Combined escape tectonics and subduction rollback–back arc extension: a model for the evolution of Tertiary rift basins in Thailand, Malaysia and Laos

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Abstract: The Tertiary rift basins of Thailand and adjacent countries show considerable variability in the timing of rift initiation, termination, the timing and magnitude of thermal subsidence, and the timing and intensity of inversion episodes. The rift basins developed on continental blocks that were extruded south-eastwards. Hence their development must be tied into Himalayan extrusion tectonics. Current tectonic models propose that the Tertiary basins opened up as pull-apart basins associated with strike-slip faults. Published geochronology of strike-slip fault zone rocks, mapping of fault patterns in the Tertiary basins and mapped releasing-restraining bend geometries all indicate that in Thailand major sinistral strike-slip motion ceased at about 30 Ma, prior to the formation of most rift basins the Thailand. The effects of later dextral slip were minor and probably a result of reactivation during episodes of inversion during NW–SE to NE–SW (Himalayan) compression. Dextral slip was not responsible for opening most of the rift basins in Thailand. An alternative mechanism to open the rift basins is subduction rollback of the Indian plate to the west of Thailand. It is proposed that subduction rollback can help explain some of the characteristics of the rift basins such as non-uniform lithospheric extension, deep sag basins, and the diachronous onset and termination of rifting.

Keywords: Thailand, Himalayan Orogeny, rift zones, strike-slip faults, subduction.

Tapponnier et al. (1982) and Molnar & Tapponnier (1975) greatly influenced geological thought about the evolution of China and SE Asia in their classic work on escape tectonics as a result of the India–Eurasia Himalayan collision. They constructed analogue models, the first of which intruded a wooden block into a cake of plasticine with one constrained margin (to the west) and an unconstrained margin (to the east) (Tapponnier et al. 1982). Later models with sand, silicone and syrup employed more realistically scaled materials (e.g. Jolivet et al. 1990). The resulting patterns of deformation predicted extrusion of continental blocks east and southeast of the Himalayas (Indochina) towards the unconstrained margin resulting in hundreds of kilometres of strike-slip motion on several major shear zones (Fig. 1). The two most important faults bounding the crustal blocks discussed in this paper are the Sagaing fault (c. 450 km dextral displacement, Mitchell 1981; Torres et al. 1997) and the Red River fault (c. 500 km sinistral motion, followed by dextral slip in the order of tens of kilometres, Leloup et al. 1995).

The Tertiary rift basins of Thailand and adjacent countries (Malaysia, Myanmar and Laos) evolved on continental blocks involved in escape tectonics (Fig. 1). Some prominent NW–SE (Mae Ping, Three Pagodas) and NE–SW (Klong Mariu, Ranong, Uttaradit) trending strike-slip faults mapped in pre-Tertiary rocks strike into areas covered by Tertiary rift basins. Tectonic models currently applied to the rift basins link regional escape tectonics, with locally prominent strike-slip faults to explain the formation of the rift basins (Polanchan & Sattayarak 1989; Packham 1993; Hall 1996; Madon 1997a, b). Using offsets of Triassic granite belts in western Thailand, Tapponnier et al. (1982) inferred several hundred kilometres of sinistral displacement on the Three Pagodas and Mae Ping fault zones associated with escape tectonics (i.e. Oligocene–Miocene). The timing of sinistral displacement has been disputed. Collisions of continental blocks during the Permo-Triassic and the late Cretaceous–Early Tertiary collision of western Burma with the Shan Thai block may also have caused left-lateral slip (e.g. Bunopas 1981; Cooper et al. 1989; Polanchan & Sattayarak 1989). However more recent studies indicate sinistral motion on the Mae Ping fault zone ended at about 30 Ma (Ahrendt et al. 1993; Lacassin et al. 1997). Polanchan et al. (1991) proposed that Oligocene–Recent strike-slip movements in Thailand were dominated by right-lateral slip on NW–SE-striking faults and left-lateral slip on NE–SW–striking faults, with transtensional dextral shear being dominant. Maximum horizontal displacements were estimated in the order of tens of kilometres. Polanchan et al. (1991) proposed that the Tertiary basins formed at releasing bends within a virtually pervasive system of conjugate strike slip faults. This remains the model most widely applied to the basins of Thailand today.

This paper discusses a new tectonic model for the region based on evaluation of a considerable amount of oil and coal company subsurface data from the Tertiary rift basins and on outcrop data. Information about the subsurface basins in Central Thailand and the Gulf of Thailand has come from MSc research projects conducted at the University of Brunei Darussalam by employees of PTTEP and Unocal using 2D and 3D seismic reflection data sets (e.g. Morley et al. 2000; Watcharanantakul & Morley in press; Morley & Wongnan in press). A comprehensive review of the structural evolution of the Tertiary rift basins based on the new data mentioned above and published data is presented in Morley et al. (in press).

Evolution of Tertiary rift basins

This section provides a summary of the main characteristics of Tertiary rift basin evolution that must be incorporated into any regional tectonic model.
Timing of rift activity

Patchy Eocene–Oligocene rifting is known from onshore Thailand (e.g. Krabi basin) and the northern Gulf of Thailand (e.g. Chaodumrong et al. 1983; Ratanasthien 1990; Ducroq et al. 1991; Jardine 1997; Vilaihongs & Areesiri 1997). The extent and geometry of these basins is poorly defined: Lockhart et al. (1997) states that the oldest well penetrations to date in the Gulf of Thailand are possibly Late Oligocene and Early Miocene. Depocentre locations changed in the northern Gulf of Thailand (e.g. Krabi basin) and the northern Gulf of Thailand discussed in this paper are in dark grey.

