Tertiary Evolution of the Three Pagodas Fault, Western Thailand

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ABSTRACT

The Three Pagodas Fault Zone (TPFZ) developed as a consequence of the Indian-Asian Collision. As the northeast syntaxis of India migrated northward, stresses rotated >100° clockwise. The TPFZ initially developed as a wide ductile left-lateral shear zone in a transpressional environment as it accommodated the southeastward extrusion of Indochina. As stresses rotated clockwise, individual fault strands within the TPFZ reactivated with right-lateral slip in a transtensional environment with the opening of small mid-Tertiary basins located at releasing bends. In late Tertiary time, a distinct period of erosion resulted in an extensive network of meandering streams. Renewed, probably Holocene activity involved right-lateral transpression, regional uplift with meander incision, and small magnitudes of right-lateral slip in the northwestern section of the TPFZ.

Keywords: *tectonics, Three Pagodas Fault, geomorphology; strike-slip fault*

1. INTRODUCTION

The convergence between the Indian and Asian plate has over its nearly 50 million year history created a complex network of deformation that has included both larges scale vertical and lateral tectonic motions within the Asian plate (Le Pichon et al., 1992; Tapponnier et al., 1982; Tapponnier et al., 1986). The southeastward extrusion of Indochina away from the collisional zone is the most spectacular and controversial component of this tectonic zone. Much of the controversy has focused on the relative importance of distributed crustal "flow" versus movement of rigid fault-bounded blocks (Clark and Royden, 2000; Tapponnier et al., 2001). Resolving this controversy, and understanding the detailed kinematic history of Indochina requires better knowledge of the major strike-slip faults of Indochina. The parallel, northwest-striking Mae Ping and Three Pagodas Faults cut through the northwestern part of Indochina (Fig. 1) and likely share a similar origin and history. The two faults doubtless played a major role in accommodating the deformation related to Indochina's extrusion. In this report we focus on the tectonic history of the Three Pagodas Fault Zone.

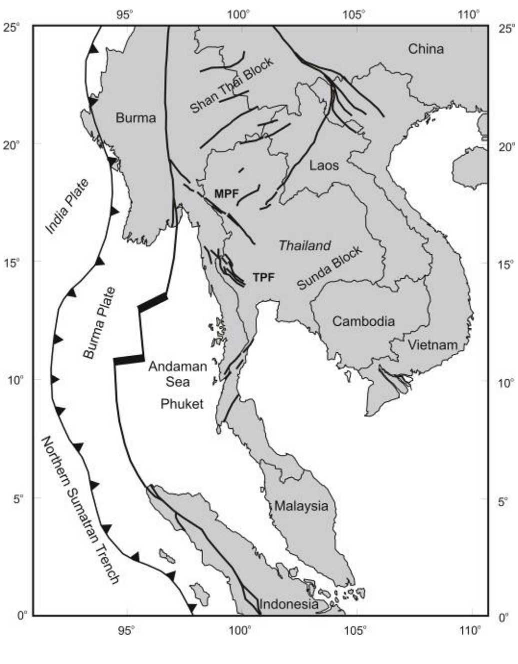

Figure 1. Tectonic setting of Indochina showing the location so the Three Pagodas Fault Zone (TPF).

The Three Pagodas Fault Zone (TPFZ) consists of a north-west-striking 50 km wide zone of deformation marked by several distinct fault traces and long, resistant strike ridges of Paleozoic limestone. It lies south of and parallel to the Mae Ping Fault (also known as the Wang Chao Fault) and likely shares a similar origin (Lacassin et al., 1997; Morley, 2002; Tapponnier et al., 1986). To the northwest, the TPFZ extends into Burma where it eventually dives beneath the Andaman Sea (Fig. 1). Here it either merges with or is cut by the north-south striking right-lateral Sagaing Fault. To the southwest, Tertiary and Quaternary sediments of the Chao Praya Basin – Gulf of Thailand cover the fault zone. Morley (2002) suggested that east-west oriented aeromagnetic anomalies within the northern Gulf of Thailand,, presumably derived from the structural grain in the underlying basement rocks, mark the continuation of a northern strand of the TPFZ, with a southern strand curving southward parallel to the northern Thai-Malay Peninsula.

