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Variations in Late Cenozoic–Recent strike-slip and oblique-extensional geometries, within Indochina: The influence of pre-existing fabrics

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Abstract

From Yunnan to Northern Thailand, Late Cenozoic–Recent faults strike predominantly NNE–SSW, N–S to NNE–SSW and NE–SW to ENE–WSW. Associated sedimentary basins are aligned NE–SW to N–S. The regional fault patterns are commonly interpreted as strike-slip dominated deformation throughout the area. Releasing bend and en echelon stepping patterns on faults bounding sedimentary basins indicate sinistral displacement on NE–SW to ENE–WSW trending faults. Yet, in the escape tectonics model left lateral displacement on the NE–SW to ENE–WSW faults is thought to have occurred late in the Miocene, whilst earlier motion was dextral. However, in Yunnan the NE–SW Shmax direction required for dextral motion on the N–S Sagaing, Nanting and Gaoligong fault zones is consistent with sinistral motion on ENE–WSW striking faults, which is still their sense of motion today. In Northern Thailand the dextral–sinistral switch model during the Miocene is not tenable because the Fang basin is of Late Oligocene–Pliocene age, and requires similar age sinistral motion on the ENE–WSW Mae Chan fault in order to have opened. In an alternative model, Northern Thailand is interpreted to have evolved predominantly by oblique extension. The Golden Triangle area marks a transition from transtensional deformation in the north to oblique extension in the south. The activation of pre-existing fabrics strongly affects both strike-slip and extensional faults and has given rise to the similar extensional and strike-slip fault patterns. Multiple episodes of basin inversion in Northern Thailand during the Miocene require short-term changes in stress pattern. To produce the inferred changes in stress pattern it is suggested that stresses radiating out from the Himalayan syntaxis exert a strong influence, but were not the only important forces acting on the region.

Keywords: Strike-slip; Extension; Reactivation; SE Asia

1. Introduction

The region of Asia from Yunnan through Laos, Thailand and Myanmar that is the focus of this study contains an abundance of Cenozoic sedimentary basins (Fig. 1). Some of these basins display a long-lived history of deposition, faulting and folding, and consequently have recorded the variations of stresses during the Cenozoic (e.g. Morley et al., 2000, 2001; Morley, 2001; Socquet and Pubellier, 2005). This study discusses evidence for a lateral transition zone between strike-slip dominated deformation in the northern part of the area and extensional dominated deformation in the southern part. One of the main problems is the transitional extensional zone appears to display quite similar map view structural geometries to those typically assumed to be characteristic of strike-slip deformation. Hence, older interpretations have tended to class all the basins as pull-aparts associated with strike-slip or oblique slip faults (e.g. Tapponnier et al., 1986; Polachan et al., 1991; Lacassin et al., 1998). The patterns of basins and faults across the region are superficially similar, being dominated by N–S to ENE–WSW striking faults (Fig. 1). This paper discusses the considerable variety in the range of geometries and in the origin (i.e. strike-slip vs transtension, vs oblique extension) and structural evolution of the basins.

The Indochina area has been tectonically very active during the Cenozoic as a consequence of India–Eurasian collision,

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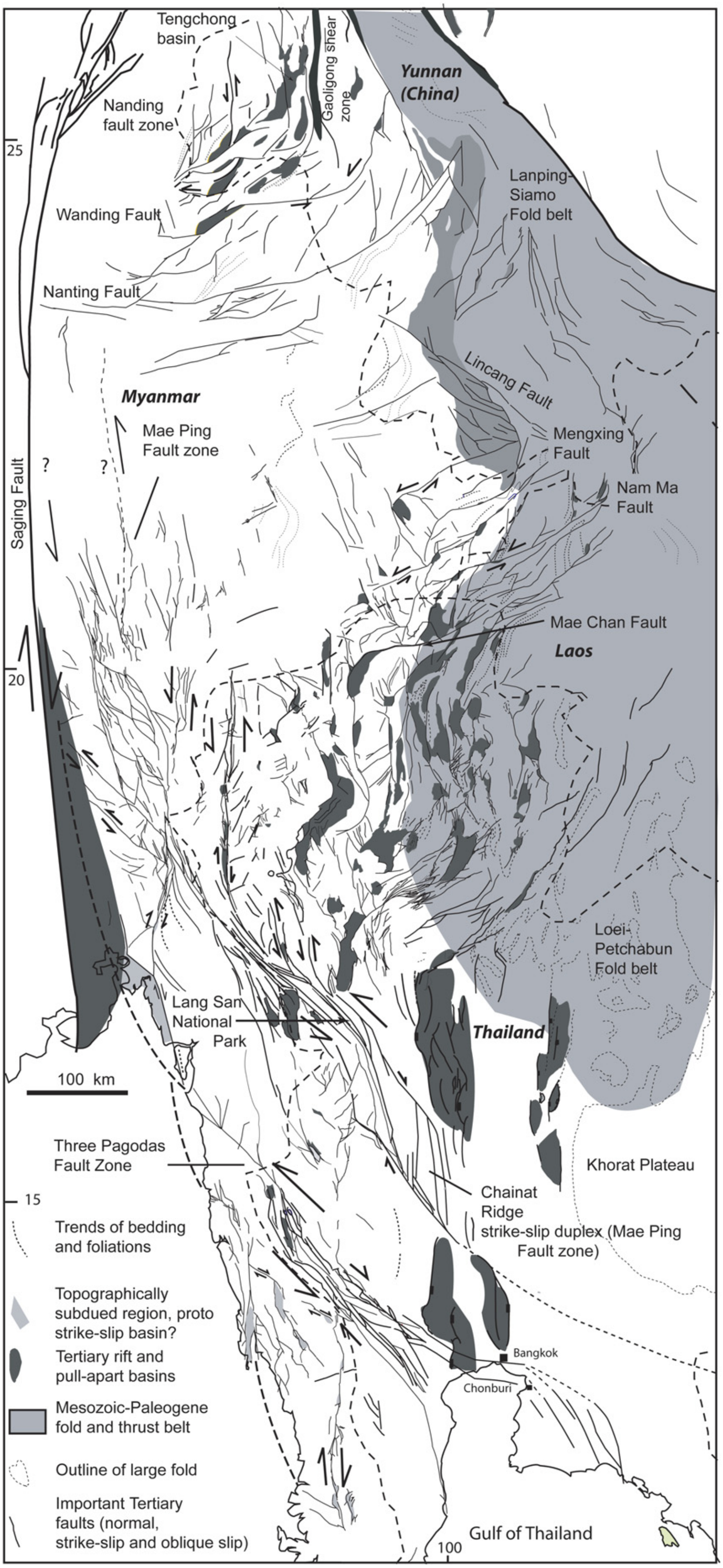


Fig. 1. Regional map of northern South East Asia. Fault pattern largely derived from satellite interpretation aided by geological maps.

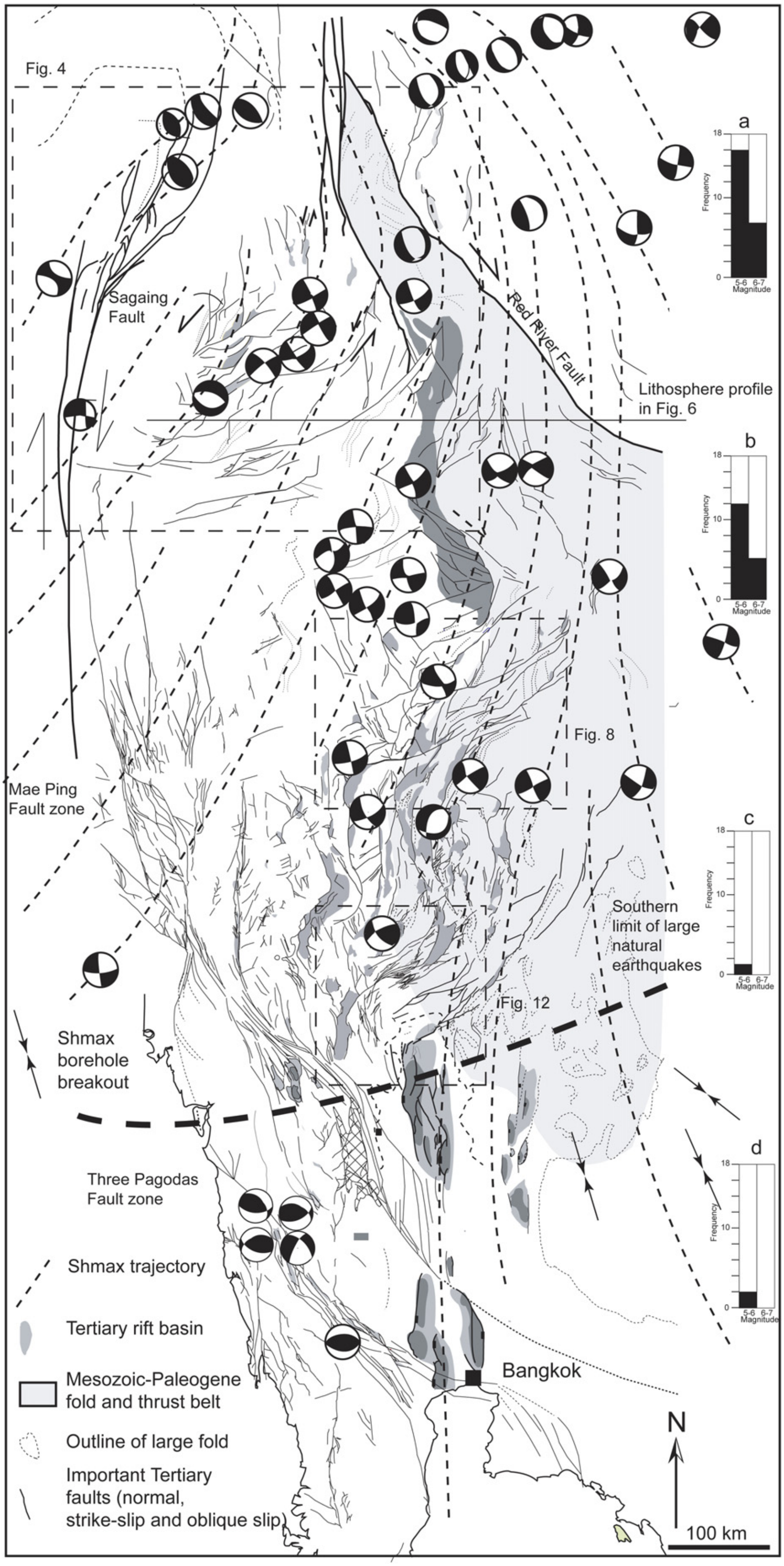


Fig. 4
Sagaing Fault
Red River Fault
Lithosphere profile in Fig. 6
Mae Ping Fault zone
Fig. 8
Southern limit of large natural earthquakes
Fig. 12
Shmax borehole breakout
Three Pagodas Fault zone
Shmax trajectory
Tertiary rift basin
Mesozoic-Paleogene fold and thrust belt
Outline of large fold
Important Tertiary faults (normal, strike-slip and oblique slip)
Bangkok
N
100 km
a
b
c
d
Frequency
18
10
0
5-6
6-7
Magnitude

local tectonic events within SE Asia and the Australia−Sundaland collision in southeastern Indonesia (as reviewed in Hall, 2002). In the simplest models for SE Asia Cenozoic tectonics the rift systems in Thailand, the Gulf of Thailand and offshore Vietnam have been viewed as driven by escape tectonics, where the rifts form as pull-aparts along strike-slip fault traces (Tapponnier et al., 1986; Polachan et al., 1991; Leloup et al., 2001; Replumaz and Tapponnier, 2003). One clear evolution in the escape tectonics system that has been identified is the switch from left lateral to right lateral displacement on major NW−SE trending strike-slip faults (Three Pagodas, Mae Ping and Red River shear zones) (Leloup et al., 1995, 2001; Lacassin et al., 1997, 1998; Replumaz and Tapponnier, 2003). These authors determined the timing of the termination of sinistral motion for the Mae Ping and Three Pagodas fault zones to be Late Oligocene. For the Red River Fault a tendency to quiescence, if not a switch to dextral motion probably occurred around the latest Early Miocene, while the onset of dextral motion was probably during the latest Miocene−Pliocene (Leloup et al., 1995). This variation in timing is compatible with the northwards progression of the Himalayan syntaxis with time, and the consequent sweeping north of radial maximum horizontal stress (Shmax) trajectories emanating from the syntaxis (e.g. Huchon et al., 1994). In the model of Huchon et al. (1994), the northward indenting corner of the Indian plate is the main driver of the stress pattern in Indochina. During the Oligocene the initial NE−SW oriented maximum horizontal stress direction (Shmax), required for left lateral motion on the Three Pagodas and Mae Ping fault zones, evolved to a radial pattern emanating from the NE corner of the Indian plate as the Himalayan syntaxis developed. This pattern swept northwards with little change in geometry until the present day.

2. Modern fault and stress pattern

The sedimentary basins discussed in this paper lie within the region of Yunnan in the north to Northern Thailand in the south. The line of basins continues further south too, with predominantly N−S trends in Central Thailand (Fig. 1), and offshore in the Gulf of Thailand.

The Shmax direction determined from earthquake focal mechanisms is one of the key sources of Shmax orientation in the world stress map (Zobak, 1992; Reinecker et al., 2005). The modern stress pattern as determined from earthquake focal mechanisms shows regionally consistent patterns (Fig. 2). Indochina is predominantly under strike-slip deformation, whilst the region east of the Ailao Shan−Red River shear zone is under extension, and the Himalayan syntaxis region west of the Sagaing Fault is under compression. The maximum horizontal stress (Shmax) trajectories form a curvilinear radial stress pattern emanating from the syntaxis. Within Indochina the Shmax orientation is N−S to NNE−SSW. The curving stress trajectories are consistent with the recent sinistral displacement histories of curving strike-slip faults in Yunnan (Lacassin et al., 1998). The number and magnitude of recorded earthquakes decrease southwards towards Thailand, and between about 15° and 16° north, large, natural earthquakes become very rare. The earthquakes shown to the south of this region in Fig. 2 are the result of water loading from reservoirs (Bott et al., 1997). The seismic front in Thailand approximates the southern limit of the intermontaine rift basins in Northern Thailand. To the south the rift basins lie beneath a broad, flat plain, that is the early stage of largely post-rift subsidence.

