinarai Group is defined as the syn-rift megasequence. The group are consisted of sediment which are deposited in the Triassic half-grabens or graben. This group can be divided into three parts. The upper part is consisted of light to moderate dark grey, buff to tan, red brown to rust brown claystone, and shale. The middle part is consisted of dark lacustrine shale with minor amounts of siltstone, and

sandstone. The lower part is made of basal conglomerate. The age of half-grabens filling indicates Late Triassic in age.

The Huai Hin Lat Group

The Huai Hin Lat Group is defined as the earliest post-rift megasequence. The group is consisted mainly of claystone, and siltstone interbedded claystone, siltstone, chert, and quartz-conglomerate that deposited during the Late Triassic based on the plant remains, pollen and spores, and a conchostracan. This group is defined as the earliest post-rift megasequence and is separated from the Kuchinarai Group. Although this group is found in the local area, the seismic data show it to be unconformable upon the Kuchinarai Group. Thus, the Hua Hin Lat Group should be separated from the syn-rift megasequence.

2.3.5 Pre-Himalayan Megasequence

The Pre-Himalayan Megasequence is consisted of sedimentary units between the Indosinian II and the Himalayan unconformity. The Himalayan Orogeny that caused the unconformity in northeastern Thailand is dated as Late Cretaceous to Miocene. The Pre-Himalayan Megasequence overlies the Pre-Indisinian II or older Megasequences. It is composed Khorat and Phon Hong Groups.

The Khorat Group

The Khorat Group is defined as the post-rift megasequence. The group is consisted of very high thickness of red clays, siltstone, sandstone, and conglomerates (continental sediments) that deposited during the Jurassic to Cretaceous. This unit is found in both the Loei-Phetchabun fold belt and the Khorat Plateau. This group can be devided into six formations.

Nam Phong formation is the lowest unit of the Khorat Group. The unit can be considered into two parts. The upper part is consisted of predominantly siltstone, minor sandstone, and claystone together with thin limestones. The siltstone is dusky red to red brown to purple, is none to slightly calcareous, and commonly cantains lithoclastic of claystone, and limestone and quartz grains. The lower part is consisted of red-brown sandstone, siltstone, and claystone. The formation overlies the Huai Hin Lat formation conformably. At some localities, it overlies the Permian limestone unconformably.

Phu Kradung formation is consisted of interbedded sandstone and siltstone, with occasional limestone lenses and concretions and thin bed of claystone. The sandstone ranges from light grey, light to medium brown, red brown, medium green to off white with varicoloured grains. The formation overlies the Nam Phong formation or the Permian rock, if the Nam Phong formation is not present.

Phra Wihan formation is consisted of cross-bedded white quartz sandstone with thin bed of siltstone, and occasionally thin beds of claystone and nodular limestone. The sandstone is off white to grayish green, fine to medium grained but locally coarse to very coarse grained, with calcareous cemented.

Sao Khua formation is consisted of interbedded sandstones and siltstones with minor claystones, with occasional nodular limestone occurrences towards the base.

Phu Phan formation is consisted of fine to medium-grained sandstone interbedded with siltstone. The sandstone is off white to light grey, grey green, reddish brown, occasionally light brown, moderately hard, sub angular, party

micaceous, with traces of siltstone and limestone lithoclasts. The unit underlies the Khok Kruat formation and overlies the Phra Wihan formation.

Khok Kruat formation is consisted of interbedded sandstone, siltstone, and claystone with traces of limestone. The sandstone is off white to light grey to reddish brown, very fine to medium grained, rounded to sub rounded, friable, silty/argillaceous matrix, and with fair to poor visible porosity. The siltstone is red to brown to purple, hard, slightly very calcareous, commonly sandy, and grading to sandstone, and containing limestone lithoclasts and nodules. The claystone is red to reddish brown, soft to moderately hard, noncalcareous, and commonly silty.

The Phon Hong Group

The Phon Hong Group is defined as the post-inversion megasequence. The group is consisted of hypersaline lacustrine and aeolian sediments that deposited the Early Late Cretaceous. This group can be devided into Maha Sarakham and Phu Tok formation.