Within Thailand, the TPFZ consists of several fault strands that form distinct lineaments on topographic maps and Landsat images. The southeastern part of the zone is dominated by the >100 km long, subparallel Sai Yok and Kwae Yai Faults (Fig. 2). To the northwest, the Sai Yok Fault bends abruptly northward and forms the eastern boundary of the Huai Malai Basin. The Kwae Yai Fault merges with the Sai Yok Fault near the north end of this basin. Farther to the north, The Sai Yok Fault turns back to the northwest. Its continuation is called Song Ka Lia Fault which continues across Three Pagodas

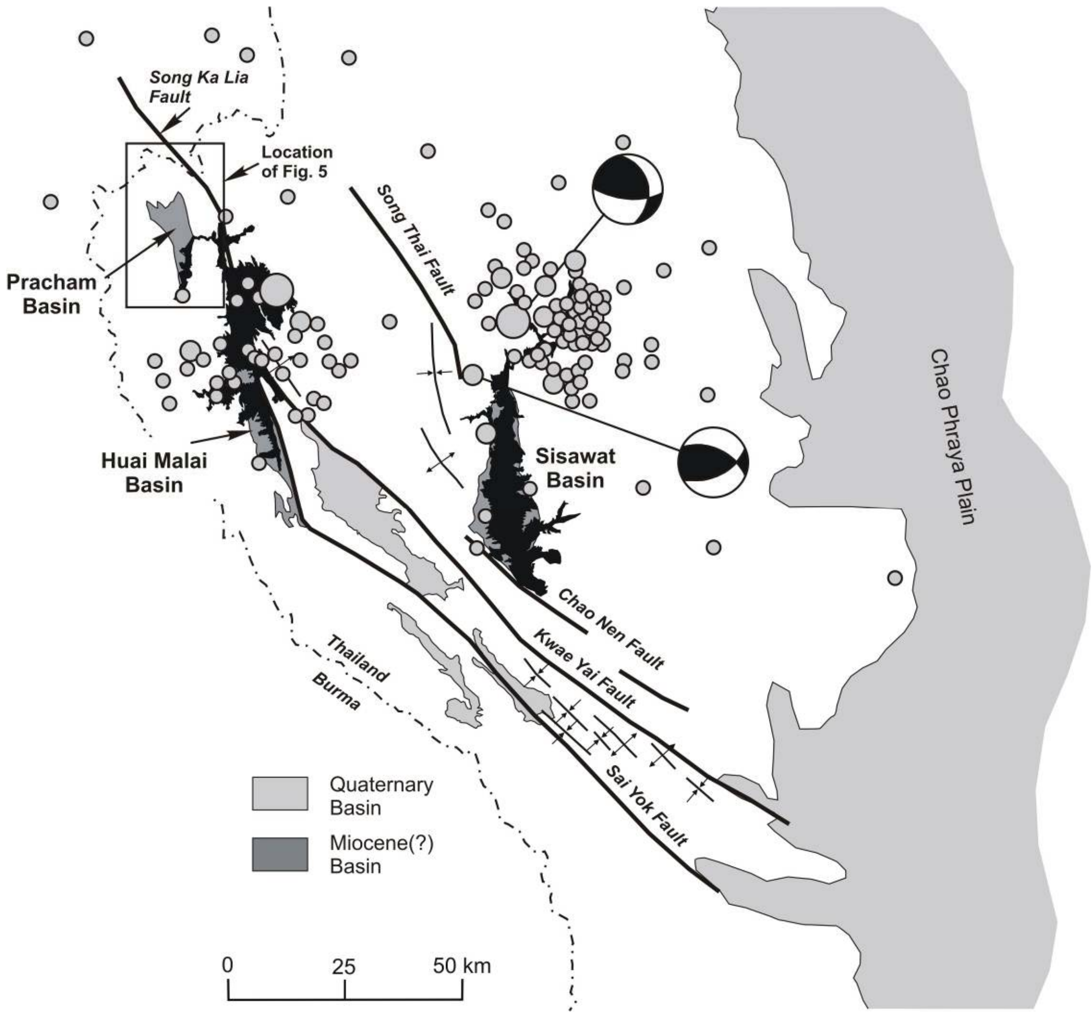

Figure 2. Map of the Three Pagodas Fault Zone. Earthquake epicenters range from M6 to M3. Black shading indicates locations of large reservoirs that partially obscure underlying Tertiary basins. Fold axes from Bunopas (1976). Geology after Bunopas (1976), Siripakdee (1985), and Siripakdee et al. (1985).

Pass into Burma. The 50 km long trace of the Song Thai Fault marks the northeastern boundary of the TPFZ. At its southeast end, The Song Thai Fault appears to die into the north end of the Sisawat Basin where it links via a right step with the Chao Nen Fault which emerges from the basin's south end. While other short fault segments may exist within the TPFZ, most of the shorter lineaments visible on Landsat images probably represent lithologic contacts that that have been rotated into parallelism with the fault zone.

