2 Geology

2.1 General Geology

The geologic setting of Thailand reflects a long and complex evolution, with regional differences in geological history. The main part of Central Thailand is covered by Quaternary sediments which conceal a number of basins formed in response to dextral shear on the Mae Ping and Three Pagodas Fault Zone systems during the Tertiary. The northern, western, and peninsular regions of Thailand are dominated by Paleozoic rocks (Bunopas, 1983) with small, deformed outliers of Mesozoic strata, and occasional small Tertiary basins. In Northeastern Thailand, an extensive outcrop of Mesozoic rocks occurs on the Khorat Plateau. The Khorat Plateau is rimmed by an escarpment of mostly steeply dipping sediments which form cuestas rising from 600 - 1 000 m above sea level on its western and southern margins. The Khorat Plateau has a "sauce-pan morphology" (Piyasin, 1995), covering an area of about 170 000 km2. It is a gently undulating plateau elevated 150 to 500 above mean sea level and slopes gently towards the Mekong River. The Plateau extends northward and eastward across the Mekong River into Laos. It is divided by the Phu Phan Range into two depositional basins, the Khorat in the south and the smaller Sakhon Nakhon in the north. The dominant landforms are low hills and ridges with board crests and gentle straight slopes of 20 to 30 m relief separated by broad valleys (Löffler et al, 1984).

In the Khorat area the sedimentary sequence consists of an initial rift sequence of Carboniferous to Triassic age sediments, and a "sag" sequence of Late Triassic to Cretaceous age sediments (herein termed "post-Indosinian"). The two sequences are separated by a regional erosive unconformity, known as the Indosinian Unconformity, which represents the main collision of Indochina with its neighbors. The Khorat Plateau Basin is the term in use for the area of outcrop of the post-Indosinian sequence.

Seismic data and petroleum exploration wells from the Khorat Plateau demonstrate the existence of a number of Paleozoic and Triassic basins at depth with outcrop analogues in the extensive Loei-Phetchabun Foldbelt to the west. Cooper et al. (1989) drew the simplified geological map of Thailand as shown in Figure 2.1 and they also showed the broad relationships between the megasequences by a cross-section through Northeastern Thailand (Figure 2.2; the line of section is indicated on Figure 2.1). It illustrates the links between Mesozoic sedimentations and regional tectonics. It records the following: transitions from an active margin in the Permian to subsequent continent-continent collision in the Early to Middle Triassic (the Indosinian Orogeny); a Late Triassic extensional event; thermal subsidence for the remainder of the Mesozoic allowing the deposition of the Khorat Megasequences; Early Tertiary inversion. This section also illustrates that the compressional structures formed during the Early Tertiary inversion are thick-skinned (because the amplitude and wave-length of individual structures indicate a deep level of detachment) and a Mid Crustal Detachment depth of 15 km.

The Khorat Monocline (Figure 2.1 and 2.3) seems to be a true inversion structure linked to the faults that controlled the development of Triassic basins; likewise, the Phu Phan Uplift originated as a Triassic depocentre which is now inverted. Part of the more recent geological map of Thailand published in 2001 by the

Department of Mineral Resources is shown in Figure 2.3 and its explanation is shown in Figure 2.4.

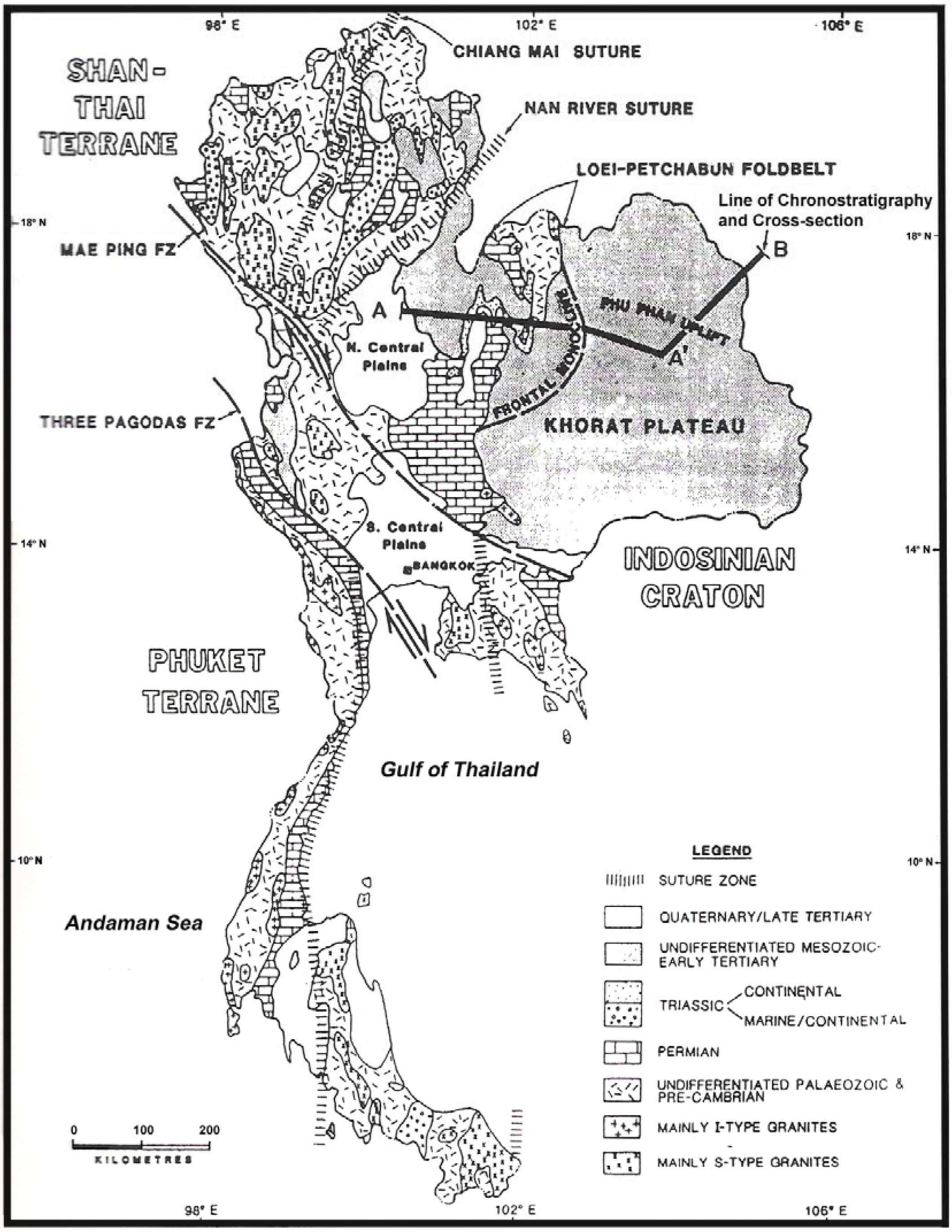

Figure 2.1 Simplified geological map of Thailand and line A-A'-B indicates the trace of the geologic cross-section through Northeastern Thailand (Cooper *et al.*, 1989). The details of these cross-section are shown in Figure 2.2.

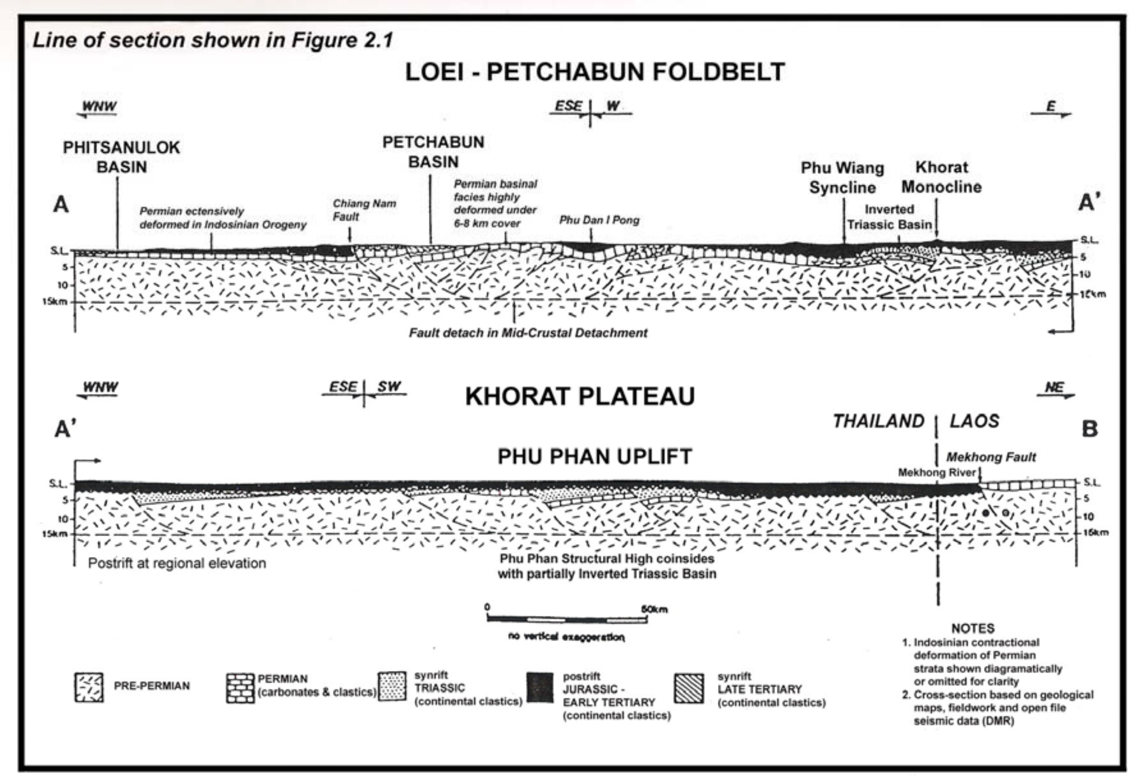

Figure 2.2 Geological cross-sections through Northeastern Thailand
(after Cooper *et al.*, 1989)

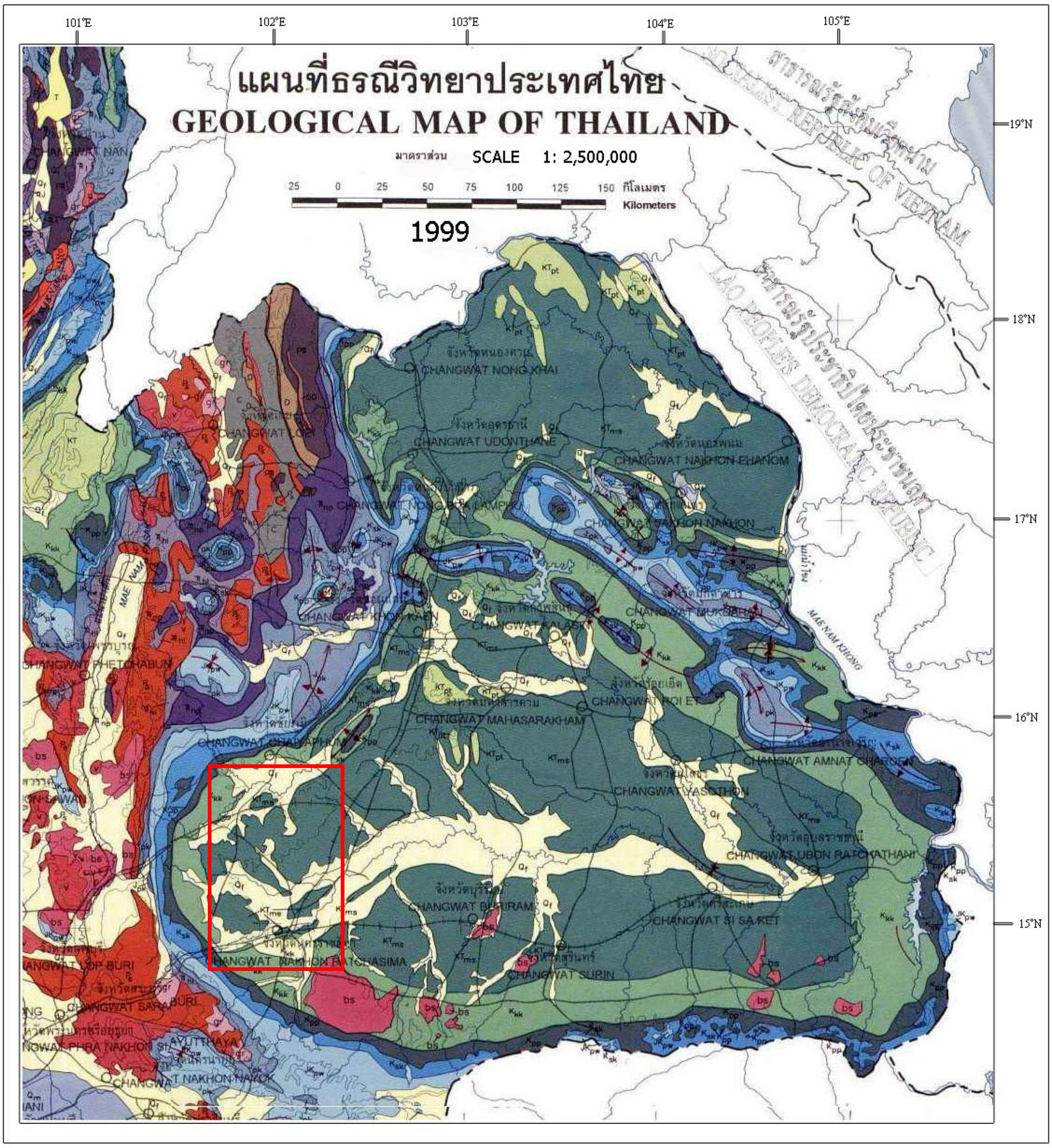

Figure 2.3 Geological map of Northeastern Thailand (DMR, 1999). The study area is shown by the red rectangle.