The Maha Sarakham formation is consisted of siltstone and shale in the upper part and anhydrite and salt in the lower part. This formation is composed of three thick layers of halite with minor anhydrite which separated by claystone. The halite is clear to translucent, white, occasionally grayish, orange to pink, brittle, elongate, and coarse to granular sized. The anhydrite is white, light grey, pale red, very fine to finely crystalline, brittle, and blocky to sub-blocky. The salts indicated a non-marine restricted hypersaline lacustrine depositional environment. Based on paleomagnetic and isotopic dating, the age of formation is abount 100 Ma or Late Cretaceous.

The Phu Tok formation is consisted of thick massive reddish sandstone, claystone, and siltstone which indicated in an aeolian depositional environment. In Phu Tok Noi, Sri Vilai district, Nong Khai province, sandstones with very high angle and very large scaled cross bedding interbedded with channelized fine-grained that interpreted to have been deposit by stream and wind.

2.3.6 Post-Himalayan Megasequence

The Post-Himalayan Megasequence is consisted of rocks between the Himalayan unconformity and the base of the Quaternary sediments and comprised the Tha Chang formation.

The Tha Chang formation is consisted of semi-consolidated to consolidated, mudstone, and conglomerate. Its relationship with the underlying formation cannot be demonstrated but is inferred to be unconformable. The vertebrate fossils are indicated Middle Miocene age.

The Quaternary sediments underlying the soil cover along the edge of the edge of the Khorat Plateau is consisted of gravel bed and lateritic soil layer. Petrified woods are found in gravel beds ranging in age from Late Cretaceous to Early Quaternary.

2.4 Basin evalution

The Khorat Plateau underwent six tectonic events, in four of which is an orogenic event. A number of tectonic events of different ages produced a structural style which has most influence on the petroleum geology. The basin evolution of the Khorat Plateau can be summarized in Figure 2.2 which represents the tectonic events.

2.4.1 Early Carboniferous Vasrican Orogeny

The presence of a Varisan unconformity is somewhat speculative because it is usually not well defined by either seismic or outcrop data in the area. However, from seismic data in the Phu Kao/Phu Horm area (Kozar, Crandall, and Hall, 1992) recognised an angular unconformity in which an orogenic event porceded erosion. In northern Thailand, this orogeny involved large scale thrusting as well as volcanic activity and plutonism. To date, wells drilled below the Variscan unconformity have encountered undifferentiated volcanics, granite (329±3 Ma), metasediments, and sedimentary rock (Pradidtan, S., 1995).

2.4.2 Late Carboniferous to Late Permian main rifting and rejuvenation

According to Kozar et al. (1992), Late Carboniferous rift was the primary event influencing the subsidence and development of the Khorat basin. This rifting began during the Late Carboniferours as the region was subjected to back arc extension and the extension continued through Middle Triassic. The rift structures are expressed as a series of NW-SE striking normal faults, and NE-SE and E-W trending oblique faults. Major rift structures include half and full grabens, horsts, rotated blocks, and trapdoor and dogleg trends. The orientations of some doglegs were likely influenced by faults formed during the Variscan Orogeny. Rifting may have abated during Permian and was rejuvenated in the Early Triassic. The Triassic siliciclastic sediments accumulated in some grabens as indicated by seismic data is over 20,000 feet.

Within the central portion of the Khorat Plateau, three high parallelogram-shaped platforms developed. Half grabens bound the southern and northeastern flanks of the Dong Mun and Si That platforms. The eastern portion of the

Phu Horm platform is bounded by a full graben. Along the western margin, normal faults have NNE-SSW orientations.

As extension proceeded through Late Carboniferous, a triple junction developed between the three platforms. The Dong Mun and Si That platforms were structurally modified by NW-SE extension while the Phu Horm platform was structurally modified on its western margin by the extension of the developing seaway. During the Permian, these high platforms provided favorable locations for the carbonate accumulations of shallow water.