One of the major ramification of Indochina's extrusion is the resulting rotating stress field within Indochina as it moves to the southeast past the eastern syntaxis of the Indian Plate. Huchon (1994) modeled this stress field by taking the modern stress field and superimposing it on a reconstruction of India's northward movement (Fig. 3). In this model, principle compressive stress in the region of the Three Pagodas and Mae Ping Faults rotated more than 100° between the middle Eocene and middle Miocene. Given the northwest-southeast strike of these faults, the changing stresses orientations should have resulted in a reversal of strike-slip from Eocene – Oligocene left-lateral to Miocene right-lateral. Such a reversal of motion has been describe for several other faults within the region (Lacassin et al., 1997; Lacassin et al., 1998; Leloup et al., 2001; Rhodes et al., 2004).

Our studies of the structural geology and geomorphology, including trenching, were undertaken to provide a regional test of the slip history and chronology predicted by the rotating stress field. Our data suggest that a more complicated sequence of four distinct phases of activity along the Three Pagodas Fault as follows: 1. Eocene - Oligocene left–lateral transpression, 2. an early-middle Miocene reversal to right-lateral transtension, 3. a significant period of post mid-Miocene erosion with little or no slip, and 4. a Pliocene (?) to Holocene reactivation with right-lateral transpression. This report focuses primarily on the Miocene-Holocene events.

2. EARLY TERTIARY HISTORY OF THE TPFZ

The TPFZ cuts obliquely across the north-south-trending structural grain of Thailand's Western Ranges. Within the fault zone, lithologic contacts have been nearly completely reoriented to the northwest. Slivers of pre-Cambrian (?) gneisses and Permian limestone within

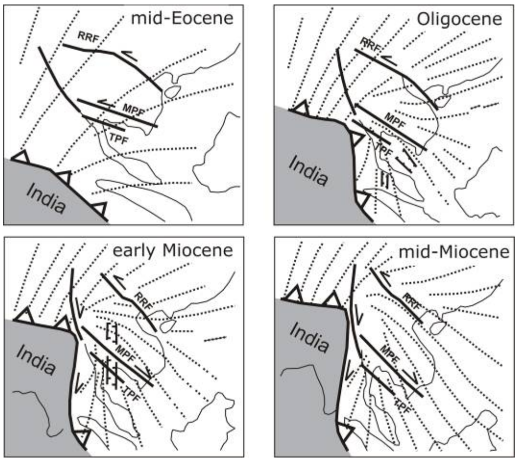

Figure 3. Model of rotating stresses aroyunf the eastern syntaxis of the Indian Plate (Huchon, 1994). Dotted lines indicate the direction of maximum horizontal compressive stress.

the zone contain strong northwest oriented foliations and lineations consistent with ductile deformation within a left-lateral shear zone (Morley, 2002). Ar-Ar dating of the gneisses within the zone show clear plateau ages of 34 Ma, suggesting that the ductile left-lateral slip is pre-late Oligocene (Lacassin et al., 1997). These observations combined with the 50 km width of the TPFZ suggests that over most of its history it formed a major intraplate ductile strike-slip zone. This phase of slip likely ended with the uplift and cooling of the Western Ranges documented by the 34 Ma Ar-Ar date and numerous younger apatite fission track dates from granitic rocks to the north (Upton et al., 1999).

A left-lateral offset in the north-trending belt of Triassic granitic rocks within the Western Ranges suggests approximately 300 km of combined slip along the Mae Ping and Three Pagados Faults (Tapponnier et al., 1986). According to the classic model of the extrusion of Indochina, the TPFZ accommodates an early phase of extrusion, with the Thai-Malay Peninsula region (Sunda Block) moving southeast relative to a stable Shan Thai block (Fig. 1).

Within the southeastern part of the TPFZ, between the traces of the Kwae Yai and Sai Yok Faults, Permian and Triassic limestones form a set of northwest-trending tight folds. The average trend of the folds' axial traces is slightly, but distinctively oblique to the faults in a pattern consistent with a large magnitude of left-lateral slip. Furthermore, the intensity of folding and lack of any evidence for the formation of pre-late Oligocene basins along the fault suggests that the left-lateral slip involved significant transpression. Such transpression is consistent with a NE-SW compressive stress, as predicted by Huchon's (1994) model.

3. MIOCENE TRANSTENSION

Three small Tertiary Basins lie along the TPFZ. The two largest of these, the Sisawat and Huai Malai Basins now mostly lie beneath large reservoirs (Fig. 2). Geologic maps completed prior to the filling of the lakes (Bunopas, 1976; Siripakdee, 1985; Siripakdee et al., 1985) indicate that both basins are underlain by consolidated Tertiary sediments overlain by younger alluvial deposits. The Tertiary deposits consist of moderately consolidated siltstone and gravel in the Sisawat Basin and consolidated to semi-consolidated, medium- to thick-bedded sandstone, siltstone and mudstone of the Ban Rai Formation in the Huai Malai Basin (Bunopas, 1976). However, the total thickness of Tertiary strata within these two basins is unknown.