Onset of thermal subsidence

The termination of rifting clearly youngs northwards from the earliest Miocene in the south (West Natuna basin, Malay basin), to the Late Miocene and Pliocene in the Central Plains (Fig. 2). Northern Thailand underwent little or no thermal subsidence due to late cessation of rifting and persistent uplift (Fenton et al. 1997; Upton et al. 1997). Uplift mechanisms include: magmatic underplating (Late Cretaceous–Tertiary igneous activity), crustal shortening (compression and strike-slip events), isostatic uplift due to normal faulting associated with metamorphic core complexes (Palaeogene?) and rifting. Uplift was both relatively slow, long-term uplift from the Late Cretaceous onwards and more local short-term rapid uplift over a few million years (Upton et al. 1997). Central Thailand is a low relief area of relatively low crustal temperatures (3–4°C 100 m). Thermal subsidence began during the Pliocene (Flint et al. 1988). The Gulf of Thailand began thermal subsidence during the Miocene (Bustin & Chonchawalit 1995; Jardine 1997; Fig. 2). The western half of the Gulf of Thailand is relatively cool (heat flow up to 70 mW m²; geothermal gradients between 4–5°C 100 m; thermal sag basin thickness up to 2 km), while to the east the Pattani and Malay basins have anomalously high geothermal gradients for thermal sag basins (heat flow 78 mW m² to 101 mW m²; geothermal gradient 6–7°C 100 m; thermal sag basins up to 4 km thick, Bustin & Chonchawalit 1995; Madon 1997b; Watcharanantakul & Morley 2000).
Synchronous onset of the three main rift stages (rift initiation, rift climax, transition to thermal subsidence) across Thailand has been cited as support for regional tectonic events (e.g. Polachan & Sattayarak 1989; Chinbunchorn et al. 1989). However, as reviewed above increasing documentation of the Tertiary basin evolution shows that the notion of synchronous rift evolution is far too simplistic.

Inversion

Basins affected by inversion can be divided into three provinces with gradational borders based on the intensity and timing of inversion. They comprise (1) Northern Thailand, (2) Central Plains and the northern Gulf of Thailand and (3) the southeastern province comprising the Malay, Penyu and West

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**Fig. 2.** North–south to NW–SE variations in gross rift structure along the strike of the rift system passing from the West Nantuna basin in the south to the Fang basin in the north. Note there is considerable variation in the onset of thermal subsidence (Early Miocene in the south, late Pliocene– Pleistocene in the north if it occurs at all), and the duration of extension. Correlation of structural events passing from north to south in the region. Some palaeostress orientations are shown for the north; such detail cannot be established for Central Thailand and the Gulf of Thailand where the rifts are only known in the subsurface. Compiled from Knox & Wakefield (1983); Flint et al. (1988); O’Leary & Hill (1989); Pradittan (1989); Chinbunchorn et al. (1989); Ratanasthien (1990, 1992); Watanasak (1990); Remus et al. (1993); Bustin & Chonchawai (1995); Phillips et al. (1997); Madon (1997a); Jardine (1997); Wongpornchai (1997); Morley et al. (2000).

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*Diagram showing North-south to NW-SE variations in gross rift structure along the strike of the rift system passing from the West Nantuna basin in the south to the Fang basin in the north. Note the considerable variation in the onset of thermal subsidence (Early Miocene in the south, late Pliocene–Pleistocene in the north), and the duration of extension. Correlation of structural events passing from north to south in the region. Some palaeostress orientations are shown for the north, and such detail cannot be established for Central Thailand and the Gulf of Thailand where the rifts are only known in the subsurface. Compiled from various sources.*
Natuna basins (Morley et al. in press). Relatively strong inversion tectonics characterize the northern Thailand and southeastern provinces, while the Central Plains and northern Gulf of Thailand experienced relatively mild inversion (Fig. 2).

Northern Thailand experienced patchy, locally intense inversion at various stages from the Late Oligocene–Late Miocene (Morley et al. 2000, 2001). The timing and frequency of inversion episodes within and between basins varies considerably. Some coal mines reveal four or five episodes of inversion which span the Late Oligocene–Early Miocene to the Plio-Pleistocene (e.g. Li basin, Morley et al., 2000; Figs 2 and 3). While other mines reveal only one episode of inversion (e.g. Mae Moh, Morley et al. 2001). The most widespread inversion event in northern Thailand occurred during the Plio-Pleistocene and is associated with a NW–SE to NE–SW oriented maximum horizontal compression direction (Morley et al. in press). Modern stresses determined from earthquakes (Bott et al. 1997) indicates a similar stress system operates today, as predicted by finite element models of the Himalayan collision (Huchon et al. 1994).

Central Thailand and the northern Gulf of Thailand underwent only minor, local inversion during the Early, Mid- and Late Miocene (Figs 2 and 3). For example some localized inversion events occurred around the Oligocene–Miocene boundary (e.g. Jardine 1997). In the Kra basin seismic data shows evidence for very local, mild inversion in the Middle Miocene (Areanachaleekorn 1998). Minor inversion affected the Phitsanulok basin in the Late Miocene (Knox & Wakefield 1983) while inversion is strongest during the Pliocene in the Phetchabun basin (Remus et al. 1993).