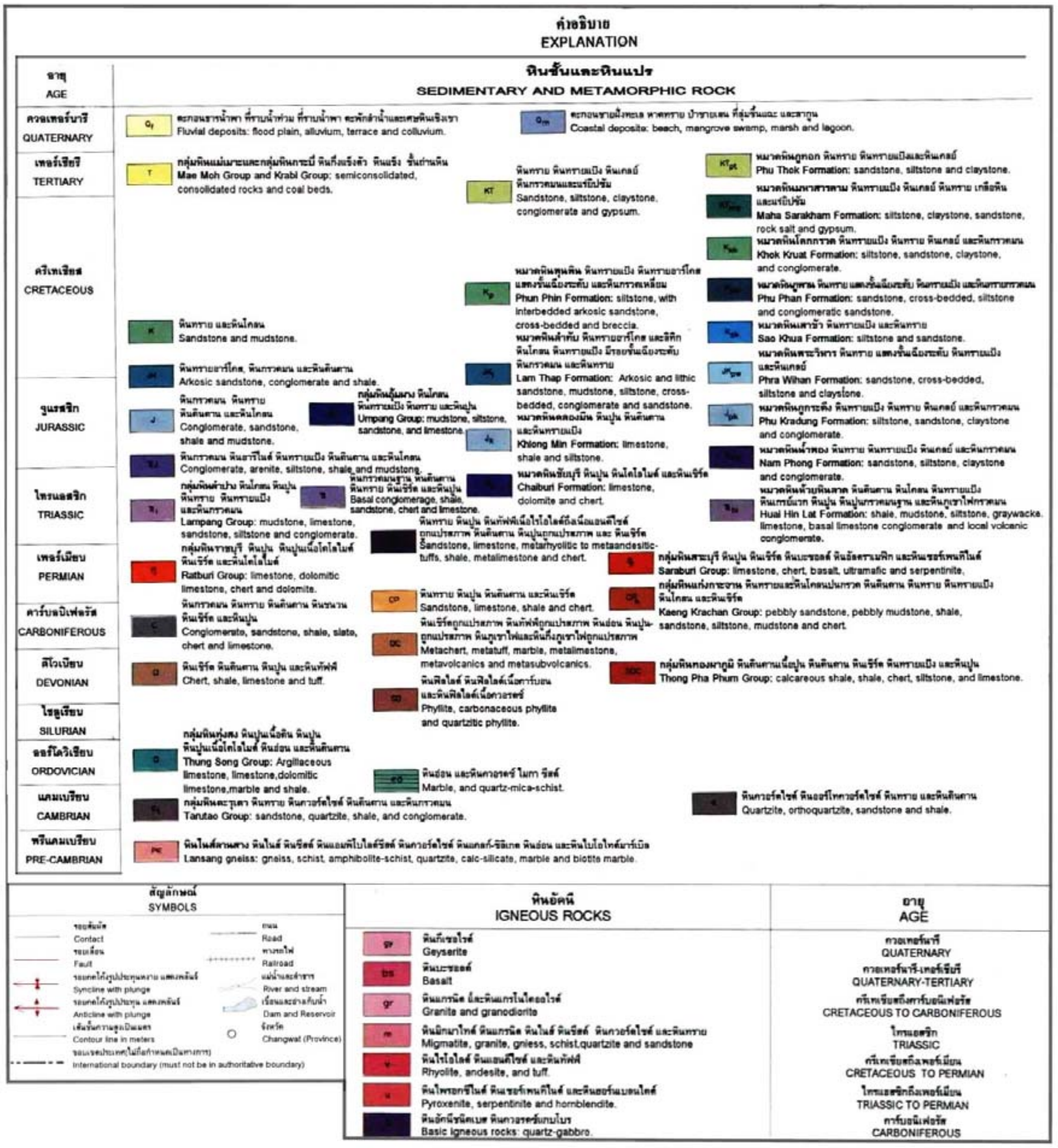

Figure 2.4 The explanation of the geological map of Northeastern Thailand (DMR, 1999).

2.2 Regional Plate Tectonic Development

Metcalfe (1988) proposed that the Continental SE Asia is a composite of allochthonous terranes which originated from rifting of the margin of Gondwana and accreted to one another during the Paleozoic and Mesozoic. There is general agreement that they were all sutured to each other by the Late Triassic (Figure 2.5).

Indochina is sutured to South China in the NE at the Song Ma and Song Da sutures, and to Shan Thai (Sibumasu) in the west along the Nan-Uttaradit suture. The Precambrian granulite core outcrops in massifs within the Truong Son (Annamitic) Foldbelt of Vietnam. The SE margin of Indochina is a passive margin connected to the South China Sea by extended continental crust. In the south, wrench-related Tertiary rift basins cover the assumed boundary between Indochina and Malaysia.

The sutures (shown in Figure 2.6) have been interpreted mainly from outcrop geology. Their correlation is indicated by ophiolites, metamorphic belts, imbricate thrust zones, major wrench faults, volcanic arcs and intrusive granites. The timing of suturing is constrained by the ages of pre-collision ophiolites, by isotopic dating of collision related metamorphic and igneous minerals, and by biostratigraphic dating of post-collision, unconformably-overlying sedimentary rocks. In some areas, data of this kind are sparse, leading to uncertainties in the age and location of the sutures.

Basin development in the region has been controlled by the rift, drift, collision and post-collision history of the Gondwana continental fragments as they became sutured to the Eurasian margin. The northward movement of terranes involved the opening and closing of successive Tethyan oceans. Cooper *et al.* (1989) interpreted the tectonic history and its relation to the stratigraphy in the Khorat Plateau as summarized in Figure 2.7.

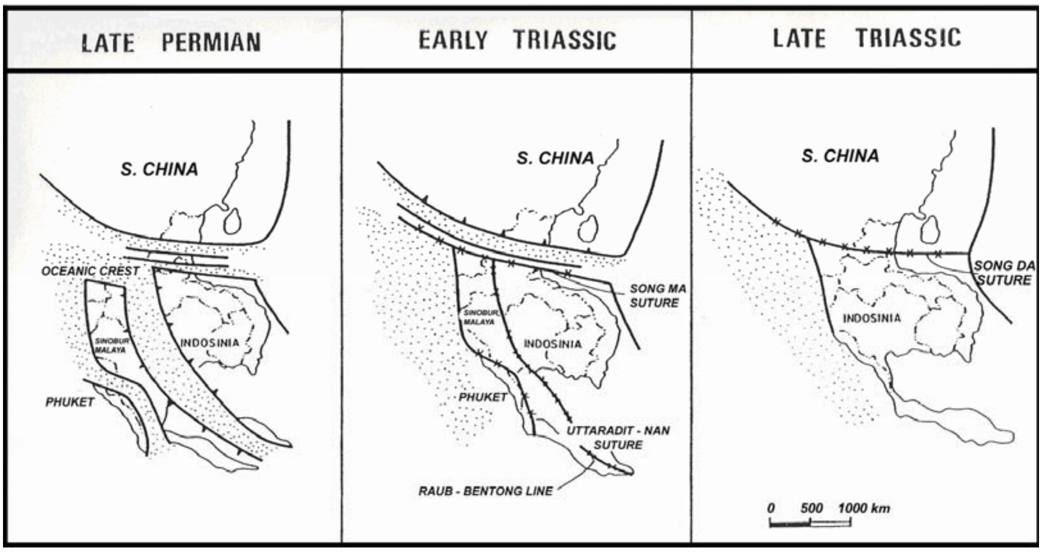

Figure 2.5 Cratonisation of Indochina (Cooper *et al.*, 1989)

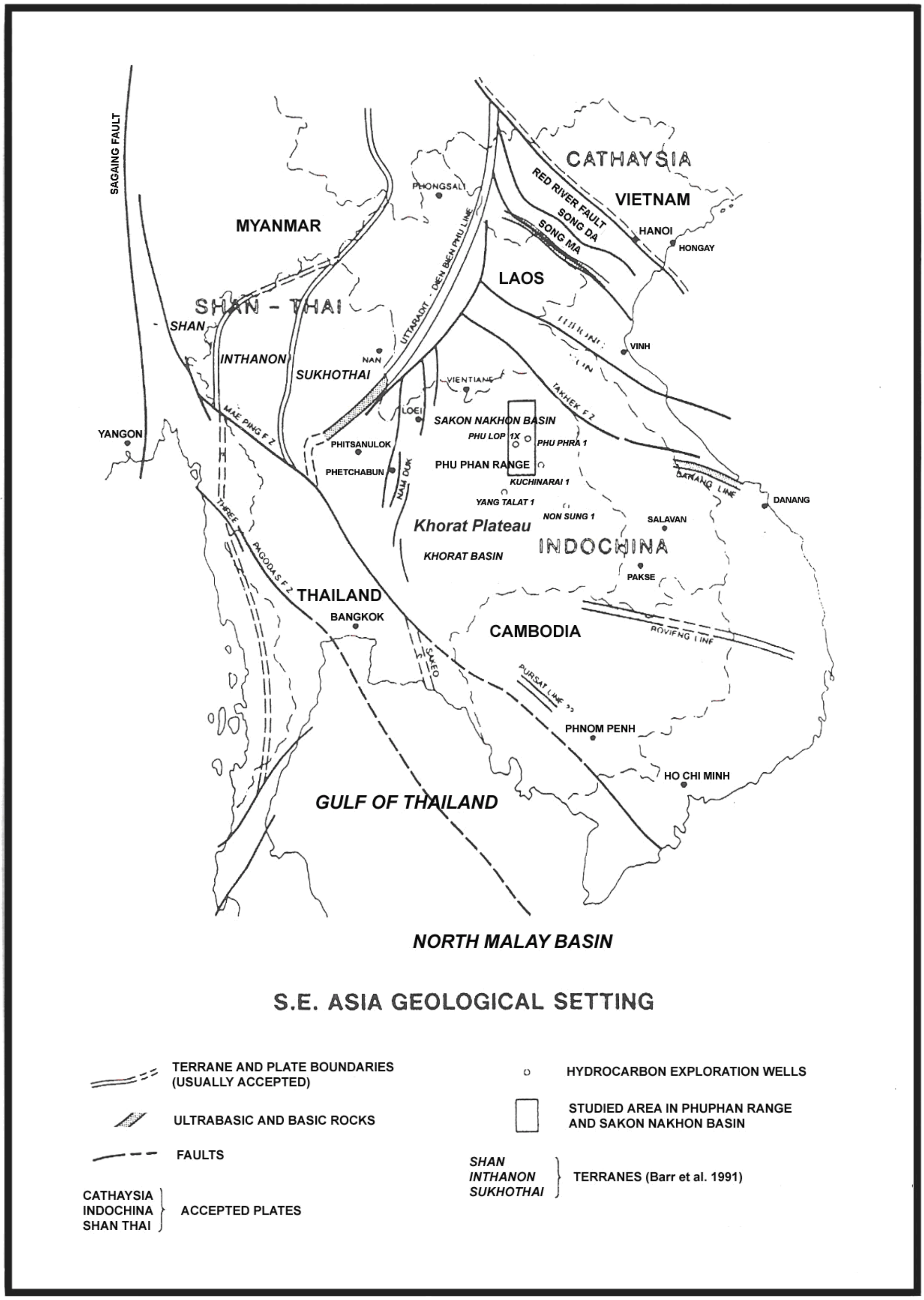

Figure 2.6 Southeast Asia geologic setting (Mouret, 1994).