Our own reconnaissance field work indicates that the smaller Pracham Basin is underlain by only locally exposed consolidated sandstone and conglomerate that have been uplifted and tilted up to 25^{o} (Fig. 4). The east flank of the basin is a west dipping high-angle normal fault. Clasts within the conglomerate consist mostly of sandstone consistent with a local source in the Triassic sedimentary rocks to the east across the normal fault. Contacts between the sediments and basin floor were observed in several places within the basin, suggesting the basin is shallow. In sharp contrast to our own observations, an older geologic map (Siripakdee, 1985) shows the Pracham Basin as being underlain by the Mae Chan Formation which consists of siltstone, shale, and sandstone, with locally occurring coal and gypsum beds containing gastropod and bivalve fossils. This description indicates a lacustrine environment with the presence of coal indicating at least a moderate depth of burial. The dense vegetation and very sparse exposures within the basin likely prevented our observation of these finer-grained facies. Thus, it seems likely that the Pracham basin is filled with a thick sequence of lacustrine sediments interfingered with alluvial fan gravels.

The age of the basin fill in all three of these basins is problematical. Most likely, the basins opened during or following the uplift and cooling of the ductiley deformed gneiss described above, thus indicating an age of less than 34 Ma (early Oligocene). Elsewhere in Thailand, widespread rift basins formed during late Oligocene and early–mid Miocene; perhaps these basins are of similar age.

The location of these basins relative to the individual fault stands of the TPFZ is consistent with extension at releasing bends during right-lateral slip (Fig. 2). The Sisawat Basin lies between the right-stepping Song Thai and Chao Nen Faults strands. Similarly, the Huai Malai Basin lies adjacent to a right step between the Song Ka Lia and Sai Yok Faults, with The Pracham

Figure 4. Photo of conglomerate overlying sandstone within the Pracham Basin. Note the gentle eastward dip.

