REGIONAL TECTONIC SETTING AND SEISMIICITY OF THAILAND WITH REFERENCE TO RESERVOIR CONSTRUCTION

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ABSTRACT

The overall tectonic patterns in Thailand and SE Asia are essentially controlled by collision between the Indo-Australian plate, the Eurasian plate, and the West Pacific plate. Major southeastward displacement of Indochina relative to South China blocks occurred along the Red River Fault during Eocene times. The collision of India and Asia causing a major clockwise rotation of SE Asia during Oligocene-Miocene mark the essential tectonic evolution of SE Asia. Movements of major fault systems in the region have been attributed to the Western Burma / Shan-Thai (70-80 Ma), and Indo-Burma / Western Burma (40-55 Ma) continental collision. These tectonic activities as well as epicentral distribution define three distinct seismic-source zones in Thailand i.e., zone L in central-western Thailand,and zone G and zone H in northern Thailand. Zone L is dominated by the NW- trending Three-Pogoda, NNW-trending Si Sawat and NW-trending Mae Ping Faults whereas zone G is considered to be influenced by the N-trending Mae Hong Son Fault, and zone H by the ENE-trending Chiang Rai and NE-trending Mae Tha, Li and Phrae Faults. Some earthquakes are attributed to movements along these faults. Two essential mechanisms of quakes are inferred: stress release by fault movement and adjustments due to reservoir impoundment. We propose that Reservoir-Induced Seismicity (RIS) is responsible for several quakes with epicenters in Thailand since 1980 and this perhaps play a more important role than movement along fault planes. Eventhough some of the major faults seem presently inactive; they appear to constitute weak zones in the crust and need to be taken into account when large man-made structures, such as dams and reservoirs are constructed.

Key words: seismicity, seismic source zone, earthquake mechanism, plate tectonic

INTRODUCTION

Earthquakes worldwide are known to be associated with tectonic setting, and tectonic activities both regional and local scales. However the causative mechanism of earthquakes are not always understood and can only be deduced on the basis of geotectonics, field investigation, and past historical earthquakes. The aims of this paper are two fold (1) describe and critically review the tectonic activities of Thailand and mainland SE Asia, and relationship between tectonics and seismicity of Thailand and adjacent areas and (2) to discuss occurrence of seismicity related to reservoir impoundment. So in our study, we complied all available and existing information form both publish geological works. Then we analyzed the space-borne image data particularly those of LANDSAT TM5, JERS, and SPOT together with ground - truth surveys.

REGIONAL TECTONIC FRAMEWORK

During either the Late Triassic (Charusiri et al., 1991, 2000), Permo-Triassic (Hutchison, 1983, Bunopas and Vella, 1983) or even earlier (Helmke, 1985), Thailand and her adjoining countries occupied major parts of the two major blocks joined together by continent-continent collision (Fig. 1). These two microcontinents, which were once part of Gondwanaland and attached to the Australian continent (Bunopas, 1981), include: the Shan-Thai (-Malay) craton (western half of Thailand); eastern Myanmar; the northwest Malay Peninsula; and the Indochina craton (castren half of Thailand, Laos, Kampuchea, southern Vietnam, and eastern Malay Peninsula) (Bunopas, 1981, Bunopas and Vella, 1983, Charusiri et al., 2002). The Lampang-Chiang Rai and Nakhon Thai blocks, lie along the western and eastern parts of the Shan-Thai and Indochina blocks, respectively (. 1). Both blocks which consists principally of oceanic crustal materials (see Tulyatid and Charusiri, 1989, Charusiri et al. 2002), have been dislocated by gigantic sinistral strike-slip faults and their N-trending have been modified by sinistral oroclinal bending associated with this faulting (Fig.1). These faults are thought to have been active during 70 - 80 Ma, 55 Ma and 45 Ma (Charusiri, 1989). The Nan River suture zone (Barr & Macdonals 1987) in northern Thailand, is also the result of the collision of the two microcontinents. This suture (or the so-call "tectonic line" in this paper) may extend southward (Fig.1) to the Sra Kaew zone in eastern Thailand, the Bentong - Raub zone in Malaysia (Hutchison, 1983) and northward into Laos and southern