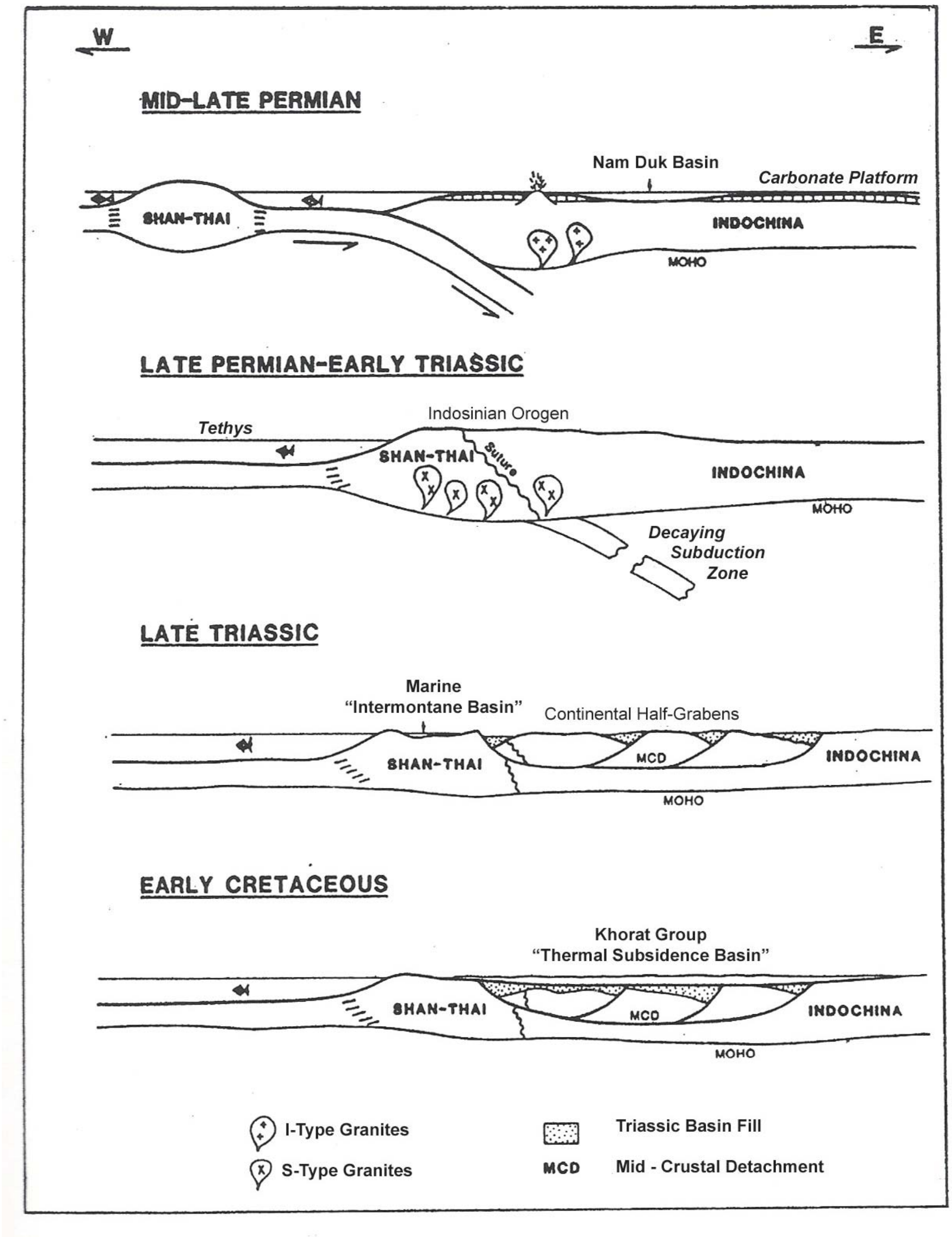

Figure 2.7 Scenario for Mesozoic basin formation in Indochina
(Cooper *et al.*, 1989)

2.3 Structural Framework

The major structural elements of the Khorat Plateau Basin run parallel to the sutures at the northern and western margin of Indochina. Northwest-southeast trending inversions such as the Khammouane and Namleuk Uplifts in Laos and Phu Phan Uplift in Thailand (Figure 2.8) are parallel to the Song Ma suture to the north (see Figure 2.6). This trend predominates in the central and eastern parts of the basin and controlled extensional and flexural depocenters since the Devonian (at least) and into the Late Triassic. It is also controlled by compression-related deformations and wrenching up the Early Cenozoic.

The N-S trending Phetchabun Foldbelt is associated with the Nan-Uttaradit suture in the west, which is highly tectonised and eroded. N-S trends have been reported in the Devonian (Chairangsee *et al*., 1990), and control the Permian Nam Duk Basin in the west of the Phetchabun Foldbelt. Kozar *et al.* (1992) show this trend to control basin development during the Late Carboniferous to Permian times. There is evidence that structures seen at the surface in the Khorat Plateau Basin are basement controlled. The density of faults affecting the Cretaceous sediments is much lower than the density of faults seen both on seismic sections and in outcrops of basement around the basin margins. Satellite imagery clearly shows that the Cenozoic faults have inherited their orientation from the pre-existing structural grain.

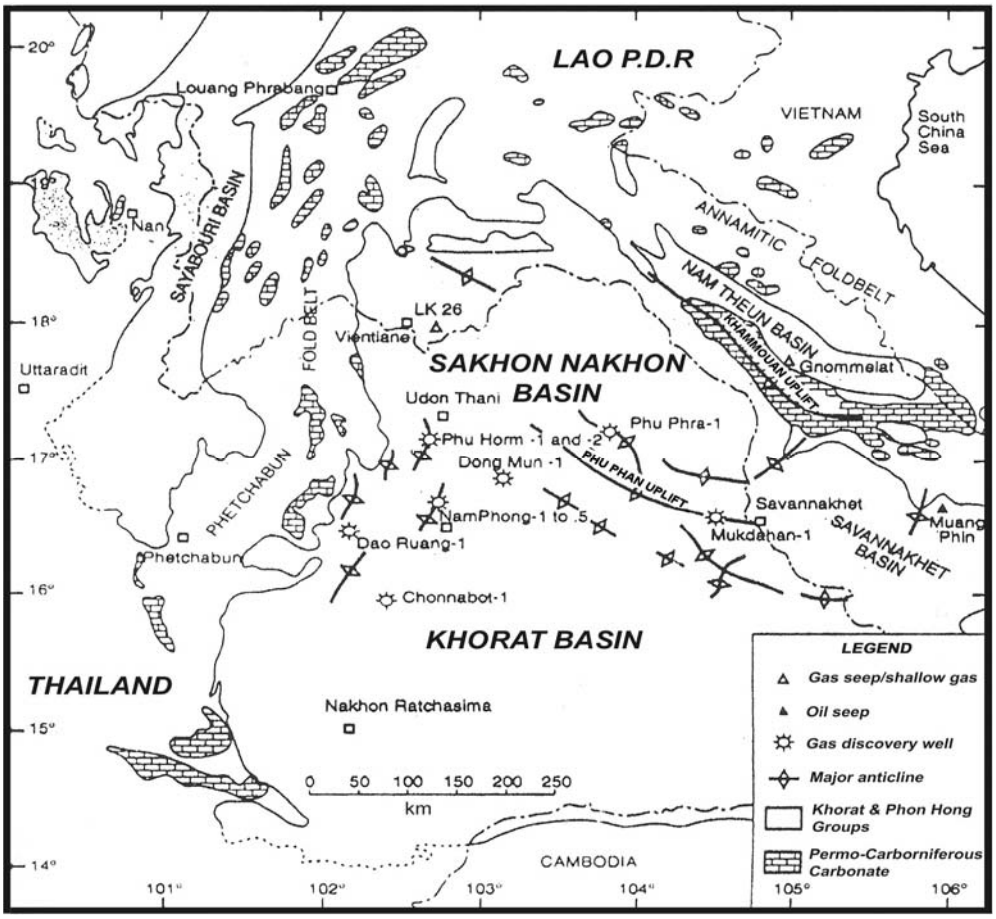

Figure 2.8 Surface geological elements of the Khorat Plateau and hydrocarbon discoveries (after Lovatt, Smith & Stokes, 1997)

Chuaviroj (1997) interpreted lineations of the Khorat Plateau from Landsat TM5 imagery as shown in Figure 2.9, and he suggested 3 deformations of the Mesozoic rocks as follows:

- F_1 is the oldest deformation with N-S fold axes trends inherited from the suturing of Shan Thai to Indochina. It is possibly Late Cretaceous in age. This trend is seen at Phu Luang (Loei) and Phu Wiang (Khon Kaen).
- F_2 resulted from the collision between India and Eurasia and produced the Phu Phan Range. The NW-SE trend was interpreted as the consequence of NE-SW compression. This trend is seen at The Phu Wiang Syncline, the Si Saket Syncline, the Khon Kaen Syncline, and the Ubon Anticline.
- F_3 was probably produced during the later stages of the Himalayan Orogeny, which caused up-doming in the Neogene/Pleistocene. Compression was believed to be NW-SE causing the axes of F_3 folds to be almost parallel to the Kumpawapee Syncline.

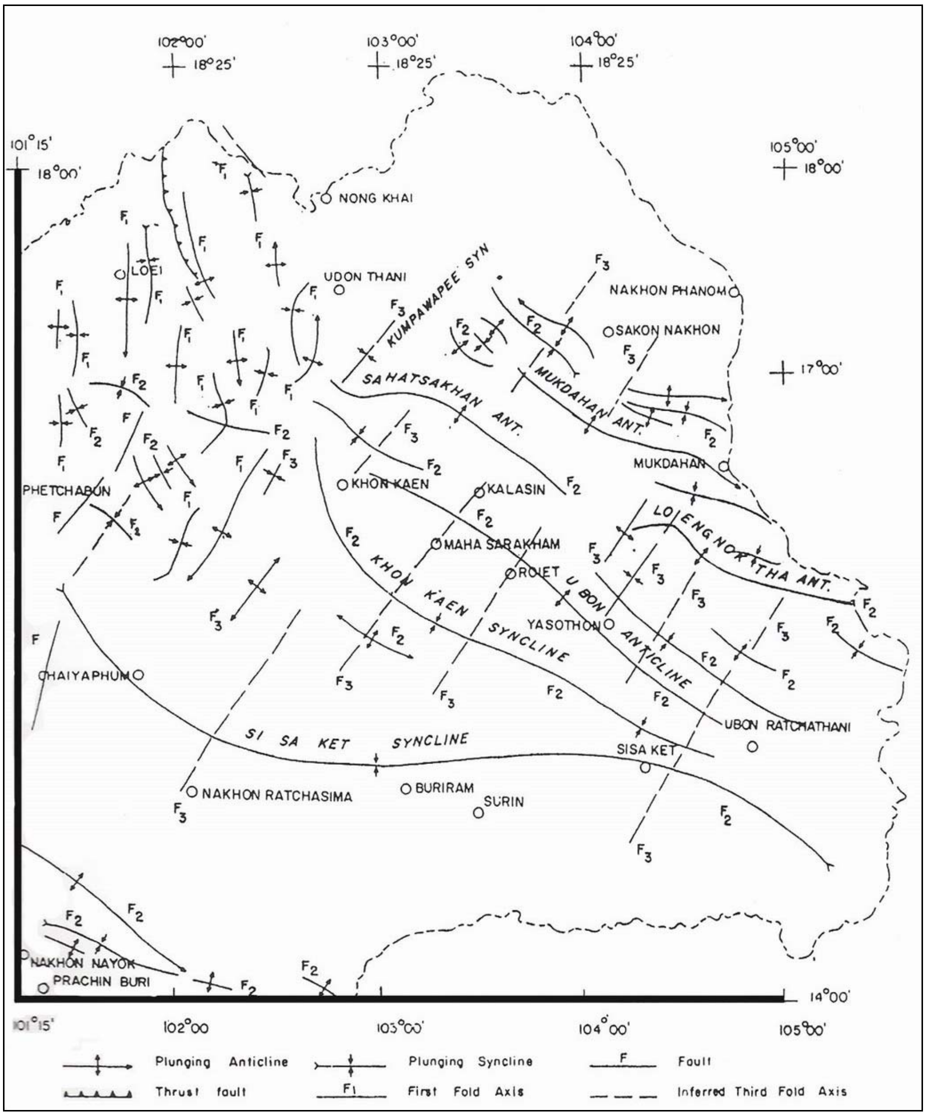

Figure 2.9 Deformations in the Khorat Plateau interpreted from Landsat 5 imagery (Chuaviroj, 1997)

2.4 Lithostratigraphy and Sedimentology

The study of wells drilled by oil companies, including seismic interpretation, contributes to better understanding of the stratigraphy of the Khorat Plateau area. The stratigraphic classification of the sedimentary sequences is established in relation to their structural styles and tectonic development (Figure 2.10 and Figure 2.11).
The stratigraphy sequences of the Khorat Plateau region range in age from the Early Paleozoic to Neogene. The dating of Paleozoic sediments is usually quite accurate due to prolific marine fauna. However, the younger Mesozoic sediments (Khorat Group and younger units) contain a high percentage of fluviatile facies yielding few or no fossils, and the dating of these sediments is based mainly on vertebrate faunas and rare palynomorphs. The sedimentary column reflects a variety of facies ranging from marine (shallow to deep water) to continental (delta plain, lacustrine to fluvial) depositional environments.