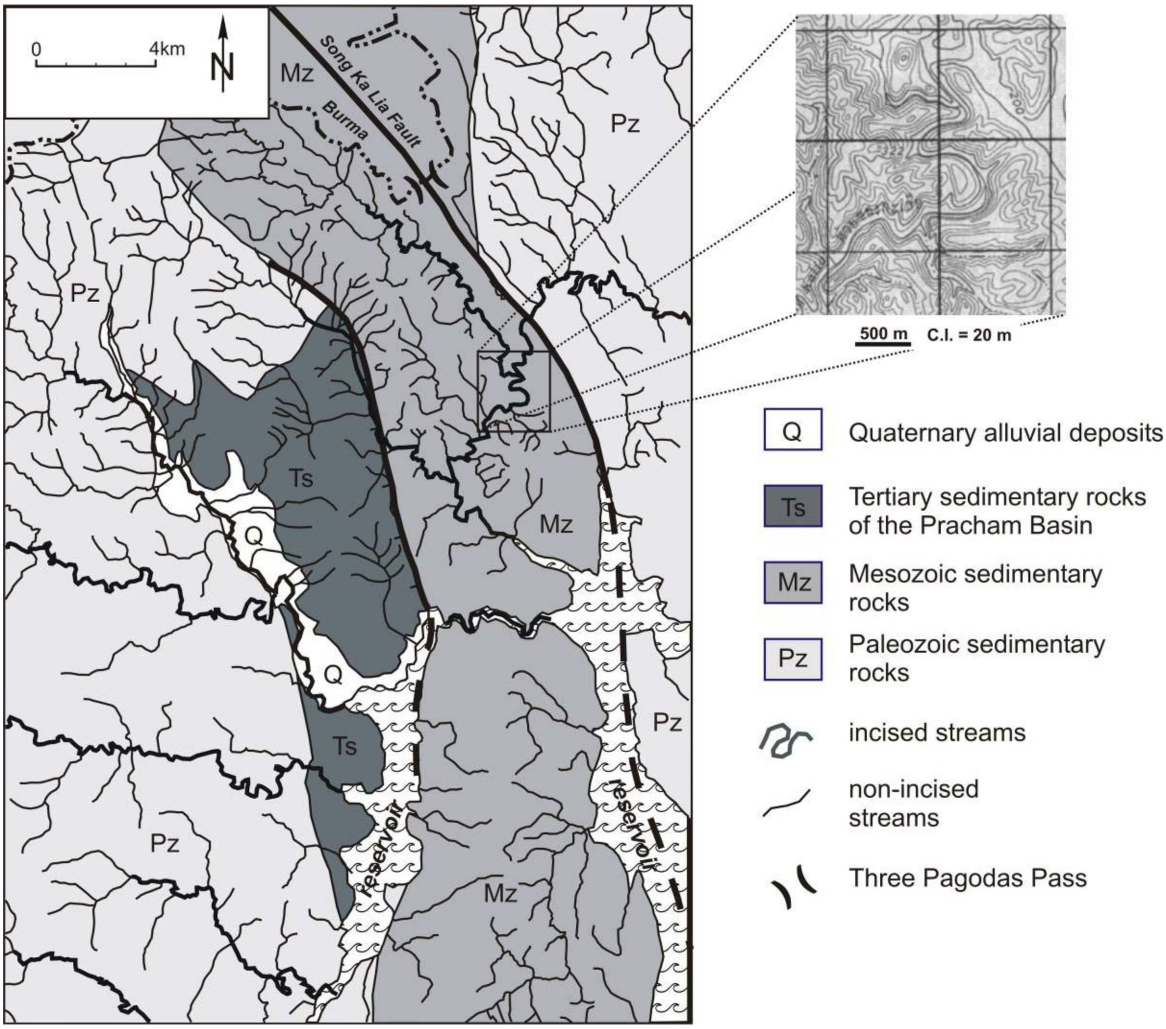

Figure 5. Geologic map and drainage network in the Pracham Basin area. Geology after Siripakdee et al. (1985). See Fig. 2 for location.

Basin located just to the north along the same step. If the Huai Ma Lai and Parcham Basins were, prior to erosion, more extensive, they may be part of a single basin that opened during right-lateral slip.

The opening of these pull-apart basins suggests that the overall stress regime during this right-lateral reactivation may have been transtensional. Within the TPFZ, extensive Quaternary (?) sediments underlie narrow basins between the Sai Yok and Kwae Yai Faults. The sediments are essentially unexposed, and underlie low, but gently rolling terrain. We propose that these areas may conceal older Oligocene-Miocene sediments. If so, their position between faults strands requires significant transtension.

Slivers of ductiley deformed limestone within the TPFZ also shows evidence for this right-lateral reactivation. Locally, large exposures of this limestone contain a near-vertical, northwest-striking foliation. While we observed no clear kinematic indicators within this foliation, it most likely formed during large magnitude left-lateral slip. Tension gashes cut this foliation, with an orientation consistent with right-lateral shear. The tension gashes also suggest a change from ductile to brittle deformation.

The amount of right-lateral slip during this reactivation is not known. Most of the pre-Tertiary lithologic contacts parallel the reactivated fault strands, and this phase of slip predates erosion that likely obliterated any geomorphic evidence for the magnitude of slip. Better knowledge of the depth and geometry of the basins would help this analysis. Nevertheless, the relatively small size of the basins argues for right-lateral slip of only a few kilometers at most, much less than the magnitude of older left-lateral slip.

We suggest that the pre-34 Ma left lateral slip along the TPFZ created a wide shear zone that was uplifted and exposed during mid-Tertiary uplift. The post 34 Ma reactivation utilized the favorably oriented planes of weakness represented by foliations and/or similarly oriented lithologic boundaries, creating the discrete fault stands that now form the spectacular lineaments visible on Landsat images.

4. POST-MID-MIOCENE (?) EROSION

Detailed analysis of 1:50,000 scale topographic maps reveal that in numerous localities within and adjacent to the TPFZ extensive reaches of incised river meanders exist within dense drainage networks (Fig. 5).

Spectacularly meandering streams now lie within canyons up to 100 m deep. Since the Tertiary basins within the TPFZ contain coarse gravels indicating significant amounts of topographic relief during deposition, the low-topographic relief represented by this extensive system of meandering streams must have developed after the opening and filling of the pull-apart basins. Incised meanders are not preserved within the Pracham Basin (Fig. 5). However we do not believe this indicates that incision occurred during basin opening and uplift of the adjacent area. The absence of incised meanders in the basin is more likely caused by a lithologic control on the incision process; the easily eroded sediments of the basin allowed for stream readjustment during the uplift, whereas the relatively resistant Triassic and Paleozoic rocks allowed the meanders to become entrenched. Such a broad region of meander entrenchment requires more regional uplift with very little tilting of the topography (Rodgers et al., 2002). Such a regional uplift is inconsistent with the localized subsidence and uplift involved in the formation of the pull apart basins.

The low-relief implied by such an extensive system of meandering streams requires considerable erosion without significant concurrent vertical tectonic movements. This period of tectonic quiescence must have followed the transtensional regime. Right-lateral movement may have continued on some of the faults of the TPFZ, but motion must have been nearly pure strike slip, without a significant vertical component. Thus, stresses may have rotated slightly into an ideal orientation to allow for pure right-lateral slip without a tensional component. However, the lack of large-scale offsets along the incised meanders where they cross the Song Ka Lia Fault (Fig. 5) suggests that any such pure strike slip was very small. Alternatively, this period of erosion may have occurred in a low-stress regime, with no slip accumulating on the TPFZ. Elsewhere in Thailand, similar regions of incised meanders suggest that this erosional event effected a large area, and therefore may represent a tectonically quiet period throughout northwestern Indochina.

