Evolution from an oblique subduction back-arc mobile belt to a highly oblique collisional margin: the Cenozoic tectonic development of Thailand and eastern Myanmar

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Evolution from an oblique subduction back-arc mobile belt to a highly oblique collisional margin: the Cenozoic tectonic development of Thailand and eastern Myanmar

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Abstract: Previous tectonic models (escape tectonics, topographic ooze) for SE Asia have considered that Himalayan–Tibetan processes were dominant and imposed on cool, rigid SE Asian crust. However, present-day geothermal gradients, metamorphic mineral assemblages, structural style and igneous intrusions all point to east Myanmar and Thailand having hot, ductile crust during Cenozoic–Recent times. North to NE subduction beneath SE Asia during the Mesozoic–Cenozoic resulted in development of hot, thickened crust in the Thailand–Myanmar region in a back-arc mobile belt setting. This setting changed during the Eocene–Recent to highly oblique collision as India coupled with the west Burma block. The characteristics of the orogenic belt include: (1) a hot and weak former back-arc area about 200–300 km wide (Shan Plateau) heavily intruded by I-type and S-type granites during the Mesozoic and Palaeogene; (2) high modern geothermal gradients (3–7 °C per 100 m) and heat flow (70–100 mW m^{-2}; (3) widespread Eocene–Pliocene basaltic volcanism; (4) Late Cretaceous–earliest Cenozoic and Eocene–Oligocene high-temperature–low-pressure metamorphism; (5) *c.* 47–29 Ma peak metamorphism in the Mogok metamorphic belt followed by *c.* 30–23 Ma magmatism and exhumation of the belt between the Late Oligocene and early Miocene; (6) a broad zone of Eocene–Oligocene sinistral transpression in the Shan Plateau, later reactivated by Oligocene–Recent dextral transtension; (7) diachronous extensional collapse during the Cenozoic, involving both high-angle normal fault and low-angle normal fault (LANF) bounded basins; (8) progressive collapse of thickened, ductile crust from south (Eocene) to north (Late Oligocene) in the wake of India moving northwards; and (9) the present-day influence on the stress system by both the Himalayan orogenic belt and the Sumatra–Andaman subduction zone.

Thailand and Myanmar lie in a tectonically active region, south of the Himalayan orogenic belt, and east of the Sumatra–Andaman Trench (Fig. 1). The general Cenozoic tectonic history of the area is well established (Lee & Lawver 1995; Hall 2002): NE-directed subduction of the Indian plate oceanic crust under Sumatra and Myanmar lasted from the Mesozoic to the early Cenozoic. The arrival of the Indian continental crust in the vicinity of Myanmar during the Eocene terminated the role of the subduction zone as a sharply defined plate boundary. India coupled with western Myanmar and detached the western part of Myanmar (known as the west Burma block) from the continental core of SE Asia called Sundaland. During the Oligocene this coupling became manifest as a north–south-trending belt of dextral strike-slip or dextral transtension some 300 km east of the trench, that developed between the west Burma block and Sundaland as India dragged the west Burma block progressively north with respect to Sundaland (Curray 2005).

Until recently eastern Myanmar and Thailand were viewed as having a relatively passive involvement in the development of the Himalayan orogenic belt. Eastward to southward extrusion or escape of rigid crustal blocks along large Cenozoic strike-slip faults emanating from the eastern margin of the Himalayan–Tibetan orogen was the main model for Cenozoic deformation of the region (e.g. Tapponnier *et al.* 1986; Lacassin *et al.* 1997). In Thailand escape tectonics was proposed to be manifest as strike-slip faults and the development of associated rift basins, which largely represented the sum of Cenozoic tectonic activity (Tapponnier *et al.* 1986; Polachan *et al.* 1991). Little contractional deformation, magma generation or metamorphism was suspected. However, a wide range of new geological and geophysical data has been acquired in the last 15 years that suggests that considerably more varied deformation has affected NW Sundaland during the Cenozoic than that offered by the escape tectonics model.