2.4.3 Middle Triassic Indosinian Orogeny

During this Indosinian Orogeny in Middle Triassic, the basins in northesat Thailand were subjected to strong compressions from both the west and northeast probably as a result of the continental collision of Indochina plate with Shan Thai plate to the west and Southeast China plate to the northeast. Rhyolitic volcanism and granitic plutonism occurred (Kozar et al., 1992; Pradidtan, S., 1995).

According to Kozar et al. (1992) the structural features resulted in reverse dip slip. Inversion of normal faults. Reactivations of existing normal fault with reverse dip slip producing vary degree of inversion. Inversion caused the post Variscan sediment pile to be deformed into fault-propagated folds. Inversion was greatest on faults whose strike was perpendicular to the stress direction. Foreland thrust fault. Some basement thrust faults with throws of 100 to 2,000 feet were generated. Deformation of graben-fill sediments. Local detached thrust faults were accompanied by fault propagation folds or fault bend folds. Disharmonic folds were formed with overpressured shale cores. Shale diapirs were also generated.

2.4.4 Late Triassic to Early Tertiary (Interior sag)

According to Kozar et al. (1992) after the Indosinian Orogeny, the Khorat basin was gradually subsided due to interior thermal sagging. The subsidence began in the Late Triassic and continued through the Early Tertiary. During this period of uniform subsidence, very thick monotonous red beds (continental sediments) of the Khorat Group were deposited. Where preserved, the thickness of this group average around 10,000 feet. The Late Triassic that Huai Hin Lat formation overlies the base of the Khorat unconformity and is believed to be the seal for gas accumulation found to data. Peak hydrocarbon migration is thought to have occurred at the conclusion of Huai Hin Lat deposition.

2.4.5 Early Tertiary Himalayan Orogeny

Interior sag and associated deposition culminated during the Early Tertiary, Paleocene or Eocene, the Khorat basin was subjected to compression and contraction from both the northeast and west again. These events resulted from back arc compression of the Shan Thai plate to the west and continental collision with the Southeast Indochina plate to the northeast. Deformation resulted by this orogeny includes forming of the Phu Phan anticlinorium and most of the Khorat structures as evidenced at the surface (Pradidtan, S., 1995).

Kozar et al. (1992) described to structural features were observed are direct results of this event includes a N-S trending foreland fold thrust belt showing significant basement contraction is located on the western margin. Reactivation ranging from 100 to 1,000 feet of Indosinian basement involved thrust faults. Gentle anticlinorium that as positive inversions generated by reverse slip of graben bounding faults are observed on seismic. Reactivation of Indosinian age grabenfill detached

thrusts resulted in the generation of broad and fault propagation folds within the Khorat Group and regional uplift.