Geomorphological features and trenching through Holocene clastic deposits indicates some faults in Northern Thailand must still be considered geologically active (e.g. Fenton et al., 1997, 2003). These N−S to NE−SW striking faults show evidence for predominantly normal displacement. However, the ENE−WSW striking Mae Chan fault shows demonstrable sinistral offset of drainage systems by up to 600 m (Fenton et al., 2003). According to Fenton et al. (2003), segments of the major strike-slip faults on the western side of Thailand (Mae Ping, Three Pagodas, Ranong, Klong Marui as well as smaller faults) also appear to have been recently active, with dextral motion on the NW−SE striking faults. Further south borehole breakouts from oil wells in the Gulf of Thailand indicate a variable but generally N−S striking Shmax direction. Some young, small normal faults in the Pattani basin extend throughout the section to the seafloor indicating episodic, young, minor (E−W?) extensional activity.

The modern basin morphology and earthquake activity ties together to form a consistent story of stress magnitude diminishing towards the south. Stresses magnitudes in Yunnan favour major strike-slip activity, they progressively diminish until in Northern Thailand the predominant deformation mode is extensional, and further south quiescence. There also appears to be an important west−east variation too, on the western side of Thailand in the highlands, the active deformation style is dominated by strike-slip or thrust faults (Fenton et al., 2003). This is not surprising since further west in Myanmar is the active, major dextral strike-slip boundary (Sagaing Fault zone) that accommodates much of the northwards motion of India relative to Indochina (e.g. Bertrand and Rangin, 2003; Vigny et al., 2003). East of the highlands in Thailand is the extensive undeformed Chao Phraya post-rift basin of the Central Plain which overlies inactive Cenozoic rifts.

The GEODYSSEA GPS study e.g. Simons et al. (1999), Chamot-Rooke et al. (1999), augmented by infill GPS data

Fig. 2. Modern stress state of northern Indochina, showing how inferred Shmax directions based on major fault displacements matches the modern stresses based on upper crustal earthquake focal mechanisms. Earthquake data (1975−Recent, 0−15 km depth, M_s or $M_w \geq 6$) from the Harvard database. Borehole break out data in the Khorat region from Reinecker et al. (2005). Earthquakes in the Three Pagodas fault area are from Bott et al. (1997), and are believed to have been trigged by water loading from reservoirs associated with new dams. Plots of earthquake frequency (0−18) vs size (magnitudes 5.1−6 and 6.1−7), for four province of similar area: (a) 24−28°N, 97−101°E, (b) 20−24°N, 97−101°E, (c) 16−20°N, 97−101°E, and (d) 12−16°N, 97−101°E, from the Harvard database (1975−Recent), illustrating the decreasing magnitude and frequency of earthquakes passing south within the study area. Note that the two recorded events for area (d) are thrusts (N−S Shmax) along the Three Pagodas fault zone.

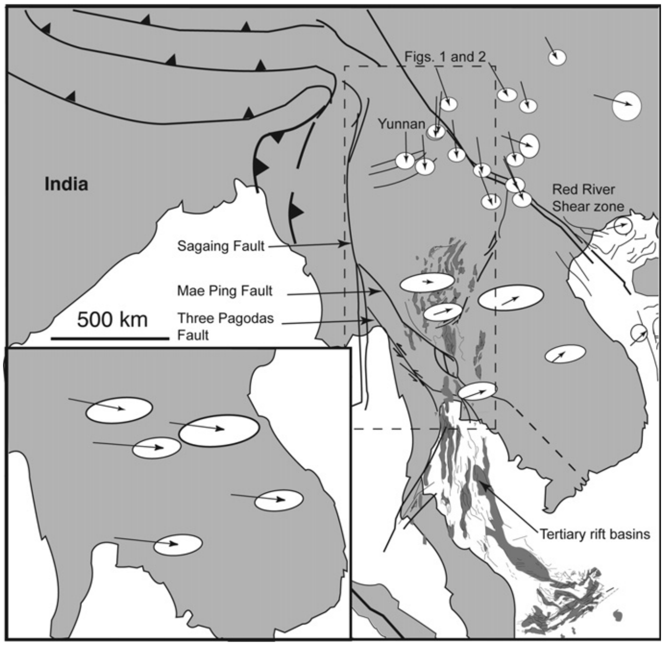


Fig. 3. Combined velocity field of GPS measurements compiled by Iwakuni (2001). The map combines different data sets within the displacement velocity of Kotake (2000), ellipse 95% confidence, period 1976/01/01 to 2000/12/31. Inset shows the original GPS velocity field for Thailand that was input to the combined velocity field (Iwakuni, 2001).

from five stations in Thailand (Iwakuni, 2001) shows a profound difference in modern displacement between Thailand and Yunnan (Fig. 3). Relative to Eurasia, Yunnan is experiencing relatively large motions towards the south to SSE. In Thailand, displacements are moderate and towards the ENE. GPS data are not available for the intervening region of Myanmar and Laos, which are transitional between the two regions. Whilst the GPS data are just a snapshot of the tectonic picture in terms of geological structural evolution, the GPS data suggest that a significant change in block motions occur in the vicinity of the Golden Triangle.

Based on structural style, geomorphology and structural history of the Yunnan–Thailand region can be divided into three main provinces from north to south and they are, Yunnan–Myanmar (strike-slip province with releasing bend basins); Myanmar–Laos–Northern Thailand (Golden Triangle; the transition from strike-slip to extension) and Central Thailand–Gulf of Thailand (extension-dominated province influenced by oblique pre-existing fabrics (Fig. 1)). The Yunnan–Myanmar and Golden Triangle provinces are discussed in the following sections. For a detailed discussion of the extension-dominated province of Central Thailand and the Gulf of Thailand, see Morley et al. (2004).

3. Yunnan–Myanmar

3.1. Fault geometry and timing

The Yunnan–Myanmar area comprises a triangular block of crust bounded on its western margin by the NNE-striking Sagaing Fault, and on its eastern side by the NW–SE striking Ailao Shan–Red River shear zone (Figs. 1, 4 and 5). The region is up to 500 km wide and 600 km long. The southern margin is gradational into the Myanmar–Laos–Northern Thailand (Golden Triangle) province. Crustal thickness changes from about 65 km in western Tibet to about 38 km in southern Yunnan near Myanmar (Chan et al., 2001). The Yunnan–Myanmar area is characterised by prominent, young strike-slip faults (Ding and Zhong, 1992; Lacassin et al., 1998; Jianquing et al., 2000). Cenozoic basins are scattered along the strike-slip faults (e.g. Zhang et al., 1999). On satellite images these strike-slip faults form curved trajectories with right and left-stepping segments (Figs. 4 and 5). Passing northwards the arcuate strike-slip faults link with major N–S to NE–SW striking shear zones which are commonly high grade, metamorphic belts 10–30 km wide, with steeply dipping foliations, and sub-horizontal strike-slip stretching lineations, (Leloup et al., 1995; Jianquing et al., 2000; Akcriz et al., 2003a,b; Fig. 4). From west to east they are the Gaoligong; Chang Shan and Ailao Shan–Red River shear zones. These major shear zones follow older Tethyian suture zones: the Ailao Shan–Red River shear zone overlies a SW dipping Tethyian suture between the Yangtze and Simao blocks (Liu et al., 2000; Figs. 5 and 6), the Chang Shan shear zone separates the Simao and Baoshan blocks, and the Gaoligong fault lies along the Luxi suture between the Tengchong and Baoshan blocks.

For their Late Oligocene–Middle Miocene history the Chang Shan and Ailao Shan–Red River shear zones were sinistral (Leloup et al., 2001), whilst the Gaoligong shear zone was dextral (Jianquing et al., 2000; Akcriz et al., 2003b). Later these faults reversed their sense of motion (Leloup et al., 1995; Jianquing et al., 2000; Akcriz et al., 2003b). At the southern end of the Gaoligong shear zone the three largest curved strike-slip faults are the Longling–Ruili, Nanting and Wanding Faults (Figs. 4 and 5). West of the Gaoligong shear zone are some important N–S trending basins, including the Tengchong basin, which has outcrops of Neogene sedimentary rock (Tao and Du, 1982; Figs. 4 and 5). These basins are less well defined on satellite images than the NE–SW striking basins like the Ruili basin. The reason for the geomorphological difference is due to the timing of basin activity. The Tengchong basin would have opened as a pull-apart along the N–S dextral Gaoligong fault during the Oligocene–Miocene. However, when the fault reversed motion to sinistral displacement the basin became partially inverted, uplifted and eroded.

Akcriz et al. (2003b) state that right lateral motion on the Gaoligong shear zone ended around 18 Ma. However, Jianquing et al. (2000) dated syn-tectonic muscovites and hornblendes from the N–S striking Gaoligong and Nabang shear zones (Fig. 4) and found two peak deformation ages between 19–24 Ma and 11–14 Ma within faults zones exhibiting dextral strike-slip (Ding and Zhong, 1992). The main phase of dextral shearing along the northern extension of the Gaoligong shear zone into the Jiali fault zone has been dated between 18 and 12 Ma (Lee et al., 2003). Hence the reversal to sinistral motion on the Gaoligong, Nabang and associated N–S faults probably post-dates 11 Ma, i.e. is likely to be Late Miocene or younger.

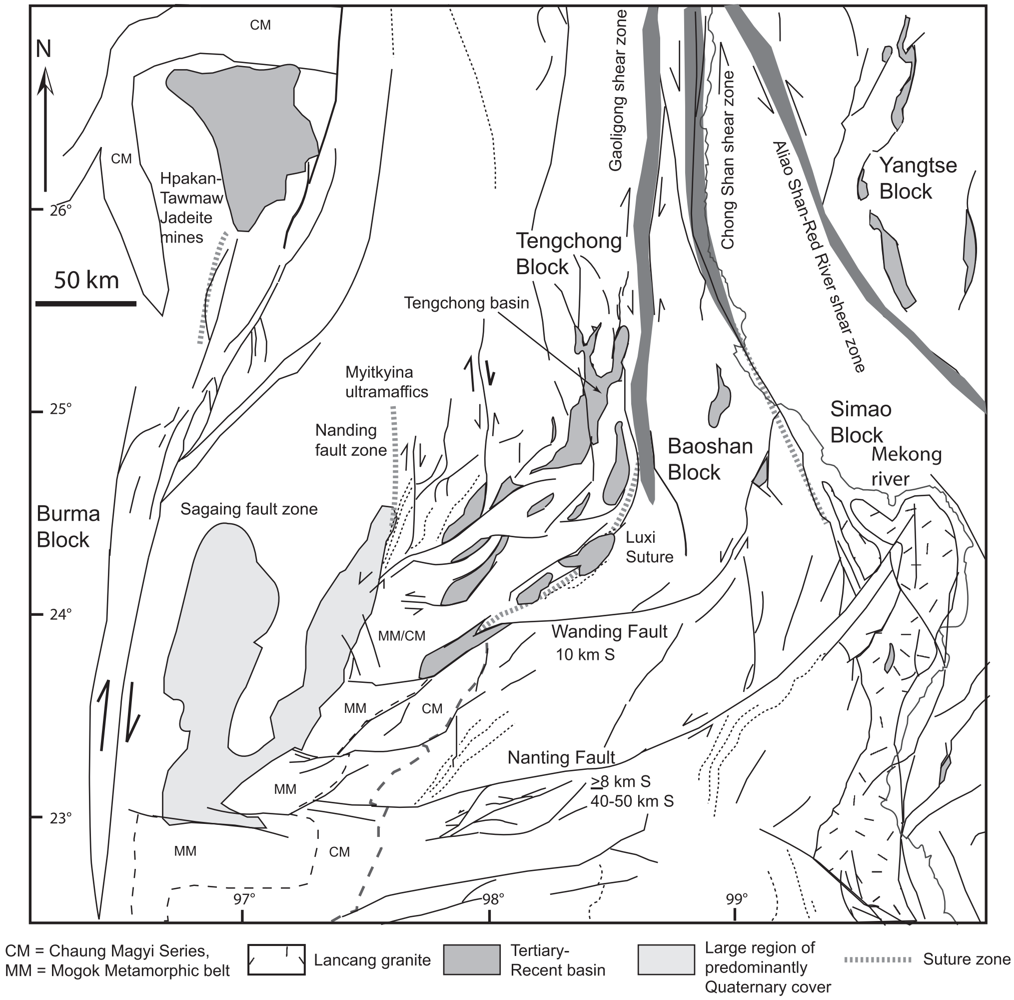


Fig. 4. Map of the Yunnan–Myanmar region derived from satellite data, augmented by Jianquing et al. (2000).

In contrast to the eroded basins with ragged outlines associated with dextral motion on the N–S trending faults (marked I on Fig. 5), the NE–SW faults are associated with well-defined basins that form prominent topographically subdued areas within hilly topography on satellite images (Fig. 5). These intermountain basins represent basins or proto-basinal areas at bends in faults and at en echelon steps between faults and fault segments; consistent with extension at releasing bends or left-stepping faults on left lateral fault systems. Several of the basins are developed, not with a simple restraining bend geometry, but where two important faults of different angle meet (Fig. 5). The basins reach a maximum width of about 15 km and length of 50 km (Fig. 5). Hairpin bends in rivers, including the Salween River are also consistent with sinistral motion, and four of the largest faults show individual (minimum) sinistral (Pliocene–Recent) offsets between 5 and 9 km (Lacassin et al., 1998).