Some of the important types of recent research over the last 15 years are outlined below. Progressive building of radiometric age databases and improvements in techniques by a number of research groups have begun to shed considerable new light

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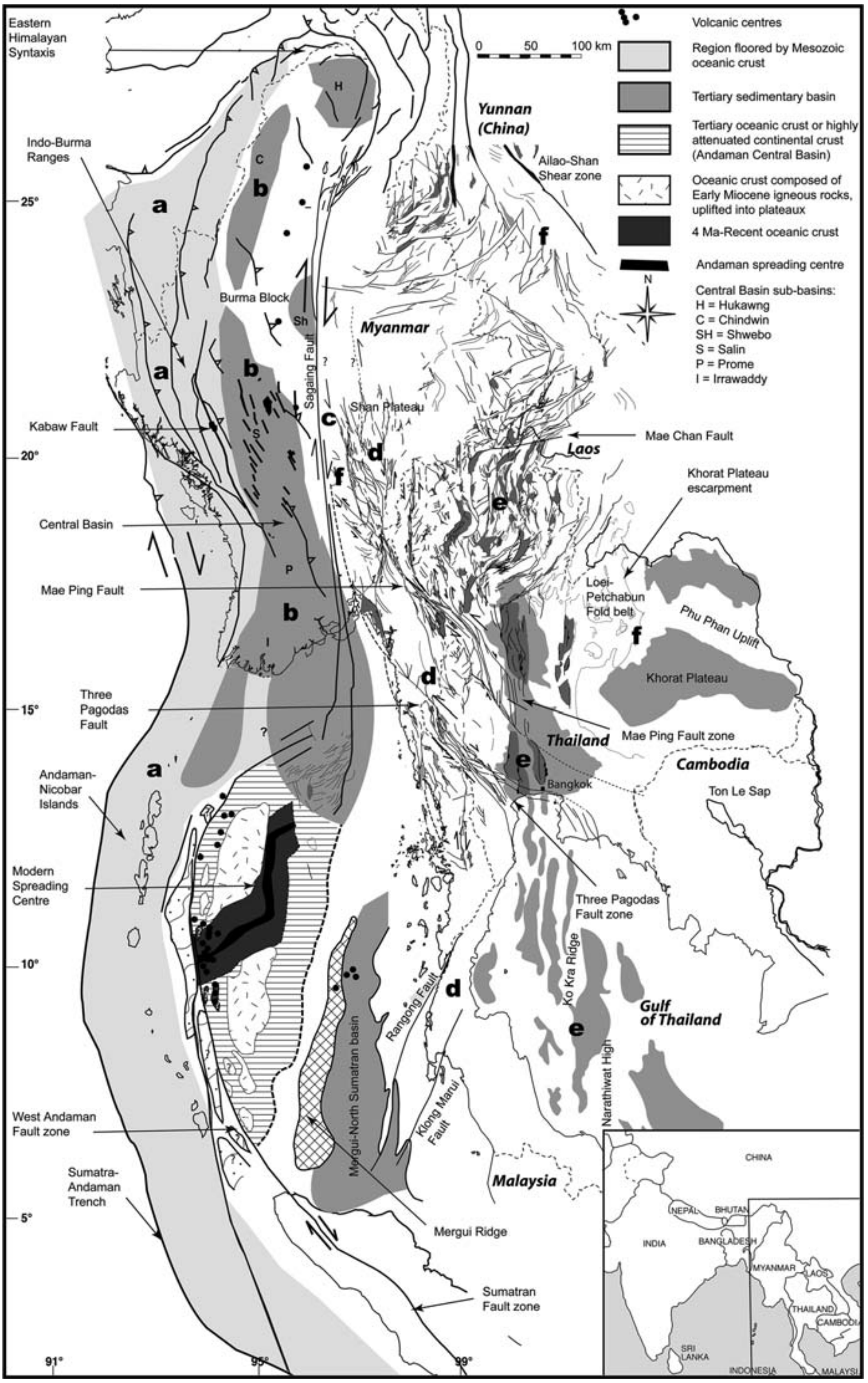

Fig. 1. Location map for the Myanmar–western Thailand region. Compiled from Pivnik *et al.* (1998), Morley (2004) and Curray (2005). (**a**) Sumatran-Andaman trench, Andaman Islands and Indo-Burma Ranges (developed on Mesozoic oceanic crust); (**b**) Central Basin; (**c**) Sagaing Fault-Sumatran Fault strike-slip system; (**d**) Shan Plateau; (**e**) Eocene-Miocene rift basins onshore and offshore Thailand; (**f**) Palaeogene folds and thrusts.