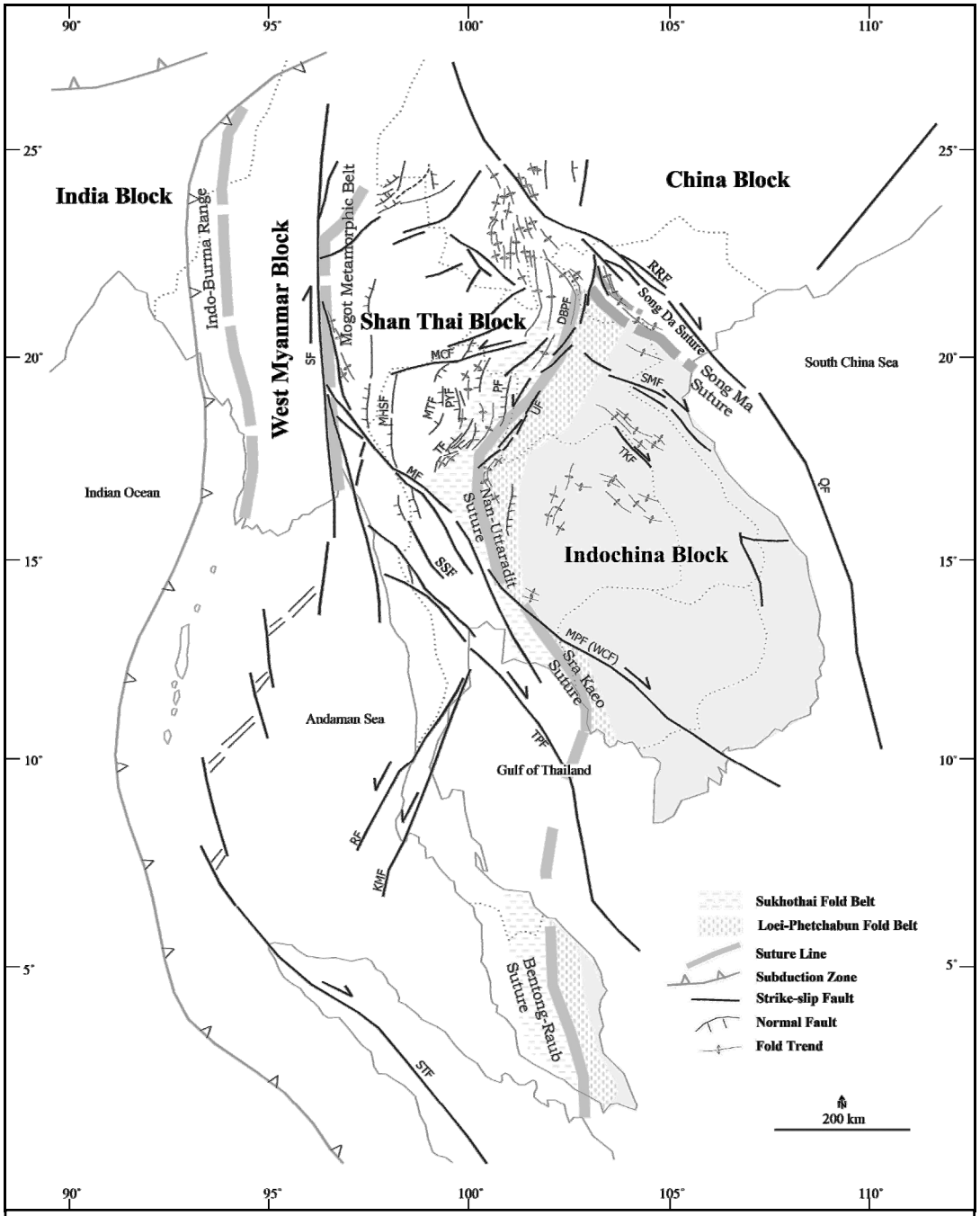
2.4.6 Early Tertiary to Recent (uplift and erosion)

Erosion, accompanying the post-Palaeocene uplift has removed 3,000 to 3,500 meter of post-Phra Wihan sediments from crests of anticlines in the Phu Phan range. The lack of mountains formed during this period indicates that erosion kept place with, or even exceeded uplift.

The reversed topographic expression suggests plateau uplift followed by deep erosion. The timing of this uplift is uncertain but Harding and Henshaw (1981) suggest that it is Late Neogene to recent in age. Based on (1) dating of the erosion of the post-sag fill in the Phitsanulok basin, (2) the belief that thermal arching in the region followed the development of normal faulting in the central basins, and (3) the Quaternary basalts along the southern rim of the basin suggest a young thermal event.

2.5 Structural framework

The northeastern of Thailand, which forms part of the Indochina plate, comprises two main areas which are Loei-Phetchabun fold belt and Khorat Plateau. The major structural elements of the Khorat Plateau run parallel with the Nan-Uttaradit sutures zone at the northern and western margin of the Indochina plate (Figure 2.3). The northwest-southeast trending anticlines form the Phu Phan range which are parallel to the Song Ma suture to the north. Nearly to the Nan-Uttaradit suture in the west margin of the Khorat Plateau is the N-S trending Loei-Phetchabun fold belt which is highly tectonised and eroded (Chontong, W., 2005).