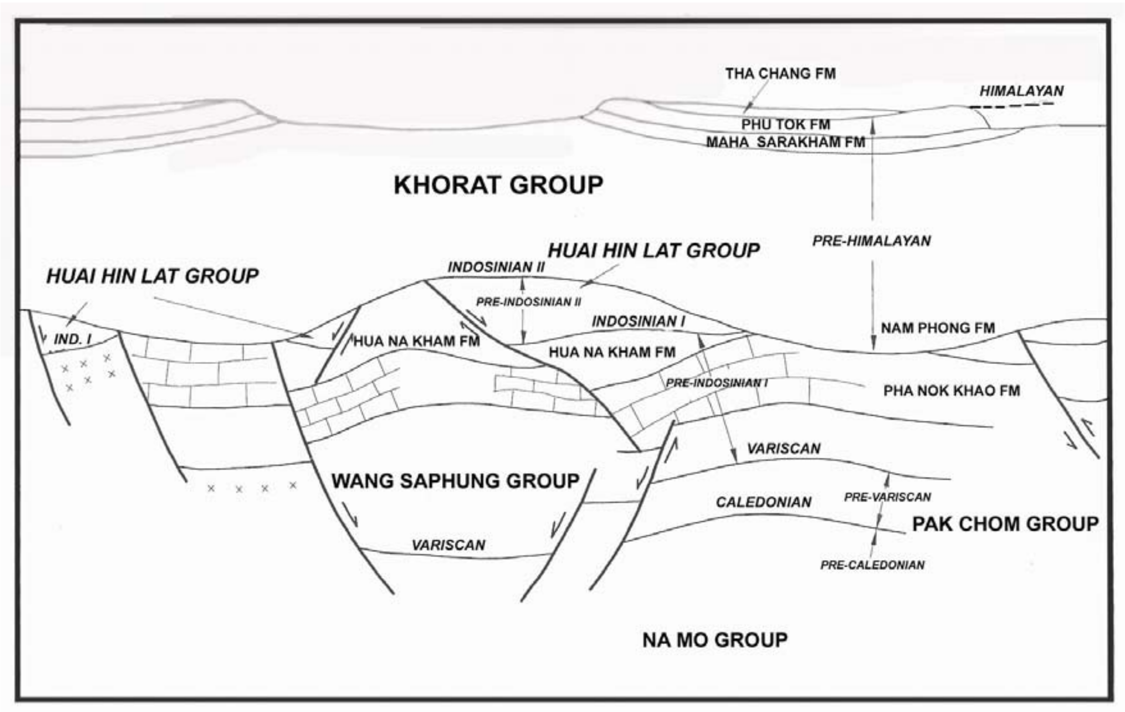

Figure 2.10 Lithostratigraphic units of rock sequences of the Khorat Plateau and their structural setting (after DMR, 1999).

An unpublished report on the petroleum potential assessment of northeastern Thailand (DMR, 1999) divided the thick sedimentary pile of the Khorat Plateau region into 6 main groups or megasequences. The divisions are based on bounding major unconformity surfaces and may be referred to as the tectono-stratigraphic units. The six groups are as follows:

Group VI Post-Himalayan Megasequences : Tha Chang Formation.
Group V Pre-Himalayan Megasequences : Phu Tok Formation.
: Maha Sarakham Formation.

	: Khorat Group.
Group IV Pre-Indosinian II Megasequences	: Huai Hin Lat Group.
Group III Pre-Indosinian I Megasequences	: Saraburi Group.
	:Wang Saphung Group.
Group II Pre-Variscan Megasequence	: Pak Chom Group.
Group I Pre-Calcedonian Megasequences	: Na Mo Group.

2.4.1 Pre-Caledonian Megasequence - The Na Mo Group

The Na Mo Group forms the metamorphic basement exposed in the Loei area, on the northwestern margin of the Khorat Plateau. It consists of low grade metamorphic rocks of the upper greenschist facies (phyllite, chlorite and pelitic schist, metatuff, and quartzite). The metamorphism is dated stratigraphically as resulting from the pre-Late Silurian (Caledonian) Orogeny.

2.4.2 Pre-Variscan Megasequence - The Pak Chom Group

The Pak Chom Group consists mainly of shallow marine sediments of diverse lithologies (limestone, greywacke, shale, conglomerate, and tuff). The Pak Chom Group unconformably overlies the Na Mo Group. It contains a prolific fauna indicating ages ranging from the Late Silurian to Serpukhovian (Early Carboniferous) (Workman, 1975). The Pak Chom Group can be frequently detected in the subsurface below the Variscan Unconformity on seismic profiles.

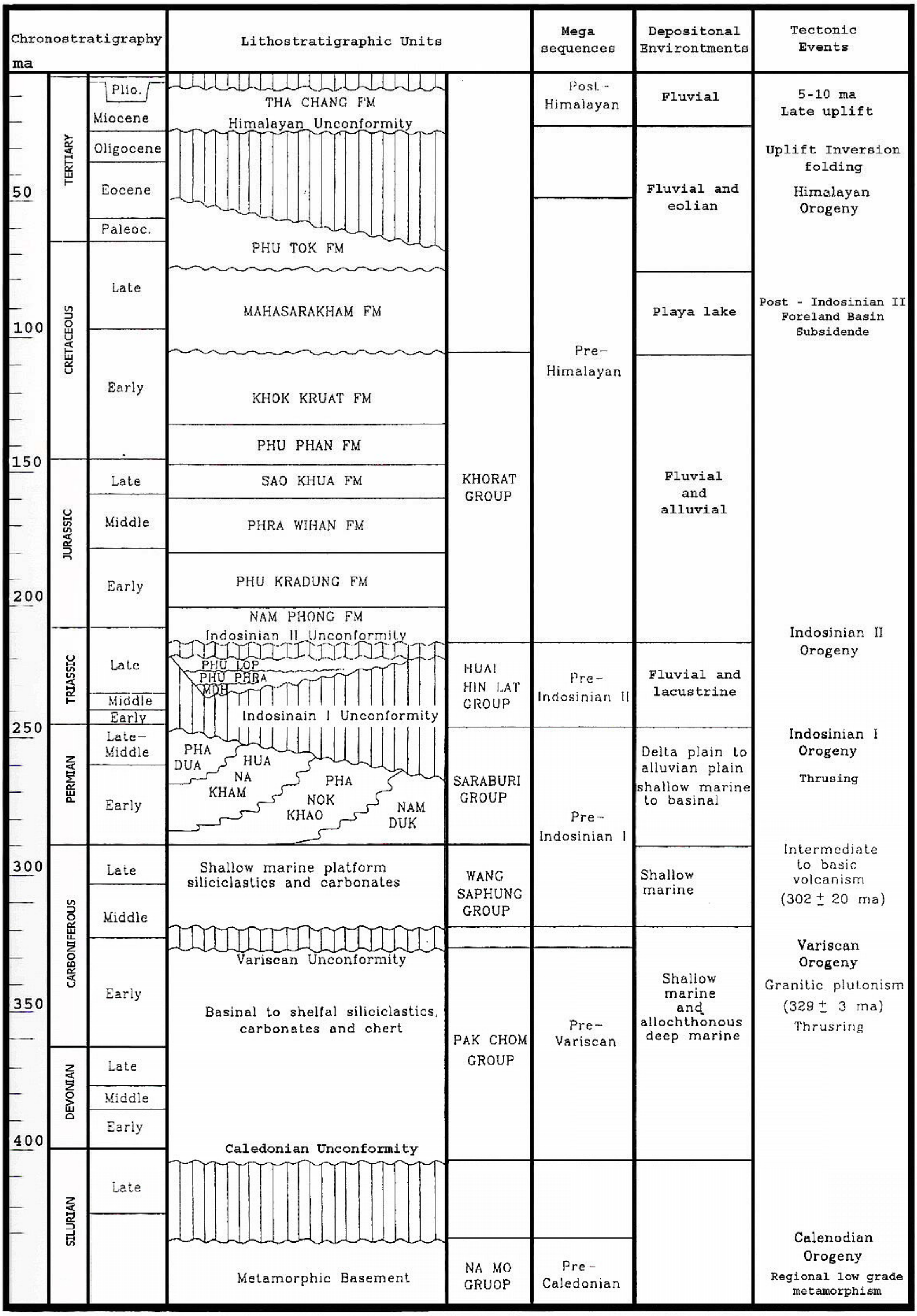

Figure 2.11 Stratigraphy of the Khorat Plateau and related tectonic events (DMR,1999).

2.4.3 Pre-Indosinian I Megasequence

The Pre-Indosinian I Megasequence unconformably overlies the pre-Variscan Megasequence. It is below the Indosinian I Unconformity which is dated as Late Permian to Late Triassic. It is divided into the older Wang Saphung Group and the younger Saraburi Group.

2.4.3.1 The Saraburi Group

The Saraburi Group can be subdivided into 4 units (in descending order): the Pha Dua, the Hua Na Kham, the Pha Nok Khao, and the Nam Duk Formations. These formations are partly coeval and represent sediments deposited in different environments ranging from delta plain, shelf platform, to deep basin.

The Pha Dua Formation
The Pha Dua Formation consists of thin-bedded fine grained clastic sequence with dark shale and siltstone.

The Hua Na Kham Formation
The Hua Na Kham Formation consists of intercalated light and dark gray siltstone, sandstone, claystone, and limestone.

The Pha Nok Khao Formation
The Pha Nok Khao Formation consists predominantly of massive to thick-bedded gray limestone and dolomite, and thin-bedded gray shale and black, nodular or thin-bedded chert may occur locally.

The Nam Duk Formation
The Nam Duk Formation consists of pelagic shale, clastic turbidites, and thin-bedded allodapic limestone.

2.4.3.2 The Wang Saphung Group

The Wang Saphung Group conformably underlies the massive Permian Pa Nok Khao Formation. It has been informally called the "Lower Clastics" of the "Ratburi Group". It can be delineated from the seismic profiles and occupies a section between the base of the Pha Nok Khao Formation and the Variscan Unconformity. In the Loei area the Wang Saphung Group unconformably overlies the Pak Chom Group in outcrop. In the subsurface, on seismic profiles, the base of the Wang Saphung Group is marked by a major unconformity above either the Pak Chom or economic basement (metamorphic). The Wang Saphung Group consists of siliclastics (conglomerate, shale, and sandstone) interbedded with limestones and volcanics. It is well exposed in the northwestern margin of the Khorat Plateau.

2.4.4 Pre-Indosinian II Megasequence - The Huai Hin Lat Group

The Pre-Indosinian II Megasequence unconformably overlies the Pre-Variscan or Pre-Indosinian I Megasequences. It is overlain unconformably by the Khorat Group of the Pre-Himalayan Megasequence. It consists mainly of clastics with some intercalations of limestone and has been called the “Huai Hin Lat Formation”. Its age is Late Triassic based on invertebrate, vertebrate and plant fossils.

Data from wells drilled in the northern Khorat Basin by oil companies indicate that the Huai Hin Lat contains two intraformational unconformities. Hence the formation is raised to the Group status for subsurface workers and for oil companies, and the classification of the Huai Hin Lat Group based on well data is as follow:

The Phu Lop Formation
The Phu Lop Formation consists of siltstones and shale, with a few sandstones. The interpretation of seismic profiles in the Phu Phra area indicates that the Phu Lop Formation overlies the undifferentiated unit of Phu Phra and Mukdahan Formation.

The Phu Phra Formation
The Phu Phra Formation consists predominantly of dark shale with minor amounts of sandstones and siltstones. The fine-grained sediments show varves, coaly plant remains, ripples and occasional sand-filled mud-cracks.

Mukdahan Formation
The Mukdahan Formation is the basal unit of the Huai Hin Lat Group. It consists of green to greenish gray volcanogenic sandstone and poorly sorted sandy conglomerate with intercalations of green siliceous tuff and tuffaceous shale.

2.4.5 Pre-Himalayan Megasequence

The Pre-Himalayan Megasequence consists of sedimentary units between the Indosinian II and the Himalayan Unconformity. The Himalayan Orogeny which caused the unconformity in Northeastern Thailand is dated as Late Cretaceous to Miocene. The Pre-Himalayan Megasequence overlies the Pre-Indosinian II or older Megasequences. It comprises the Khorat Group, the Maha Sarakham Formation and the Phu Thok Formation respectively in ascending order. The total thickness of the Pre-Himalayan Megasequence is over 5 000 m.

2.4.5.1 The Khorat Group

The Khorat Group consists of a thick sequence of red clays, siltstone, sandstone and conglomerates. The Khorat Group is divided into 6 units (in descending order): the Khok Kruat, the Phu Phan, the Sao Khua, the Phra Wihan, the Phu Kradung, the Nam Phong Formations respectively.

The Khok Kruat Formation

The Khok Kruat Formation is characterized on seismic profile by a sub-transparent pattern with discontinuous markers of moderate energy. It rests conformably on the Phu Phan Formation and forms the uppermost unit of the Khorat Group. The Khok Kruat Formation consists of siltstone and sandstone with some caliche pebble conglomerates. The sandstones are pale red to grayish-red and reddish brown in colour, fine- to medium-grained, thick bedded to flaggy, and cross-bedded. They are generally micaceous or arkoses, and often contain clay rip-up casts. The upper part of the Formation contains a thin gypsum bed.

The Phu Phan Formation

The Phu Phan Formation is represented on seismic profiles by two parallel, relatively continuous markers. It consists of fine- to coarse-grained and conglomeratic sandstone containing rounded pebbles of quartz and chert. The sandstones are often stacked into 15 to 40 m thick units. They are yellowish-gray to pale orange, pinkish-gray and pale red. Trough and planar cross-bedding are normally observed. The lower contact with the underlying Sao Khua Formation is very sharp and erosive, characterized by sand-supported caliche pebble conglomerates; red silty claystone and caliche are occasionally present.