on the type, geometry and timing of deformation, and metamorphism, experienced by the region during the Cenozoic (e.g. Charusiri *et al.* 1993; Macdonald *et al.* 1993; Dunning *et al.* 1995; Ahrendt *et al.* 1997; Lacassin *et al.* 1997; Bertrand *et al.* 1999, 2001; Upton 1999; Barr *et al.* 2002; Barley *et al.* 2003; Searle *et al.* 2007). Seismic reflection and well data have provided considerable insights into the styles of synrift and post-rift basin deformation and history (e.g. Polachan *et al.* 1994; Jardine 1997; Morley 2002; Chantraprasert 2003; Uttamo *et al.* 2003; Morley *et al.* 2004, 2007*a*, *b*). Fieldwork and satellite data have more clearly revealed Cenozoic structural timing and styles (e.g. Mitchell 1989; Lacassin *et al.* 1997; Rhodes *et al.* 1997, 2000, 2005; Morley *et al.* 2000, 2001; Mitchell *et al.* 2002; Morley 2004). New marine geophysical data have considerably improved understanding of the Andaman Sea region (Nielsen *et al.* 2004; see review by Curray 2005; Fig. 1). Global positioning system (GPS) and earthquake data have defined the modern plate geometries and strain rates (e.g. Chamot-Rooke *et al.* 1999; Vigny *et al.* 2003, 2005). This body of data has only just reached the stage where the interrelationships of mantle, crustal and surface processes across a wide region can be integrated in the context of a unifying orogenic model. Many aspects still require considerable further study. In particular, the remote region that straddles eastern Myanmar and western Thailand, called the Shan Plateau (Fig. 1), remains poorly described: the thickness of the crust is not established in any detail, radiometric age dating of igneous and metamorphic events is sparse, and even basic geological maps are unreliable in detail. Clearly, much more work is required and there are significant limitations to the available data. However, there is considerable information that can be reviewed and synthesized in this paper, which indicates that the region experienced very dynamic tectonics during the Cenozoic.

This paper reviews the evidence for Cenozoic orogenic events in Myanmar and Thailand and describes some of the unusual characteristics of this region of NE Sundaland. Building on the regional geology of SE Asia discussed by Hall & Morley (2004), this paper proposes that the prolonged subduction history of the region strongly influenced the way deformation has progressed in eastern Myanmar and Thailand during the Cenozoic. The tectonic evolution of the region is described in two main sections, corresponding to the key tectonic stages. The first stage represents the subduction-dominated deformation and magmatism from the Mesozoic to the Early Cenozoic. The second stage marks the highly oblique collisional orogenic event when eastern India coupled with western Myanmar and subsequently developed a transform margin through eastern Myanmar. The main focus of the section is to describe the resulting deformation seen in NW Sundaland (i.e. eastern Myanmar and Thailand). A review of the Central Basin in Myanmar follows, because of its anomalous deformation history with respect to regions to the east and west. The discussion section addresses what plate-scale scenarios best explain the metamorphic, igneous and structural characteristics of the region described here. Before the evolution of the region can be described a broad outline of the geographical distribution of the main tectonic elements is necessary, and is given below.

Cenozoic tectonic elements of Myanmar and Thailand

Thailand and Myanmar form a region of Cenozoic deformation that extends *c.* 900 km in an east–west direction and *c.* 1800 km north–south. The region can be divided into six main Cenozoic tectonic provinces that trend approximately north–south (Fig. 1). Passing from west to east these provinces are: the Sumatra–Andaman Trench, Central Basin, Sagaing Fault zone, Shan Plateau, Eocene–Miocene rifts, and a region of Palaeogene folds and thrusts. A brief introduction to the provinces is given below:

(1) *The Sumatra–Andaman trench and overlying Andaman Islands–Indo-Burman ranges accretionary prism complex.* Oceanic crust has been subducted beneath the trench from the Mesozoic to Recent. Convergence became increasingly oblique as the overlying plate rotated clockwise during the Cenozoic (e.g. Lee & Lawver 1995; Curray 2005). The Indo-Burman ranges contain Cretaceous olistostrome mélanges, with blocks of gabbro, pillow basalt, serpentinite, banded chert, limestone and schist interpreted as having developed as a result of north- to NE-directed subduction during the Mesozoic–Cenozoic (Mitchell 1981).

(2) *The Central Basin.* In the south of Myanmar the basin forms a broad, flat-lying region of persistent and rapid subsidence and fluvial to shallow marine sedimentation from the Late Cretaceous to Recent, in a forearc location (Pivnik *et al.* 1998). Passing northward the topography becomes more hilly in places, as a result of inversion of the basin. Remnant arc-related volcanism affects the eastern part of the basin.