Abbreviation : KMF: Khong Marui Fault; RF: Ranong Fault; TPF: Three Pagodas Fault; MPF: Mae Ping Fault (or WCF: Wang Chao Fault); RRF: Red River Fault; DBPF: Dien Bien Phu Fault; SMF: Song Ma Fault; TKF: Tha Kaek Fault; QF: Quinhon Fault; SF: Sagaing Fault; STF: Sumarta Fault; SSF: Sri Sawat Fault; UF: Uttaradit Fault; MF: Moei Fault; MCF: Mae Chan Fault; TF: Thoen Fault; PYF: Phra Yao Fault; MTF: Mae Tha Fault; PF: Pua Fault; MHSF: Mae Hong Son Fault.

Figure 2.3 Tectonic setting of Thailand (Modified from Chantong, W., 2005).

The structural framework (Pradidtan, S., 1995) can be defined into five main areas in northeastern of Thailand but without explaining their characteristics. It would appear from his accompanying diagram of the base Khorat unconformity (Figure 2.4) that they may be characterised as follows;

1) The Phu Phan anticlinorium is a zone of strong fault inversion and numerous pre-Khorat sequence antiform trending NW-SE and the base Khorat unconformity at relatively shallow depth (1-1.5 seconds).

2) The western area is a zone with faults and pre-Khorat sequence antiform trending N-S to NNE-SSE, and the base Khorat unconformity at moderate depth (1.5-2 seconds).

3) The Sakon Nakhon basin is an apparently structureless zone with the base Khorat unconformity at relatively shallow depth (1-1.5 seconds).

4) The central Khorat basin is a zone with faults trending NW-SE and the base Khorat unconformity at relatively deep depth (>2 seconds).

5) The rim area is the southern flank of the Khorat basin that lacking data.

Piyasin, S. (1995) can be subdivided into five subbasins based on the structural setting in the Khorat Plateau (Figure 2.4) as follows;

1) Ubon subbasin is the largest subbasin and elongated from E-W direction, covered in the southern part. The basement slopes downwards towards the east with the deepest part being approximate 6 kilometers at Ubon Ratchathani province.

2) Khon Kaen subbasin is located north of the Ubon subbasin and elongated E-W direction. There is a small and narrow ridge divided these two subbasins. The Chonabot prospect and Nam Phong gas field are on the margins of this subbasin. The depocenter is in the middle of basin.