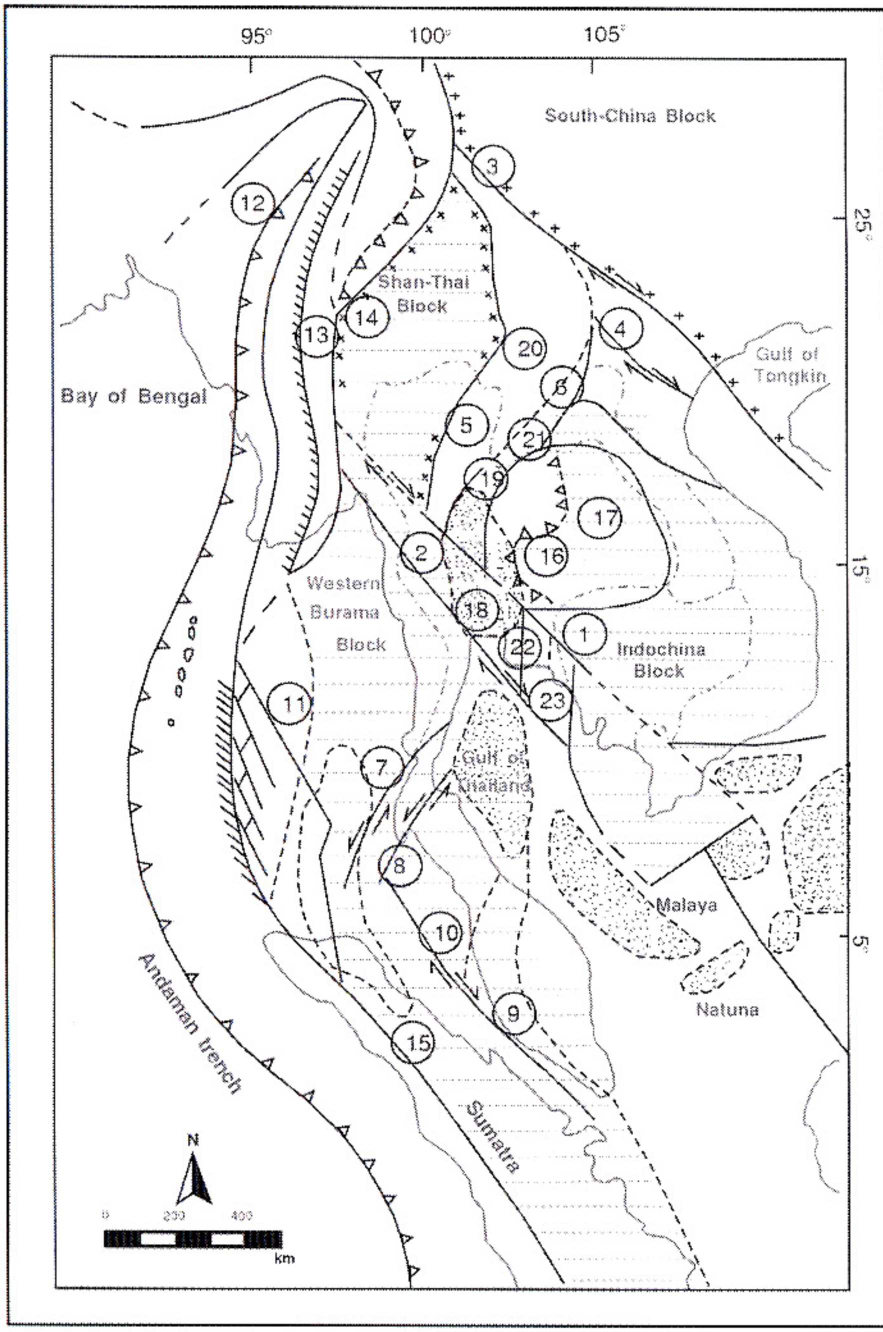


Fig. 1. Tectonic map of Southeast Asia showing major structures, basins, and tectonic blocks (modified after Charusiri et al., 2002, Morley, 2004, Curray, 2005). 1 = Mae Ping Fault, 2 = Three Pagoda, 3 = Red River Fault, 4 = Song Ma Fault, 5 = Mae Tha Fault, 6 = Nan- Uttaradit Fault or Suture, 7 = Ranong Fault, 8 = Klong Marui Fault, 9 = Bentong - Ruab Fault or Suture, 10 = Malacca Faul, 11 = Mergui Fault, 12 = Indo - Burma Thrust, 13 = Tertiary Volcanic Belt, 14 = Pegu - Yoma (Sagaing) Belt, 15 = Sumatra Fault, 16 = Khorat Monoclin, 17 = KhoratBasin, 18 = Chao Phraya Basin, S = Sukho Thai Fold Belt, L = Loei Fold Belt.

China (Huang, 1984. Other, and probably more important, tectonic lines are the tectonic activities of SE Asia are thought to be very intricate with a major and rapid modification between 20-30 Ma (Suensilpong et al., 1981) and 45-55 Ma (Charusiri, 1989). These younger tectonic activities are regarded to have been superimposed on the older activities and some of them have, to some extent, destroyed their earlier imprints, as visualized from space-borne images. The changes in tectonic style caused the Shan-Thai and Indochina blocks as well as the Western Burma and Indo-Burma blocks (Mitchell, 1981 & 1985, Charusiri et al., 1991a) united together to form a southern part of the Eurasian plate (Fig. 2) prior to 45-55 Ma when the Indian plate collided with the Eurasian plate. GPS and seismicity data have recently defined the modern tectonic geometries and strain rates (Chamot – Rooke et al., 1999, Vigny et al., 2003, 2005).

Plate tectonic setting and tectonic history

The present-day tectonic framework of SE Asia or more regionally eastern Asia (Fig. 2) is dominated by the interaction of three adjoining major lithospheric plates: the continental-oceanic Indo-Australian plate in the west and the south; the continental Eurasian plate in the middle; and the oceanic West Pacific plate in the east (CCOP-IOC, 1974). It is also recognized (Metcalfe, 1997, Charusiri et al., 1999, 2002) that particularly in the Eurasian plate there exist few smaller combined crustal blocks whose motions, at present, bear only weak relationship to those of the larger plates. According to Reading (1980), Thailand is part of the Eurasian plate whose boundary is marked by an active east-dipping subduction zone extending from north India (Himalaya Frontal Thrust), passing to west Myanmar and west of Andaman - Nicobar island, and swinging eastward to southward to southward along the Sumatra-Java trench (Fig. 3). The major plate intra- and inter-plate actions are inferred to have been established during Mesozoic, but their structures in the existing arc-trench zone have been overprinted by the major Tertiary tectonic-orogenic activities which in several cases are still active.

Major changes in tectonics of Thailand may have occurred at the end of Mesozoic (Bunopas and Vella, 1983, Charusiri et al., 2002, Morley, 2004) and are likely to have coincided with or be related to the north to northeastward progressive collision of the Indian plate with the Eurasian plate (Rhodes et al., 2000).. The occurrence of a major southeastward displacement of Indochina relative to South China along the Red River fault zone (Fig.3) by the Indian-Eurasian collision during Eocene (40 -50 Ma, Searle et al., 1987) possibly marks the major tectonic evolution of east and southeast Asia.

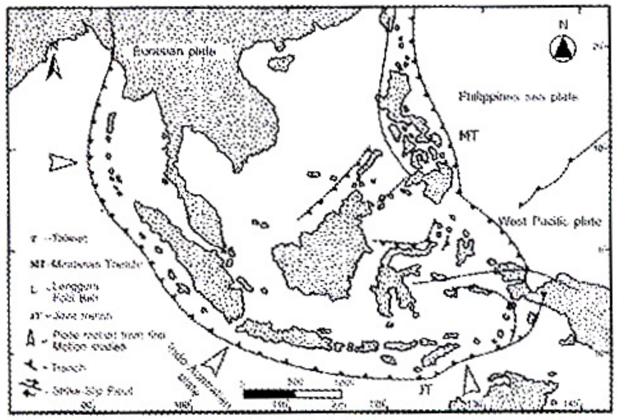


Fig. 2. Index map of Southeast Asia showing three major tectonic plates (modified after Suensilpong, 1971and Polachan, 1988).

The collision of continental India with Asia could have caused the extrusion (1,000 km displacement) to the southeast and the clockwise rotation of Indochina and Sunda shelf during Oligocene-Miocene (20-30 Ma). This phenomenon eventually accounted for the *sinistral* displacement along the large-scale strike-slip faults in SE Asia. Such displacement may have led to the opening of the South China, the Gulf of Thailand and Andaman seas prior to the late Miocene Epoch and is thought still active. Similar deductions were also made by Polachan (1988), Polachan and Satayarak (1989) and Curray (2006), regarding the evolution of the Mergui, Basin and the development of several Tertiary basins in Thailand. As the Indo-Australian plate was subducting obliquely beneath the SE Asian plate (Eurasian plate) in the Andaman Sea, the Mergui Basin developed rapidly during 25 Ma (Late Oligocene) as a result of NW-NNW-trending rifting and ocean-floor spreading (Fig. 3). The Mergui basin developed as a series of N-trending half - grabens simultaneously with the development of N-trending extensional normal fault system. The associated syn-sedimentary fault system is interpreted to have occurred as a result of the transtensional dextral shear movement along the NW-trending Sumatra (or Semanko) fault system, bounded to the east by the sinistral Ranong-Klong Marui fault system. The shear movement was eventually accommodated within the NNW-trending Mergui fault system and the NNE-trending echelon normal fault system.