(3) *The Sagaing Fault–Sumatran Fault (SFSF) strike-slip system.* This is the main province that accommodates the northward motion of the west Burma block with respect to Sundaland. The SFSF system is a series of dextral transform fault zones that meet in the Andaman Sea at a large releasing bend that forms a back-arc spreading centre

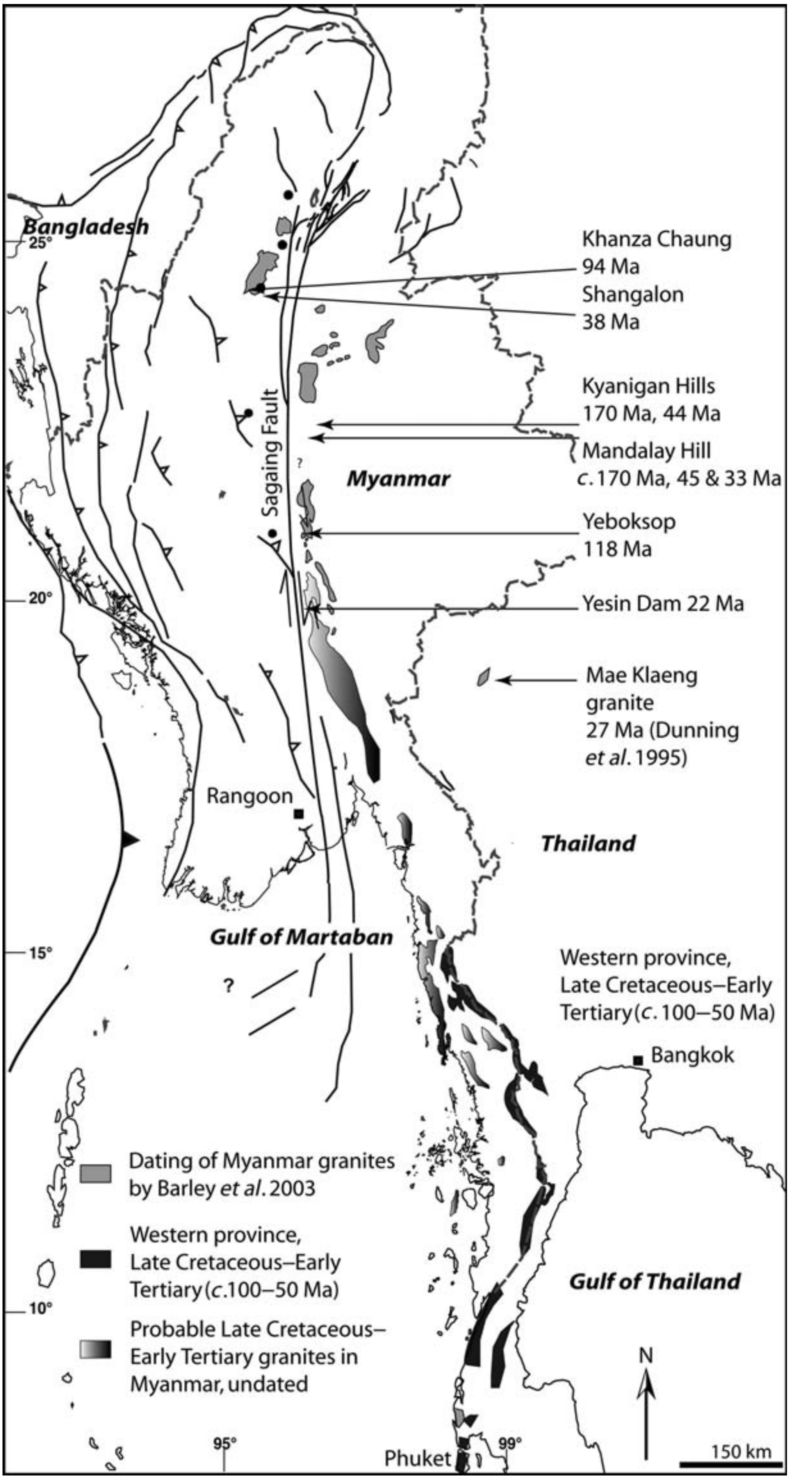

Fig. 2. Distribution of probable and dated Cretaceous–Cenozoic granite in Myanmar and Thailand. Compiled from Charusiri *et al.* (1993), Schwartz *et al.* (1995), Puttahpiban (2002) and Barley *et al.* (2003).

(Curray *et al.* 1978; Curray 2005). The Sagaing Fault is one of the largest and most active strike-slip faults in the world, with modern dextral slip rates of the order of *c*. 2.4 cm a^{-1} (Vigny *et al.* 2003; Curray 2005).