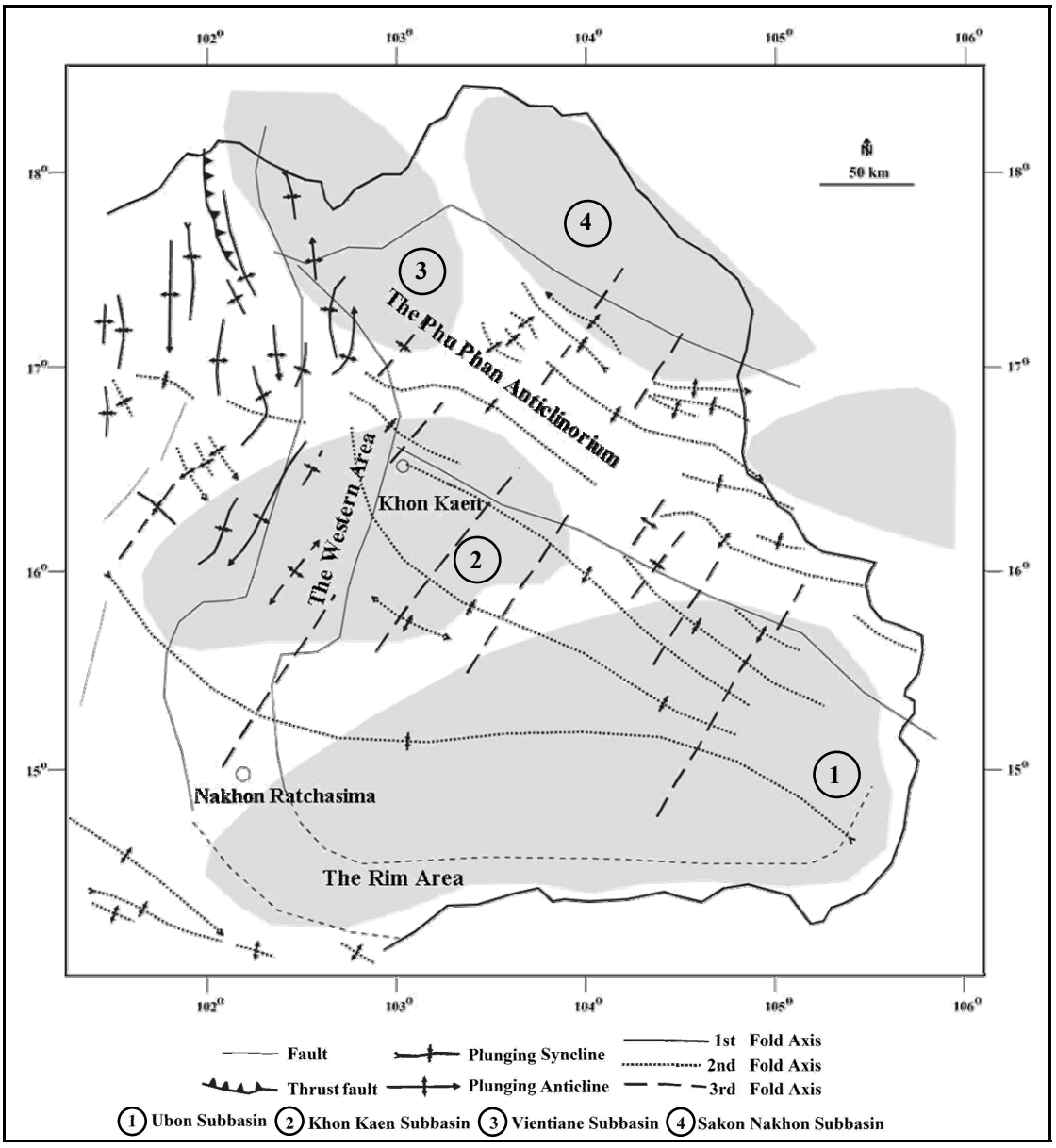


Figure 2.4 The major areas, subbasins, and deformation in the Khorat Plateau (Modified from Chantong, W., 2007).

3) Vientiane subbasin is elongated in NW-SE direction and extending into the Laos PDR, covers Vientiane and the flat plain north of Vientiane to Udon Thani province in Thailand. It is separated from the Khon Kaen subbasins by the Phu Phan anticlinorium.

4) Sakon Nakhon subbasin is a similar size and has the same elongate and orientation as the Vientiane subbasin. Most of the basin is confined in Thailand, only the SE part extends into the Laos PDR at Muang Tha Khek. It is interpreted as a half graben with basement sloping to the NE and with the bounding fault running along at the Mae Khong river where outcrop of Pra Wihan sandstone exposed and vertically dipping.

5) Savannakhet subbasin is kidney-shaped basin and elongated in E-W direction, extending from the Mae Khong river in the west to the Vietnamese border to the east. Oil seepage is found at Muang Phin, abount 10 kilometers west of Xepone on the No.9 Highway.

An analysis of lineartions (Figure 2.4) from Landsat 5 images by Chuaviroj, S. (1997) to suggested three deformations of Mesozoic rocks of the Khorat Plateau as follows;

First deformation (F_1) is the oldest deformation with N-S fold axes trends inherited from the Shan Thai and Indochina plates collision. It is possible Late Cretaceous in age. This trend is seen at Phu Luang (Loei province) and Phu Wiang (Khon Kaen province). Apart from the Mesozoic rocks deformed, the Upper Paleozoic rocks that Permian limestone is suffered at Loei province's area.