In the Malay, Penyu and West Natuna basins, considerable inversion occurred during a number of episodes in the Early and Mid-Miocene while the Late Miocene and Pliocene was a period of tectonic quiescence, with no inversion after about 10 Ma (Ginger et al. 1993; Phillips et al. 1997; Madon 1997b; Fig. 2). Estimates of (NNW–SSE) shortening associated with the inversion for the southern Malay basin from Madon (1997a, f), and for the West Natuna basin from balanced cross-sections in Ginger et al. (1993). Extension in the northern Gulf of Thailand from extrapolation of β=1.3 across the gulf (Watcharanantakul & Morley in press).

Fig. 3. Location map of Tertiary rift basins of northern and central Thailand. Basin data compiled from: Knox & Wakefield (1983); Gibling et al. (1985); Chibunchorn et al. (1989); O’Leary & Hill (1989); Praditdum (1989); Remus et al. (1993); Muraoka et al. (1997); Vilaihongs & Areesiri (1997); Wongpornchai (1997); earthquake data from Bott et al. (1997); faults from Dunning et al. (1995) and Fenton et al. (1997). Palaeostress summary from this paper and Morley et al. (2000). L.O.-E.M, Late Oligocene–Early Miocene; M.M., Mid-Miocene; L. M., Late Miocene; P.P., Plio-Pleistocene.

Fig. 4. Geological map of the main Oligocene–Miocene rift basins in the Gulf of Thailand. Basins and faults compiled from Madon (1997a), Madon et al. (1997), Brown et al. (1981); Lockhart et al. (1997), Ginger et al. (1993); Phillips et al. (1997). Estimates of shortening associated with the inversion for the southern Malay basin from Madon (1997a, f, 6) and for the West Natuna basin from balanced cross-sections in Ginger et al. (1993). Extension in the northern Gulf of Thailand from extrapolation of β=1.3 across the gulf (Watcharanantakul & Morley in press).
Differences in the timing of extension, and basin orientation between the Thailand rifts and the Penyu and West Natuna basins seem to reflect different origins for the extension. The Penyu and West Natuna basins are probably related to rifting associated with the South China seas spreading centre, while the Thailand rifts are related in some way to the Himalayan orogeny as discussed in this paper. Quite how these different rift systems blend together via the Malay basin is unclear.

**Metamorphic core complexes**

Much recent work on the Tertiary tectonic evolution of northern Thailand has focused on uplifted pre-Tertiary 'basement' rocks (Cretaceous and Triassic granites, Palaeozoic sedimentary and metasedimentary rocks and gneisses). Until recently mylonitic amphibolite-grade ortho- and paragneisses and granitic rocks of the region were thought to be Precambrian (e.g. Suensilpong et al. 1982). Now U-Pb geochronology indicates a late Cretaceous and early Miocene age (Ahrendt et al. 1993; Dunning et al. 1995). Dating of uplift using the passage of micas through the 300°C isotherm (Ahrendt et al. 1993, 1997; Lacassin et al. 1997) and apatite-fission track analysis (Upton et al. 1997) indicates the gneisses west of the Chiang Mai-Tak line underwent about 10 km uplift during the late Oligocene–Early Miocene, if an average geothermal gradient is assumed. Macdonald et al. (1993); Dunning et al., (1995) and Rhodes et al. (1997) attribute the uplift, at least in the Doi Suthep and Doi Inthanon areas west and southwest of Chiang Mai to isostatic footwall uplift associated with the development of metamorphic core complexes bounded by low-angle normal faults (Fig. 5).

**Driving mechanisms**

As previously discussed, many workers attribute the formation of Tertiary rift to pull-apart structures associated with strike-slip faults (O’Leary & Hill 1989; Polachan & Sattayarat 1989; Polachan et al. 1991; Fig. 6). The model was proposed when little detailed data were available about the exact relationships between strike-slip faults and extensional faults. In this section the evidence for strike-slip faults is re-examined and then an alternative driving mechanism (subduction rollback) discussed.

**Testing the strike-slip model**

(1) Timing of strike-slip fault activity. Understanding the role played by NW–SE- and NE-SW-trending faults in Thailand requires establishing whether the strike-slip faults played an active or passive role in rift structure (Morley 1999; Watcharanantakul & Morley 2000). In the active mode they are the dominant fabric and create a through-going strike- or oblique-slip fault zone. The entire length of the fault zone should be active, have a consistent sense of displacement and cross-cut any other trend. A passive oblique fabric bears no relation to the regional extension direction, it is a pre-existing fabric that is partially reactivated by younger faults (Morley 1999). Segments of the oblique fabric form the preferred orientation for an unlinked or partially linked collection of faults. Watcharanantakul & Morley (2000) discuss evidence in the Pattani basin for active and passive strike-slip fabrics and conclude that syn-rift normal fault geometries, largely mapped from 3D seismic reflection data (e.g. Lockhart et al. 1997; Watcharanantakul & Morley 2000, fig. 4) support passive reactivation by late Oligocene–early Miocene normal faults. There is no evidence for pronounced strike-slip fault activity in the northern Gulf of Thailand after about 30 Ma.

(2) To open up the Pattani basin as a pull-apart in the Oligocene requires dextral motion on the Three Pagodas fault and displacement transfer across right-stepping faults bounding the Malay basin (Polachan & Sattayarat 1989; Fig. 1). This model is incompatible with the broad NW–SE-trending sinistrally sheared proposed to drive Oligocene extension in the Malay basin (Madon 1997a, b). Later in the Early Miocene extension continued in the Pattani basin, but ceased in the Malay, W. Natuna and Penyu basins to the SE (Madon 1997a; Ginger et al. 1993; Phillips et al. 1997; Fig. 2). Hence there is a problem transferring dextral strike-slip motion on faults opening up the Pattani basin into the (thermally subsiding) Malay basin.