The Sao Khua Formation

The Sao Khua Formation is almost transparent on seismic profiles, with discontinuous low amplitude markers. It consists of an alternation of grayish-reddish brown siltstone and clay and pale red to yellowish-gray, fine-grained to medium-grained sandstone. Rare pale red to light gray conglomerates, containing carbonate pebbles, are also characteristic of this Formation.

The Phra Wihan Formation

The Phra Wihan Formation can not be clearly differentiated on seismic profiles. It consists predominantly of white, yellowish, light brown sandstones, less abundant grayish-red siltstone and rare green or dark red clay. The sandstone is medium- to coarse-grained, consisting of clean quartz sand grains with a few scattered grains of gray to black chert.

The Phu Kradung Formation

The Phu Kradung Formation at its type locality in Loei Province measures 1 001 m in thickness. The lower half of the section consists mostly of soft, micaceous, reddish-brown and grayish-red siltstone with rare grayish-red to greenish-gray calcareous conglomerate beds. Interbedded calcareous, micaceous siltstone and sandstone characterize the upper half of the formation.

The Nam Phong Formation

The Nam Phong Formation is the basal unit of the Khorat Group. It consists of resistant, red-brown, micaceous sandstones, conglomerates, siltstone and mudstone of mainly fluvial origin. The sandstones are medium to very fine-grained and are usually calcareous. The conglomerates contain pebbles of quartz, brown and gray chert, and reddish brown siltstone. Cross-bedding and plane-bed stratification are common in the sandstones and conglomerates. The sandstones and conglomerates make up approximately 30% of the formation.

2.4.5.2 The Maha Sarakham Formation

The Maha Sarakham Formation overlies the Khok Kruat Formation with a very sharp boundary at the bottom of the basal anhydrite (Hite & Japakasetr, 1979). The Maha Sarakham Formation is preserved within the northern Sakon Nakhon Basin and the southern Khorat Basin. The two basins are separated by the Phu Phan Range. The Formation averages 250 m thick at the type locality (Gardner *et al.*, 1967). The sequence comprises claystone, siltstone, and three rock salt beds; the Lower, the Middle and the Upper salt members which are the main sources of soil and groundwater salinization in the Khorat Plateau (Figure 2.11). Most of the current margins of the basins are dissolution, as are the upper and lower contacts of the salt units (Warren, 1999). Salt domes and salt anticline of the Maha Sarakham Formation occur in several places.

2.4.5.3 The Phu Tok Formation

The Phu Tok Formation consists of massive red sandstone with very large cross-beds interbedded with channelized fine-grained, red to purple sandstone and siltstone with red clay horizons.

2.4.6 Post-Himalayan Megasequence

The Tha Chang Formation
The Post-Himalayan Megasequence consists of rocks between the Himalayan Unconformity and the base of the Quaternary sediments and is called the Tha Chang Formation. Its relationship with the underlying formations cannot be demonstrated but is inferred to be unconformable. The formation consists of semi-consolidated sandstone more than 20 m thick.

2.5 Rock Salts in the Khorat Plateau

2.5.1 General Overview

The Khorat Plateau of northeastern Thailand contains a large evaporite basin of Cretaceous age. It is divided into a northern (Sakon Nakhon) Basin and a southern (Khorat) Basin covering an area of about 50 000 km2. The evaporite beds are included in the Maha Sarakham Formation (Sattayarak, 1985). These evaporites were thoroughly investigated by DMR aided by a UN Special Fund related to the Mekong Project (Japakasetr and Workman, 1981). It was planned to use the salt as a source for soda ash production by utilizing natural gas piped from the Gulf of Thailand. Additional feasibility studies on a Rock Salt and Soda Ash Project and a Potash Engineering Project in Bamnet Narong areas were conducted (Japakasetr, 1985).

The histories of rock salt studies in the Khorat Plateau can be briefly concluded as follows:

Rock salt has been well known for its use in Northeast Thailand since pre-historic time. Lee (1923) studied the geology of the area and reported the probability of rock salt underneath the northeastern area but no one has been done any systematic study then.

Ward & Bunnag (1964) studied the stratigraphy and named the Khorat Group, and they also reported the uppermost strata and named them “Unnamed Formation”, which comprises sandy clay, sandstone, thick rock salt layers and gypsum beds with total thickness more than 600 meters.

Gardner *et al.* (1967) studied stratigraphy from well logs of the groundwater well F-34 at Wat Ban Chiang Hein, Maung District, Maha Sarakham Province and named the Ward & Bunnag’s Unnamed Formation as “Maha Sarakham Formation”. This formation comprises mainly weathered gray, reddish, brown and purple sandy clay and claystone and brown, reddish-gray and white fine-grained sandstone with rock salt and gypsum fragments. The bottom part of the lower rock salt bed overlies conformably the Khok Kruat Formation. Gardner et al. (1967) also assigned the age of this formation to Late Cretaceous to Eocene.

Hite (1971) published his first report entitled “Potential for potash and related mineral resources, Khorat Plateau, Northeast Thailand and Central Laos”. He first assumed that the salt bed is flat lying and recommended that evaporite beds should be found in the other formations also.

Japakasetr (1974) published a report of the progress of potash investigation after the drilling of four holes. All the first four holes were drilled in the northern basin in Udon Thani, Nongkhai, Sakon Nakhon and Nakhon Panom Provinces.

Sundharovat (1976) outlined that the origin of potash in northeast Thailand is related to the warping of the rock in the Khorat Group, the transgression of sea water and the deposition of evaporites in later Tertiary or Pleistocene.

Sundharovat (1977) also discussed the hypothesis of low structure of potash in the small basin, which is disseminated in the Khorat Plateau.

Thiramongkol (1978) proposed that rock salt was deposited in an inland sea or lagoon environment in the Late Cretaceous and was affected later by epeirogenic movements like warping and block faulting.

Hite & Japakasetr (1979) commented that differential loading affected the shape and attitude of a rock salt stratum.

Hite (1982) published a report of potash investigation by emphasizing the three main structural areas of Bamnet Narong, Khon Kaen and Non Sung. But his idea about the genesis of salt anticline has been changed from the differential loading to paleochannel.

Yumuang (1982) studied the boreholes logging in Bamnet Narong area. He proposed that three phases of marine transgression and regression had occurred and generated three units of rock salt and associate minerals.

Suwanich (1983) presented his idea about the potash and rock salt in Thailand in the Conference on Geology and Mineral Resources of Thailand. He emphasized the genesis of salt domes which are formed by differential loading. The differential loading should occur after the lower salt had been deposited and the lower clastic started to deposit gradually.

Sheldon (1984) published his report on phosphate exploration on the Khorat Plateau. He commented that the fourth cycle of transgression on the Khorat Plateau might be suitable for phosphate deposition and that the basin structure was related to the salt tectonics. He also supported the hypothesis of differential loading.

Sattayarak (1985) separated the Maha Sarakham Formation from the Khorat Group on the ground that the depositional environment was changed from continental basin to marine basin.

Suwanich (1986) divided the Maha Sarakham Formation into 6 units from bottom to top as follow; the lower salt, the lower clastics, the middle salt, the middle clastics, the upper salt and the upper clastics.

Warren (1989) proposed that where the Maha Sarakham rock salt is deeply buried, it becomes mobilized and may flow upwards to form salt domes and anticlinal structures. The salt might also be deformed into discordant bodies and filling in surrounding gaps and dragged adjacent strata.

Mohamed et al. (1995) studied detailed stratigraphy of the Maha Sarakham Formation. They found that the sequence is not always consistent throughout the basin because of erosion, salt flowage, tectonic and natural dissolution.

Donald (1996) compared the depositional characteristic of Khorat Basin with Sergipe, Brazil and Congo-Gabon. He summarized the common characteristics as follows:

1. The basin contains massive quantities of tachyhydrite.
2. The basin occurs directly on terrestrial sediments, with very little anhydrite and essentially no dolomite in or near the deposit.
3. There are subsequent basaltic intrusions in and adjacent to the deposit.
4. He concluded that the Maha Sarakham Formation was deposited in a terrestrial and not a marine environment.

Warren (1999) commented that the Khorat and the Sakon Nakhon Basins are lacking MgSO4 salt, indicating a likelyhood for a continental or basinal brine source.

Based on Suwanich (1986) and Mohamed *et al.*, (1995) the stratigraphy of the Maha Sarakham Formation can be summarized as follows:

(1) Basal Anhydrite Member (Intersected thickness 0.75-6.20 m)

The Basal Anhydrite is found at the base of the Maha Sarakham Formation throughout both the Khorat and the Sakhon Nakhon basins. It conformably overlies the Khok Kruat sandstone of the Khorat Group. The generally reddish-colored sandstone of the Khok Kruat Formation is typically greenish and may be Cu-stained in proximity to this contact. Although in areas of slumping or dissolution the anhydrite layer locally varies in thickness from 0.75-6.20 m, a mean thickness of 1.0 m characterizes the unit across the regional extent of the Maha Sarakham evaporites in the basin.

(2) Lower Salt Member (Intersected thickness 30.00-500.00 m)

The Lower Salt is the most widespread of the salt units in the Maha Sarakham Formation. Halite with accessory anhydrite is the dominant mineral. However, a zone rich in potash minerals characteristically occurs near the top of the unit. A layer of depositional-textured anhydrite up to 3.45 m in thickness separates the Lower Salt into upper and lower portions, and is correlatable throughout the basin. The contact with the Basal Anhydrite is sharp while that with the potash-rich zone is generally gradation.

(3) Lower Clastics Member (Intersected thickness 10.00-60.00 m)
The Lower Clastics Member comprises reddish brown claystone, invariably containing randomly oriented fractures filled with halite spar. The color of the claystone may be greenish-gray in the vicinity of the contacts with the underlying and overlying salt units.

(4) Middle Salt Member (Intersected thickness 20.00-180.00 m)
The Middle Salt comprises well-bedded halite with similar repetitive bed forms to those found in the upper part of the Lower salt. Rare sylvite and carnallite grains are occurring sporadically, and rarely a poorly developed potash zone may top the sequence.

(5) Middle Clastics Member (Intersected thickness 20.00-70.00 m)
The Middle Clastics Member consists of massive red to purple claystone and silty mudstone. Bedding in this unit is well defined with cryptalgal lamination and root traces.

(6) Upper Salt Member (Intersected thickness up to 20.00 m)
The Upper Salt is the least preserved halite member in the Khorat Basin because of later dissolution and possible non-deposition in some parts of the basin. However, these salt beds, when observed, are the least deformed beds in the sequence.

(7) Upper Clastics Member (Thickness up to 687 m)
The Upper Clastics Member consists of pale reddish-brown silty claystone with minor sandy intervals. In this unit bedding is well defined and even lamination, root traces, and sets of cross beds are commonly observed. The unit generally exhibits upward coarsening. The contact with the overlying Phu Thok is not defined.

The general lithostratigrphy and subdivisions of the Khorat Group and the Maha Sarakham Formation are simplified and shown in Figure 2.12.

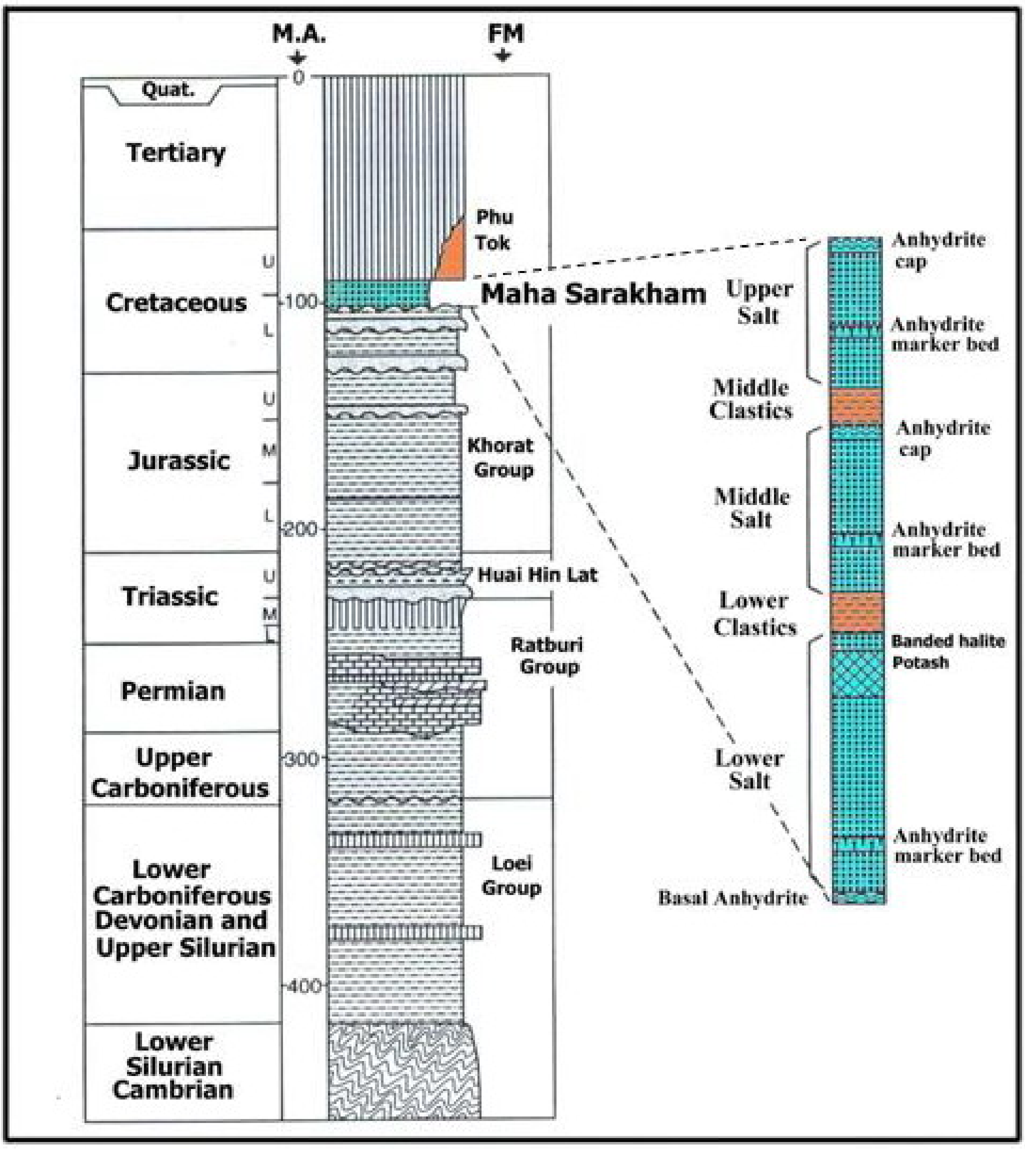

Figure 2.12 Lithostatigraphy and subdivisions of the Khorat Group and the Maha Sarakham Formation (modified after Suwanich,1986).