The absolute age of this erosional period can only be roughly estimated. It must post-date the deposition of the basin sediments that are inferred to be Oligocene to mid-Miocene. The onset of renewed uplift, meander incision, and creation of the modern rugged and high-relief topography may have occurred quite recently, perhaps during Pliocene or Pleistocene time.

5. EVIDENCE FOR QUATERNARY REACTIVATION

Several previous workers (Fenton et al., 2003; Lacassin et al., 1997; LeDain et al., 1984) have recognized the strong lineaments on satellite images, offset drainages, and scarps within the TPFZ as indicating Quaternary slip. Along the trace of the Song Ka Lia Fault south of Three Pagodas Pass, Fenton et al. (2003) reported finding numerous geomorphic features indicative of active faulting, including lateral drainage deflections, scarps on alluvium, shutter ridges, and faceted spurs. They reported several drainage offsets south of the pass that range from several meters to several tens of meters.

With only a couple of exceptions, we were unable to locate unequivocal offsets of drainages in the Three Pagodas Pass area. Most of the drainages appear to cross the trace of the Song Ka Lia Fault without any apparent offset. One exception is where the Huai Song Ka Lia (Song Ka Lia River) crosses the fault about 5 km south of Three Pagodas Pass (Fig. 5). The river emerges from incised meanders and flows to the northeast across the trace of the fault. On the 1:50,000 scale topographic map and aerial photographs of about the same scale, no unambiguous offset can be seen. However, in the field, an abandon channel of the river on the southwest side of the fault is separated from the main channel on the northeast side by approximately 20-30 m of right-lateral motion.

In order to verify Quaternary activity along the Song Ka Lia Fault, the Thailand Department of Mineral Resources trenched across the fault about 3 km south of Three Pagodas Pass (Fig. 6). The trench is oriented northeast-southwest, and is excavated into the northeast facing slope that forms the surface expression of the fault. In the trench several colluvial units can be distinguished based on color, grain size and degree of sorting. We interpret these horizons as originating via slope wash or small debris flows. Preliminary thermoluminescence dates from the upper most layers suggest that they accumulated between 16.6 and 2.2 Ka. In the central part of the trench, the middle colluvial layer pinches out along the crest of a gentle anticlinal warp. We interpret this pinch-out to represent erosion across the crest of the anticline, forming a localized angular unconformity. Within the anticline, several anastamozing fractures cut upward through the unconformity, but end within thin the overlying (upper-most) colluvial unit. The unconformity is offset by approximately 10 cm of reverse separation. We interpret these relationships as evidence for Quaternary reverse or oblique reverse slip along the Song Ka Lia Fault during a single slip-event. Furthermore, the TL dates bracket this event between 16.6 and 5.0 Ka. The trench data and stream offset together are consistent with Holocene right-lateral oblique slip along the fault.

Fenton et al. (2003) reports estimated slip-rates of 0.1 mm/yr on this segment of the Song Ka Lia Fault, and a much higher rate of 2.0 mm/yr on the Burmese segment of the fault northwest of Three Pagodas Pass. Apparently, they made these estimates by assuming arbitrarily that the total offset along the streams accumulated during the last 100,000 years. Without better age control on the stream channels, or documentation of multiple events within trenches, we believe any quantitative estimate of slip rate is premature. However, the relatively small magnitude and poor preservation of stream offsets, and the small displacement observed in the trench, suggest that the Holocene slip rate is probably very low.

Along the central and southeastern part of the TPFZ in Thailand, evidence for Quaternary activity within the TPFZ is mostly lacking. One exception is along the trace of the Chao Nen Fault. South of the Srinakarin Dam, the Chao Nen Fault follows the north side of the Kwae Yai River for several kilometers. At Baan Khaeng Khaep, a small tributary drainage crosses the fault's trace. The very distinct trace of the fault seen on a Landsat image lies along the side of the hill