A similar situation has also been documented for the development of Tertiary basins in Thailand. These sedimentary basins are mainly N - trending, pull-apart grabens or half-grabens which are inferred to have been developed since Late Oligocene (20 - 25 Ma) by the movement along the strike slip faults. Such ages range of

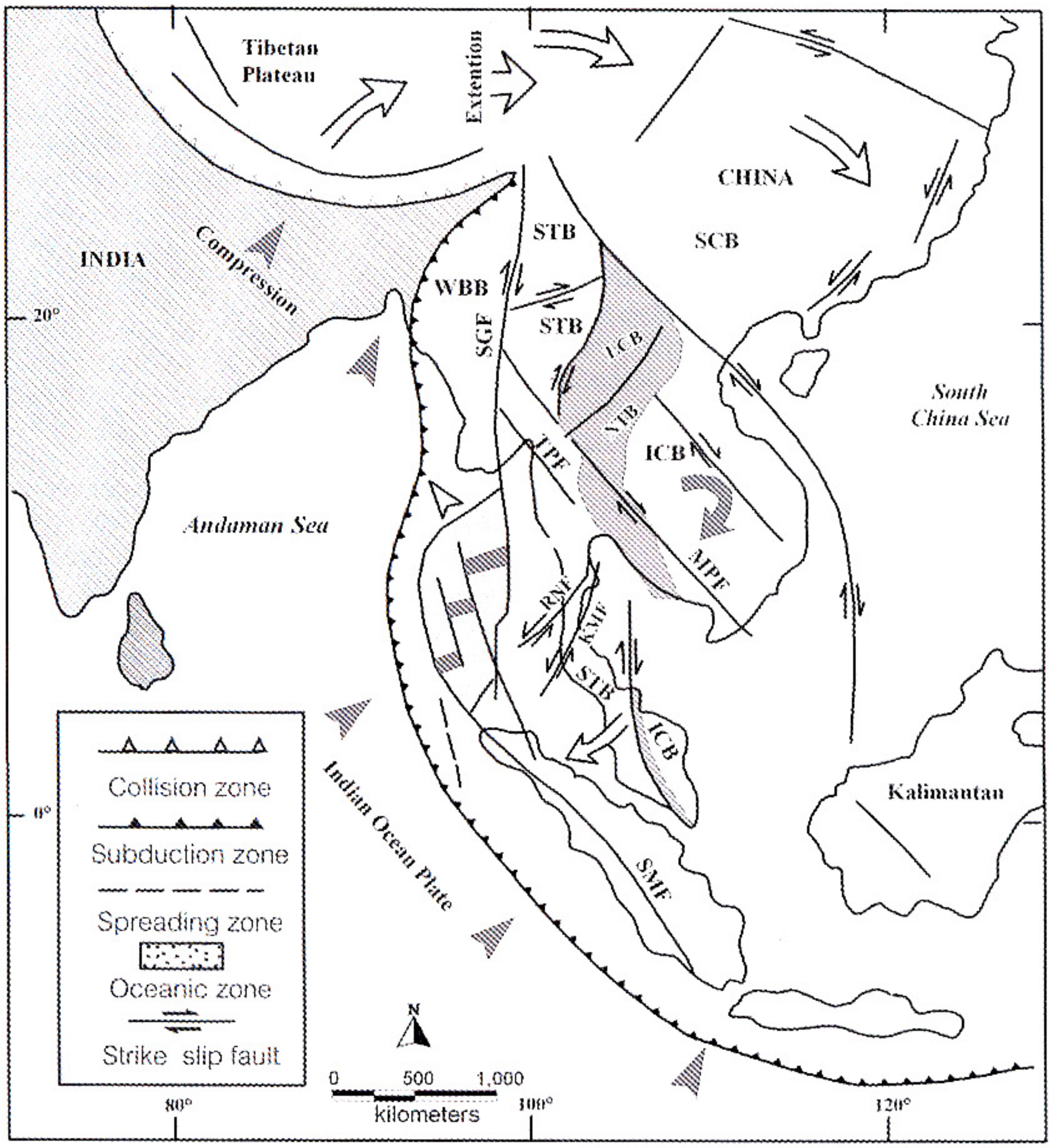


Fig. 3 Tectonic map of SE Asia showing major fault systems and the relative movement of crustal blocks in response to India-Asia collision (modified from Poolachan, 1989) (Notes: SFS = Sumstra Fault Zone; MFZ = Mergui Fault Zone; SFZ = Sagaing-Namiyim Fault Zone; UFZ = Uttaradit Fault Zone; RKFZ = Ranong-Klong Marui Fault Zone; RRFZ = Red River Fault Zone; NTFZ = Northern Thailand Fault Zone; and M = Mergui Basin).

basin development has been geochronologically proved by von Braun et al. (1976) and Charusiri et al. (1991b) The structural framework of these basins as revealed on surface geology maps and by seismic exploration data, is undoubtedly controlled by the N-trending, extensional syn-sedimentary normal fault system which is spatially and temporally closely related to the movement along the NW- and NNE- trending, conjugate strike-slip faults that have been reactivated during the Oligocene Epoch. The basin development is attributed either to the collision of the Indian plate with southern Asia (Poolachan and Sattayarak, 1989) or to the collision of the Indo-Burma block with Eastern Burma block (Charusiri et al., 1992) during 48-50 Ma, or even younger (Middle-Late Miocene; Bunopas and Vella, 1983). This phenomenon led to the movement along the large-scale strike-slip faults with the associated development of transtensional, S-shaped basins in northern Thailand and Z-shaped basin in the Gulf ((see also Poolachan, 1988, Uttamo et al., 2003).

History of Major Fault Movements

Most of the Tertiary basins in Thailand are dominated by normal and NW- and NNE-trending strike-slip faults, and N-trending, extensional syn-sedimentary suggesting that they are pull-apart basins formed by simple- shear tectonics rather than by simple extension process, e.g., Bunopas (1981), Charusiri (1989), Polachan and

Sattayarak (1989) and Charusiri et al. (1993). The geometrical relationship of these strike-slip and extensional fault, the evidence of clock-wise rotation of SE Asian crustal blocks (Fig.3), and recent earthquake analyses (Fenton et al., 1997, 2003; Bott et al., 1997) fits a regional dextral shear system. Movement of major NW- and NE- trending strike-slip fault systems in the SE Asian region are ascribed to the continental collision of the Western Burma and Indo-Burma blocks with the Shan-Thai block (or Eurasian plate) during 70-80 and 40-55 Ma, respectively (see also Charusiri et al., 1991a). Either the Cenozoic northward movement of India past Sundaland (Topponier et al., 1986) or the Indo-Burma block past western Burma block (Mitchell, 1985) is considered responsible for the dextral strike-slip motion along the N-trending Sagaing Fault in central Burma, for the clockwise rotation of SE Asia (Achache and Courtillot, 1985), and the sinistral movements along NE - trending as well as the dextral movements along NE-trending faults. At present the NW-trending faults, namely the Red River, the Mae Ping, the Three-Pagoda and the Sumatra (Semangko) Faults, represent the major dextral, strike-slip faults, and the NE - to NNE - trending faults, including the Northern Thailand fault zone (Mae Tha, Li, Long, Thoen and Phrae Faults), and the Southern Thailand fault zone (the Ranong and the Klong Marui Faults), are regarded as sinistral faults which are inferred as conjugate sets.

Consequently, the movement along the NW- and NNE-trending, conjugate strike-slip fault systems have changed from left to right and right to left, respectively, in Miocene (Tapponier et al., 1986, Charusiri et al., 2002). It is inferred that the change in stress field of the region from transtension to transpression regimes have occurred as a result of the collision of Indo-Australia with SE Asia (Charlton, 1986) which in turn caused the changes in sedimentation regimes in most Tertiary basins from lake-dominated to coarse-clastic sediments (see also Knox and Wakefield, 1983). The NW-trending Mae Ping (or Moei-Uthai Thani) fault changed its sense of movement from left to light shortly after middle Miocene, as deduced from the study of fault plane solution of a recent earthquake located approximately on the fault (Le Dain et al., 1984, Nelson et al., 2004), from our field investigation at Lansang, Tak (see also Hinthong, 1991) and from the recent structural maps with satellite image interpretation (Morley, 2004). Sinistral movement can also be clearly recognized along the NE-trending Ranong and Klong Marui fault zones, which transect granitoid rocks at several places (Garson et al., 1975, Charusiri, 1989, Khantaprab et al., 1991).