(4) *The Shan Plateau*. This is an uplifted region straddling eastern Myanmar and western Thailand, composed predominantly of Palaeozoic sedimentary and metasedimentary rocks extensively intruded by Mesozoic and early Cenozoic granites. In central Thailand the limit of the plateau is sharply defined by the low-lying topography of the Cenozoic post-rift basins (see (5) below). Typical maximum elevations in the plateau area are *c*. 1500 m. Around the western margin of the plateau are two important north–south-striking features, the Sagaing Fault and the Shan Scarp. The Shan Scarp appears to mark a Mesozoic terrane boundary between the Shan–Thai block to the east and the western Burma terrane (Mitchell *et al.* 2002). The Mogok metamorphic belt and the Carboniferous pebbly mudstones (Mergui Group) lie within the western Burma terrane. The Shan Scarp was later reactivated during the Cenozoic as the important (dextral strike-slip) Paunglaung Fault zone (Mitchell *et al.* 2002; Morley 2004). About 60–70 km west of the Shan Scarp lies the Sagaing Fault. The west Burma block came into existence during the Cenozoic as a result of development of the Sagaing Fault as a transform margin-defining fault. Extensive systems of NW–SW and north–south Cenozoic strike-slip faults also affect the Shan Plateau (Morley 2004).

(5) *Eocene–Miocene rift basins of onshore and offshore Thailand*. Post-rift subsidence has made the region of Cenozoic rift basins flat-lying and low. Offshore this region forms the Gulf of Thailand. Onshore the central plains are 450 km long and up to 125 km wide, and range in elevation from sea level to +50 m. Only in northern Thailand is the transition from the Shan Plateau less distinct and rift-related topography is still present. Over 40 isolated intermontane basins lie at elevations between 200 and 500 m. The basins are flanked by high hills with elevations up to 1500 m.

(6) *Palaeogene folds and thrusts*. This region includes surface folds seen on the eastern side of the Thailand rift basins, notably those that affect the Mesozoic clastic rocks of the Khorat Plateau (Cooper *et al.* 1989; Booth 1998). Palaeogene folds and thrusts are also seen, on seismic reflection data and in some wells, to underlie several onshore and offshore rift basins (e.g. Morley *et al.* 2004, 2007*a*).

Some of the provinces geographically overlap as a result of different timing of structural events. For example, the Palaeogene folds and thrusts were probably once present across the Shan Plateau, but folded Mesozoic rocks have been mostly removed by erosion or covered by later rift basins.

Mesozoic–Early Cenozoic geological evolution of the region

Mesozoic–Early Cenozoic plate setting of western Indochina

A number of major terranes rifted off Pangaea during the Palaeozoic and were conveyed northward as the Palaeo-Tethys was subducted beneath the proto-Asian margin (Metcalfe 1998). The collision of these terranes with the proto-Asian margin during the Permo-Triassic marks the Indosinian orogeny. Typically in Thailand and Myanmar the oldest peak metamorphic ages found in basement are Indosinian (*c*. 260–200 Ma; Ahrendt *et al.* 1997; Hansen *et al.* 2002; Barley *et al.* 2003). The most outboard of the terranes was the Shan–Thai (Sibumasu) block. Renewed rifting from northern Australia–Antarctica in the Late Triassic–early Jurassic defined the most western to southwestern terranes found in Sumatra (Sikuleh terrane) and Myanmar (western Burma terrane; Metcalfe 1998, 2002). Northward subduction and closure of the Meso-Tethys resulted in accretion of several terranes such as the Lhasa, Burma and Sikuleh blocks onto the Eurasian margin at different times during the Cretaceous (Metcalfe 1998). Finally, India rifted off the northern Antarctica–Australian margin during the early Cretaceous, resulting in closure of the Ceno-Tethys ocean, and creation of the Indian Ocean.

The transition of the SE Asian margin from post-Indosinian orogeny passive margin to Andean-type margin is marked by intrusion of Jurassic I-type granites and granitoids (*c*. 170 Ma; Searle *et al.* 1999; Barley *et al.* 2003). This margin extended westward well beyond SE Asia to at least the Karakorum region (Searle *et al.* 1999). The accretionary prism-related geology of the Indo-Burma ranges supports an Andean-type margin origin (Mitchell 1981). Cretaceous and early Cenozoic Andean-type granitoids have also been been identified in eastern Myanmar (Cobbing *et al.* 1986; Darbyshire & Swainbank 1988; Putthapiban 1992; Mitchell 1993; Barley *et al.* 2003).