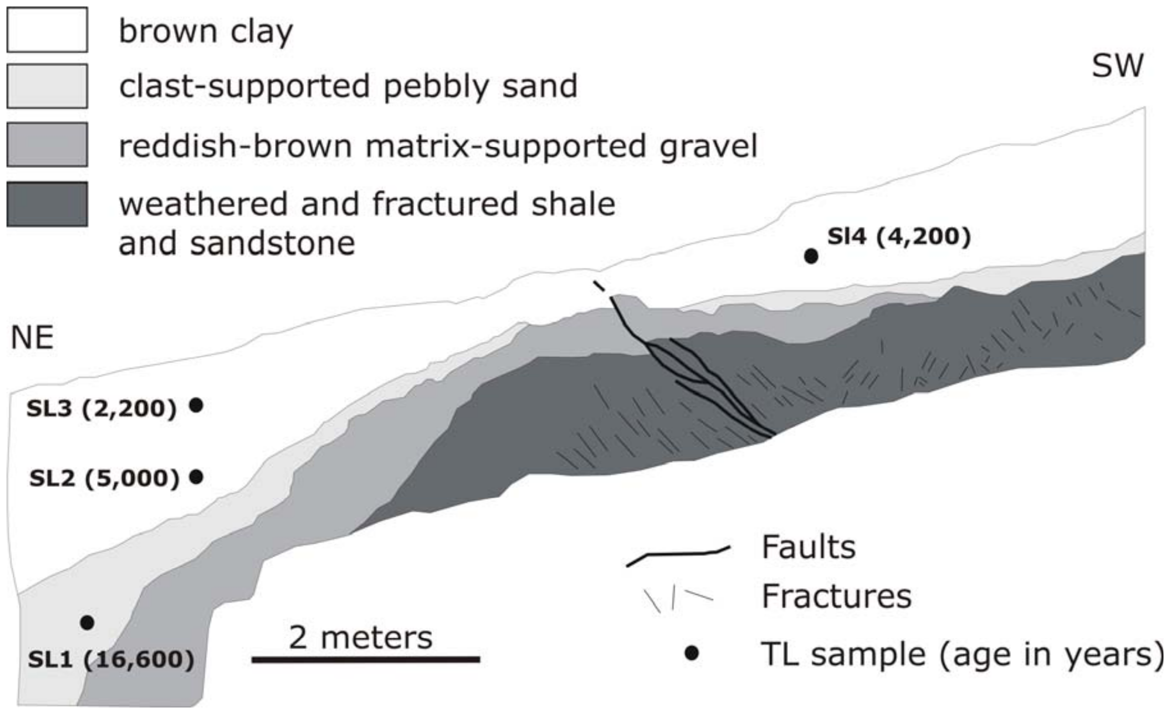

Figure 6. Log of south wall of trench across the Song Ka Lia Fault, south of Three Pagodas Pass. Points mark sample localities for thermoluminescence dating. See text for discussion.

approximately 300 m from the valley floor where it appears to offset the tributary stream with about 40 m of strike-slip separation. However, clear offset of other nearby tributaries could not verified.

Aerial photographs of a section of the Sai Yok Fault southwest of the Srinakarin Reservoir appear to show a series of sharp beheaded streams (Fig. 7). Attempts to trench the fault here failed when limestone bedrock was encountered at a very shallow depth. Our field work showed that the beheaded drainages actually continue across the fault with no offset. The apparently abrupt truncation of streams, and very sharp trace visible on the photo is probably due to a lithologic change across the fault that resulted in heavily vegetated channels on the northeast side of the fault; we found no clear evidence that the Sai Yok Fault has Quaternary activity.

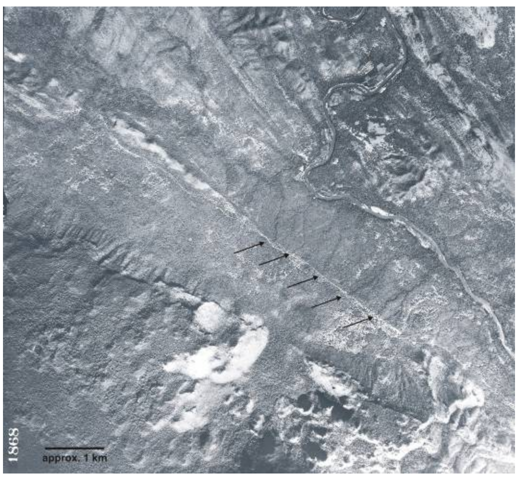

Figure 7. Aerial photo showing false beheaded streams (arrows) along an inactive strand of the Sai Yok Fault.

Seismicity along the TPFZ in Thailand is dominated by two clusters of earthquake (Fig. 2) located north of the Srinakarin Reservoir, and north of the Khao Laem Resevoir. Both clusters have been attributed to induced stresses from the loading of the reservoirs (Chung and Liu, 1992; Hetrakul et al., 1991). Even if these events where triggered by loading associated with the filling of the lakes, the resulting earthquakes probably reflect the prevailing stress regime. Focal mechanisms on two of these earthquakes (Chung and Liu, 1992) are consistent with reverse, right-lateral oblique-slip faults striking approximately northwest-southeast. Thus, both geophysical and geological lines of evidence reinforce a right-lateral, reverse, oblique reactivation of faults within the TPFZ.