MODERN SEISMITECTONIICS OF THAILAND

Judging from the distribution of earthquake epicenters in South and Southeast Asia, Thailand lies close to the east of the Andaman-Sumatra (or Alpine) earthquake belt. One can argue, as shown in Fig. 8, that Thailand is located mainly in an aseismic zone (Fig. 8) because not all of the larger South East Asia earthquakes have been felt in Thailand. However, the awareness and fear of the vilent and sudden hazard they pose undoubtedly stimulate the study of earthquakes in this region. This led to the systematic compilation of the historical earthquake database in Thailand and adjoining areas by Charusiri et al. (2004).

So far there have been only few studies on earthquakes in Thailand (e.g., Nutalaya et al., 1985, Siribhakdi, 1986, Prachuab, 1990, Hinthong, 1991, Charusiri et al., 1991b, Koesirikulkit, 1990). The historical earthquakes in Thailand were first summarized in a chronological order by Nutalaya et al. (1985) from the historical texts, annals, stone inscriptions and astrological documents in the Thai language. Only about 50 earthquakes had occurred in Thailand and Myanmar since 623 B.C. The records yield only the locations where the earthquakes were felt and not the true epicentral locations, and the earthquake intensities were assigned by Nutalaya et al. (1985) using the Modified Mercalli scale (M_M) varying from V to IX. The largest historical earthquake in Thailand was in the Chaing Saen area in 460 A.D. (Nutalatya et al., 1985, Fenton et al., 2003), and the largest instrumentally recorded earthquake in SE Asia occurred in 1941 in the Andaman Sea. In addition, fifty historical quakes with epicenters in the Yunan area (southern China) occurred between 1446 to 1909 A.D. (U.S. National Geophysical and Solar-Terrestrial Data Center, 1983).

Seismicity related to fault activity

Nutalaya et al. (1985) were the first to systematically identify the seismic-source zones in SE Asia and characterize earthquake recurrence in Thailand. The zones have recently been modified by Koesirikulkit (1992) integrating the geological setting, geological structure, tectonic setting and seismological information (Fig.. .4) According to Koesirikulkit (1992) and this paper, three significant seismic-source zones in Thailand may be defined; zone L, central-western Thailand; zone G, northern Thailand; and zone H, in the Sukhothai-Loei region. All these zones are significant and are closely related to active tectonic structures. Fig. 5 illustrates these three seismic-source zones and their associated major faults and lineaments. Details of the three seismic-source zone (L, H and G) are discussed below.

Seismic Subzone L The three seismic-source zone can be differentiated on the basis of distinct patterns of faults (Fig. 5). These faults are considered to be active during Cenozoic time (Hinthong, (1991) In zone L, there are three large-scale strike-slip faults that probably control this seismic-source zone, namely the NW-trending Three-pagoda Fault, NNW-trending Si Sawat Fault and NW-trending Mae Ping (or Moei-uthai thani) Fault. According to Nutalaya et al. (1985), these three fault zone extend northwestward, to join and become part of the N-trending Taunggyi and NNW-trending Pan Luang Faults. However, our Landsat and SPOT interpretation clearly indicates that the strike-slip faults in zone L, eventhough extending their associated discontinuous branches into zone F (Tenasserim Range), was cross cut by the "younger" N-trending, Taunggyi Fault. This leads Charusiri et al. (1991) to exclude zone L from zone F. However the original zone F described earlier by Nutalaya et al. (1985) includes zone L into it.

Mae Ping Fault: Two major earthquakes along the Mae Ping Fault occurred on 23 September 1993 and 17 February 1975 (see Fig. 10). The 1993-earthquake was erroneously reported to be felt in Mae Sod District, Tak province. The duration of ground motion was about 1 minute. However, due to the fact that there are two different locations of epicenters, we, therefore cannot count it as earthquake event. The 1975-earthquake with the magnitude of 5.6 Richter scale and the intensity of VI Mercalli scale, took place in Tae Song Yang district, Tak province, was felt throughout central Thailand and caused miner damage. Bunopas (1976) and Nutalaya et al. (1985) reveal that the fault has sinistral displacement.

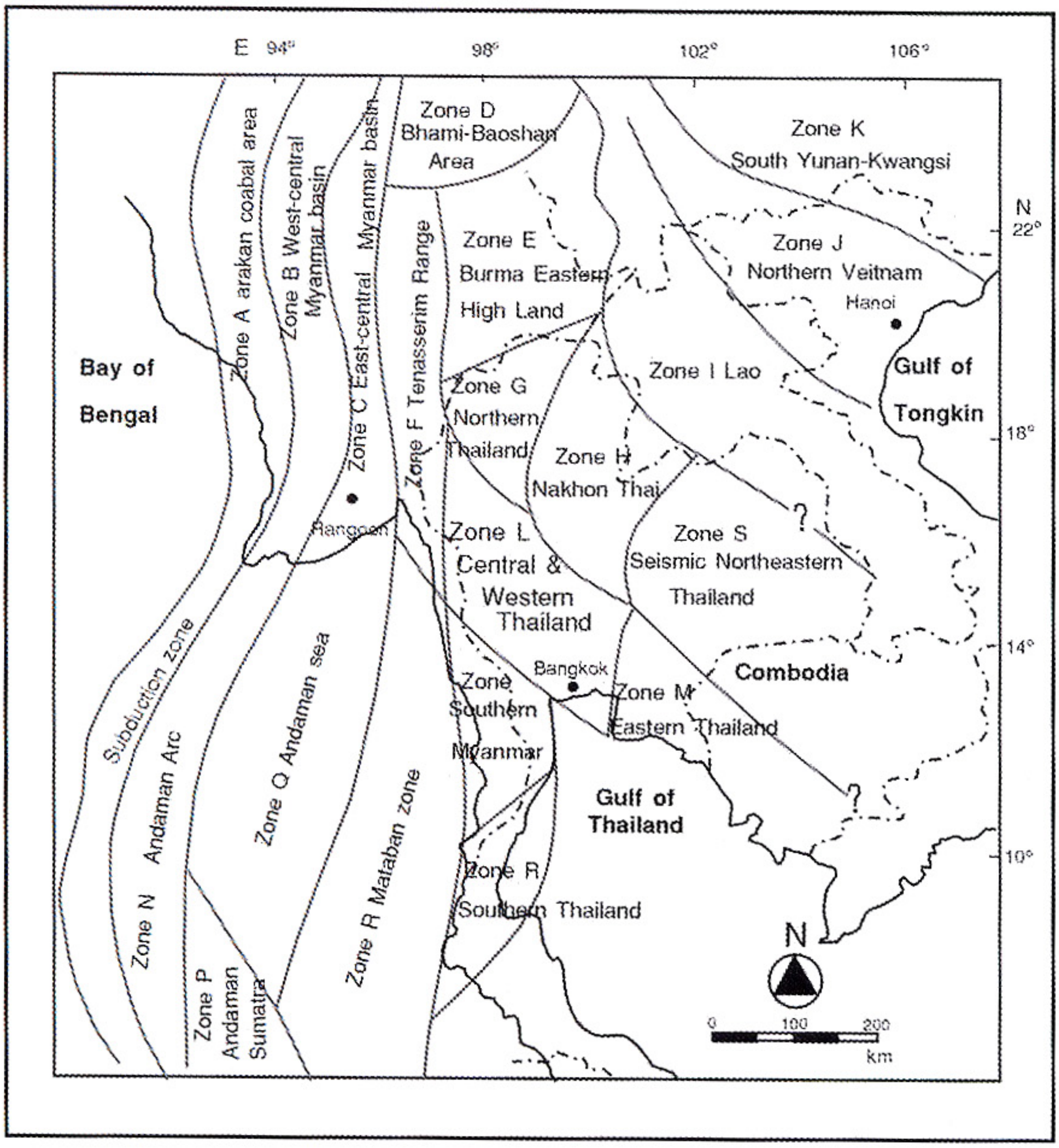


Figure 4. Major seismic-source zones in Mainland SE Asia (Charusiri et al., 1991).