The Ruili basin is up to 1.5 km thick and lies at the meeting point of the Wanding and Longling–Ruili Faults (Bai and Meju, 2003; Fig. 5). The NW dipping Longling–Ruili has undergone strike-slip and normal displacement during the Late Cenozoic (Bai and Meju, 2003; Cargill, 2004). The fault follows a ductile shear zone where basement was thrust from the northwest to the southeast, and acted as a major terrane boundary between the Tengchong and Baoshan blocks (Lin, 1990; Wang and Burchfiel, 1997). The Wanding Fault is thought to be older than the Longling–Ruili Fault and lies within the Baoshan block (Wang and Burchfiel, 1997). It is active today, lined by hot springs and shows sinistral stream offsets up to 10 km (Wang and Burchfiel, 1997; Lacassin et al., 1998). The Longling–Ruili Fault is the dominant fault in the Ruili basin, and it forms a low-angle releasing bend as it enters the northeastern corner of the basin with a ENE–WSW strike forms a NE–SW segment to traverse the basin, and then returns to a ENE–WSW strike on the southern margin of the basin (Bai and Meju, 2003).

Lacassin et al. (1998) interpret about 9.5 ± 0.5 km sinistral displacement on the Wanding Fault, and an older right lateral offset of between 38 and 58 km on the basis of the Salween River geometry. However, the interpretation of the presence of right lateral motion does not make kinematic sense, because the Wanding Fault joins the Chang Shan shear zone, and that shear zone has an early sinistral sense of motion (opposite to that of the Gaoligong shear zone to the east (Fig. 4)). Consequently differential motion of the Baoshan block, expelled southwards between the two major shear zones would seem

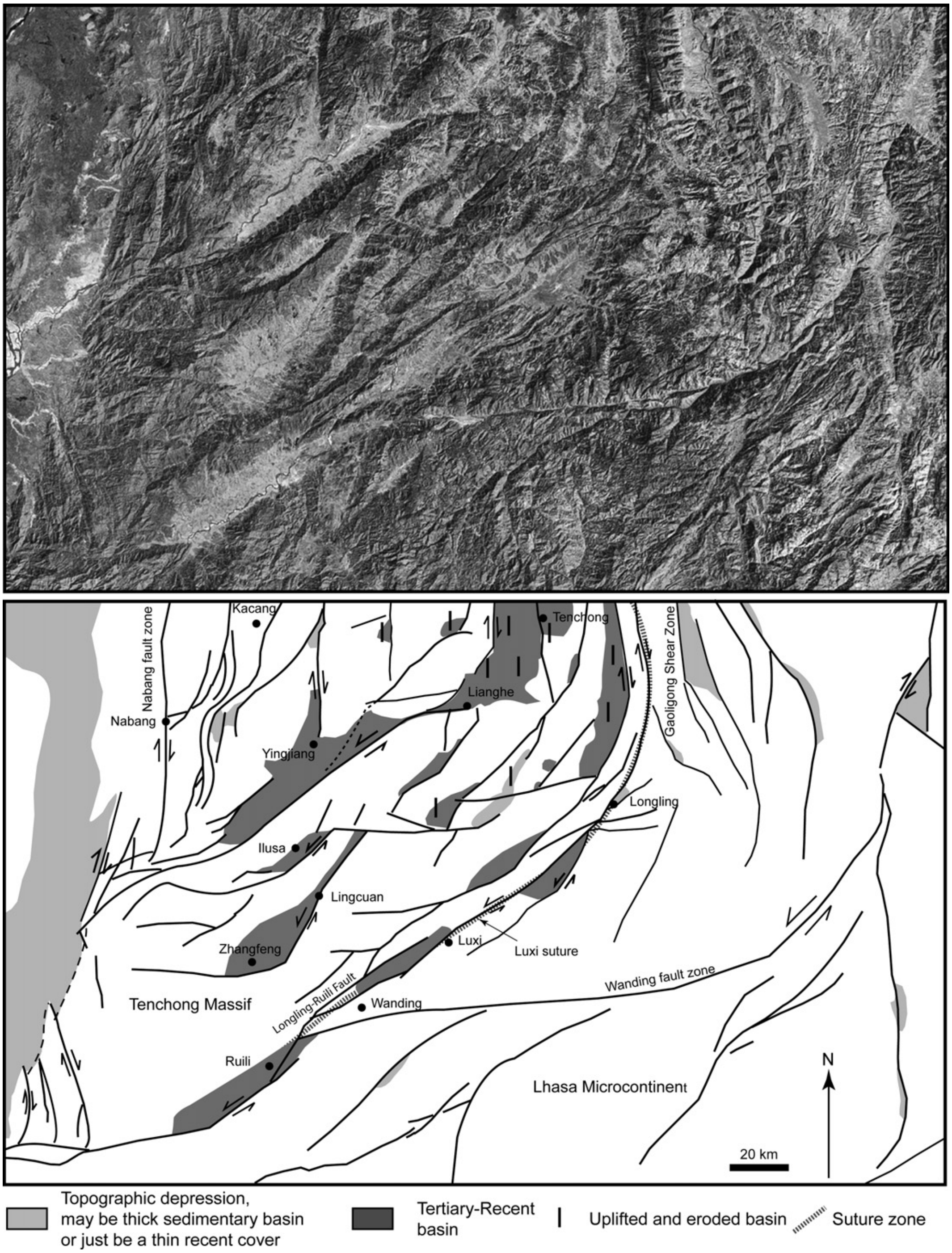


Fig. 5. Satellite image of pull-apart basins at the western ends of the Nanting and Wanding Faults (see Fig. 4 for location).

to require a consistent sinistral not dextral sense of motion on the Wanding Fault. Hence the inferred river offset geometry by Lacassin et al. (1998) might simply be a coincidental feature, not one actually related to strike-slip motion. This contradiction is also seen in the Nanting Fault to the south, where according to Lacassin et al. (1998) the observed sinistral offset was about 8 km, but there was no indication of right lateral offset from the drainage patterns. However, Wang and Burchfiel (1997) documented 40–50 km of sinistral offset along the Nanting Fault due to offset of the Menglian ophiolitic suture. This amount of offset would indicate a more prolonged and important phase of sinistral motion, than if the neighbouring Wanding Fault developed by major dextral motion followed by minor sinistral motion.

3.2. Deep structure of the strike-slip faults in Yunnan

Many of the major strike-slip faults in SE Asia exhume at least middle crustal rocks, and in places lower crustal rocks in strike-slip shear zones or associated low-angle extensional

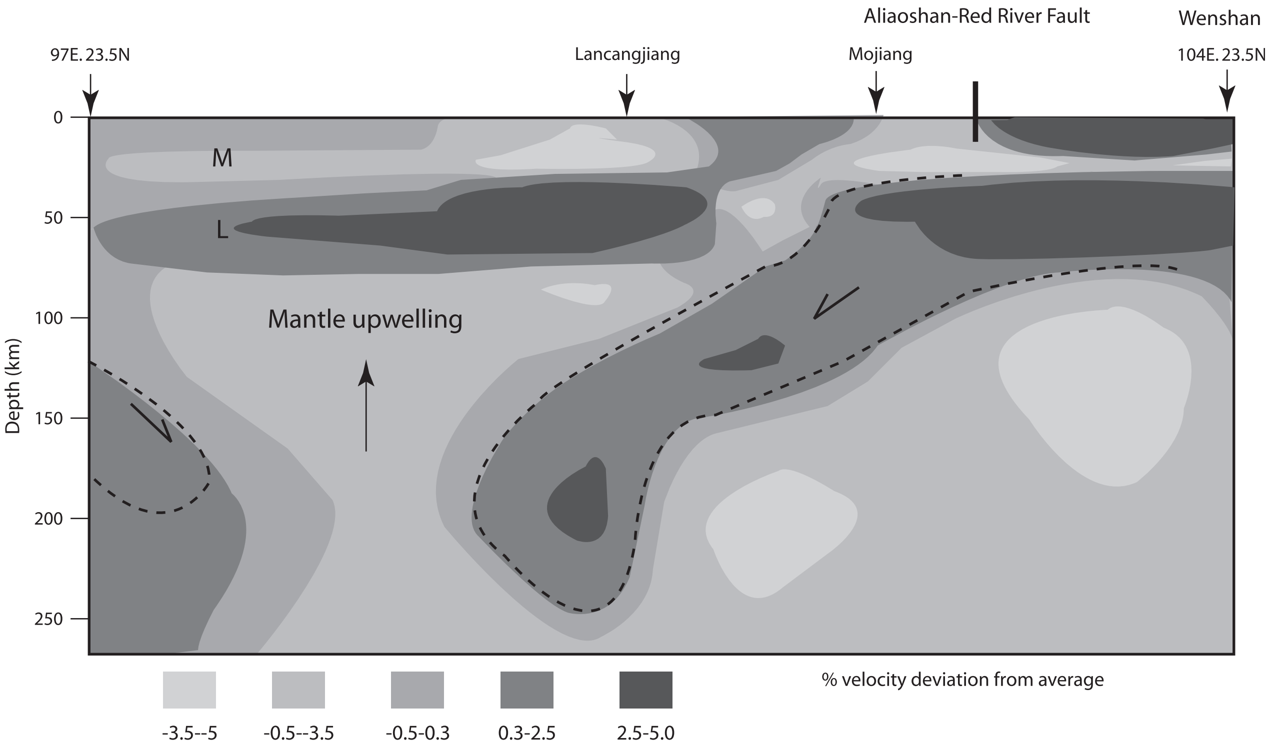


Fig. 6. Lithospheric profile based on seismic tomography (Liu et al., 2000) illustrating the relationship between major strike-slip faults (Nanting, Red River) and deeper crustal structure. The Red River Fault is located at a Tethyian suture zone (see Fig. 2 for location).

detachments (see reviews in Leloup et al., 2001; Socquet and Pubellier, 2005). This has led to a long-standing problem of whether these major strike-slip faults penetrate down to the mantle, and interact with mantle-derived magmas in the shear zone (e.g. Leloup et al., 1995, 2001), or whether they are primarily crustal features, and die out in a region of distributed ductile flow somewhere within the middle or lower crust. In the Yunnan area the available data lean towards the faults being limited to the crust. The magnetotelluric data from the Ruili basin (Bai and Meju, 2003), suggests the presence of a detachment at a conductive mid-crustal layer at about 10 km. These data fit with seismic tomography across the Ailao Shan–Red River shear zone (Liu et al., 2000; Fig. 6). The seismic tomography shows the Ailao Shan–Red River Fault (labelled the Honghe Fault by Liu et al., 2000) as only having a distinctive boundary in the upper crust. The presence of inferred relatively hot and cold mantle from velocity data appears more related to the Tethyian subduction geometry than strike-slip related effects (Liu et al., 2000). From the perspective of the tomography image the major strike-slip faults only coincides with the Tethyian zone of weakness in the upper crust, the suture zone is inclined and at the lower crustal level lies over 50 km west of the surface trace of the Ailao Shan–Red River shear zone (Fig. 6), hence there is no steeply dipping trans-crustal suture zone for the strike-slip fault zone to have followed.

One problem for understanding the Ailao Shan–Red River shear zone is that although ductile lower crust appears to be the modern state, this may not have been the case in the Late Oligocene to Early Miocene. Possibly viscous channel flow of the lower crust to the SE away from Tibet began to be more important during the Miocene (Shen et al., 2005). This flow had the effect of changing the structural style during the Miocene from extrusion of larger more rigid strike-slip bounded blocks involving the entire crust, to smaller blocks primarily located in the upper crust (Shen et al., 2005).

3.3. Summary of Yunnan basins

The Yunnan basins are examples of well developed pull-apart basin geometries that have atypical geometries due to the strong influence of pre-existing fabrics. They are probably developed along faults that lie in the upper crust and die out within the middle crust. The strike-slip faults are strongly curved, in part because they follow pre-existing fabrics, but also in part to most efficiently fulfil their role in accommodating large block rotations. The three largest basins (Yingjiang, Zhangfeng and Ruili) line up under each other in a N–S direction. Perhaps this is due to a strong NE–SW striking basement fabric in the area. The Yingjiang basin is formed at a 60 km long, low-angle releasing bend, and also at an intersection point with a N–S striking fault. This northern fault strike-slip fault zone is characterised by NE–SW and N–S striking faults. The Zhangfeng basin is developed at a highly angular fault bend. The middle province of basins is characterised by intersection of NE–SW faults and E–W faults. The southern fault zone, dominated by the Longling–Ruili Fault is characterised by low-angle jogs in a curving fault zone. The Ruili basin is formed at a short, low-angle bend in the Longling–Ruili Fault. To the south large curved strike-slip faults are present (Wanding, Nanting) but they do not have well developed basins (Fig. 4). The distribution of basins fits the explanation given by Socquet and Pubellier (2005) that the setting is transtensional, within a large fault tip region set up around the termination of the Sagaing Fault zone (Socquet and Pubellier, 2005). Passing south this transtensional province passes to the more purely rotational strike-slip setting of the Nanting Fault zone. However, displacement on the Nanting Fault dies out to the western and eastern fault tips. The maximum rotation therefore occurs in the centre of the fault, so despite its perfect rotational geometry, the fault does not appear to accommodate wholesale rotation of the block north of the fault trace (Fig. 7). Instead the faults are accommodating strain within the block.

The western termination of the strike-slip faults is a region where the NE–SW to ENE–WSW striking sinistral faults must interact with the N–S striking, dextral Sagaing Fault province. This appears to be accomplished by the development of compressional wedge-shaped blocks at the fault tips formed between NNW–SSE to NNE–SSW striking dextral faults and ENE–WSW striking sinistral faults (Figs. 5 and 7).