In Thailand interpretation of the origin of the Late Cretaceous–Early Cenozoic (*c*. 90–50 Ma; Charusiri *et al.* 1993) granites and granitoids differs from that in Myanmar. S-type two-mica, tin-bearing granites predominate in volume over I-type granitoids (hornblende- and biotite-bearing tonalite and granodiorite). Late Cretaceous S-type granite forms bodies up to 120 km × 15 km, whereas I-type granite forms plutons about 5 km × 5 km

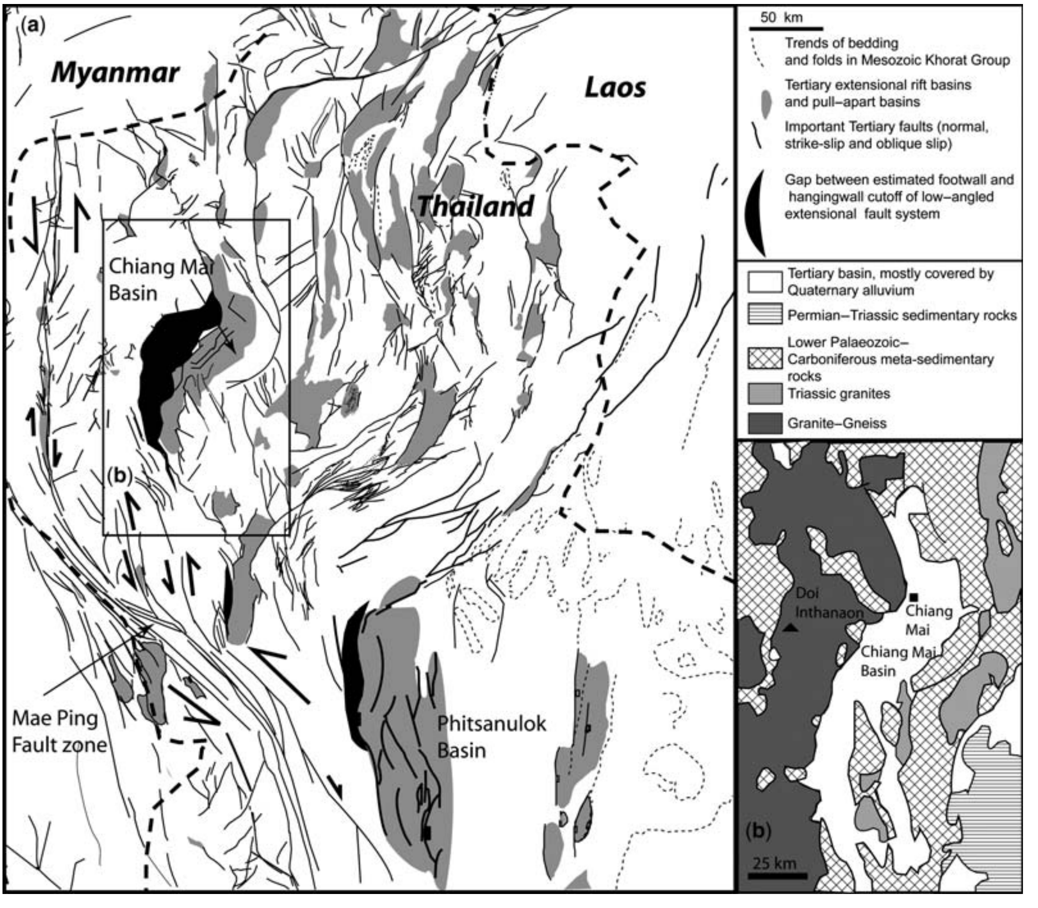

Fig. 3. (**a**) Location map for the Chiang Mai basin, northern Thailand, mostly based on Morley (2007). (**b**) Detailed location map of the highlands west of the Chiang Mai basin (modified from 1:500 000 geological map of Thailand, and Dunning *et al.* (1995)).

(Hutchison 1996). On the eastern margin of the Shan Plateau near Chiang Mai in Thailand (Fig. 3) the Doi Inthanon gneiss records a thermal event in the Late Cretaceous, as indicated by two U–Pb monazite ages of 72 ± 1 Ma and 84 ± 2 Ma (Macdonald *et al.* 1993; Dunning *et al.* 1995).