However, as stated in the previous section, Poolachan and Satayarak (1989) argue that these strike-slip faults are dextral. In our opinion, the faults may have changes their sense of movement from sinistral to dextral immediately after the mid-Miocene. Of significance are the ages of fault movements as determined by thermoluminescence (TL) dating on the Mae Ping (or the Moei - Uthai Thani) Fault Zone. Such TL age-data, especially from the faults in the vicinities of Ban Mae Salit Mon Krathing and Ban Mae Ramat, indicate that their fault activities can be dated sequentially as of 0.16, 0.21, 0.22, 0.37, 0.49 0.50, 0.58, and 1.17 Ma (see also Hinthong et al., 1992).

Sri Sawat and Three Pagoda Faults: Three other earthquakes have been recorded along the dextral Sri Sawat and Three-Pagoda Faults in western Thailand. These two faults appear to control the Kwae Yai and Kwae Noi Rivers which flow SE towards the Gulf of Thailand.. The frist earthquake occurring on 21 March in the Klongdo district, Kanchanaburi province, at the Kwae Noi River. A newspaper reported at that time, ground cracking and fountains of water being ejected from the ground.

The second earthquake took place in April, 1983 at the Srinagarind reservoir, Kanchanaburi, western Thailand. Two tremors of magnitude of 5.6 and 5.8 in Richter scale were recorded on 15 and 22 April 1983, respectively.. They caused widespread panic and some damage to buildings in the city and nearby districts. Grounds cracks and landslides were also reported in Kanchanaburi area. However, a 7 year investigation by Electricity Generating Authority of Thailand (EGAT) using seismic geologic parameters led Klaipongpun et al. (1988) to conclude that the seismicity could be due to reservoir impoundment, and the subsequent release of the pre-existing strain energy. The E-trending surface rupture is considered the fault plane for the main shock and is modeled as a reverse fault marking the southern end of the reactivated NW-trending fault.

A third earthquake event took place on 22 January 1985, at Khao Laem reservoir. This was followed by a magnitude 3.9 earthquake on 11 July the same year. These two events had the modified Mercalli intensity of V. Another long-term investigation on earthquakes occurring at or near Khao Laem reservoir was done by EGAT. Klaipongpan et al. (1988) and Hetrakul et al. (1988) based on the epicentral trends and hypocentral distribution of earthquakes. They interpreted the NE-trending nodal planes as faults with sinistral displacement for most of the earthquake swarms. It was noted that these followed reservoir impoundment. Our Landsat TM5, JERS, and SPOT investigations around the reservoir strongly support the existence of an echelon discontinuous fracture system in the NE-NNE direction. The results obtained from several investigations (e.g., Hetrakul et al., 1988 and Klaipongpan et al., 1988) lead us to accept the high possibility of reservoir-induced seismicity (RIS) phenomenon. The latest movement of the large-scale, right lateral, NW-trending Three Pagoda Fault is considered of Early Pleistocene (Klaipongpan et al., 1988) as determined by Electron Spin Resonance (ESR) dating. In addition, this fault was also dated by thermoluminescence (TL) dating to be older than 1 Ma (Chaturongkawanich, 1989 and Won-in, 1999). It is therefore emphasized that the NW-trending Three-Pagoda Fault, which borders the southern part of zone L and was once believed to account for earthquakes (Nutalaya et al., 1985) is not considered presently active and is not the fault controlling the focal mechanism of tremors near the Khao Leam reservoir. Rather, the activity is due to movement on smaller conjugate sets of faults as a result of surface loading by the reservoir.

Seismic Subzone G The two other distinctive subzones of which zone can be recognized on the basis of recent seismicity with the magnitude ranging from 3 to 5 in Richter scale. These include zone G; Northern Thailand, and zone H; Sukhothat-Loei zone. The former is restricted along the N-trending Mae Hong Son Fault and Thrust (Charusiri, 1989) which aligns roughly parallel to the Mae Sariang-Mae Hong Son basin. Based on $^{40}Ar/^{39}Ar$ age data, Charusiri et al. (1992), proposed a mid-Miocene displacement as a fault cuts of basaltic extrusion, which occurred in Late Tertiary (Charusiri, 1989) and marks the climax of the tectonic activity (Bunopas, 1981), indicates that the fault activity may be much younger.

Seismic Subzone H The other subzone (zone H; the Sukhothai-Loei) is characterized by a series of NE-ENE-trending, sinistral faults, known as the northern Thailand faults (Polachan, 1989), which mark the zone boundary. The zone H is bounded in the north by the Mae Chan Fault, in the south by the Phrae Fault, and in the west by the Mae Tha Fault. The latter is a N- to NNE-trending arcuate west-dipping fault. Takashima and Maneenai (1995) dated some fault-related materials by thermoluminescene (TL) and reported that fault movements associated with the Mae Tha Fault took place as early as > 1.43, 0.77 Ma and as late as 0.19, 0.31 and 0.40 Ma. In addition, the Thoen, and the Li faults are also included in this seismic-source zone. A study on the distribution of epicenters in the Chaing Mai area by EGAT (1989) discusses the occurrence of more than 70 microearthquakes scattered throughout the Chaing Mai basin to the west of the Mae Tha Fault.

Twenty microearthquakes ranging from magnitude (M_L) 3 to 4 were recorded in the Phrae basin during 1980-1983 (Fenton et al., 1997).. It is considered from our study based upon epicental distribution, that the Mae Tha, the Chaing Rai, and the other NE-trending large faults (e.g., Phrae and

Li faults) are still active.. This is also supported by an offset in Quaternary gravel beds exposed on the road cut of the Lampang - Den Chai Highway, possibly located along the Theon Fault (Hinthing, 1991). Additionally, several faults thought to be associated with the Thoen Fault (see Fig. 5) were dated, by Udchachon et al. (2005).. These studies showed the faulting as early as 1 Ma and as late as 20ka. This strongly supports the view that most of the activities on the Thoen Fault took place in the Pleistocene time. Only one TL date of 0.49 Ma has been determined so far, and this is believed to be associated with the Phrae Fault, which was active during the Pleistocene. Our field investigations on minor NE-trending faults, such as Kaeng Sua Ten reveal that they are mostly active. Special attention needs to be paid on the hot-spring distribution (Ramingwong et al., 1980) and terrestial heat-flow data (Thienprasert and Raksaskulwong, 1984). It is worth noting that the locations of hot springs (Fig. 5) and relatively high heat flow in this region (Fig. 6) are, to some extent, associated with the NE- and NW-trending major fault zones