Fig. 5. Geological cross-section across the northern Thailand rift basins illustrating the following characteristics: (1) mixed origins for the basins—possible strike-slip development of Mae Sariang Basin, metamorphic core-complex upper plate (Na Hong?), later extensional rift development associated with high-angle normal faults, in Chiang Mai, Lampang and Phrae basins, (2) changing age of basins, in general younging to the east, (3) young apatite fission-track (AFT) ages (Early Miocene) only associated with the metamorphic core complex (ages from Upton et al. 1997), (4) mica cooling ages through 300°C geotherm at 30 Ma (Ahrendt et al. 1993) requires 5–10 km of subsequent uplift. However, Na Hong basin of similar age (Late Oligocene) has high grade coal and requires burial of about 2 km followed by uplift. (See Fig. 4 for location, but note the section extends about 40 km west from the western edge of Fig. 3.) The cross-section around the metamorphic core complex is based on Dunning et al. (1995).
(3) If the Tertiary basins of northern Thailand formed as pull-aparts then offsets of pre-Tertiary lithology markers and adjacent Tertiary basins should be consistent with a strike-slip system of faults as sketched by Polachan & Sattayarak (1989) and Polachan et al. (1991) (Fig. 6). However, rarely is it possible to construct pull-apart geometries with associated strike-slip faults that show a consistent sense of offset of pre-Tertiary marker units or adjacent Tertiary rift basins and the correct releasing bend or stepping geometry. In fact most strike-slip fault trends do not offset the mapped boundaries of pre-Tertiary units (Fig. 6c).

(4) Palaeostress studies of the basins in northern Thailand show predominantly east–west extension (Morley et al. 2000, 2001; Fig. 3). Some faults have undergone extension followed by inversion indicating a change in stress conditions with time rather than a simple strike-slip story where structures of different orientations can synchronously display different senses of motion. The model of Polachan et al. (1991) predicts that NNE–SSW- to north–south-striking faults should display a dextral sense of motion (Fig. 6b). Yet at the Mae Lai mine, which lies along one of these trends, palaeostress data indicate sinistral strike-slip motion during inversion of normal faults (Morley et al. 2001). Consequently the structural evolution of some basins shows greater complexity or different kinematics to those predicted by the Polachan et al. (1991) model. Some strike-slip fault activity has occurred during the late Oligocene-Miocene activity of rift basins in northern Thailand, but not in the way predicted by Polachan et al. (1991). Strike-slip faulting may have more than one origin (Morley et al. 2001) including: (i) reactivation of older strike-slip trends during phases of inversion, (ii) strike-slip transfer faults between large extensional faults; (iii) oblique-slip transtensional faults, where extensional faults followed pre-existing fabrics oblique to the regional extension direction.

(5) The rift trend onshore and offshore in Thailand is predominantly north–south and linear, hence the overall appearance suggests an extensional rift, it would require a peculiar set of circumstances to localize strike-slip basins to a linear rift system.

(6) Palaeomagnetic data show late Neogene differential rotation between western and central Thailand (24.4\(^\pm\)7.7\(^\circ\) clockwise rotation), and eastern Thailand and Vietnam Thailand (13.5\(^\pm\)5.8\(^\circ\) clockwise rotation; McCabe et al. 1993). However within the central and eastern block McCabe et al. (1993) found no evidence for Neogene differential block rotation associated with the major strike-slip faults (the Mae Ping and Three Pagodas faults), as would be expected for important strike-slip zones. However more detailed palaeomagnetic studies would be beneficial to conclusively define whether Tertiary block rotations can be detected.

(7) The post-rift thermal subsidence story does not comfortably fit with a strike-slip setting. No strike-slip province has been documented as being associated with thermal subsidence basins, yet a widespread thermal subsidence basin post-15 Ma covers the whole of the northern Gulf of Thailand and is up to 4 km thick (e.g. Bustin \& Chonchawalit 1995; Madon 1997b; Watcharanantakul \& Morley 2000). Thermal subsidence basins are characteristic of extensional tectonics (e.g. Kusznir et al. 1995).

Strike-slip faults and rift basins have interacted, but the strike-slip faults do not appear to be the cause of rift basin formation in most cases. Possible alternative driving mechanisms are limited. Extension of areas with enhanced gravitational potential due to crustal shortening and thickening, or uplift by a mantle plume (e.g. England \& Houseman 1989; Buck 1991; Bott 1992) is one possibility. The passage of the Indian continent past the Burma block resulted in compressional events as early as the Eocene, (e.g. Mitchell 1993), hence enhanced gravitational potential due to crustal thickening may have played a role in metamorphic core complex development in northern Thailand and Burma (e.g. Dunning et al. 1995; Bertrand et al. 1999). However it seems a poor explanation for...
Fig. 7. Geological evolution of SE Asia from the Oligocene to Present based on the map in Figure 1, modified with the plate reconstructions of Lee & Lawver (1995) and illustrating details of the evolution of the Tertiary rift basins discussed in this paper. Block rates of slip from Avouac & Tapponnier (1993); Andaman Sea convergence v. transform motion from Moore et al. (1980).
extension in the topographically low Gulf of Thailand and Central Plains area. There is no documentation of a major Early Tertiary regional thickening event in southern Thailand and Malaysia that could have later led to gravitational collapse. Nor is there the widespread magmatism which thermally weakens the crust and leads to gravitational collapse. Lithospheric stresses that can generate extension include slab pull, and slab rollback (e.g. Bott 1992, 1993). There is no subducting slab attached to the Shan Thai or Indochina blocks, hence no slab pull mechanism is possible. That leaves the only remaining mechanism as subduction rollback associated with subduction of Indian Plate oceanic crust eastwards under the West Burma block (e.g. Bunopas 1981).