Origin of the Late Cretaceous–Early Cenozoic orogenic events

Charusiri *et al.* (1993) and Schwartz *et al.* (1995) suggested that the Late Cretaceous–Early Cenozoic S-type granites are related to crustal thickening caused by collision of the west Burma block with Sundaland. If there was a Late Cretaceous collision between the west Burma block and Sundaland, evidence for the suture is scant, with the Sagaing Fault lying approximately along the suture. The only candidate for ophiolite remnants are the rocks of the poorly dated jadeite belt, whose suggested ages range between Late Cretaceous and Eocene (e.g. Hutchison 1996). However, if the jadeite belt rocks are simply parts of the ophiolites present to the west and east, then their age could be Late Jurassic (Mitchell 1981, 1993). The jadeite belt lies along fault strands at the northern end of the Sagaing Fault zone.

Although the generalities of the terrane accretion story of Metcalfe (1998, 2002) outlined above describe the tectonic setting of SE Asia well, in detail the origin and timing of accretion of some of the terranes is disputed. Most critical for the Shan Plateau area is the origin of the Sikuleh terrane. Barber *et al.* (2005) proposed that the Sikuleh terrane (including west Sumatra and western Myanmar) is of Cathaysia (Indochina) affinity. This terrane was detached from Indochina and moved to a position outboard