4. Myanmar, Laos, Northern Thailand

4.1. Introduction

In Northern Thailand across the border into Laos is a structural province characterised by long, well developed ENE–WSW faults, and shorter N–S to NNE–SSW striking faults (Fig. 8). The ENE–WSW faults include the Jinhong, Wan Ha, Mengxian, Nam Ma and Mae Cham faults discussed in Lacassin et al. (1998) that exhibit significant Pliocene–Recent sinistral motion. In particular these authors estimate 12 km offset for the Nam Ma fault and 24 km for the Mengxian fault. Associated basins tend to strike NE–SW to N–S. Some basins clearly follow the strike of major folds and lithology boundaries in the pre-Cenozoic section (Fig. 8), other basins follow the strike of the faults, or both. Basin area diminishes significantly passing from Thailand into Laos. In Laos the smallest of the basins form at jogs and stepping geometries along the ENE–WSW faults. The larger basins form where the faults curve to NNE–SSW strike (sinistral releasing bend) or at the intersection between NNW–SSE striking faults and ENE–WSW striking faults (Fig. 8). This intersection of

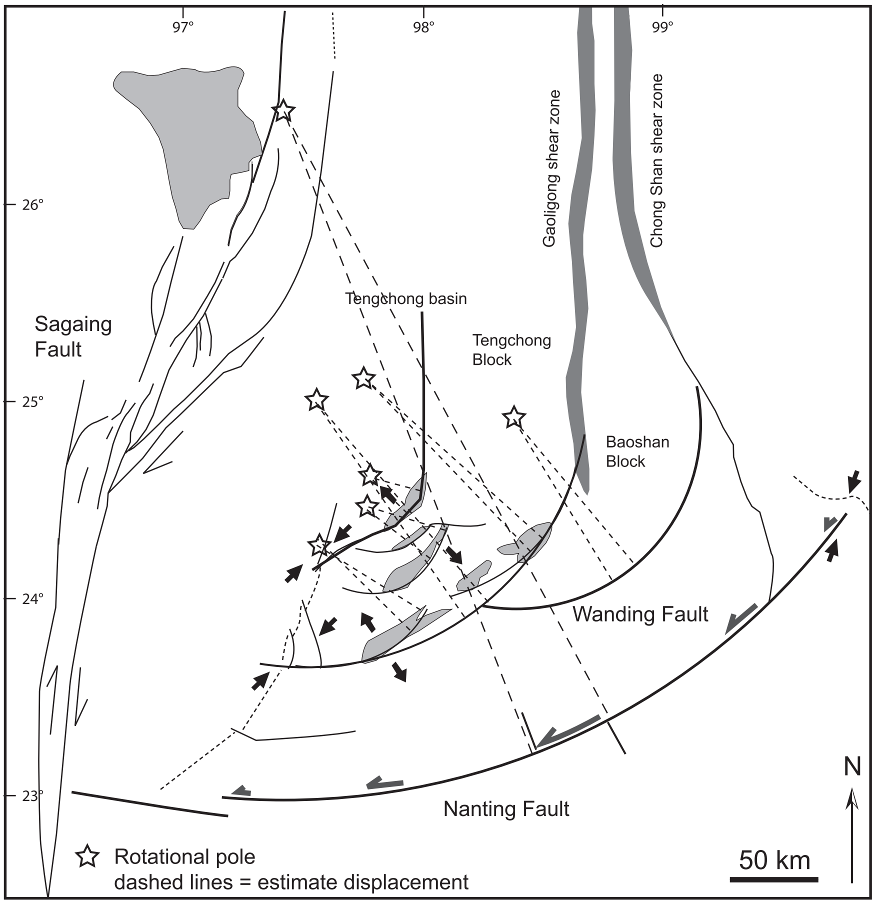


Fig. 7. Simplification of the Late Miocene–Recent strike-slip displacement pattern within the Yunnan area, illustrating the poles of rotation for the curved faults, and the compressional (fault tips) and extensional (fault centre) parts of the strike-slip fault systems. The Nanting Fault accommodates the largest motion on the block (40–50 km) and has the pole of rotation furthest from the fault trace, other faults accommodate more local rotations, and have shorter distances between the fault and its pole.

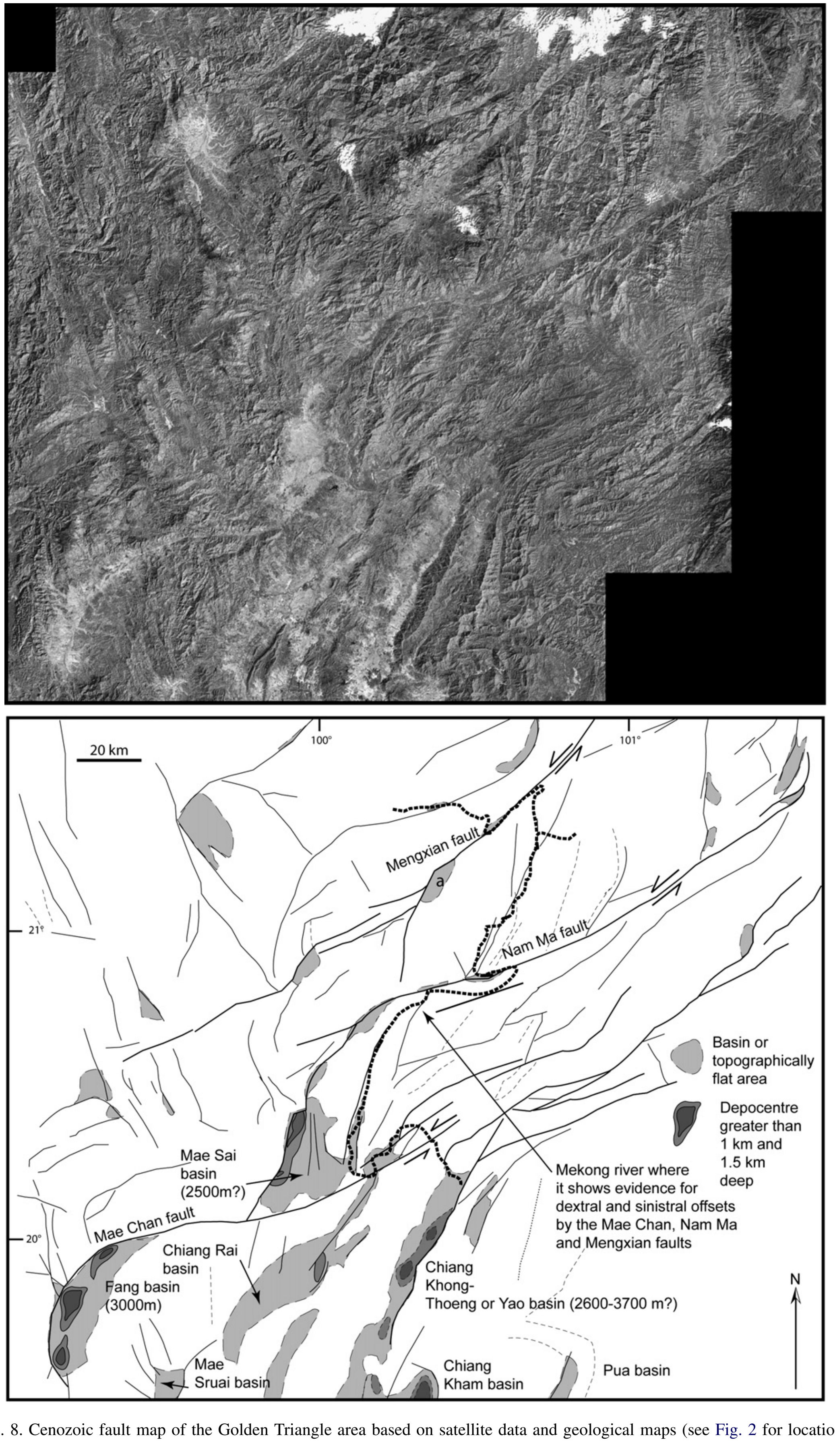


Fig. 8. Cenozoic fault map of the Golden Triangle area based on satellite data and geological maps (see Fig. 2 for location).

NNW–SSE striking faults and ENE–WSW striking faults produces characteristic triangular-shaped basins in map view.

Although superficially the pattern of basins may look similar to Yunnan, the setting of the Golden Triangle is different. Instead of major strike-slip faults forming the NNW–SE to N–S trends, minor faults and rift basins follow those trends. The ENE–WSW faults that were subordinate in importance in Yunnan, become the dominant strike-slip trend in the Golden Triangle. There is no indication in the Golden Triangle that the strike-slip faults have consistent rotational component unlike the Yunnan area (Fig. 8).

4.2. Implications of Fang basin history for strike-slip motion

Lacassin et al. (1998) tried to project river geometries and fault offsets back further in time than the sinistral displacements, and estimated tens of kilometres of Oligocene–Miocene dextral displacement on four faults in Yunnan and Laos. Although specifically for the Mae Chan fault these authors found no detectable fluvial geometry indicating offset magnitude, for two other ENE–WSW striking faults to the north (Mengxian and Nam Ma faults) they did find evidence, and proposed 30 km of dextral motion on the Nam Ma fault (Fig. 8). Assuming Andersonian fault mechanics, to activate these faults under right lateral displacement would require the regional Shmax direction to be about 90° from the present day (i.e. WNW–ESE). However, the proposed right lateral displacement is only viable if the basins at the (sinistral) releasing bend geometries are younger than the Oligocene–Miocene. Just because the most northerly faults display evidence for the dextral to sinistral change in kinematics with time, is it reasonable to assume the same applies to the Mae Chan fault, or is the lack of evidence for the switch along the Mae Chan fault significant? One clue lies in the timing of deformation in the Fang basin (Figs. 8 and 9).

The Fang basin lies at the tip of the ENE–WSW striking Mae Chan fault and is the best documented of the linked basin-strike-slip fault relationships in the Thailand–Laos border region. The Fang basin contains several oil fields and is known through seismic reflection data and wells (Sethakul and Pimasarn, 1990). The basin has undergone extension since the Late Oligocene, until the Pliocene (Sethakul, 1984; Praditan, 1989). It has also been punctuated by episodes of inversion, the strongest being a Late Miocene or Early Pliocene event (Fig. 9). The Fang basin and the Mae Chan fault are clearly kinematically related: the western extent of the Mae Chan fault does not pass beyond the Fang basin, instead the fault curves into the half graben boundary fault of the Fang basin (Fig. 8). In order for the Fang basin to have opened the Mae Chan fault must have undergone (predominantly) sinistral motion since the Oligocene. If the three intrabasinal unconformities in Fig. 9 are related to episodes of inversion with accompanying strike-slip motion then there has not been just one detectable switch in strike-slip fault activity, but four periods of sinistral motion (extensional episodes) and three periods of inversion corresponding to dextral motion. Dextral motion cannot have been very large, limited to a few kilometres at most, since the basin is largely preserved and has not been eroded due to inversion. Similar multiple inversion events are found in other basins to the south, as discussed in the next section (Morley et al., 2000, 2001).

Superficially in map view the Fang basin displays a simple pull-apart geometry associated with a sinistral strike-slip fault (Fig. 8). It also appears to be one in a series of similar structures. However, in detail there are some significant changes from north to south across the region. The largest documented strike-slip fault in the Golden Triangle is the most northerly, the Mengxian fault, which displays 24 km of sinistral offset, followed by the Nam Ma fault with 12 km, and lastly the Mae Chan fault (south) with 1.5 km (Lacassin et al., 1998). Seismic reflection data indicate the Fang basin has undergone some 6–8 km extension from the Late Oligocene to Pliocene (e.g. Sethakul and Pimasarn, 1990; Fig. 9). The strike-slip faults with larger displacements, (north of the Fang basin–Mae Chan fault) have smaller associated basins, with long axes trending NE–SW. The Mengxian fault has undergone 24 km sinistral offset during the Pliocene–Recent (Lacassin et al., 1998), yet basin ‘a’ in Fig. 8, is less than 10 km wide, only 20 km away from the river offset of 24 km and appears to be situated at a large releasing bend. The small size of the releasing bend basin can possibly be attributed to the absence of strain partitioning into normal faults, that enable a larger basins to develop. The Fang basin, and associated

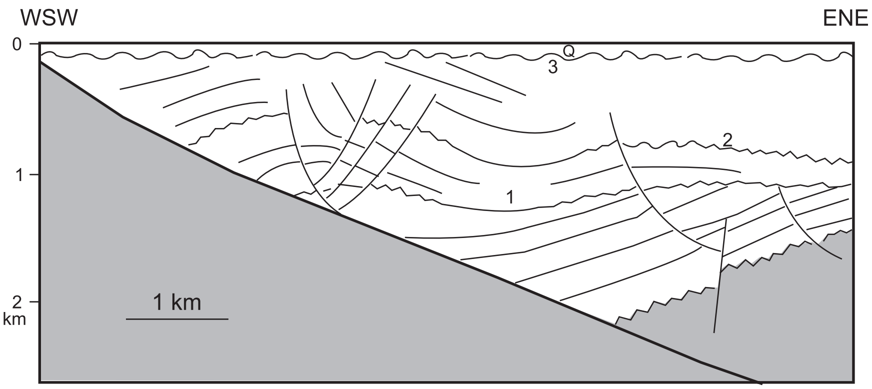


Fig. 9. Cross-section through the Fang basin based on seismic reflection data (redrawn from Sethakul and Pimasarn, 1990).

basins in Northern Thailand basins are larger and trend NNE–SSW. Hence the largest basin present along the ENE–WSW faults is associated with the smallest displacement strike-slip fault.

One possible explanation for the change in basin size and geometry passing into Northern Thailand is that the transition from predominantly strike-slip to predominantly extensional deformation occurs between the Mengxian, Nam Ma and Mae Chan faults. For the periods of extension in the Fang basin the Mae Chan fault is best viewed as an oblique transfer fault at the tip of an extensional boundary fault. For the times of inversion the fault would have operated as a dextral strike-slip fault within a compressional to strike-slip stress field (Fig. 9). Probably only since the Pliocene has the Mae Chan fault been active within a predominantly (sinistral) strike-slip stress field.

In this discussion of strike-slip vs oblique extension, the key problem is the geometric similarity between structures of strike-slip origin and extensional structures where activation of oblique fabrics play an important role. Here it is suggested that the timing of basin development is the key test for determining the kinematic development, not just the fault-basin geometry. However, once timing inconsistencies are exposed, subtle geometric differences also emerge. For example in Northern Thailand the map view angle of intersection between the strike-slip faults and the rift basins bounding faults is large, about 65–70°. In a typical strike-slip system the NNE-striking rift trend would be the R' shear trend, which would be dextral when the master fault is sinistral (Fig. 10).