Subduction rollback

The record of subduction of the Indian oceanic crust beneath Burma is somewhat uncertain. Mitchell (1993) reviewed the evolution of the area as follows: a Cretaceous magmatic arc is followed by a gap in volcanic activity between 60 and 70 Ma. In the Mid-Eocene the Manipur Ophiolite was obducted onto the western margin of Burma (arc reversal). East-dipping subduction then became re-established. South of Bannmauk Early Oligocene subduction is indicated by a granodiorite intrusion. The Guwa Chaung granite yielded Late Oligocene–Early Miocene K–Ar age dates. Late Neogene-Quaternary volcanism best documents east-dipping subduction. Satyabala (1998) noted that the paucity of late Oligocene–early Miocene arc volcanics could indicate a variety of causes including no subduction, slow subduction and obduction.

In this section reasons for accepting a subduction rollback model are discussed. However the setting is far from an ideal, simple back arc model; there are two major deviations. First the north-northeasterly movement of the Indian Plate means that subduction is highly oblique along the West Burma segment of the trench (Moore et al. 1980; Lee & Lawver 1995), and so the importance of subduction rollback can be questioned. Secondly the belt of extension lies some 700–1000 km away from the trench, this is rather a long separation. It is not, however, completely unreasonable. For example in Sumatra the distance between the trench and region of back-arc extension is 300–800 km. Despite these reservations when a subduction rollback model is applied, it seems to provide a solution to many of the detailed aspects of rift and thermal sag basin evolution as discussed below.

The modern subduction zone geometry is less steeply inclined under Sumatra (about 30°) and steepens up passing northwards, where under Myanmar it dips steeply (about 50°) and is apparently inactive (Guzman-Speziale & Ni 1996), although the active-inactive nature of the zone is disputed (Satyabala 1998; Guzman-Speziale & Ni 2000). Thus the modern slab geometry is at least compatible with a subduction rollback explanation. A subducting slab model can also explain some of the major features of the Gulf of Thailand and onshore extensional system. If subduction rollback began at the southern end of the system (Fig. 7) then extension in the Gulf of Thailand could precede extension further north. As subduction rollback moved north in the Late Oligocene so extension propagated north. One pronounced coincidence is that the cessation of extension in the Gulf of Thailand in the Middle Miocene is marked by the onset of extension in the Andaman Sea (Curray et al. 1982), while extension in northern Thailand continued during the Mid-Miocene. Hence if the driving mechanism for extension lies to the west of the Andaman Sea (i.e. subduction rollback) then the debut of extension in the Andaman Sea explains the onset of thermal subsidence in the Gulf of Thailand, whilst extension continued to the north. Finally in the latest Miocene–Pliocene the subduction zone became completely inactive and extension terminated in northern and central Thailand. This coincides with the final docking and collision of the West Burma block and the northeastern Indian continent.

Subduction rollback and geothermal gradients

Three striking features of the Tertiary rift basins are: (1) their variable geothermal gradients, which range from average (3°C/100 m) to very high (7–9°/100 m, Watcharanantakul & Morley 2000); (2) high amounts of thermal subsidence in the Gulf of Thailand (Bustin & Chonchawalit 1995; Madon 1997b); (3) low amounts of syn-rift crustal extension based on fault heaves (β=1.2–1.3, Watcharanantakul & Morley 2000). Estimates of lithospheric extension from backstripping require thinning of the mantle lithosphere in the order of β=2–3 (Bustin & Chonchawalit 1995; Madon 1997b; Watcharanantakul & Morley 2000). These data strongly suggest non-uniform lithospheric thinning. One mechanism to accomplish this is an asthenospheric mantle thermal anomaly such as mantle plume (Watcharanantakul & Morley 2000) or propagating spreading centre.

An alternative to an active mantle thermal anomaly is greater stretching of the mantle lithosphere than the crust. This differential or non-uniform stretching could be accomplished by subduction rollback. If the slab steepens as it rolls back then the deeper the slab is from the (surface) hinge line, the greater the horizontal component of extension (Fig. 8). For
example steepening of a slab from 15° to 17° results in 19 km extension at 40 km depth, and 55 km extension at the base of the lithosphere (120 km).

The zone of extension in the Gulf of Thailand is up to about 300 km wide, if crustal extension is assumed to be a uniform $\beta=1.3$ this equates to about 90 km upper crustal extension. However the thermal subsidence basin requires a $\beta=2+$, i.e. 300 km extension of the mantle lithosphere. 90 km can be related to passive extension, the remaining 210 km of extension could be explained by slab steepening. For example an increase in slab dip from 17° to 35° would generate c. 220 km of lower lithosphere extension. The effect is greatest for gently inclined slabs and decreases for higher dips. Lower-lithosphere extension at least partially independent of surface extension can help explain why high geothermal gradients are associated with the Malay, Pattani, Chiang Mai and Fang basins and not others. The modest amount of upper crustal extension only requires up to 100 km westerly rollback of the trench, which is a very minor distance for the scale of structures involved (Fig. 7).