2.5.2 Salt Structure

Evaporite deposits occur in sedimentary sequences at shallow crustal levels in many parts of the world. Layers of rock salt undergo ductile deformation more easily than do the more common sedimentary rock types such as sandstone and limestone. Salt flows at surface conditions under the force of gravity and a certain tectonic environment. The density of salt contrasts with the greater density and strength of the enclosing sediments. A great variety of structures in the subsurface can be found, ranging from shallow to deep. The internal structure of these salt features provides abundant evidence of plastic flow with folds, foliation and other structures. The conceptual salt structures developed in the Khorat Plateau are shown in Figure 2.13.

In general, the surface geology of the Khorat Plateau is separated by the highland of the Phu Phan Range and consists of the Khorat and the Sakon Nakhon basins filled with Quaternary sediments. These Quaternary sediments overly locally the Tertiary Phu Thok Formation composed of fine- to medium-grained sandstone and siltstone. Underlying the Phu Thok Formation is the Cretaceous Maha Sarakham Formation composed of claystone, siltstone, and three rock salt beds: Lower, Middle and Upper salt members (Figure 2.12). Most of the current margins of the basins are dissolutional, as are the upper and lower contacts of the salt units (Warren, 1999). The Maha Sarakham Formation overlies the Khok Kruat Formation, which is composed of sandstone and siltstone. Salt domes and salt anticlines occur in several places.

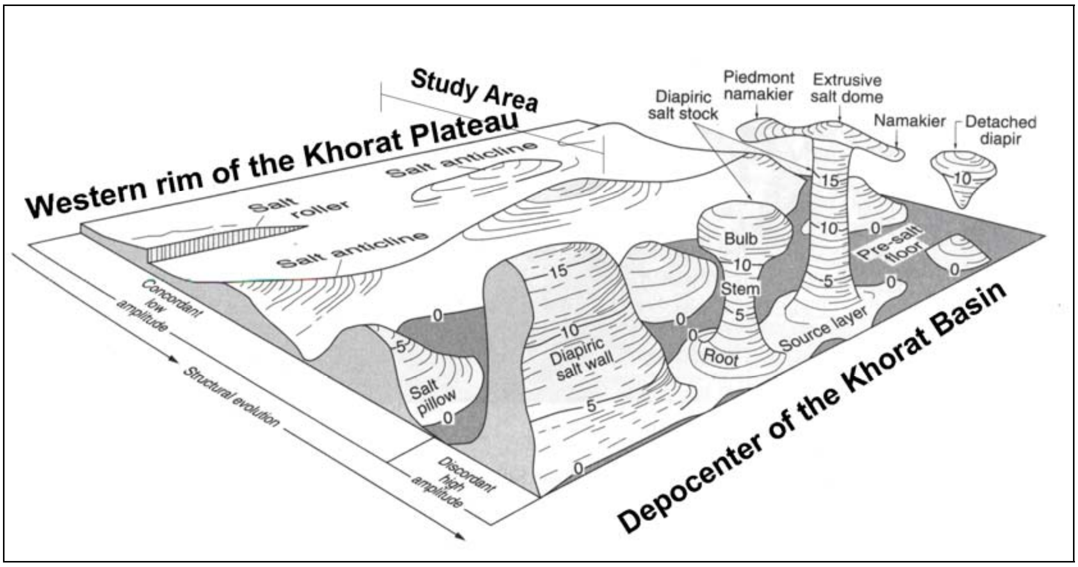

Figure 2.13 The conceptual salt structures developed in the Khorat Plateau. Numbers indicate relative elevation x 100 m above base (after Hatcher, 1995). The study area is supposed to have salt anticline and salt roller structures lie underneath.

Warren (1999) studied rock salt formations in the Khorat Plateau and some of his interpretations and conclusions can be summarized as follows:

- The Middle and the Upper Salt members of the Maha Sarakham Formation are generally flat lying and correlatable from well to well. In contrast, seismic and geomorphologic analyses show that the Lower Salt of the Maha Sarakham has flown so that the thickness is much more variable from well to well. Textures in the Lower Salt member range from well preserved depositional textures in the upper part immediately below the potash entraining intervals to flowage features lower in the section. Petrographic evidence for salt flowage includes overburden-controlled elongate flattening of crystals and pervasive recrystallisation that has destroyed original bedding features. In wells that reach deeper into the Lower Salt Member there often is a transition down core from pristine depositional textures into flowage textures, implying that flow into the pillow was fed mostly from the deeper parts of the Lower Salt member. That is also consistent with the upper portions of the salt unit still being deposited while the lower parts of the same unit were flowing into pillows.
- Like much of the halite in the Maha Sarakham Formation, the petrography, depositional style and preservation quality of potash in the Lower Salt Members has been complicated by dissolution and halokinesis (Hite & Japakasetr, 1979; Sessler, 1990; Tabakh *et al.*, 1995; Utha-aroon *et al.*, 1993). In terms of the potash minerals, carnallite dominates over sylvite throughout the basin, while traces of tachyhydrite are also found preserved as enclosed euhedral to subhedral crystals in halite.

2.5.3 Salt Flowage Mechanism

Warren (1989) classified the mechanism controlling salt movement into two groups, a shallow group controlling salt flow at shallow depths of less than 600 m, and a deeper group which is most important below such depths. The Maha Sarakham Formation, evidenced from borehole data of the ASEAN Potash Project, is considered to be shallow depths rock salt (< 600m). The two major mechanisms controlling salt movement at shallow depths are known as follow:

1) Differential Loading

The differential loading on top of the salt layer often occurs in areas of the depocenter of the sedimentary basin where it has lot of overburden sediments over an underlying salt layer (Figure 2.14).

2) Gravity Glide Folding

The gravity glide folding causes the passive rise of salt into growing anticlines. This mechanism commonly operates beneath the continental slope and margin of basin (Figure 2.15)

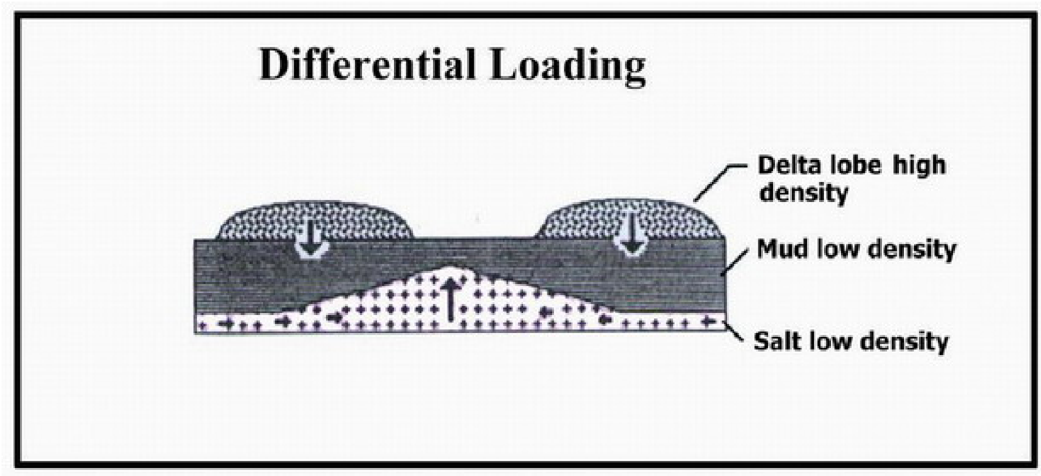

Figure 2.14 The differential loading mechanism (Seni & Jackson, 1984).

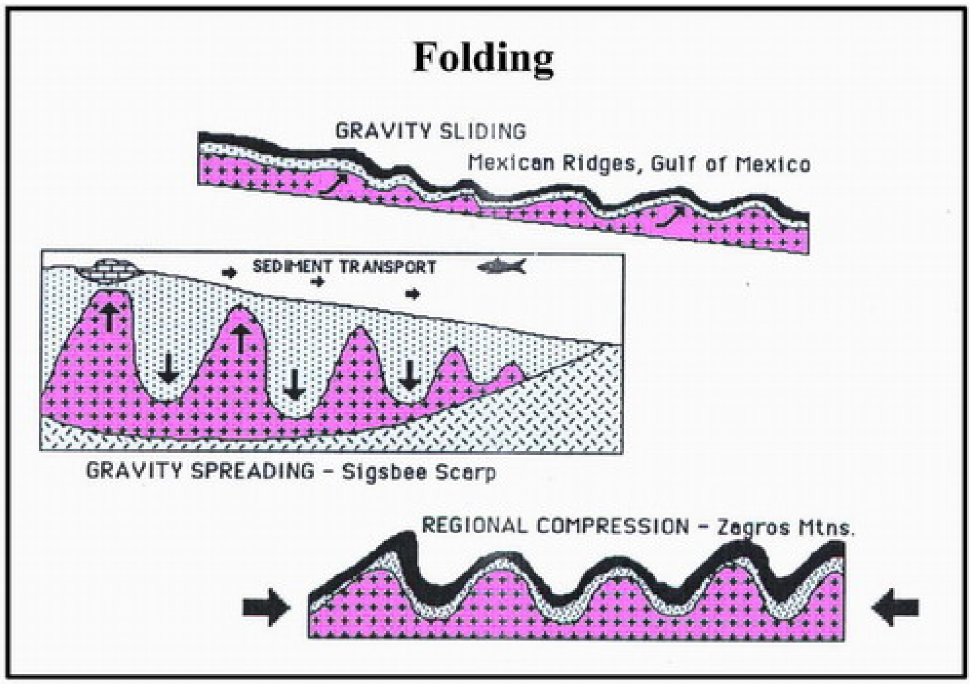

Figure 2.15 The salt folding structure initiated by gravity slides, gravity spreading and regional compression (Warren, 1989).

2.5.4 Salt Structure Developments

Warren (1989) classified the development of salt structure into three stages as follows:

1) Salt Pillow Stage

The pillow stage is a non-piercement stage. The sediments above the pillow are thin over a broad equidimensional area with maximum thinning over the crest of the structure (Figure 2.16). The area above the pillow is often a topographic high, while the area between the pillows is often a topographic low or primary rim syncline created by salt withdrawal. Rim synclines are often areas of preferential sedimentation that means a high sediment thickness.

2) Diapir Stage

The diapir stage is a piercement stage. The rate of salt movement is so rapid that sediment is usually not preserved over the crest of the structure. During the diapir stage the salt is very near to, or at the surface and any overlying sediment is periodically eroded. Salt in the crest of the diapir is near or at the surface throughout the diapir stage. It is continually dissolved in the shallow subsurface.

The "turtle structures" are also formed in the diapir stage. They grow as the locus of maximum salt withdrawal moves closer and closer to the growing salt mass. This means that the rim of the syncline also migrates toward the salt structure. As the area of salt withdrawal migrates closer the stem of the salt structure, the associated zone of subsidence moves closer to the salt neck. Thus the area of primary rim syncline of the pillow stage becomes a zone of relatively thicker sediment (Figure 2.17).

3) Post Diapir Stage

The post diapir stage is the last stage of salt structure growth. By this time the salt supply is dwindling as the volume of salt flowing into the foot of the salt mass decreases (Figure 2.18). The crest of the structure is once again buried, but still near the surface. It now feels the effects of meteoric waters as a caprock carapace forms by dissolution and alteration to encase the upper few hundred meters of the structure. The buried crest means that sediment can once again be deposited over the crest of the structure and small, localized ternary rim synclines can be adjacent to the diapir.