The following lines of evidence suggest that only the northwestern-most part of the TPFZ in Thailand is currently active and that the slip rate along individual faults probably increases to the northwest, especially near Three Pagodas Pass and into Burma: 1. Qualitatively, range-front sinuosity increases dramatically from northwest to southeast along the TPFZ. 2. Seismicity is very low or absent along the part of the fault zone in Thailand, except for the two clusters of reservoir-induced earthquakes, and increases to the northwest into Burma. 3. Geomorphic evidence of Quaternary activity, including sharp fault scarps and offset streams is more abundant to the northwest. This increase in activity to the northwest along the TPFZ suggests that the greatest seismic hazard is centered around Khao Laem and Srinakarin Dam's and the large Reservoirs behind them rather than the more populated valleys to the southeast.

6. DISCUSSION

The TPFZ most likely initiated during the Eocene as a large left lateral shear zone in response to compressive stresses emanating from the initiation of collision between India and Asia. The orientation of horizontal maximum compressive stress (σ_{max}) can be estimated from the orientation of the TPFZ at that time. Paleomagnetic data from eastern Thailand (Achache and Courtillot, 1985; Yang and Besse, 1993), west-central Thailand (Yan and Courtillot, 1989; Yang et al., 1995) and China (Yuyan and Morinaga, 1999) suggest that Indochina rotated clockwise about 15° during the Tertiary, this rotation probably occurred during the initial slip on the TPFZ. Restoring this rotation, and assuming a >30° orientation of σ_{max} to the fault to account for a component of transpression, σ_{max} would be oriented approximately NE-SW. If rotation of the fault zone occurred before significant rotation of the stress vectors, an increasingly transpressive environment would ensue as σ_{max}'s angle to the fault increased. During this early phase of slip, compression across the TPFZ resulted in tight folding of the Mesozoic and Paleozoic sedimentary rocks within and adjacent to the fault zone and rotation of lithologic contacts into parallelism with the fault zone's strike. Transpression may have also resulted in uplift within and adjacent to the TPFZ. Thus, the early history of the TPFZ is in close agreement with Huchon's model.

As stress continued to rotate relative to the TPFZ, ultimately the angle between σ_{max} and the fault would be incompatible with continued motion. During this interval of inactivity, significant uplift must have effected the TPFZ, resulting in the exposure of ductile rocks from deeper within the zone. More rotation of the stress would eventually favor reactivation of the TPFZ as right-lateral fault. Because of the large magnitude of strain that had accumulated during left-lateral motion, the TPFZ would have been a significant zone of weakness and right-lateral motion along discrete planes within the TPFZ could have started while σ_{max} was at a small angle to the fault (<30°). This may have resulted in a significant transtensive environment with extension perpendicular to the fault. The consequence was the opening of pull apart basins within the TPFZ between right stepping fault segments, as modest amounts of right-lateral slip accumulated. As India continued to move northward, the magnitude of stresses related to the collision should also have decreased; this may account for the smaller magnitude of right-lateral slip and likely much slower slip-rates.

As stress continued its clock-wise rotation and decreased in magnitude, the transtensive environment dissipated. Slow, more purely strike-slip right-lateral motion may have continued, but vertical motioned ceased and extensive erosion resulted in the development of an extensive drainage network dominated by meandering streams. This period of erosion may have coincided with a period when σ_{max} was close to the ideal 30° angle to the TPFZ. However, the preservation of entrenched meanders elsewhere in Thailand suggests that this period of erosion may have been regional in extent and not confined to the area around the TPFZ.

As σmax rotated to its present approximately north-south position, the 50° angle with the present orientation of the TPFZ may have resulted in a small magnitude of right-lateral transpression across the fault. A decrease in the magnitude of σmax to the southeast along the TPFZ would account for renewed transpression only along the northwest part of the fault in Thailand. The regional north-south σmax may have also resulted in regional uplift, with very little tilting, causing the previously developed network of meandering streams to become incised where bedrock erosional resistance was favorable.

The Mae Ping Fault Zone to the north probably shares a similar history to the TPFZ. Simliar to the TPFZ, it has accommodated a large magnitude of pre-Oligocene ductile left-lateral slip. Several small Tertiary basins lie along the Mae Ping Fault Zone and probably record a period of modest right-lateral transtension. Stream offsets and focal mechanisms (LeDain et al., 1984) suggest modern movement is also left lateral.

Finally, the significant period of erosion and the formation of a regional meandering drainage network has gone largely overlooked in discussions of the late Cenezoic and Holocene history of northwestern Indochina. This period of erosion came between the Oligocene – Miocene uplift of the Western Ranges of Thailand and formation of the rift basins of central and northern Thailand, and the modern period of renewed uplift and meander incision. A more regional study of the incised meanders, their extent, and the age of there entrenchment, would provide important data toward understanding the late-Tertiary history of northern and western Thailand.

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