The scenario discussed above assumes the dextral motion on the Mengxian and Nam Ma faults is of Oligocene–Miocene age, with the switch to sinistral motion occurring between 20 and 5 Ma as preferred by Lacassin et al. (1998). To the south the Mae Chan fault was able to undergo sinistral motion at the same time as dextral motion to the north due to the southerly passage from a strike-slip stress regime to an extensional stress regime. An alternative interpretation is that the switch from dextral to sinistral motion on all three faults occurred during or before the Late Oligocene. This in turn would require that the apparent youthful topography and meander incision noted by Lacassin et al. (1998) has actually had a remarkably long duration. Under this scenario the Fang basin could have formed at a curving strike-slip fault tip so that the NNE-striking boundary fault would have functioned as an oblique sinistral extensional fault (e.g. Uttamo et al., 2003).

The structural differences between the Fang basin boundary fault–Mae Chan fault acting as a normal fault-transfer fault system or as a sinistral strike-slip fault-releasing bend are, perhaps, indistinguishable in terms of predicted slip sense, conservation of slip, and kinematic relationships between the fault zones. The regional setting and trends offer a more compelling case: it seems difficult to understand how a simple strike-slip setting can explain the southerly trend towards the rift basins becoming longer and wider, as the NE–SW to ENE–WSW strike-slip faults become shorter, lower displacement, and generally less significant. Conversely where strike-slip faults are well developed there are only small basins.

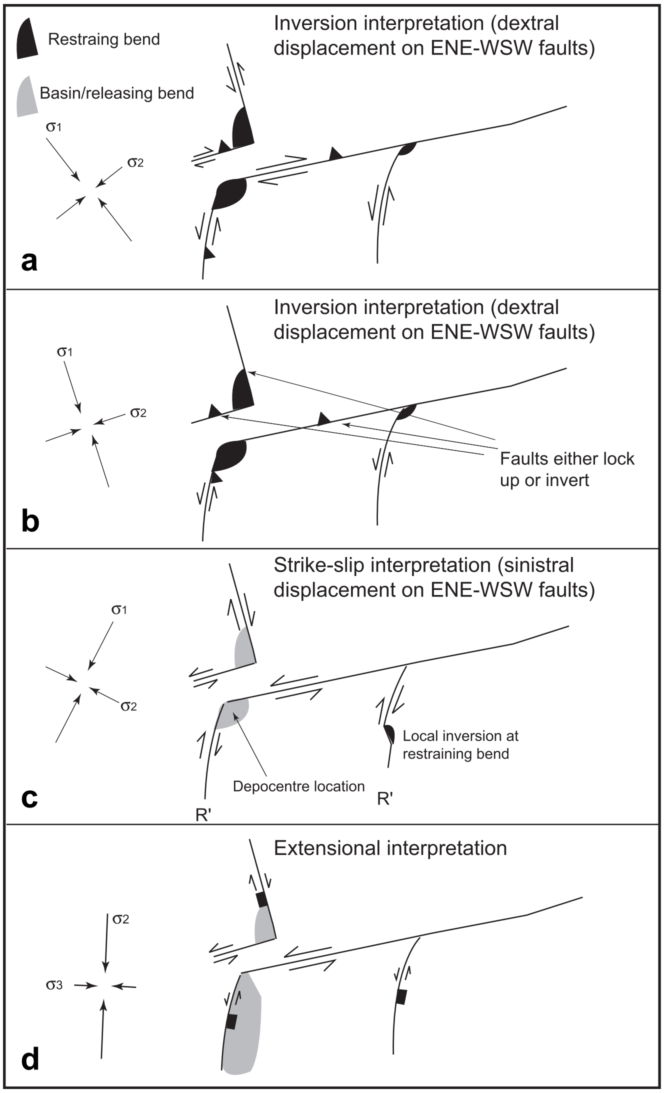


Fig. 10. Schematic maps showing the principal fault orientations in the Golden Triangle area (Fig. 8), and how the likely variations in the stress field during the Cenozoic will have affected fault displacement, basin development, inversion and uplift. The dominance of Oligocene–Miocene extensional basins suggests that at least in Northern Thailand, the dominant stress state was (d). At various times, however, it is likely (a), (b) and (c) have affected the region. The Late Miocene–Pliocene uplift and inversion probably reflects stresses similar to a and b. Whilst the modern state of stress is similar to (c) (see Fig. 2).

In the regional context of an Oligocene switch from dextral to sinistral strike-slip motion the Fang basin would still lie at the northern end of a major tectonic transition zone from extension to strike-slip. Hence it is probably futile arguing whether it can be called a strike-slip or an extensional basin. During basin subsidence stress conditions probably fluctuated between those appropriate for sinistral strike-slip (i.e. ∼NE–SW to NNE–SSW Shmax, vertical intermediate principal stress) and E–W extension (i.e. ∼N–S horizontal intermediate principal stress, vertical Shmax). Hence hybrid rift might be an appropriate term for such transition zone basins.

4.3. Extensional history in Northern Thailand

The Cenozoic basins of Northern Thailand range from small pockets of thin sediments covering a few square kilometres to large Oligo-Miocene basins such as the Chiang Mai, Phrae and Lampang basins which are 20–40 km wide, up to 140 km long and 2–3 km deep (as reviewed in Morley et al., 2001; Fig. 1). On the western margin of the basins are the putative Doi Suthep and Doi Inthanon metamorphic core complexes (Dunning et al., 1995; Rhodes et al., 1997, 2000; Barr et al., 2002). Movement on the extensional detachments may have begun in the Eocene, whilst uplift and erosion of the core complexes occurred predominantly from the Late Oligocene to Lower Miocene (Upton et al., 1997; Barr et al., 2002; Rhodes et al., 2005).

There are few good natural outcrops of the basins and associated faults. Hence subsurface data are very important. Most of what is known about the basins is due to hydrocarbon and coal exploration. The coal mines were, or are accessible to geologists, whilst the oil industry data, with some exceptions, remain confidential. Outcrop data from the mines showed extension were predominantly E–W to ENE–WSW and has a history from at least the Upper Oligocene to the Upper Miocene (Morley et al., 2000). A similar extension direction is indicated by stretching lineations associated with the core complex detachments which are typically within 10° north and south of an E–W direction (Rhodes et al., 2000).

In addition to extensional structures a number of mines and basins show evidence for reversal of motion on some extensional faults (inversion) and folding. Some of the characteristics of inversion are folding and uplift of depocentres, superimposed strike-slip striations on earlier dip-slip striations, and unconformities that separate episodes of inversion from episodes of extensional faulting (Fig. 11) (Morley et al., 2000, 2001). It is clear from the evolution of structures, and multiple unconformities that seal inversion events, that multiple episodes of inversion alternating with extension have occurred in some basins (Morley et al., 2000; Fig. 11). Hence the inversion cannot be explained as synchronous extension and strike-slip deformation due to strain partitioning in a transpressional setting. Instead significant changes in the regional stress regime have to be considered as the driving mechanisms for inversion. Inversion occurred episodically during the Miocene. The most regional and significant inversion event occurred around the Late Miocene/Pliocene boundary (Morley et al., 2001).

4.4. Kinematics of the NE–SW to ENE–WSW fault trends

One common pattern of deformation in Northern Thailand is N–S to NNE–SSW oriented basins bounded at their terminations by NE–SW to ENE–SWS striking faults (Fig. 12). This pattern could be interpreted as sigmoidal pull-apart geometries (e.g. Polachan et al., 1991). However, the NE–SW to ENE–WSW striking faults are not ubiquitously strike-slip faults. There is a strongly varied history (Fig. 13). The best documented outcrop example of strike-slip along a NE–SW trend is the Mae Kuang fault, which only shows evidence for sinistral displacement (Rhodes et al., 2004). In contrast, numerous well-exposed NE–SW striking faults in Mae Moh mine almost exclusively show either dip-slip displacement or oblique slip consistent with E–W extension (Fig. 13). The exceptions are a few faults in the northern part of the mine that display sub-horizontal striations indicative of sinistral displacement that overprint dip-slip striations. NE–SW striking faults at the Mae Lai mine, clearly show earlier dip-slip striations overprinted by later strike-slip faults that also resulted in folding of bedding.

Two important NE–SW to NNE–SSW fault zones (Thoen fault zone, Uttaradit fault zone) are present where the Northern Thailand rift province passes into the Central Thailand rift province. The Thoen fault zone could be interpreted as a NE–SW strike-slip fault linking the extensional Thoen and Phrae basins (Fig. 12). However, the Thoen fault has a recent history of activity, and both geomorphology and trenching across the fault zone have shown it to be extensional (Fenton et al., 1997, 2003). The longest NE–SW striking fault in Thailand is the Uttaradit fault, at the north end of the Phitsanulok basin. The Phitsanulok basin is dominated by extension on the N–S striking Western Boundary fault (Fig. 14), the basin displays a classic half graben geometry, trends N–S and has accumulated a maximum of about 7 km of Oligocene–Miocene continental sediment (Flint et al., 1988; Bal et al., 1992). The Uttaradit fault lies near the northern tip of the basin, and the Western Boundary fault (Fig. 14). As described by Morley et al. (2004), the ENE–WSW to NE–SW striking Uttaradit fault zone requires oblique sinistral extension for most of the Miocene in order for: (1) the depocentre thick to be focussed on the NE–SW fault segment (Fig. 14; inferred N–S to NNE–SSW Shmax direction), and (2) compatibility with the Western Boundary fault displacement. Then in latest Miocene–Pliocene inversion affected the basin, with a hanging wall anticline developed along the NE–SW striking fault segment, indicating a component of dextral motion during inversion (Fig. 14; inferred NW–SE to WNW–ESE Shmax direction). The last phase of fault activity is a return to extension.

The Uttaradit fault follows a broad NE–SW trending strength anisotropy in pre-Tertiary rocks: the Palaeozoic Nan-Uttaradit suture zone. Both outcrop and seismic reflection data from the Thoen fault and Uttaraditt fault zones indicate that displacement along the NE–SW to ENE–WSW striking fault zones has been predominantly extensional, any oblique component of motion during extension would have been sinistral.

The fault pattern described for Northern Thailand–Laos has some geometries similar to the strike-slip systems further north. However, the sedimentary basin instead of being elongate sub-parallel to the main strike-slip fault trend, are elongate in an N–S to NE–SW direction. The ENE–WSW trends with a few exceptions are generally shorter, and less important than similar trending faults in the north. Many of the fault trends also follow the strike of folds and lithological

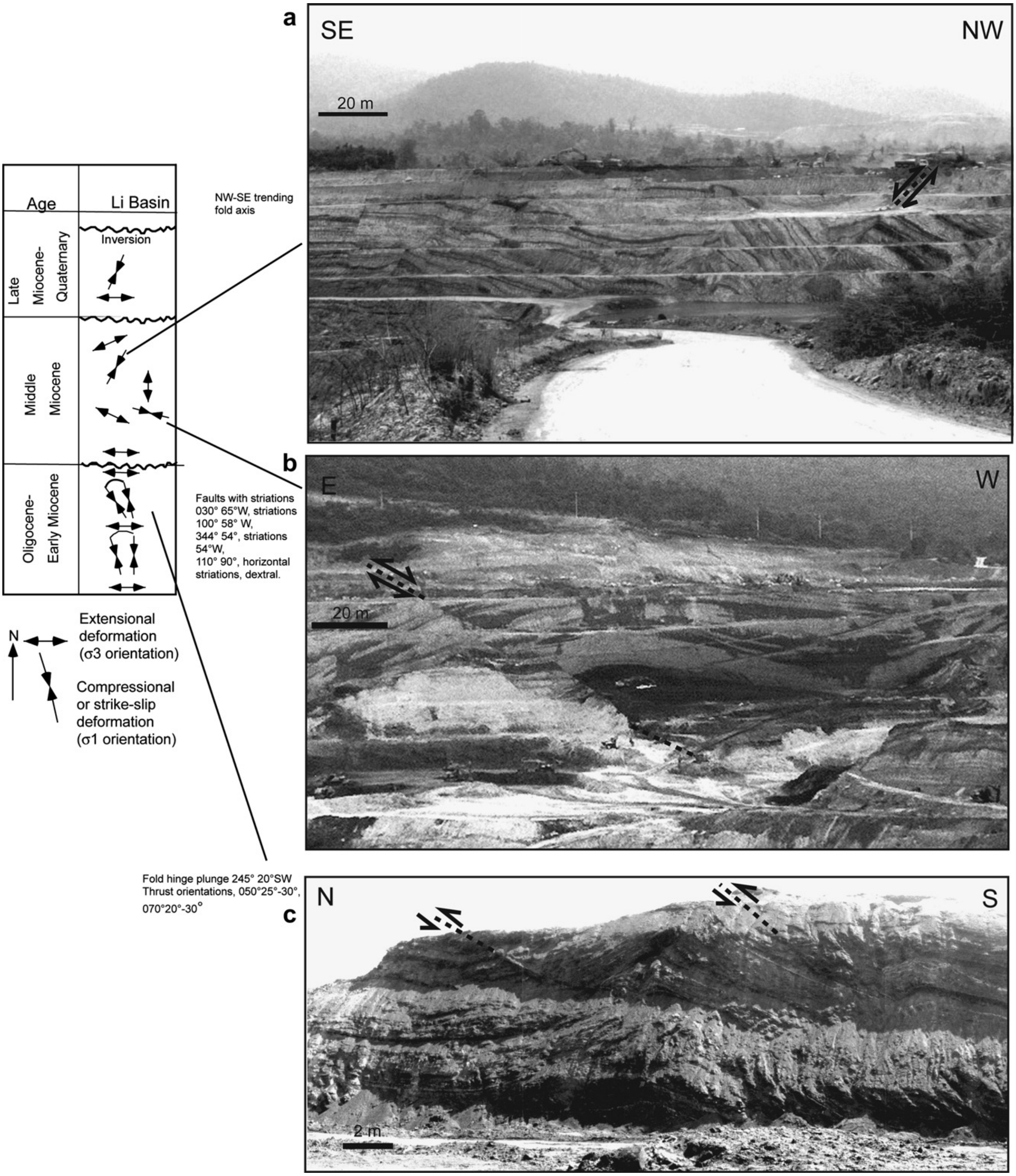


Fig. 11. Timing of extensional and inversion events in the Li basin, Northern Thailand (see Fig. 12 for location of basin). Timing from Morley et al. (2000).

boundaries in the outcropping units, suggesting pre-existing fabrics exert a strong control on fault orientation (Morley et al., 2004). Basins associated with ENE–WSW fault trends like the Fang basin/Mae Chan fault and the northern Phitsanulok basin/Uttaradit fault require sinistral motion on the ENE–WSW trends to have occurred in the Late Oligocene–Miocene, whilst if they behaved as simple strike-slip faults they should have undergone dextral motion during that time (Lacassin et al., 1998). Consequently Northern Thailand is interpreted to represent a region of predominantly extensional tectonics associated with strong oblique pre-existing fabrics.