Eocene–Recent tectonic evolution of SE Asia

This section uses the aspects of basin evolution discussed above and fits them into a regional tectonic model. The main structural elements considered are illustrated in Figure 1, which has been modified in Figure 7 to include the plate reconstructions of Lee & Lawver (1995). The evolution is discussed for four time periods (Eocene–Late Oligocene, Late Oligocene–Early Miocene, Mid–Late Miocene and Pliocene–Recent). The passage of the Indian continent past the Burma block resulted in compressional events as early as the Eocene, probably as a result of obduction of oceanic crust (e.g. Mitchell 1993). If the Indian continent and the Burma block became coupled in Eocene-Oligocene times the suture would lie north of the Thai rift basins. Subduction of oceanic crust between the southern part of the Burma block and the Indian Plate could have continued (Mitchell 1993; Satyabala 1998) and possibly driven extension in Thailand and Myanmar, but diminished towards the north.

Eocene–Early Oligocene

Brias et al. (1993) link motion along the Red River fault with extension in the South China Sea, which requires early Oligocene activity on the Red River Fault. However other workers argue against a kinematic link (e.g. Rangin et al. 1995b; Wang & Burchfiel 1997) The latter view is followed here so the Eocene to early Oligocene is characterized by little
activity on the Red River shear zone and greatest activity (sinistral) on the Mae Ping fault zone (Leloup et al. 1995; Lacassin et al. 1997) (Fig. 7).

As reviewed in the timing of rift activity section there is scattered evidence for the initial creation of some rift basins in Thailand during the Eocene–Late Oligocene. Eocene–Late Oligocene extension is best documented in the West Natuna basin (Ginger et al. 1993; Phillips et al. 1997). Samples of ultramylonites at Lan Sang national park indicate that the ductile, sinistral deformation along the Mae Ping fault zone ended around 30 Ma (Lacassin et al. 1997).

The apparent patchy development of Eocene–Late Oligocene rift basins in Thailand contemporaneous with sinistral strike-slip fault activity could mean they have a strike-slip origin (unlike most later basins). Unfortunately there is no well-documented basin geometry from seismic or outcrop data to help determine the origins of the early basins. An approximately east–west oriented maximum horizontal principal stress direction is required to cause sinistral motion on the NW–SE-trending strike-slip faults and dextral motion on the NE–SW faults. Similar observations have been made for the Red River shear zone (Rangin et al. 1995a). The origin of the east–west compression probably lies with the motion of the NE corner of the Indian continental crust past the Burma block (Fig. 7; Huchon et al. 1994). While there was some northerly motion of Burma relative to the Shan Thai block in the Oligocene, it was relatively small compared with the Miocene-Pliocene motion (Lee & Lawver 1995). Strain partitioning commonly occurs with major strike-slip faults in the upper plates of oblique convergent subduction zones (e.g. McCaffry 1992; Maclood & Kemal 1996), and the Oligocene history of the Sagaing fault appears to represent such an occurrence. Oblique convergent motion was partitioned into strike-slip motion on the Sagaing fault, while compression/transpressional stresses affected the Shan Thai and Indochina blocks. In the northern Gulf of Thailand motion on the Three Pagodas fault zone, and counter clockwise rotation of Peninsula Malaysia along NE–SW-striking faults created a complex network of strike-slip fault trends.

Late Oligocene–Early Miocene

The Late Oligocene–Early Miocene represents a marked change in structural activity in the Shan Thai and Indochina blocks. Strike-slip deformation was largely abandoned and extensive north–south-trending extensional basins developed running from the Gulf of Thailand up into Northern Thailand, Myanmar and Laos (Fig. 7).

According to Macdonald et al. (1993), Dunning et al. (1995) and Rhodes et al. (1997) metamorphic core complexes developed during the late Oligocene–Early Miocene in the Doi Suthep and Doi Inthanon areas, of northern Thailand (Fig. 6). The timing is similar to that proposed for the Mogok metamorphic belt which lies adjacent to the Sagaing fault in Myanmar (Bertrand et al. 1999). Data is still very patchy in this region, but the suspicion must at least be entertained that regionally a number of metamorphic core complexes were developed in the Late Oligocene–Early Miocene between northern Thailand and the Sagaing Fault. One explanation could be that crustal thickening, uplift and igneous intrusions associated with the Eocene–Early Oligocene transpression created sufficient gravitational potential and lithospheric instability to generate metamorphic core complexes. This instability may have been promoted by a decrease in east–west compressive stress as India moved further north. To the south and east of the core complexes rift basins associated with relatively high-angle normal faults and low amounts of extension were developed. Episodically these extensional basins were subject to varying degrees of inversion (Morley et al. 2000, in press).

Another possible explanation of the metamorphic core complexes is that non-uniform lithospheric stretching related to subduction rollback resulted in anomalous lower lithospheric thinning under the Doi Suthep and Doi Inthanon areas. Consequently the crust was heated, isostatically uplifted and partially melted (resulting in the emplacement of Oligocene granites) this situation triggered low-angle detachment faulting.