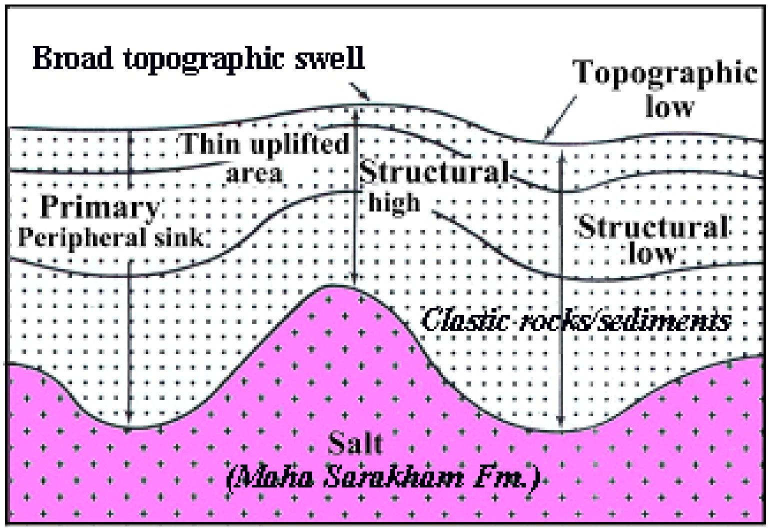

Figure 2.16 The salt pillow stage (modified after Seni and Jackson, 1983a).

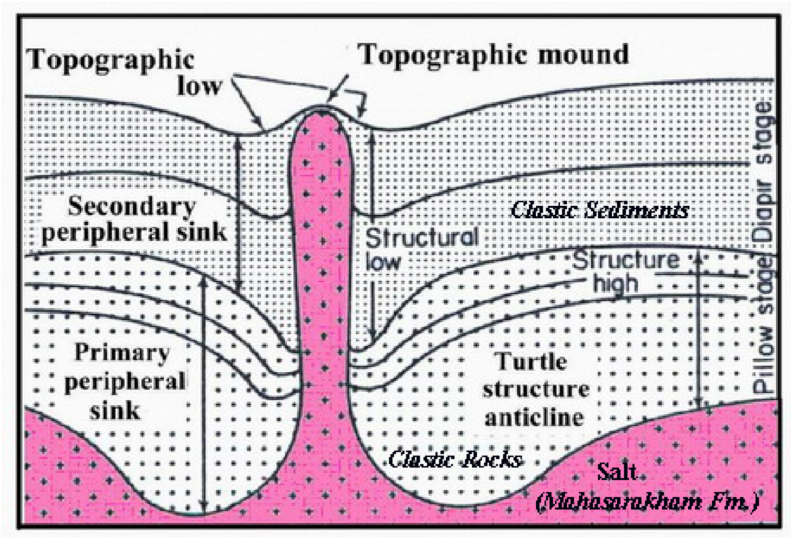

Figure 2.17 The diapir stage associated with the development of turtle structures and overhangs (modified after Seni & Jackson, 1983a).

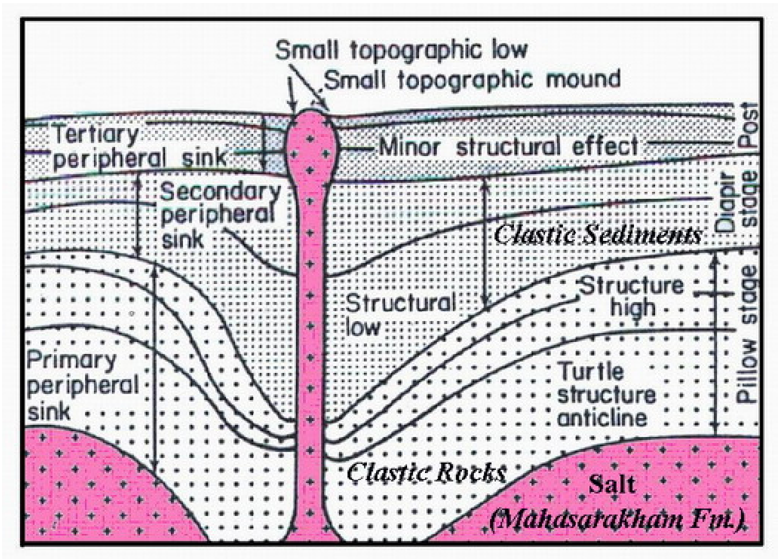

Figure 2.18 The post diapir stage (modified after Seni and Jackson, 1983a).

These three stages are believed to have taken place throughout the Khorat Plateau through geologic time.

Sattayarak (1985) proposed a conceptual model to clarify the development of the Khorat Plateau relating to the uplifting of the Phu Phan Range which also corresponds to the salt structure development in this region (Figure 2.19). His works can be briefly summarized as follows:

- After the Khorat Group had been deposited (Figure 2.19a) during the Early Cretaceous, the Petchbun Belt began uplifting probably during Late Early Cretaceous times causing erosion and weathering of the Khorat Group in the west (Figure 2.19b).

The sediments then were transported and deposited in the subsidence area of central and eastern parts of the Khorat Plateau. Later on, during the Early Late Cretaceous, sea water transgressed from the east causing deposition of alternative layers of three rock salt beds and salty claystones (Figure 2.19c). The sea water then began to retreat and dry out, resulting in sedimentary basins of desert condition controlled mainly by wind in the Late Cretaceous (Figure 2.19d).

- During the early Tertiary orogeny causing the folding in the Khorat Group, the Petchbun Belt increased in uplifting, altogether with the uplifting of the Phanom Dongrak Mountain, Phu Phan Mountain, and the left lateral movement of Thakak-Jiapone Faults (Figure 2.19e). It is believed that the movement of rock salts along the bedding planes into the center of the basin at this period produced large salt domes in the area of Borabu and Na Chuak District, Maha Sarakham Province.
- The erosion process of the main rivers that flew through the Khorat Plateau caused the erosion and weathering of the Phu Tok Formation and rock salts in several areas. Around Miocene, the deposition of red bed clay sediments mixed with salts began and overlaid the Maha Sarakham and Phu Tok Formations in the alluvial plains and old river beds (Figure 2.19f).
- During Quaternary, the center of the Khorat Basin (or Khorat-Ubon Basin according to Sattayarak, 1985) subsided more and more. The folding of the Khorat Group and basin subsidence are stronger in the Khorat Basin, resulting in salt domes and the effects of salts to groundwater are more prominent than in Sakon Nakhon Basin (or Udorn-Sakon Nakhon Basin, according to Sattayarak, 1985).

Therefore, mainly based on Sattayarak's model and Malila (2001), the conceptual model for rock salt structure development and salt dissolution of the Khorat Plateau can be divided into 6 stages through the geologic time as follows:

Stage 1
In the Late Cretaceous, the Maha Sarakham Formation was deposited in a dry and arid environment in a land-locked hypersaline lake. The unconformity was observed from Potash exploration bore-holes between the Lower Anhydrite layer and siltstone of the Khok Kruat Formation.

Stage 2
In the Early Tertiary, the Phu Phan uplift was formed as a result of collision between the Indian plate and the Eurasian plate. The sediments of Phra Wihan, Phu Phan and Khok Kruat Formations were strongly eroded in the uplifted area. The Maha Sarakham salt layers were generally folded with broad and shallow anticlinal and synclinal structures (salt pillow stage).

Stage 3
Still in the Early Tertiary, the Phu Thok Formation was deposited in an arid and semiarid environment by aeolian and fluvial processes. Salt flowage was developed probably driven by sediment loading and gravity glide folding. This process destroyed the original flattening bedding features (salt diapir stage).

Stage 4
In the Early Tertiary to Miocene, fracture development was affected by the Himalayan orogeny. The dissolution process continued to take place at shallow salt layers (salt post diapir stage).

Stage 5
During Miocene to Pleistocene, natural sinkholes were initiated by salt dissolution with capillary force, adhesion and water table changes.

Stage 6
In the Pleistocene to Quaternary, modern landform was developed. The sediment particles transported to the dissolution collapse are presented at the surface as a lake or a surface depression, or sinkhole and higher soil salinity.

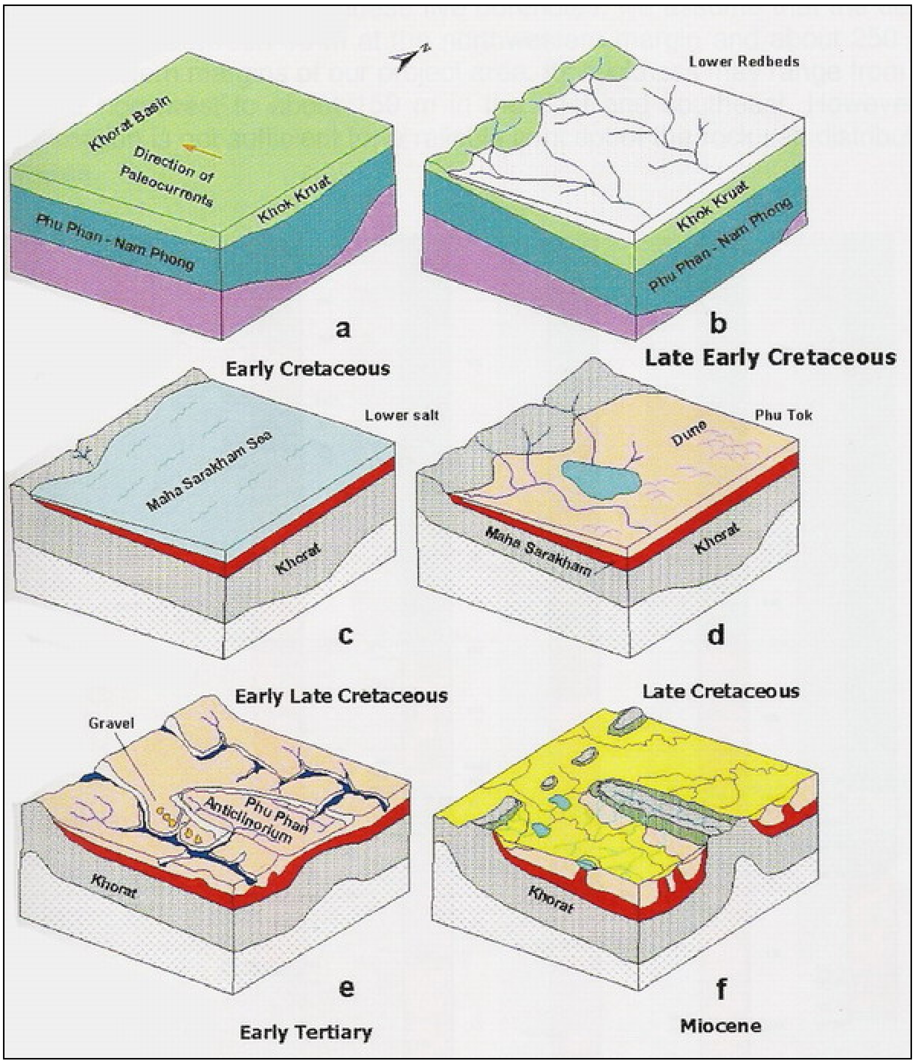

Figure 2.19 Conceptual model of the development of the Khorat Plateau (after Sattayarak, 1985).

2.5.5 Recent Surface Topographic Features

At a regional scale, the circular features follow curvilinear trends typically subparallel to the present basin margin. Initiation of the salt flow in the Maha Sarakham Formation is probably continuous and driven by sediment loading from various depocenters moving across the salt bed. In the Cretaceous, the depocenters were tied to the deposition of the Lower Clastic Member; today they are tied to the fluviatile deposits of the Mekong River and its tributaries. Such feedback systems between depositional loading and salt buildups (pillows and anticlines) characterize the western margin of the Maha Sarakham Formation in the vicinity of Khon Kaen, Chaiyaphum and west of Nakhon Ratchasima Provinces. Some pillows in the Lower Salt Member, especially those associated with sylvinite along the western margin of the basin, were probably initiated syndepositionally, as they are truncated by sediments of the Lower Clastic Member. Other salt flow features are probably active today, driven by laterally shifting surface river systems, including the Mekong, Chi and Mun River and their tributaries.

As a growing salt structure approaches the land surface and enters the zone of active phreatic flow, the rising salt is breached and altered by fresh ground water. It is also believed that the geologic deformation of the Khorat Plateau caused some fissures or fractures to stimulate and give way to fresh water going down to rock salts beneath and dissolving those rock salts as well. With the time this create first a topographic high, then, as the salt breached, it transformed into a dissolution collapse graben often marked by a lake or depressions e.g. marshes, swamps and paddy fields, which are mostly located in low-lying areas, and along the river courses or lineaments, in the present-day landscape.

On contrast, the highland topography of village sites indicates salt sub-basins (three or two salt beds) beneath where less dissolution by groundwater and mostly discharge took place. The conceptual cross-section of the area over the salt beds and salt dome is shown in Figure 2.20.