The structural evolution of rift basins in Northern Thailand shows that there is an important change around the Late Miocene–Pliocene transition, when rifting slowed considerably

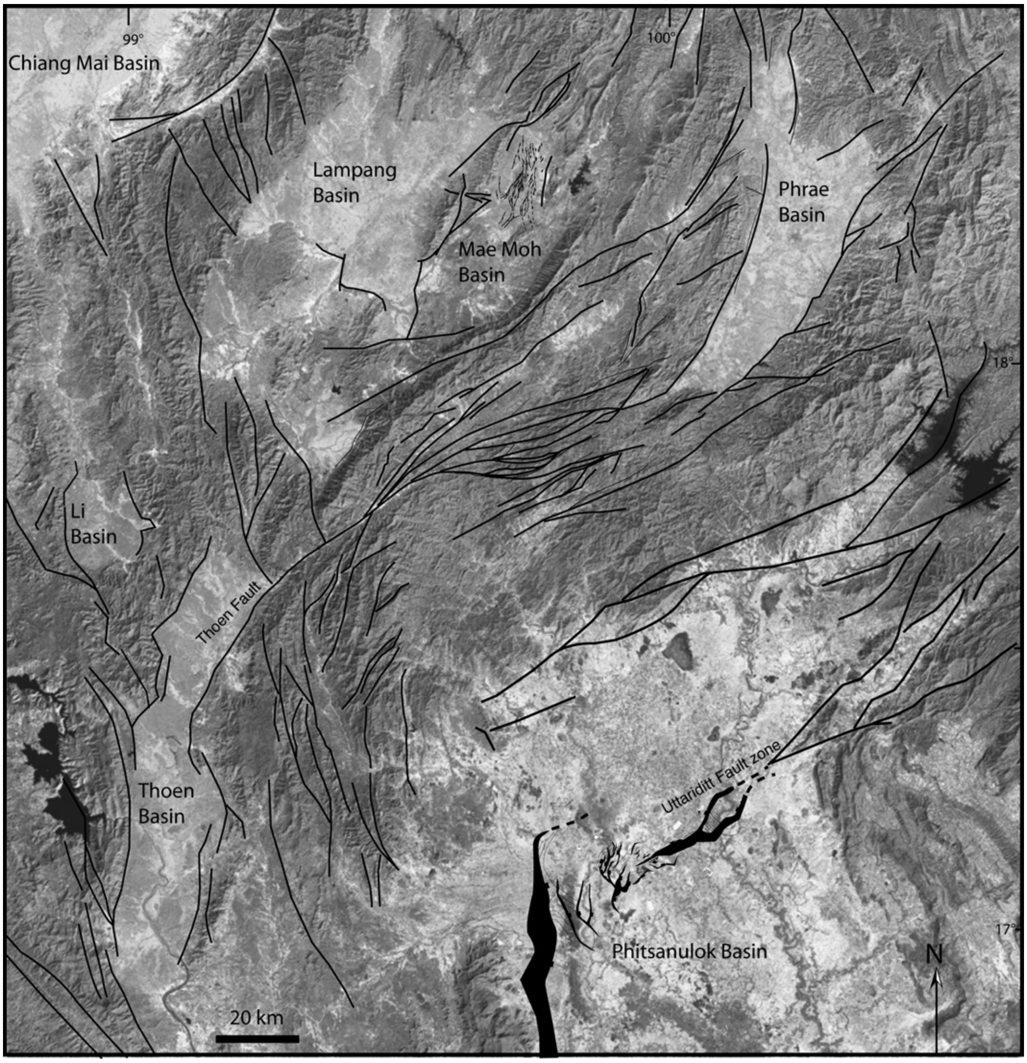


Fig. 12. Fault and basin map of south Northern Thailand illustrating a mixture of Cenozoic fault orientations, the NNE–ENE–WSW trends are interpreted to follow zones of weakness in pre-Cenozoic rocks, NE–SW to ENE–WSW fabrics related to the Indosinian orogeny are particularly prominent in the region (see Fig. 2 for location).

and inversion was widespread. However, this is not an isolated event, other important inversion events have also been identified during the Miocene. The NNE–SSW to ENE–WSW fault trends in Northern Thailand show a variety of characteristics, they can: (1) appear to be pure extensional trends, displaying dip-slip striations and host some deep rift basin depocentres (Fig. 8), (2) display oblique sinistral extensional characteristics (e.g. the NE–SW to ENE–WSW Uttaradit and Thoen faults; Figs. 12 and 14) appropriate for E–W extension, and (3) show strike-slip senses of motion with evidence of both sinistral and dextral displacements from different fault zones. These observations differ from the regional dextral (older) to sinistral (younger) switch models for NE–SW to ENE–WSW strike-slip faults seen further north and west (Lacassin et al., 1997, 1998).

Here it is suggested that southwards from the Golden Triangle area in Central and Northern Thailand extensional stresses have dominated over the strike-slip dominated stress systems found to the north. However, the stress system during the Neogene in Northern Thailand has gone through episodes where strike-slip stresses or even compressional stresses have dominated, and given rise to inversion features and active strike-slip faulting (Fig. 10). Certain basin boundary fault strike-slip fault configurations (e.g. Fang basin) may, under stresses appropriate for either extension or strike-slip, produce approximately similar slip patterns on the linked extensional-strike-slip faults. The effects of pre-existing fabrics coupled with rapidly evolving stress regimes have given rise to fault patterns that at first glance may seem to display classic simple strike-slip characteristics. However, this belies the complexity of tectonic events recorded in the basins.

There is a problem with simply assuming that faults that lie oblique to the regional extension direction will display oblique slip motion. That such assumptions are not necessarily the case is illustrated by the normal faults in Mae Moh mine, which tend to display dip-slip striations on both N–S and NE–SW oriented trends (Fig. 13), possibly indicating some strain partitioning effects. In some cases the stress orientation

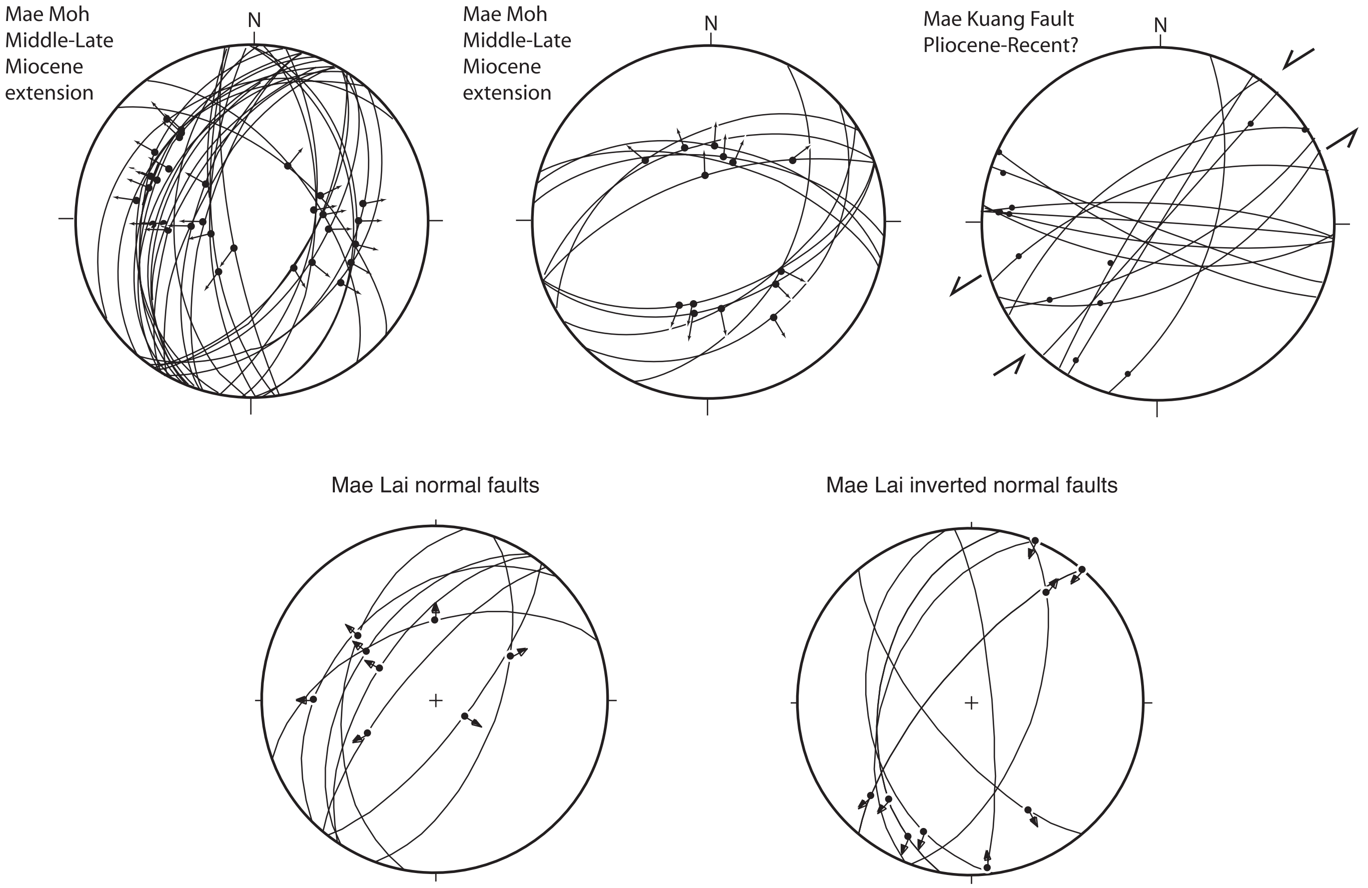


Fig. 13. Examples of fault slip data from NE−SW striking faults in Northern Thailand, showing that for faults of similar orientation the kinematics are highly variable: Mae Moh basin, predominantly simple dip-slip extension; Mae Kuang Fault, sinistral displacement, Rhodes et al. (2004); Mae Lai Basin Miocene extension followed by inversion with sinistral displacement.

appears to change locally in response to the oblique fabric, hence dip-slip strain is produced in places where oblique slip would be predicted (possibly the Thoen Fault is one example). Such a change in stress orientation can possibly be seen in the world stress map data for the curved Western Branch of the East African Rift (Reinecker et al., 2005). The rift follows a relatively weak Proterozoic mobile belt trend and avoids the Tanzania Archean craton (McConnell, 1972). The Shmax direction determined from earthquakes follows the pre-existing fabric pattern and swings around from NNW−SSE in the southern part of Lake Tanganyika, to a NE−SW direction around Lake Albert (Reinecker et al., 2005) within a region of assumed overall E−W extension. This pattern suggests that the present stress system is responding to the pre-existing fabric rather than the rift being kinematically partitioned into pure dip-slip or oblique slip faults depending upon orientation within a regionally consistent stress field. Where the oblique fabric acts as a stress guide, the curved system would be dominated by dip-slip faults.

5. Comparison of fault patterns from three provinces

Outcrop and analogue model examples of fault patterns in different structural provinces are important for helping understand fault patterns derived from seismic reflection data, or other remote sensing data, where fault displacements cannot be directly measured. In the oil industry, one of the most common structural problems is distinguishing strike-slip fault patterns from extensional fault patterns from subsurface data. In this paper, faults from Yunnan to Northern Thailand show similar fault patterns dominated by N−S, NNE−SSW and ENE−WSW fault direction that have developed in strike-slip, transtensional and extensional stress regimes.

The characteristics of transtensional basins in Yunnan are as follows: (1) the major strike-slip faults with tens of kilometres of sinistral strike-slip displacement show strongly curved trajectories, (2) probably the steeply dipping major faults die out or detach within the middle to lower crust, (3) basins are up to 15 km wide and 50 km long, they tend to align approximately NE−SW, along a range of releasing bend fault geometries (Fig. 15), (4) strain partitioning appears to be associated with some of the larger, better developed pull-apart basins (Figs. 15a and 16), and (5) reversal of motion on major N−S strike-slip faults in the Late Miocene (?) resulted in inversion, uplift and erosion of basins formed at releasing bends geometries under dextral motion.