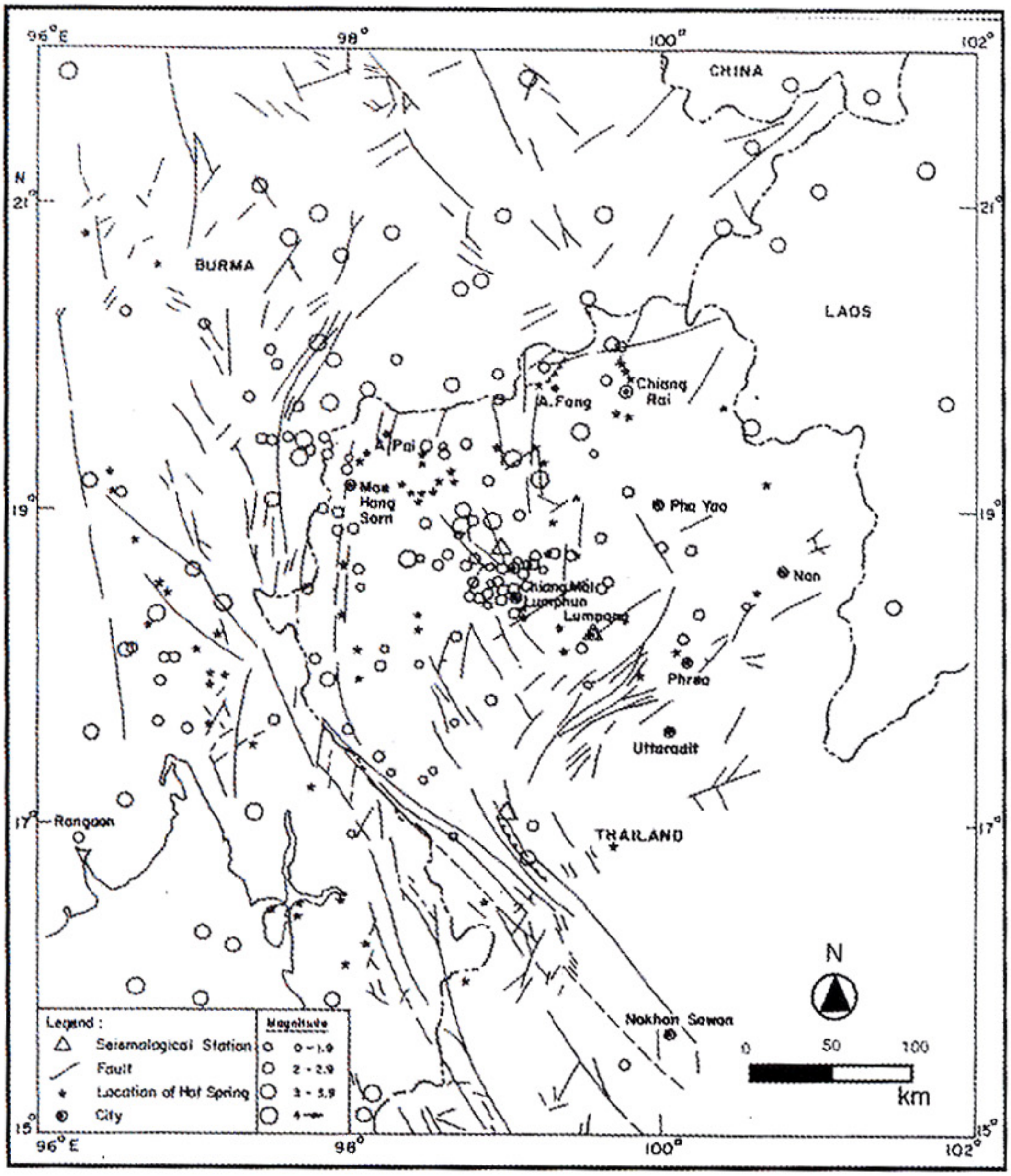


Figure 5 Distribution of hotsprings, faults, and earthquakes in northern Thailand and adjacent countries (modified from Ramingwong et al., 1980).

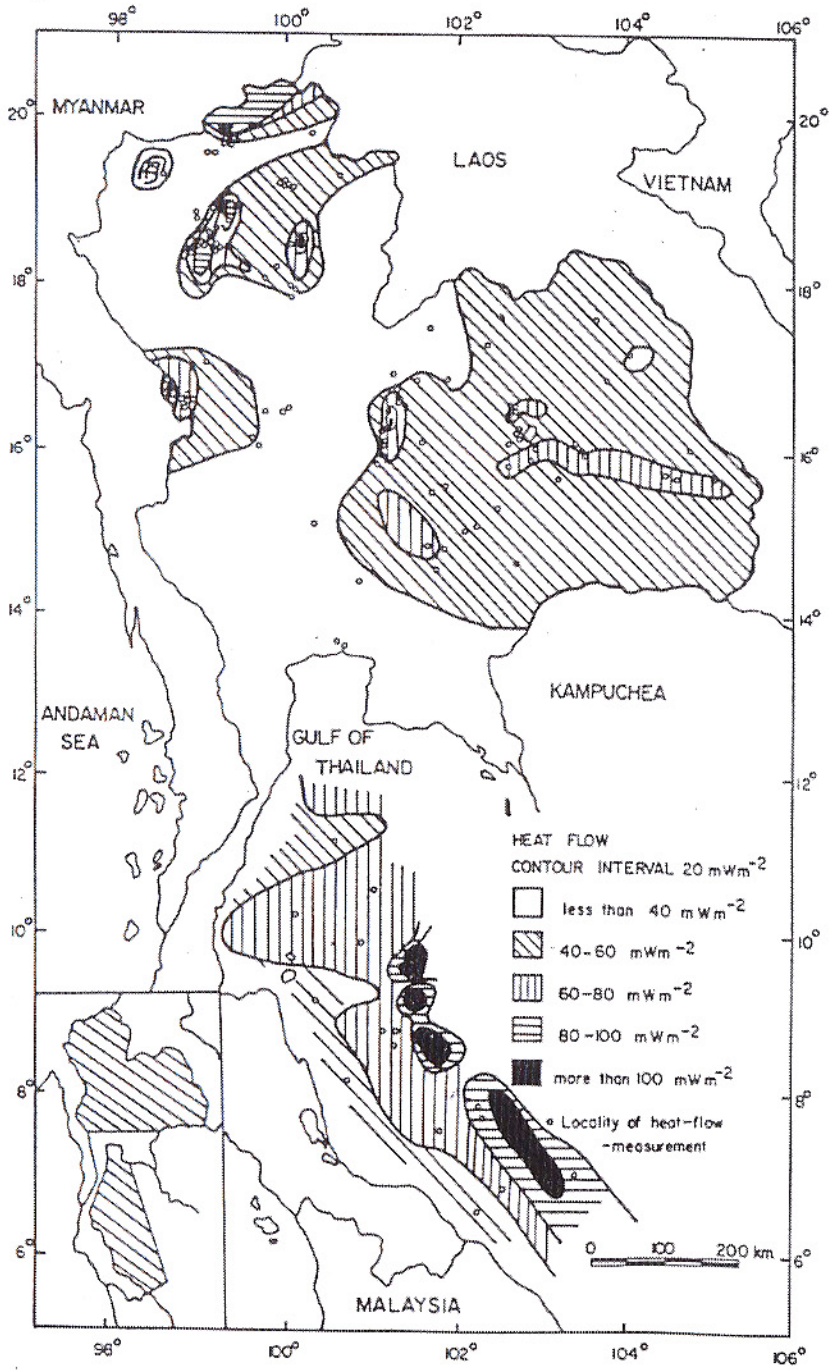


Figure 6 Contour map of terrestial heat-flow in northern and north-eastern Thailand (1 ucal cm^{-2} s^{-1} = 41.9 mW/m^2) (Thienprasert & Raksaskulwong, 1984).