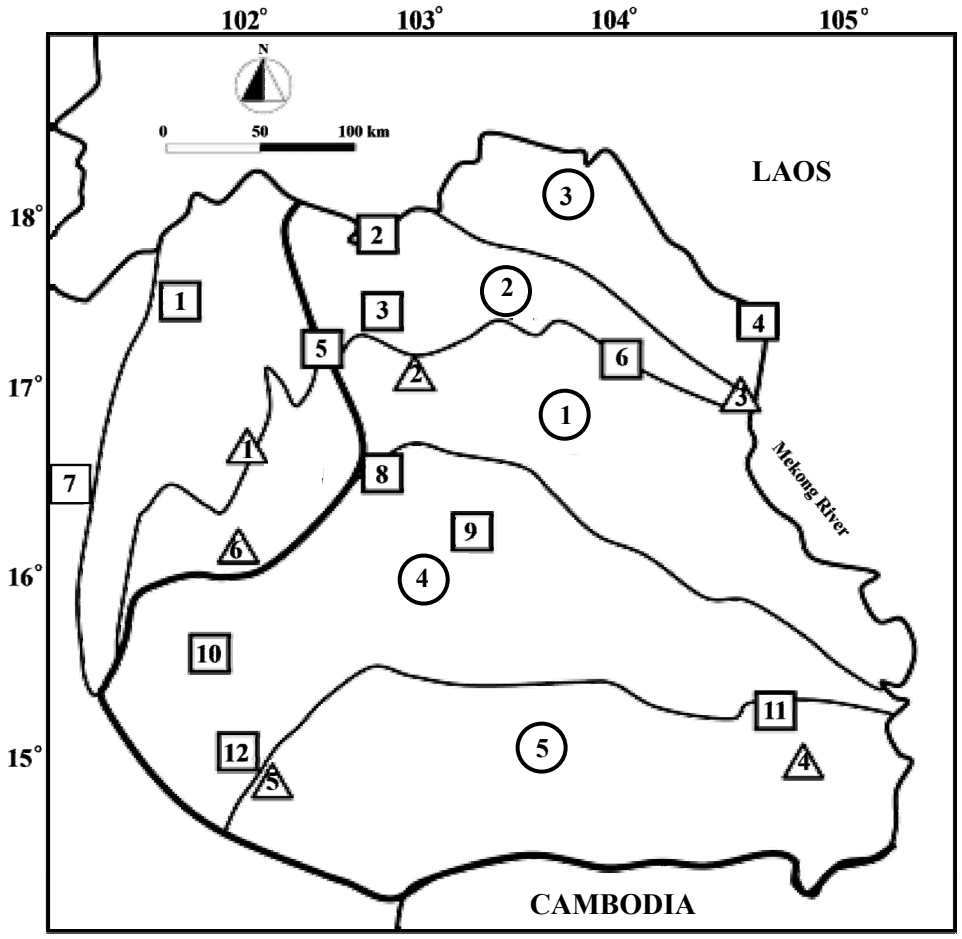
Second deformation (F_2) resulted from the collision between India plate and Eurasia plate in the Early Triassic and produced the Phu Phan range. The NW-SE trend is interpreted as the consequence of NE-SW compression. The Phu Wiang syncline (F_1) on the western margin of the Khorat Plateau is deformed again slightly. The main structures formed were Phu Khiew syncline, Sisaket syncline, Khon Kaen syncline, and Ubon anticline.

Third deformation (F_3) is probably produced during late stage of the Himalayan Orogeny which caused updoming in the Miocene to Pleistocen. Compression is believed to be NW-SE direction causing the axes of F_3 fold to be almost parallel to the Kumpawapee syncline.

2.6 Petroleum provinces

The petroleum province in northeastern part of Thailand can be divided into 5 petroleum provinces (Figure 2.5) based on geology, geomorphology, and geologic structures excluding the western part covering Loei-Petchabun fold belt and Chum Phae areas (Sattayarak, N., 2005). The detail of each province as follows;

1) Phu Phan anticlinorium is consisted of complex anticlines and synclines trending more or less NW-SE. It covers from Nam Phong and Khao Saun Kwang anticlines to the west to the Phu Phan mountain range and Pha Taem to the east. The area is underlain by Permo-Carboniferous formation, non-marine Triassic Pre-Khorat rocks, and the minor folding of Jurassic to Cretaceous redbeds in the upper part.