Extensional stresses may not have been continually imposed on the Thai rift basins. The ease of motion along strike-slip faults of adjacent blocks (South China and West Burma blocks) would presumably have an effect on how stresses were distributed in the continental crust. Episodic inversion affected the region in the Late Oligocene–Early Miocene (e.g. Li Basin, Morley et al. 2000). Both east–west-directed compression and NW–SE to north–south compressional events are recorded, which may reflect transpressional events from the West Burma block (east–west), and from the South China block (NW–SE to north–south) during periods of less active displacement on the Sagaing and Red River strike-slip fault zones. When these faults locked compressional stresses may have built up in the vicinity of the Thai rift basins and led to inversion.

Evidence for brittle, right-lateral slip on the Mae Ping fault zone can be seen in well developed stepped striations on the approach road to the Lan Sang national park in NW Thailand. Their age is after or at the later stages of uplift that followed sinistral motion on the Mae Ping fault zone which terminated around 30 Ma (Lacassin et al. 1997). The magnitude of dextral displacement is not known, nor is it known whether the fault was active during the extensional or inversion stages of rift basin development. However following the arguments given in the driving forces section for the Three Pagodas fault, it is suggested that the Mae Ping fault played no significant active role in the development of most of the large Late Oligocene–Miocene rift basins with the possible exception of the Mae Sariang basin (Fig. 6). Certain small basins found along the traces of the strike-slip faults are also probably of strike-slip origin. Episodes of inversion where NW–SE to north–south compressive stresses affected the region are the favoured cause of right-lateral motion on the Mae Ping fault.

Regionally during this time the Red River shear zone experienced its greatest sinistral displacement (in the order of 500+ km, Leloup et al. 1995). In terms of relative motion the Shan Thai-Indochina block was expelled southeastwards relative to the South China block.

Mid-Miocene–Late Miocene

The Mid-Miocene marks another important reorganization of extension. At the beginning of the Mid-Miocene extension ceased in the northern Gulf of Thailand and was replaced by thermal subsidence. Continental extension in the Andaman Sea area followed by sea floor spreading in the Late Miocene coincides with this change, and could reflect the transfer of subduction rollback-related extension from the Gulf of Thailand to the Andaman Sea. Onshore in Thailand extension
continued, and in northern Thailand new Late Miocene–Mid-Miocene extensional basins (e.g. Lampang, Phrae, Mae Moh basins) tended to open eastwards of existing Late Oligocene rift basins (e.g. Chiang Mai, Li, Fang basins). Episodic inversion affected some basins (e.g. Fang and Mae Lai, Morley et al. in press) but appears to be much less significant than the preceding and following inversion events.

Regionally during the Mid–Late Miocene the Red River shear zone experienced little uplift and erosion after 15 Ma (Leloup et al. 1995). However left-lateral deformation is recorded on the Red River fault zone offshore up to 5 Ma (Rangin et al. 1995b). In terms of relative motion the Shan Thai–Indochina blocks and South China block were more or less coupled and expelled to the SW at similar rates. There was a little differential motion (probably kilometres to 10+ km) between the Peninsula block and the Shan Thai block as recorded by the dextral motion on the Mae Ping fault, which reflects episodic differential motion between the blocks.

The Pattani basin is pervaded by strands of minor conjugate extensional faults which affect the post-rift section and exhibit β<1.1. They are a very distinctive and unusual structural style. The faults develop semi-independently of the syn-rift faults, but nevertheless are closely related to them in terms of location. They probably represent a short-lived oblique extension event. Further to the southeast inversion in the Malay and West Natuna basins is thought to be due to episodic broad dextral shear which trended NW-SE (Ginger et al. 1993; Madon 1997b; Phillips et al. 1997). The origins of this shear are uncertain. Shortening is estimated to be about 20–40 km for the Early–Mid-Miocene inversion (Ginger et al. 1993; Madon 1997b; Fig. 5).

Pliocene–Recent

Extension ceased in most of the onshore Thai rift basins by the Late Miocene–Early Pliocene (Fig. 2). Thermal subsidence began to affect the onshore Central Plains area of Thailand. In northern Thailand Plio-Pleistocene inversion is widespread in many rift basins including the Li, Lampang, Mae Moh and Fang basins (Morley et al. 2001). The inversion events occurred during renewed (right-lateral) activity on the Red River shear zone, where the South China block was expelled southwards faster relative to the Shi–Thai and Indochina blocks (Allen et al. 1984; Leloup et al. 1995; Rangin et al. 1995a). Inversion features and modern earthquakes both indicate NW-SE to NE-SW horizontal maximum principal compressive stress directions (Figs 1 and 3). These orientations fit with the predicted stress orientations from finite element models of the collision of the indenting Indian Plate with the Eurasian Plate (e.g. Huchon et al. 1994, and Kong & Bird 1996).