Seismicity Related to Reservoir Impoundment

Seismic records and reservoirs From the geological and seismological information discussed above and from the map in Fig. 7, it is inferred that Thailand, with the exception of the northern part of the country, is located in the stable and aseismic zone of the Indochina peninsula. Japan International Cooperation Agency or JICA (1989) made a detailed study on seismicity and proposed a seismic-risk map of Thailand (Fig. 8) based upon Gumbel's Extreme Value Theory (Gumbel, 1967 and Table 1), asymptotic distribution, the maximum amplitude of earthquake-induced ground motion, and maximum velocity in base rocks (Table 2). The map includes seismological data from the years 1901 to 1977 with assumed magnitude from 4 to 6 and focal depth of 20 km. According to this map (Fig. 8) six seismic-risk zones were recognized ranging from first-degree (greatest risk) to fifth-degree zones (least danger), the sixth being an area with no seismic risk. Northern and western Thailand fall into the fourth-and fifth-degree seismic zones showing that seismic activity in Thailand is remarkably low compared with adjoining regions such as Myanmar, southern China, and Andaman Sea.

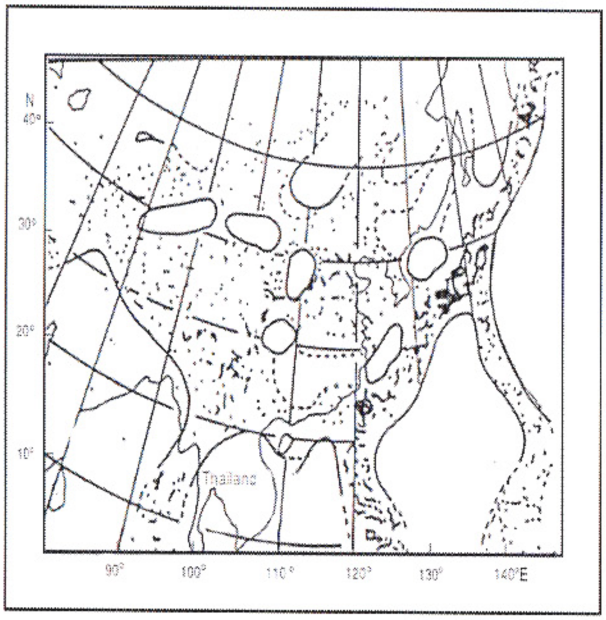
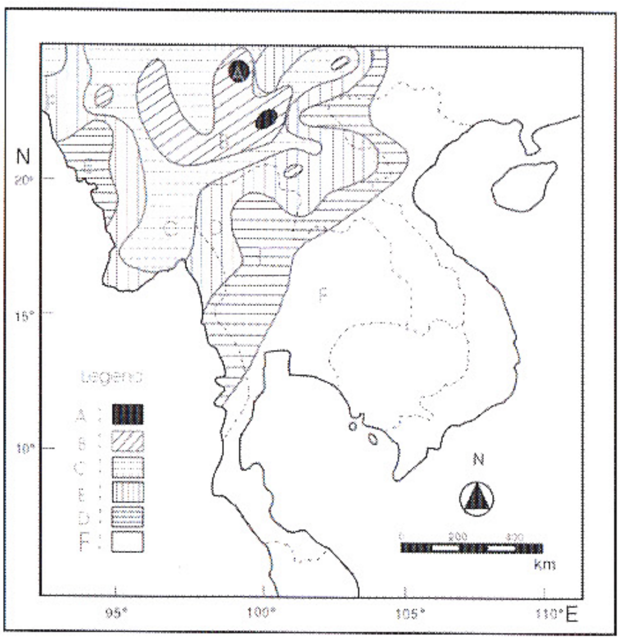


Figure 7. Distribution of aseismic areas in South and East Asia (modified after JICA, 1989).



F g. 8. Seismic zoning map for Thailand and the adjacent region based upon Vmax value (JICA, 1989) (Notes: A = 1st degree, B = 2nd degree, C = 3rd degree, D = 4th degree, E = 5th degree, and F = no degree).

As shown in Fig. 9, earthquakes of magnitudes 3 to 6 in Richter scale have been recorded by JICA during the period from 1900-1991 in Thailand. Also several historical earthquakes and tremors, with epicenters near Thailand, have been felt and caused damage. One earthquake (with M_L close to 6) in Kanchanaburi is significant and caused some damages. Fig. 10 illustrates the epicentral distribution of earthquakes and the locations of fracture systems. It reveals that most of the earthquakes felt had epicenters in Myanmar and the Andaman Sea and that several events on land may have occurred as a result of active-fault movement in the 500 km radius region. Our detailed analyses discussed above shows that the Mae Ping fault does not appear to contribute to the seismicity of the area, although it is believed the fault is still active. According to available seismic data, only three medium-size earthquakes, with magnitudes of 3 to 5, were recorded during 1975-1984 in the vicinity of the area, indicating a low probability of earthquake recurrence.

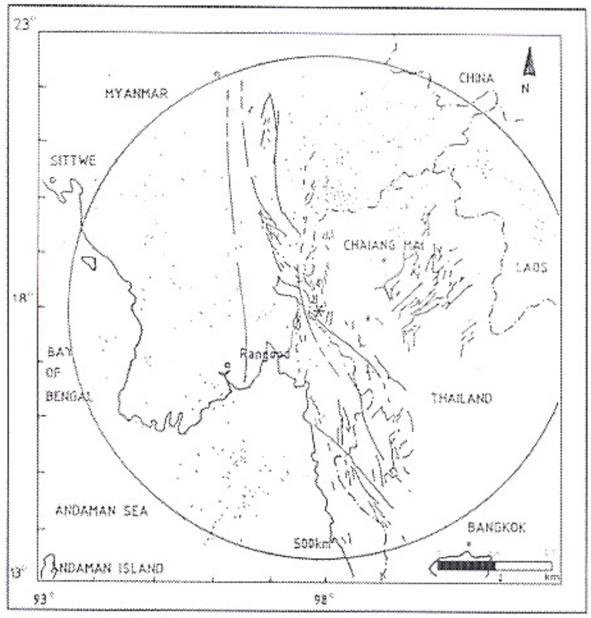


Fig. 9. Index map showing epicentral distribution in Thailand and adjacent areas (modified after Prachaub. 1990).

Future reservoirs Maximum acceleration experienced during 1959 to 1987, as determined by JICA (1989), using four different models and equations (Table 1) together with earthquake magnitude and hypocentral distance data, shows that only the 1975 magnitude 5.6 earthquake, recorded with an epicentral displace of 19 km and with a depth of 6 km, is important. Table 2 shows the maximum acceleration excepted at the Nam Yuam area, Mae Hong Son for 4 return periods (i.e., 50, 100, 200, 500 years) as reported by JICA (1989) using various equations. The results from these as can de seen are relatively similar. The average value is nearly the same as the 1975 earthquake suggesting that if a similar size earthquake occurred in the future, it would not create a serious problem.