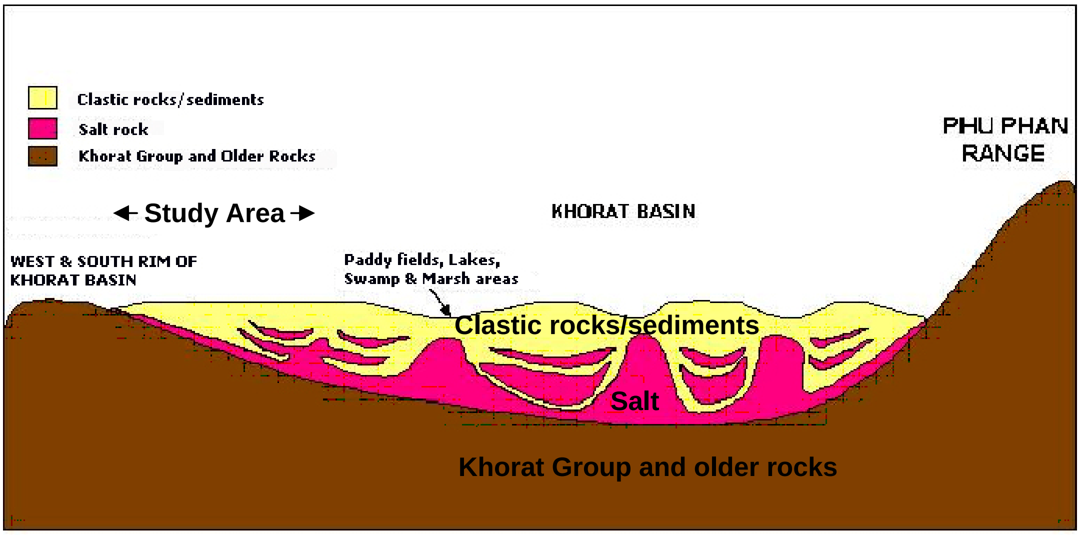

Figure 2.20 The conceptual cross-section of the area over the salt beds and salt dome (modified after Suwanich, 1986).

2.6 Subsurface Geology

Sattayarak (1990) drew a geologic cross-section between Khon Kaen and Nong Khai Province based on seismic reflection data of oil companies showing the location of salt domes along this line (Figure 2.21). It also indicates that the depth to the rock salt (yellow color) increases from the west rim of the basin and toward the depocenter of the basin.

Perry (1996) published a generalized geologic cross-section showing the relation between structure, stratigraphy and topography of the western margin of the Khorat Basin (Figure 2.22). His section also shows the folding characteristic of the Maha Sarakham Formation due to the tectonic.

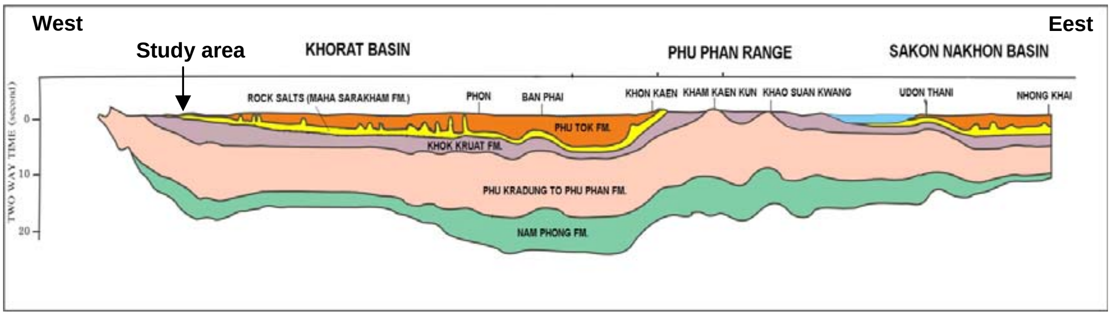

Figure 2.21 Geologic cross-section from Ban Phai, Khon Kaen Province to Udon Thani Province (modified after Sattayarak, 1990).

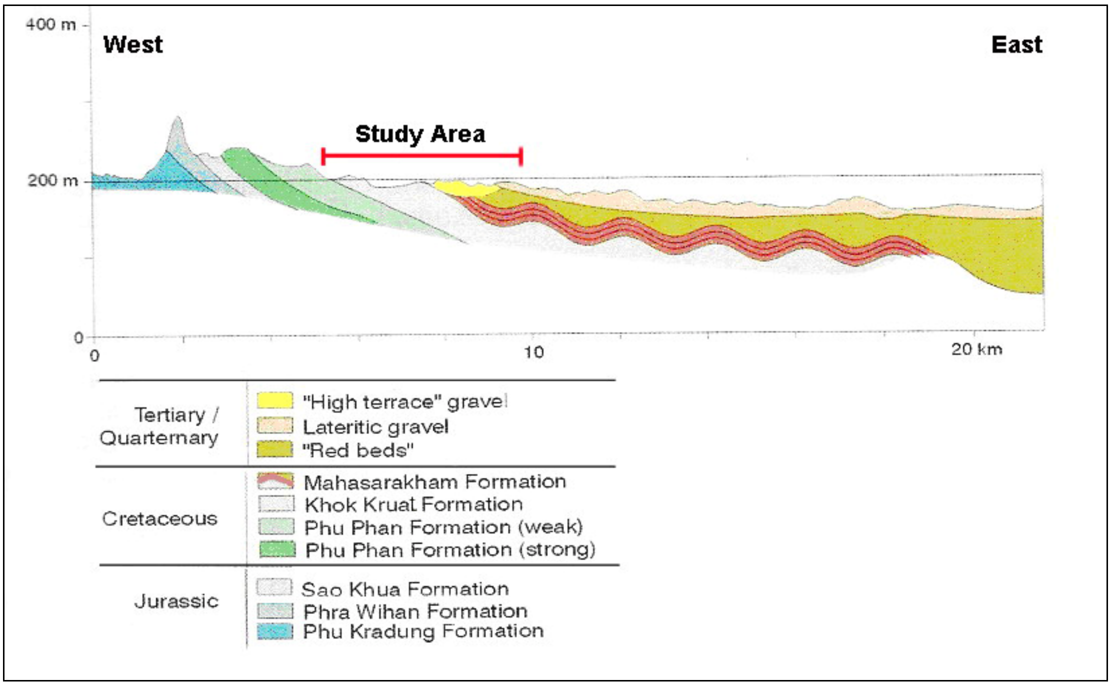

Figure 2.22 Generalized geologic cross-section of the western margin of the Khorat Plateau (modified after Perry, 1996) showing gentle dipping eastwards of the Khorat Group and the foldings of the Rock Salt Members (red color) of the Maha Sarakham Formation.

Suwanich (1986) classified the boreholes drilled in the Khorat Plateau as three groups: 1) Three-salt-bed, 2) Two-salt-bed, and 3) One-salt-bed boreholes, respectively. The details of each borehole type are as follows:

Three-salt-bed boreholes

In the Three-salt-bed boreholes, significant members usually lie in the same series from the uppermost to the lowermost as follows:

Upper Clastic or Phu Tok Formation
Upper Salt
Middle Salt
Middle Clastic
Lower Clastic
Potash Zone/Lower Salt
Basal Anhydrite

Two-salt-bed boreholes

Significant members of rock usually lie within the following formations, from the uppermost to the lowermost:

Upper Clastic or Phu Tok Formation
Middle Clastic
Middle Salt
Lower Clastic
Potash Zone/Lower Salt
Basal Anhydrite

The Upper Salt might be destroyed by geological processes such as weathering and erosion through geological time, and the Upper Clastic is normally being the recent sediment.

This type of boreholes is found more frequently than other types. Therefore, it can be concluded that the major part of the rock salt sub-basins in northeastern of Thailand normally contain two beds of rock salt.

One-salt-bed boreholes

One-salt-bed boreholes represent about one-third of the total boreholes drilled in the study area. Suwanich (1986) interpreted this fact in the way that the salt in one salt bed boreholes belongs to the Lower salt layer. Because of the extreme variation in thickness and tilting of beds, this Lower Salt is expected to form salt domes. Result of salt doming, the upper portions or layers of the Maha Sarakham Formation such as the Upper Salt, Middle Salt and/or Potash Zone were eroded.

One-salt-bed boreholes comprise of various members and units, from upper to lower parts:

Upper Clastic or Phu Tok Formation
Middle Clastic
Lower Clastic
Potash Zone/ Lower Salt
Basal Anhydrite

Borehole data from the vicinity of Maung Chaiyaphum, Bamnet Narong, Chakrarat, Ban Thum, Ban Prakham, Khon Sawan, Phon, Jaturat, Ban Luam, Bua Yai, Prathai, Nong Song Hong, Nong Bua Khok, Kham Sakae Saeng, Khong, Chum Puang, Ban Kra Beaung, Dan Khun Thot, Non Thai, Non Sung, Ban Phut Sa, Lam Plai Mas, Sung Neon, Maung Nakhon Ratchasima and Ban Sa Ra Phi area were collected and were analyzed. The main aims are to correlate the depth to the rock salt beds and to generate the generalized subsurface topography of each rock strata both in 2 and 3 dimensions in the study area. The Rockwork99 software and Surfer32 software were used for this purpose. The locations of boreholes used in this study in shown in Figure 2.23. The subsurface conditions derived from borehole data within the study area are discussed in detail in chapter 6.

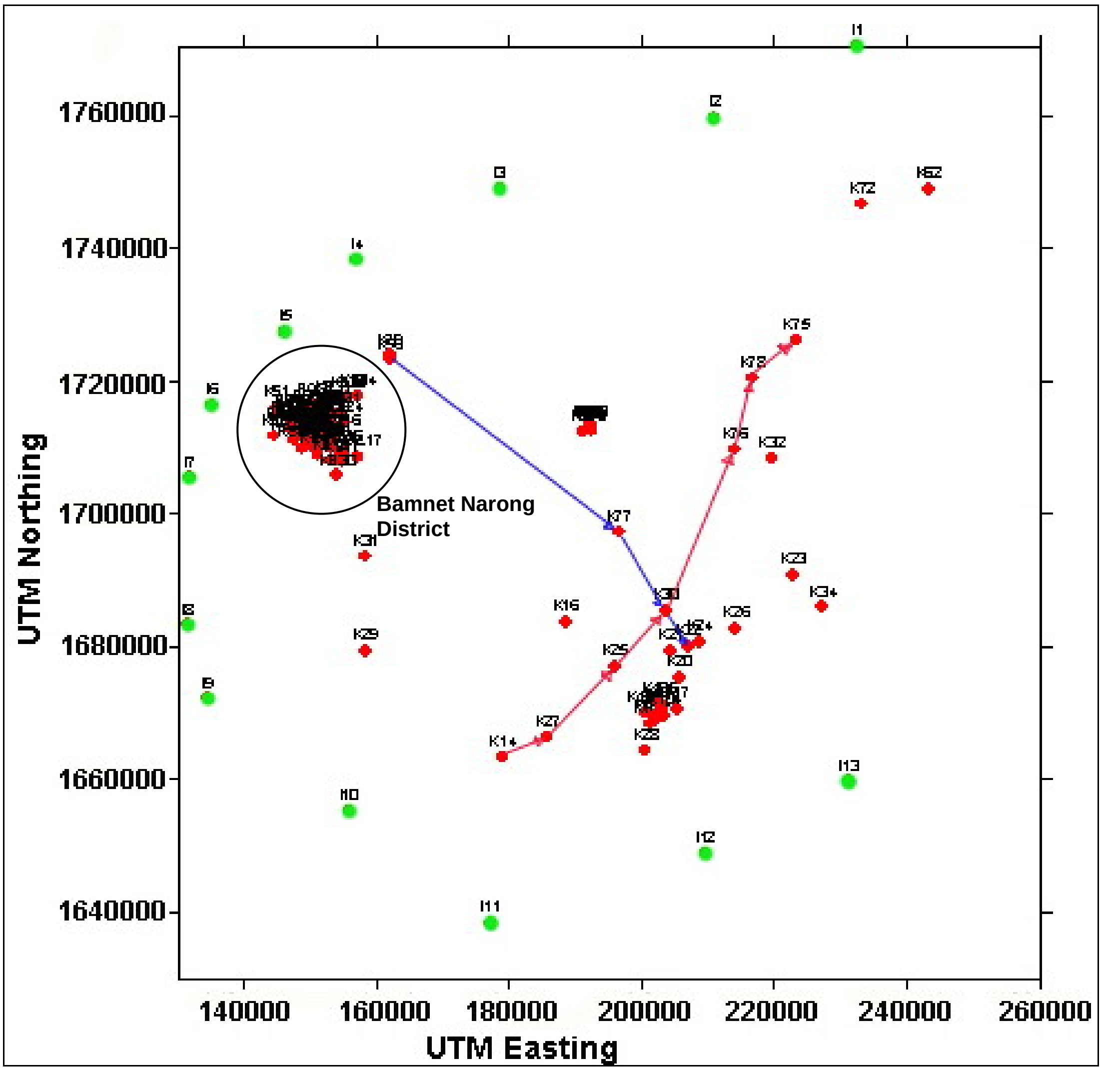

Figure 2.23 Location map of boreholes used in this study (red dots), and the Khorat Basin's boundary (green dots) was taken from Suwanich (1996). The blue line represents the geologic cross- section in northwest to southeast direction, and the red line represents those in southwest to northeast direction. Many of boreholes drilled in Bamnet Narong District (within the circle) for salt mining.