Discussion and conclusions

The results of palaeomagnetic studies indicate that during the Late Tertiary Borneo rotated counter clockwise by about 45° and peninsula Malaysia rotated 15° counter clockwise (Fuller et al. 1991, 1999; Hall 1996). It has been convenient to use the strike-slip model for Thailand (e.g. Polachan et al. 1991) to help explain how both regions have rotated. Hall (1996) shows about 200 km dextral strike-slip displacement through the GOT during the Miocene from 20 to 10 Ma. This amount of displacement is based upon accommodating the counterclockwise rotation of Borneo not on the geological requirements in Thailand. Active strike-slip deformation was important prior to 30 Ma. From 30 Ma to the Recent large strike-slip displacements cannot exist because as discussed in the driving forces section. (1) It is impossible to drive a through-going strike-slip fault zone through the predominantly north–south-trending overlapping extensional fault sets found in the Gulf of Thailand. Segments of extensional faults may well follow pre-existing NW–SE and NE–SW pre-existing inactive strike-slip fabrics in pre-rift ‘basement’. (2) After 15 Ma in the northern Gulf of Thailand, and 25 Ma in the Malay and West Natuna basins thermal subsidence dominated the region. Thermal subsidence is a characteristic of extensional, not strike-slip deformation and post-rift basin would seal any pull-part activity if it had occurred previously. Hence the proposed strike-slip deformation and associated extensional faulting is completely mis-timed. (3) Some broad regional right-lateral shear or NW–SE compression did affect the Malay and West Natuna basins in the Early and Mid-Miocene in order to generate predominantly east–west to NE–SW-trending inversion anticlines and faults (Ginger et al. 1993; Madon 1997b; Phillips et al. 1997). However shortening is in the order of only 40 km on overlapping, predominantly soft-linked fault systems, (Fig. 4). Consequently for the Peninsular Malaysia–Thailand region the plate reconstructions by Lee & Lawver (1995) are favoured because they minimize strike-slip motion on the Mae Ping and Three Pagodas faults during the Miocene. However it leaves a question mark over the palaeomagnetic data and how the rotations of Peninsula Malaysia and Borneo can be accommodated.

The initial wooden block and plasticine model of Tapponnier et al. (1982) showed extrusion of blocks with constant senses of slip on the major strike-slip faults and a northerly younging in the onset of block activity as the collision zone developed. The escape tectonics of SE Asia as presently understood shows the following characteristics (Figs 7 and 9).

(1) A progressive northerly younging of initiation of Tertiary strike-slip faulting. This is best characterized by the cessation of sinistral slip on the Mae Ping fault zone at 30 Ma (Lacassin et al. 1997), with similar timing on the Klong Mariu and Three Pagodas faults; while the main period of sinistral activity on the Red River fault zone was from 27 to 17 Ma (Leloup et al. 1995; Harrison et al. 1996; Lacassin et al. 1997). This progression coincides with the northerly motion of India (Lacassin et al. 1997).

(2) Progressive extrusion of more northerly crustal blocks with time. The more southerly blocks were squeezed out faster, relative to their more northerly neighbours. This gave rise to sinistral strike slip. The blocks left behind as India moved further northwards became less active or inactive and developed extensional basins over portions of the older strike-slip faults (particularly the Shan–Thai, Indochina and Peninsula blocks). As the northerly propagation of block extrusion continued faults that were initially sinistral (when the southerly block was extruded) switched to dextral (as predicted by Huchon et al. 1994). The switch resulted from the more northerly block taking over extrusion from the block to the south, or extruding at a relatively faster rate. After reduced activity during the Late Miocene (activity is recorded in offshore sedimentary basins, Rangin et al. 1995b), Pliocene dextral motion on the Red River fault zone (Allen et al. 1984;
Leloup et al. 1995) reflects the continued progressive northwards activation of crustal blocks.

(3) A modification to the simple extrusion model is the percentage of India–Asia convergence accommodated by extrusion v. crustal thickening in Southern Tibet and the Himalayas. Harrison et al. (1996) suggested that the slowing of Red River fault activity in the Early Miocene reflects a progressive increase in the amount of convergence accommodated by crustal thickening. The evidence for inversion of rift basins in northern Thailand also indicates that a shorter period tectonic cyclicity existed during the Miocene when east–west extension was episodically interrupted by inversion. These minor crustal-thickening episodes, presumably occurred during periods when strike-slip faults to the north became locked.

(4) In addition to extrusion tectonics, regional east–west extension has been superimposed on the extruding blocks. The lithosphere has a complex thermal structure and thermal history as indicated by the diachronous onset of thermal subsidence, marked variations in heat flow and geothermal gradient between rift basins, the very deep thermal sag basins in the Gulf of Thailand, and rapid uplift associated with the gradient between rift basins, the very deep thermal sag basins. Subsidence, marked variations in heat history as indicated by the diachronous onset of thermal extension has been superimposed on the extruding blocks. The origin of the east–west extension is not completely clear, but a strike-slip pull-apart mechanism is completely inadequate. Subduction roll-back of the Indian Plate seems to offer at least some solutions to the timing and origin of the basins. Finite element models of the India–Asia collision have only modelled the effect of the Indian plate indenter on Asia (e.g. Huchon et al. 1994; Kong & Bird 1996). Consequently the modelled predictions about stress distribution do not entirely explain the complex rift and inversion history described in this paper. The models do, however, demonstrate that episodes of inversion are generally compatible with stresses originating from the Himalayan collision zone. Huchon et al. (1994) also showed that early in the collision history (Eocene–Oligocene) Thailand was likely to have been associated with east–west-trending maximum horizontal principal stresses, which fits well with early sinistral strike-slip on NW–SE-trending faults. Subsequently the maximum horizontal principal stresses in Thailand trended NW–SE to north–south, which fits well with later inversion structures.

(5) The assumption of rigid crustal blocks with strain concentrated on major strike-slip bounding faults (e.g. Tapponnier et al. 1982) simplifies plate reconstructions (e.g. Lee and Lawver 1995; Hall 1996). However using rigid models creates problems with the plate restorations and as Hall (1996) noted, results in overestimation of displacements in the Gulf of Thailand. Further evidence of strain internal to the blocks is the inability to take large displacements onland on the Red River fault zone into the offshore area (Rangin et al. 1995b; Wang & Burchfiel 1997). Inversion and extension in Thailand is another example of non-rigid behaviour.

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