The damsite proposed by EGAT and located in the Nam Yuan area on the Mae Ping Fault, which is regarded as a weak zone, could possibly result in a release of local stress at a future time. The impoundment of the reservoir water may trigger microseismic activity in the area as in the case of the Srinagaring and Khao Laem Dams. The reservoir-triggered seismicity (RTS, or reservoir-induced seismicity - RIS) is inferred herein to be the result of the combined effect of several geological and hydrological factors. The crust beneath the study area must be fractured resulting from the relaxation of plate adjustments after continental collision. Such crust within the hydrological regime of the reservoir must be stressed sufficiently prior to water impoundment. A gradual increase in stress, due to reservoir loading plus changes in effective stress appears to be sufficient to trigger the release of energy along pre-existing planes of weakness; the NE-trending dextral faults in this case. We, therefore, strongly believe that the local microseismic activity occurring in the Khao Laem and Srinakarin regions in Kanchanaburi resulted directly from the effects of RIS.

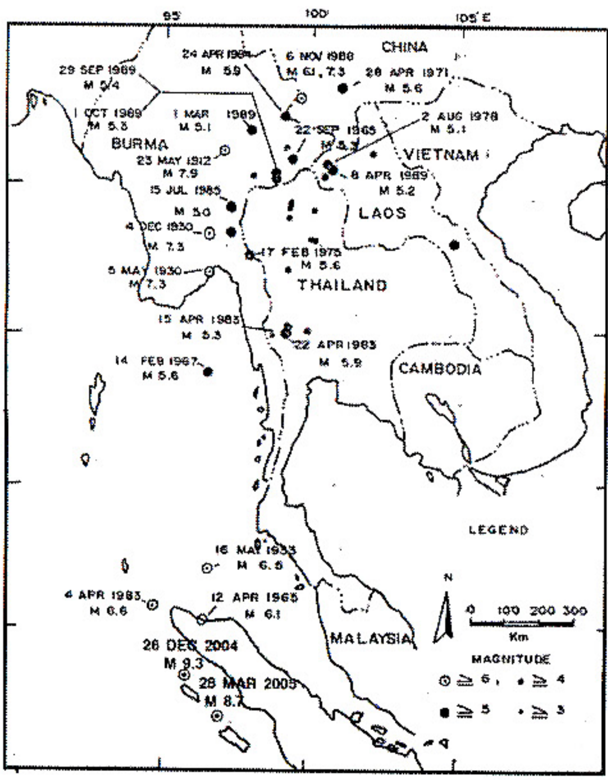


Figure 10. Epicentral distribution of main earthquake events and major fracture zones about 500 km radius around the 1975-earthquake Nam Yuam raea, Mae Hong Son.

It should be pointed out that the maximum RIS at Khao Laem and Srinakarin dams occurred within the first five to six years after impoundment and the maximum earthquake magnitude did not exceed 6. Since several dams prepared by EGAT are, to some extent, situated directly on faults or weak planes, a concrete-faced rockfill dam is recommended as the best type because of this designs inherent high resistance to seismic loading. It is also recommended, owing to the changes in water levels which may cause periods of increased seismicity, that a seismic monitoring network be installed around the impoundment to detect any reservoir induced seismicity. This can be expected to continue for several years after impoundment. This proposed network is also essential to provide information from far-field earthquakes which could contribute to damage at the damsite.

Table 1 Maximum annual acceleration of the Nam Yuam area, Mae Hong Son Province during from 1959 to 1987.

Year	Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)
1959	0.22	3.53	0.30	0.99
1960	0.19	3.32	0.28	0.95
1961	0.27	3.97	0.35	1.11
1962	0.40	5.43	0.52	1.78
1963	0.22	3.62	0.31	1.06
1964	0.58	6.98	0.71	2.45
1965	0.77	7.44	0.80	2.29
1966	0.93	8.31	0.93	2.58
1967	0.44	5.32	0.51	1.55
1968	0.50	5.29	0.52	1.39
1969	0.44	4.95	0.48	1.30
1970	0.55	7.52	0.77	1.30
1971	0.72	6.64	0.69	2.00
1972	0.72	7.12	0.75	2.17
1973	0.46	6.04	0.59	2.07
1974	0.45	5.09	0.49	1.36
1975	53.77	120.67	80.38	67.52
1976	0.67	6.34	0.67	1.71
1977	0.53	5.53	0.55	1.47
1978	1.38	11.02	1.35	3.78
1979	0.90	8.42	0.93	2.75
1980	0.57	6.21	8.63	1.86
1981	0.47	4.86	0.48	1.18
1982	0.67	6.13	0.65	1.57
1983	2.24	13.86	1.99	4.48
1984	0.59	6.09	0.62	1.92
1985	2.75	14.74	2.41	4.36
1986	0.56	5.86	0.59	1.63
1987	0.42	4.86	0.47	1.32

N.B.
Eq.1 Olivera 's equation: $\text{Log } A = 3.090 + 0.347M - 2\text{Log }(R+25)$;
Eq.2 McGuire 's equation: $\text{Log } A = 2.674 + 0.278M - 1.301 \text{ Log }(R+25)$;
Eq.3 Esteva and Rosenbluthe 's equation: $\text{Log } A = 2.041 + 0.347M - 1.6 \text{ Log } R$; and
Eq.4 Katayama 's equation: $\text{Log } A = 2.308 + 0.411 M - 1.637 \text{ Log }(R+30)$.
Where A= peak ground acceleration (gal), M= earthquake magnitude (Richter scale),
and R = hypocentral distance (km).

Table 2 Maximum Acceleration of Earthquakes Expected at the Nam Yuam Damsite for 4 Return Periods (gal)

Attenuation Model	Return Period (Year)			
	50	100	200	300
(1) Oliveira's	56.0	57.2	57.8	58.0
(2) McGuire's	123.2	124.4	124.8	125.1
(3) Esteva & Rosenbluthe's	82.5	83.4	83.7	83.8
(4) Katayama's	69.3	70.1	70.4	70.5

CONCLUSION

Our conclusions, reached on the bases of the above-mentioned geological and seismological information, are below.

(1) Two major types of earthquake activities exist in Thailand - one as a result of stress release resulting movement along the fault planes, and the other is triggered by the impoundment of reservoir water.

(2) Several small- to medium-scale earthquake events taking places after 1980 in Thailand are considered to be caused by reservoir induced seismicity rather than fault movement.

(3) Natural earthquake occurrences are generally associated with the major dextral strike-slip faults serving as planes of weakness of the crust.

(4) The occurrences of major faults clearly define three new significant seismic-source zones in Thailand. These are located in the northern and central parts of the country.

(5) The major faults are considered to be caused by the Western Burma and Shan-Thai micro-continental collision, forming the southernmost part of the Eurasian plate.

(6) Present-day tectonic activities of Thailand and SE Asia are governed by the interaction of the Western Pacific, Eurasian and Indo-Australian plates.

(7) Major earthquakes, with epicenters located in the Andnman Sea, have been caused by the east-dipping Indo-Australian plate sudducting beneath the Eurasian plate and occur more frequent than land earthquakes which have been produced by intra-plate strike slip movement.

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