In the Golden Triangle, the characteristics of the strike-slip basins are as follows: (1) sinistral strike-slip displacements up

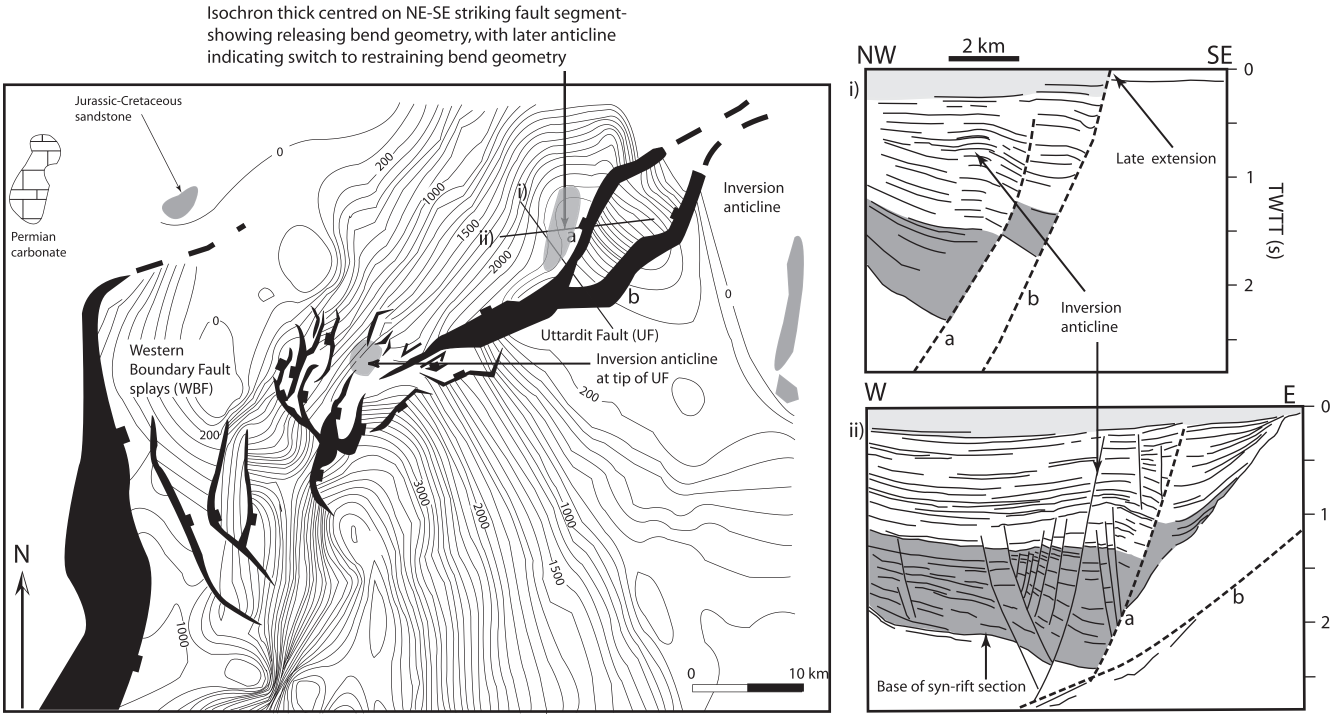


Fig. 14. Detailed time-structure map of the Northern Phitsanulok basin and cross-sections based on interpretation of 2D seismic reflection data. The data illustrate that the Uttaradit fault zone is an oblique-extensional fault, that dies out towards the SE and displacement is transferred from the NNW dipping Uttaradit fault to the SSE dipping Western Boundary fault. The geometries are predominantly extensional, not strike-slip. However, oblique extension has caused inversion at the compressional tip of the Uttaradit fault, and enhanced subsidence at the NE–SW striking releasing bend orientation of the fault zone (see Fig. 1 for location).

to 30 km, (2) small pull-apart basins at low-angle releasing bends, larger area triangular basins at high-angle fault intersections (Fig. 15), (3) basins either show no strong elongation, or are elongate sub-parallel to the main strike-slip faults, (4) basins are poorly developed in comparison with Yunnan, and (5) the strongly rotational geometries seen in Yunnan are not present in the Golden Triangle.

In Northern Thailand, the characteristics of the extensional basins are (Figs. 16 and 17): (1) basins elongate in a N–S to NE–SW direction, up to 130 km long, 40 km wide and about 3–4 km maximum depth, (2) E–W to NE–SW striking faults reactivated a weak pre-existing fabric and either show strike-slip, normal dip-slip, or oblique dip-slip senses of motion. Where strike-slip senses of motion are present the faults either represent sinistral transfer faults at basin margins, or faults reactivated during episodes of inversion (either dip-slip or strike-slip). (3) Depocentres tend to occur in the centre of or at several places along N–S to NE–SW striking faults, displacement on these faults declines towards any bounding faults with an E–W to ENE–WSW strike, suggesting incomplete displacement transfer.

Key differences between strike-slip and extensional basins in the study area as follows: (1) strike-slip basins tend to be sub-parallel to main strike-slip fault trends or low-angle releasing bends, or triangular-shaped where basins are set up between N–S and ENE–WSW strike-slip fault trends (Figs. 15 and 16). Extensional basins in Northern Thailand tend to trend N–S to NE–SW, at a high angle (about 40°–80°) to the E–W and ENE–WSW strike-slip fault trends. The E–W to ENE–WSW trends are rarely associated with basins, and when the basins are present they are smaller than those along N–S trends. (2) Strike-slip basins rarely attain dimension as large as 50 km long, 15 km wide, maximum depths are uncertain. The largest rift basins are 130 km long, 30–40 km wide and in Northern Thailand 3–4 km deep (further south the maximum dimensions are greater still). (3) In the Golden Triangle ENE–WSW strike-slip faults changed from dextral to sinistral motion sometime during the Miocene (Lacassin et al., 1998). In Northern Thailand the ENE–WSW Mae Chan fault is a transfer strike-slip fault to the Fang basin, and consequently its motion has been predominantly sinistral since the Late Oligocene. (4) The extensional basins may have a longer life (Late Oligocene–Late Miocene/Pliocene) than the sinistral strike-slip basins (Late Miocene–Recent).

6. Discussion of regional tectonic models

Two recent publications by England and Molnar (2005) and Shen et al. (2005) have used GPS data to determine whether the observed present day pattern of displacement associated with the Himalayan orogeny better fit a rigid block, visco-elastic or viscous sheet with channel flow models. Although the papers include the Yunnan area in their coverage the analysis does not extend into Thailand. Both papers favour viscous or visco-elastic models over a rigid block model, although in detail the GPS data indicates the deformation in western Yunnan departs from the ideal visco-elastic model (Shen et al., 2005). This may be due to the displacement transfer effects between

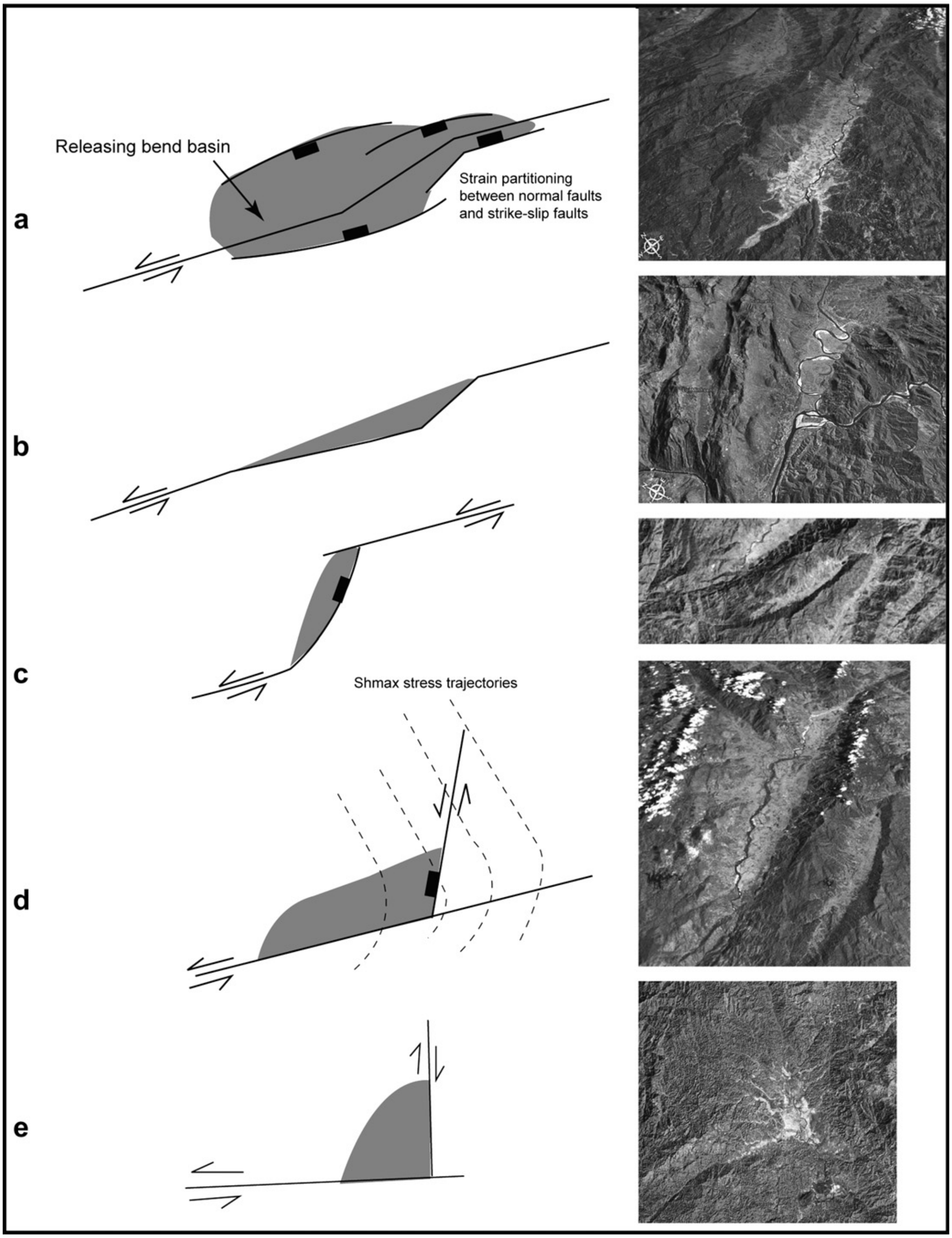
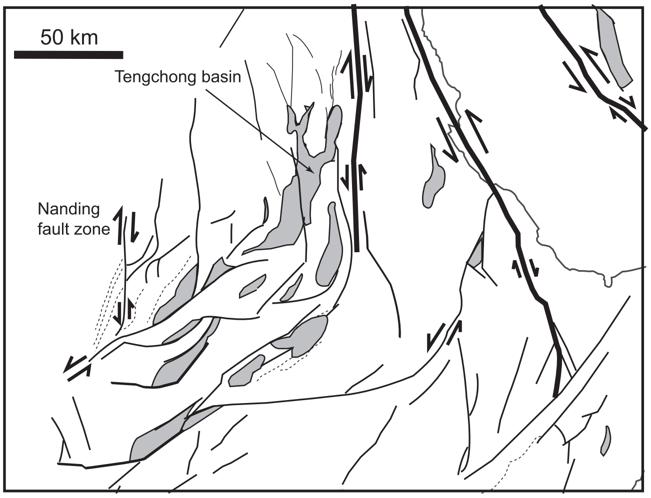


Fig. 15. Summary schematically illustrating some of the different types of strike-slip related basin found in the Yunnan−Golden Triangle area.

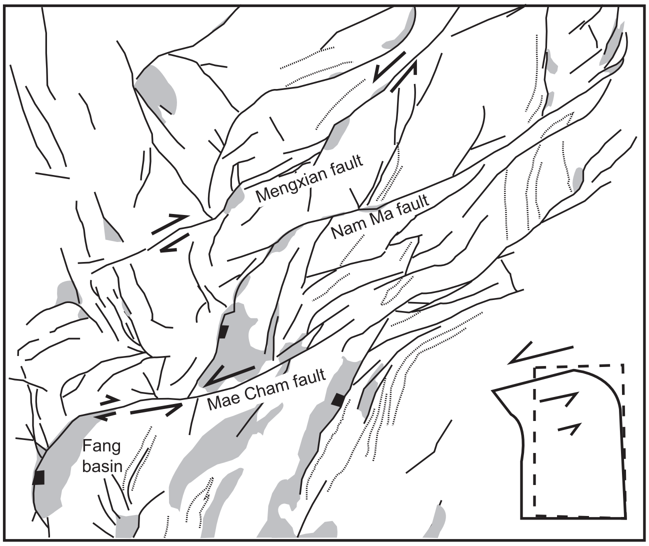
the Sagaing Fault deformation and the faults of western Yunnan (Socquet and Pubellier, 2005). The rapidly evolving tectonics described in this paper indicate that using GPS data to validate any single model for the duration of an evolving orogen is dangerous. In SE Asia differential stress magnitudes must have been higher in the past than at present, in order to give rise to the extensional, strike-slip and possibly compressional deformation observed throughout western Thailand, and along the length of the Red River Fault zone (and other strike-slip faults) in Vietnam. During the Pliocene the area where differential stresses were large enough to cause significant faulting retreated towards the Himalayan syntaxis. Presumably this retreat is either due to diminishing driving forces with time, or large-scale strain softening in the region of present day visco-elastic deformation, or a combination of the two. Hence whilst the present day motions may favour a visco-elastic model that does not exclude a rigid block model being more appropriate in the past (especially if strain softening occurred), (also as noted by Shen et al., 2005). This is particularly the case for the major sinistral displacement (500 km?) on the Ailao Shan−Red River shear zone, which is thought to be Oligocene−Early Miocene in age (Leloup

Yunnan. N-S to NW-SE major strike-slip faults with 100 + km displacement. Curved faults which pass to ENE-WSW to E-W strikes, with NE-SW trending pull-apart basins developed at left-stepping segments and releasing bends. Notably most basins lie west and SW of the Gaolingao fault, that on a regional scale would correspond with the extensional releasing bends during sinistral displacement.



Myanmar-Laos-Northern Thailand, (Golden Triangle). NE-SW to ENE-WSW faults are dominant. NNE-SSW and NNW-SSE trends are also important. All trends may be following pre-existing fabrics in basement. Sedimentary basins become larger to the south. The longest deepest basins tend to be aligned NNE-SSW. Small basins and depression also form at the intersection of NNW-SSE and ENE-WSW trends. This region represents the transition from strike-slip dominated deformation to oblique-extension dominated deformation.

Note: this region has probably undergone considerable variations in principal stress orientation and magnitude during the Tertiary. Consequently although it is inferred that the Mae Cham fault is predominantly a transfer fault active during extension. There may have been times when it acted as a strike-slip fault under a strike-slip stress regime.



South Northern Thailand, NE-SW to N-S trending rift basins are dominant. NE-SW to ENE-WSW trends serve to link basins, and tend to follow older trends in basement, particularly Indosinian structures. The NE-SW to ENE-WSW trends are shorter than in the regions above. The major NNE-SSW to N-S trending rift basins are longer than the basins to the north.