Petroleum Province : 1) Phu Phan Anticlinorium, 2) Nong Khai-Tat Phanom Area, 3) Phon Phisai-Nakhon Phanom Area, 4) Khon Kaen-Ubon Area, and 5) Chok Chai-Det Udom Area

Changwat/Province : 1) Loei, 2) Nong Khai, 3) Udon Thani, 4) Nakhon Phanom, 5) Nong Bua Lamphu, 6) Sakon Nakhon, 7) Petchabun, 8) Khon Kaen, 9) Maha Sarakham, 10) Chaiyaphum, 11) Ubon Ratchathani, and 12) Nakhon Ratchasima

Amphoe/District : 1) Chum Phae, 2) Khoa Saun Kwang, 3) Tat Phanom, 4) Det Udom, 5) Chok Chai, and 6) Phu Kiew

Figure 2.5 Petroleum provinces and geographical names in the northeastern region of Thailand (Modified from Sattayarak, N., 2005).

2) Nong Khai-Tat Phanom area is located north of the Phu Phan anticlinorium, having a roughly E-W alignment from Nong Khai in the west extending to Udon Thani and Nakhon Phanom in the east. The area is covered by a plain represented by the younger sediments such as Phu Tok and Maha Sarakham formations which overlie the redbeds of the Khorat Group and the Triassic lower part of Pre-Khorat rocks. The Permo-Carboniferous formation may by present at the lowest section in some areas.

3) Phon Pisai-Nakhon Phanom area is located north of the Nong Khai-Tat Phanom area. Its northern edge is bounded by Mekong River. The subsurface data reviewed a stratigrapy that the underlying units are thick sandstone of Phu Tok formation which was deposited by eolian process. The lower units encountered are rock salt of the Maha Sarakham formation and the redbeds of the Khorat Group respectively on the basement rocks.

4) Khon Kaen-Ubon area covers mainly Chaiyaphum and Khon Kaen from the west to Ubon Ratchathani province lying in a E-W direction. The stratigraphy is similar to the Nong Khai-Tat Phanom area. Nevertheless, the thickness of the Khorat Group and overlying sediments are much greater. These sediments are underlain by the granite of 329±3 million years from Yang Talat-1 well, or Permo-Carboniferous formation such as Permian carbonate from Phu Wiang-1 well, or even older formation such as Devonian shallow marine Carbonates that might extended southeastward from their outcrops in the Loei-Petchabun fold belt.

5) Chok Chai-Det Udom area is covered by gravel beds and basalt which overlie the redbeds of the Khorat Group and the basement rocks. The Pre-Khorat Group is found in some place based on the well data.

Sattayarak, N. (2005) discussed that the deep-sea Nam Duk shale containing a good source rock property are overcooked from the maturity level. Beside the severely high degree of folding and faulting on the Permo-Carboniferous formation, the Khorat Group on top of them is only capping in a small area. The petroleum potential on each petroleum provinces can be summarized as follows;

1) The Phon Phisai–Nakhon Phanom area is another place having a low petroleum potential. Seismic sections show a flat, presumable long denudated of old crystalline basement. How ever, gravity anomaly map in this area revealed a deeper gravitational basement compare to that of acoustic one. Reprocessing and reinterpreting of the old seismic acquisitions are urged.

2) The Chok Chai–Det Udom area, so far only Triassic Pre-Khorat basins are believed to floor the Khorat redbeds in some place. Geological risk in this area is trap type. Structural trap that is more convincing for drilling program is quite difficult to notice. Triassic Pre-Khorat sandstone and conglomerate with stratigraphic trap and buried hill play are anticipated to be proved.

3) The Chum Phae area is a junction area between the N-S folded Permian strata to the west and the mainly NW-SE trends in the Khorat Plateau. It already shows a successful petroleum system in this province. Gas has been found in Dao Ruang-1 well. More understanding on the reservoir rock is necessary. Further more, thrust play is also another possibility.

4) The Nong Khai–Tai Phanom area is the province having predominantly Pre-Khorat half graben basins potential. More study on the nature of the Triassic sediments is needed. By the ways, possibilities of finding petroleum from Permo-Carboniferous in a simple play type or thrust plays are open.