Commonly the main depocentres follow NE-SW to N-S trends. NNW-SSE trends are common but are not associated with well-developed basins.

The extension direction has probably varied considerably with time, but is predominantly E-W to NW-SE

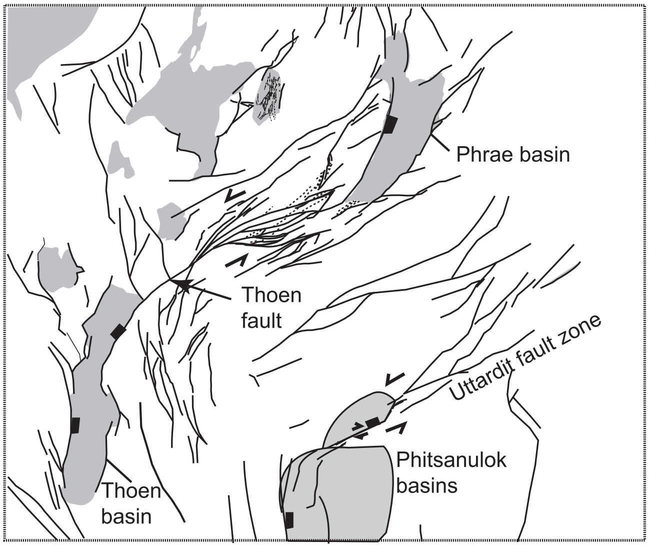


Fig. 16. Summary maps of the fault patterns from Yunnan–Myanmar, the Golden Triangle and Northern Thailand, with discussion of their similarities and differences.

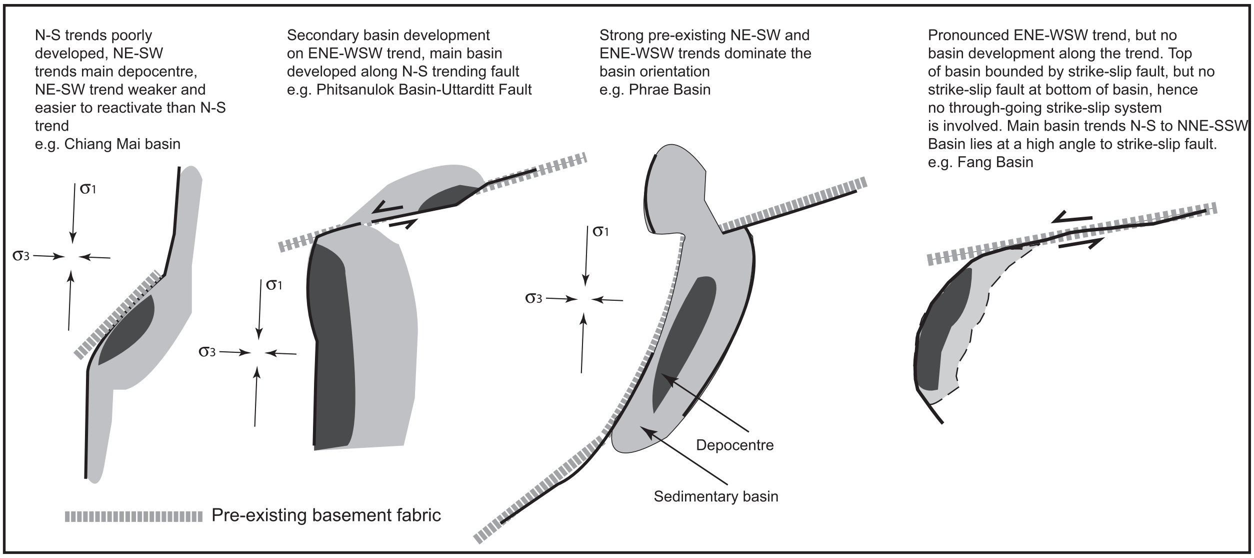


Fig. 17. Summary schematically illustrating of some extensional basin geometries found in Northern Thailand and how pre-existing fabrics have influenced their geometry and given rise to pseudo strike-slip geometries.

et al., 2001; Replumaz and Tapponnier, 2003). Hence, the present day GPS measurements in Southeast Asia may have little bearing on the earlier tectonic situation.

Whilst the argument has been made here for more rigid block style deformation in the past, this does not mean that the author agrees with all aspects of the simple rigid block model either (see Morley, 2004). One aspect of this disagreement is simply how far into SE Asia can the rigid extrusion model be viewed as dominating the Late Cenozoic tectonics? Both the visco-elastic and rigid block models are focussed on defining models for lithospheric deformation associated with the India–Eurasian collision. They do not consider interactions between forces arising from other plate boundaries or intraplate locations within SE Asia and Himalayan orogenic forces (Hall and Morley, 2004). Whilst such considerations are not important to the aims of visco-elastic modelling undertaken by England and Molnar (2005), and cannot be used to test such a model, they are important for testing the rigid extrusion model. Northern Thailand lies on the southeastern margin of the region dominated by the Himalayan orogeny. The marked change in tectonic style, passing from extension-dominated deformation to strike-slip deformation to the north and west of Thailand provides limits on how far rigid block-dominated tectonics have extended to the south. The alternation between extension and strike-slip or compressional deformation with inversion indicates more is happening to the stress field that just a progressive waxing or waning due to the northwards progression of India (cf. Huchon et al., 1994). Other plate boundary and intraplate forces within SE Asia are interacting with forces arising from the Himalayan orogenic belt (e.g. Hall and Morley, 2004) and thus have created a more complex tectonic evolution in Thailand, than has been predicted from simple escape tectonics (e.g. Tapponnier et al., 1986; Lacassin et al., 1997; Leloup et al., 2001). One recent example that illustrates strains induced in Thailand from non-Himalayan causes is the 26 December 2004 Sumatran earthquake which induced horizontal motions in Thailand as measured by GPS stations of: 27 cm in southern Thailand (Phuket), 8 cm in Bangkok, and 3 cm in Northern Thailand (Chiang Mai) (Vigny et al., 2005).

This view of complex interaction of forces at the southern limit may not just apply to Thailand. The rigid block model has most significantly been applied to the Red River shear zone, where the estimated 500 km of sinistral motion is proposed to be transferred to the South China Seas spreading centre (e.g. Tapponnier et al., 1986; Lacassin et al., 1997; Leloup et al., 2001; Replumaz and Tapponnier, 2003). However, there are considerable geometric and timing problems associated with this model (Rangin et al., 1995; Morley, 2002), and there is no clear cut fault zone of the appropriate age (Oligocene–Early Miocene) that can be traced across seismic reflection data along the eastern offshore area of Vietnam to the South China Seas oceanic crust (e.g. Morley, 2002). A recent study of the Yinggehai basin by Clift and Sun (in press) shows that major strike-slip faults within the Late Oligocene–Miocene section of the basin are difficult to define on seismic data and extension in the Yinggehai basin occurred earlier than 34–17 Ma period of sinistral activity for motion on the Red River shear zone defined by Gilley et al. (2003). What is noticeable is that approaching the coast the Red River shear zone passes from being a discrete narrow zone, to a much broader zone of splays (Fig. 18), and that the offshore history of deformation as defined by Rangin et al. (1995) is remarkably different from the onshore history (e.g. Lacassin et al., 1995; Leloup et al., 2001; Gilley et al., 2003). These factors suggest that instead of the rigid block termination at a spreading centre, the termination of the Red River Fault zone is more complex due to interaction of stresses near the limit of Himalayan orogenic influence. It has been argued by Leloup et al. (2001) that the coincidence in timing between the cessation of sinistral motion on the Red River Fault zone and the South China Seas spreading centre indicates a mutual link, related to

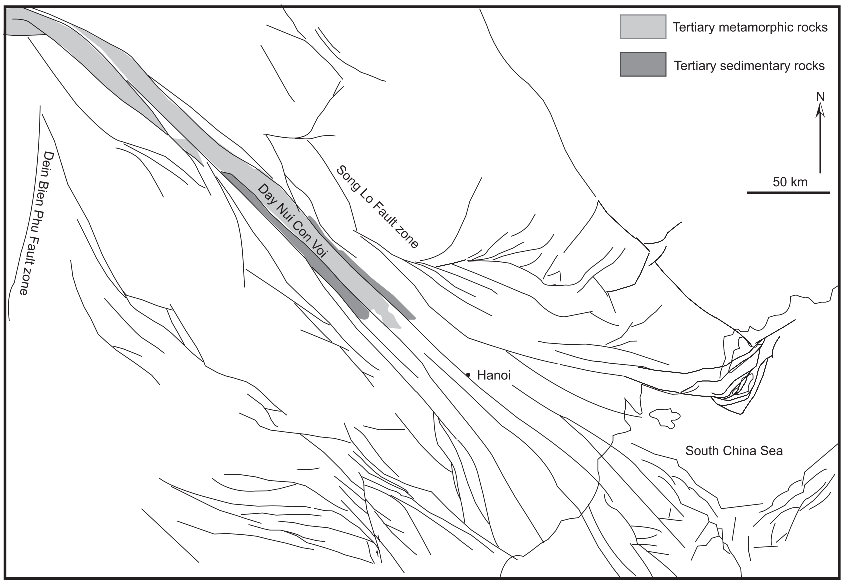


Fig. 18. Map of Cenozoic faults that could be transferring displacement away from the main Red River Fault zone trend passing from onshore to offshore, Vietnam. Fault patterns based on Leloup et al. (2001) (onshore), Rangin et al. (1995) (offshore) and satellite interpretation. The many fault strands and splaying pattern suggest that a considerable amount of the Red River Fault zone displacement may be lost around the onshore/offshore transition.

escape tectonics. However, there is another coincidence, the jamming of the NW Borneo trench, by the Dangerous Grounds thinned continental crust in the latest Early Miocene (e.g. Hazebroek and Tan, 1993; Hall, 1996, 2002; Hutchison et al., 2000). Hence rather than rigid extrusion driving South China Seas spreading, an alternative view is that cessation of subduction and the loss of the slab pull force inhibited seafloor spreading in the South China Sea, which in turn inhibited Red River Fault zone activity. The difference in timing between onshore and offshore deformation along the Red River shear zone (Rangin et al., 1995) may well reflect the fault zone lying within progressively different stress regimes, and not the imposition of rigid block motions on ‘passive’ SE Asia.

7. Conclusions

Northern Thailand is a region of Late Cenozoic extensional basins bounded to the west by a major N–S trending dextral, and to the north by a fanning array of strike-slip faults emanating from N–S to NNW–SSE trends in the southeastern Tibetan plateau. Whilst to the east, in areas like the Khorat Plateau there is very little Late Cenozoic deformation. Within this regional pattern of strain variation, the Cenozoic structural history, modern block motions determined from GPS, and the distribution of earthquakes all point to the Golden Triangle area as marking an important transition between strike-slip and extensional structural styles.

This study emphasises the difficulty in making map view interpretation of fault patterns in terms of simple structural styles. Most commonly the problem is that when basins and oblique faults are present, there is a strong tendency for pull-apart basin interpretations to be made. The alternative explanations, in particular extensional activation of oblique fabrics, tend to be less favoured. However, in areas like Northern Thailand the two different styles can appear quite similar and juxtaposed, consequently purely strike-slip explanations have been mistakenly applied to the origins of the Thailand rift basins (e.g. Tapponnier et al., 1986; Polachan et al., 1991; Leloup et al., 2001; Replumaz and Tapponnier, 2003; Fig. 15). In transitional areas like the Fang basin the rift basins may be hybrid, evolving under stresses that fluctuate between extension and strike-slip. To assess the different structural styles it is necessary to: (1) have detailed information about the timing and evolution of fault-bounded sedimentary basins, (2)be able to regionally correlate structural events and test the regional consistency of palaeo-stress patterns associated with those events, and (3) understand how reactivation of basement fabrics has affected basin geometries, fault patterns and fault slip characteristics under different stresses. A considerable part of the problem with understanding the Yunnan–Northern Thailand region is the patchy nature of these critical data. Escape tectonics is important, but the complicated tectonic evolution within a major strike-slip bounded continental block is beyond that predicted by the basic escape tectonics model. Consequently interaction of a variety of mechanisms that influence regional stress patterns is required, not just a simple Himalayan indentor model (as discussed in Hall and Morley, 2004).

In the three areas studied similar N–S, NE–SW and ENE–WSW pre-existing fabrics are available for reactivation. However, the resulting basin geometries in the three areas are significantly different in terms of basins’ size, orientation with respect to ENE–WSW fabrics, basin timing, and degree of strain partitioning, as summarised in Figs. 15–17. In all areas the crust is relatively hot, hence both extensional and strike-slip faults may well die out or detach within the middle crust, leaving the lower crust to accommodate strain by more distributed flow.

The transition between extension in the Gulf of Thailand and strike-slip dominated deformation in Yunnan and

Myanmar occurs in the Golden Triangle region. One of the key problems in defining the different structural styles is the similarity in geometric features between strike-slip reactivation of oblique pre-existing fabrics and extensional reactivation of pre-existing fabrics (e.g. Morley et al., 2004). Not only is there a lateral transition in the dominant deformation style, through time the deformation style has changed and evolved. The region including the Golden Triangle and to the south has predominantly undergone ENE–WSW to WNW–ESW extension, but has also undergone shorter episodes of deformation where the Shmax direction (under strike-slip or compressional stress conditions) is oriented from NW–SE to NE–SW directions (Fig. 10). The latter episodes have resulted in inversion of some extensional faults. This paper has suggested that although the Himalayan indentor model does have broad, first order applicability particularly in the early history of the area, in detail it falls short of explaining the structural geometries and kinematics present from Yunnan to Northern Thailand. The changes in deformation style at the southeastern margin of the Himalayan orogen do not conform with either a simple rigid block or visco-elastic model. Both for Thailand and the Red River shear zone, the answer probably lies in interaction with other regional forces, rather than a simple diminishing of stress away from the Himalayan orogen, or transfer of rigid block motions into other plate boundaries.

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