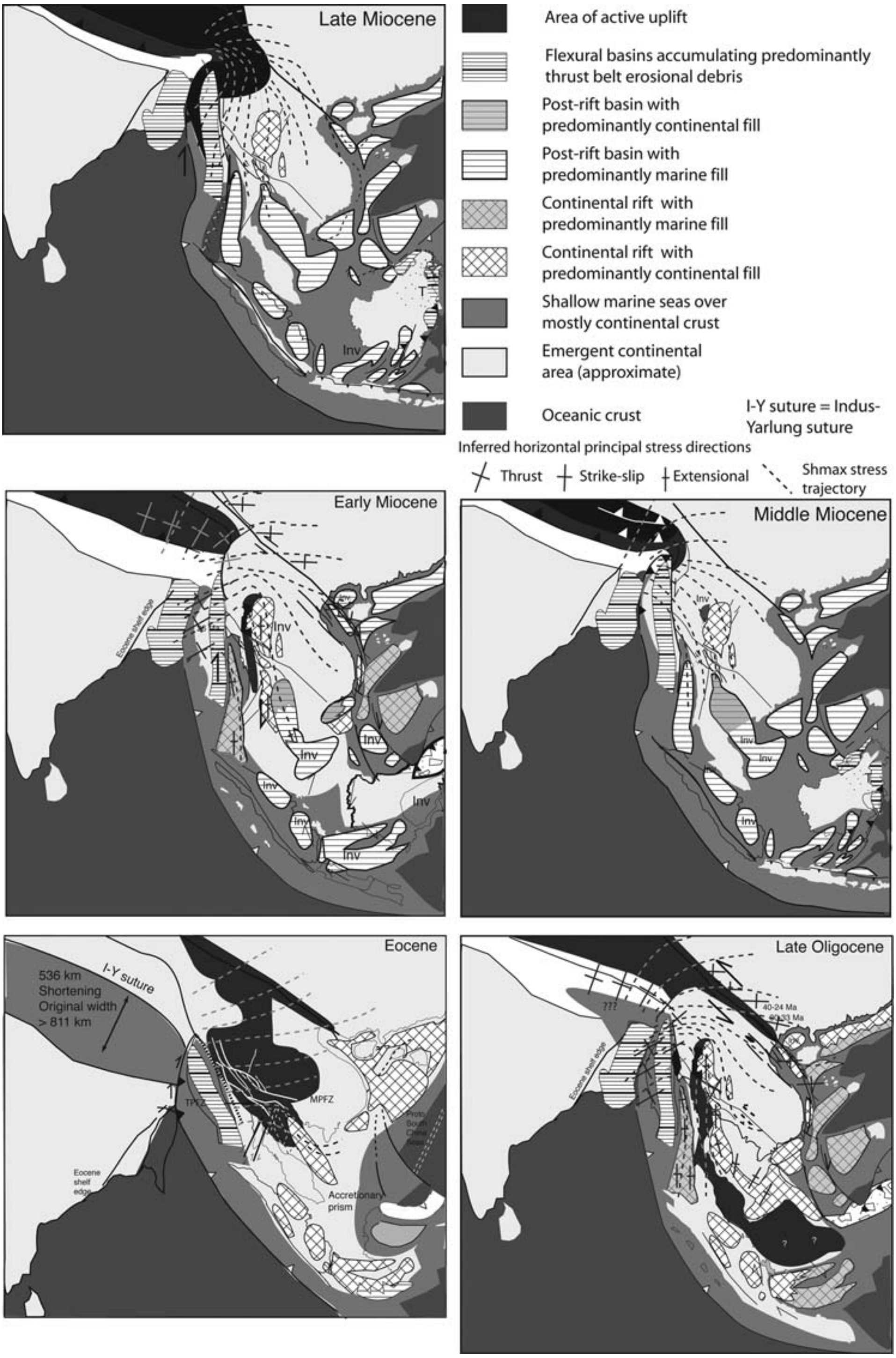

Fig. 4. Regional restoration of plates, and associated basins. Reconstruction based largely on Hall (2002), Hall & Morley (2004) and Morley (2004) with palaeostress orientations modified from Huchon *et al.* (1994). INV, basin undergoing inversion; MPFZ, Mae Ping fracture zone; T, Tarakan Basin; TPFZ, Three Pagodas fracture zone.

of the Sibumasu terrane along a transcurrent fault during the Triassic. Subsequently, an island arc collided with the west Sumatran block in the mid-Cretaceous. This scenario implies that late Cretaceous collision of the west Burma block with the Shan–Thai block could not have occurred as a result of closure of the Meso-Tethys. In an alternative scenario, Mitchell *et al.* (2007) suggested that early Cretaceous collision of an east-facing island arc with the Shan Plateau (including the west Burma block) was followed by early Cenozoic metamorphism in the Mogok metamorphic belt as a result of a reversal of tectonic polarity following arc–Shan Plateau collision.

Although there remains considerable variety in the current terrane accretion scenarios it seems reasonable to state that, despite its previous popularity, Late Cretaceous terrane collision in Myanmar is an unlikely cause of the Late Cretaceous–Early Cenozoic orogenic event. Accretion appears to have occurred considerably earlier in all current scenarios. One subduction-related event that could cause deformation, and a considerable thermal event, is subduction of a spreading centre (e.g. Thorkelsen & Taylor 1989; Schoonmaker & Kidd 2006; Whittaker *et al.* 2007). Hafkensheid (2004) has used restoration of estimated volumes of subducted material based on seismic tomography to test various plate-tectonic scenarios for the Tethyan realm. The best-fit model for the India–Eurasia collision was found to be that of Stampfli & Borel (2004). This model has a small back-arc ocean (Spontang Ocean) lying between the Indian plate oceanic crust and Eurasia. The reconstructions show that oblique subduction of the Spontang Ocean spreading centre during the Late Cretaceous–Early Cenozoic in the Myanmar–Sumatra region is a distinct possibility.

Another potential effect of subduction on continental deformation has been recently highlighted by Watkinson *et al.* (2009), who noted that the Sunda Trench between 90° and 100°E was the site of a dextral transform zone that accommodated differential motion between the fast (21 cm a^{-1}) northward moving India plate to the west and the slow or stalled Australia plate to the east. They proposed that ductile dextral deformation present along the NE–SW-striking Khlong Marui and Ranong faults in the Thai Peninsula (Fig. 1) was related to this differential motion. The timing of the dextral deformation is loosely constrained between 72 and 56 Ma intrusive events (Watkinson *et al.* 2009).

It is not the purpose of this paper to try and resolve the problems of interpreting sparse information on the Early Cretaceous–Early Cenozoic history of the region. The important key elements for the Cenozoic evolution of NW Sundaland are that Late Cretaceous–Early Cenozoic granite and granitoid emplacement occurred whether there was a Late Cretaceous microplate collision or subduction-related processes along an Andean-type margin. In either case, the Shan–Thai block (Shan Plateau area) is thought to have developed hot, thickened crust by the early Cenozoic (e.g. Charusiri *et al.* 1993; Mitchell 1993; Schwartz *et al.* 1995; Barley *et al.* 2003; Searle *et al.* 2007). This region of hot, weak crust became an important site of deformation when India tangentially collided and coupled with the Burma block during the Palaeogene (Fig. 4).

Coupling of India with western Myanmar

Regional tectonic evolution of the Andaman Sea region

During the early Cenozoic the western margin of what became the Andaman Sea region was probably an oblique convergence subduction zone–island arc system similar to present-day Sumatra to the south (Hall 2002; Curray 2005). The relative movement rate and direction of India with respect to Sundaland changed considerably during the Cenozoic (Curray 2005; Fig. 5). These changes affected the spreading rate in the Andaman Sea and whether deformation in Myanmar and Thailand was transpressional or transtensional. The key points from Curray (2005) are listed below, and illustrated for the Oligocene–Recent in Figure 6.

(1) *44–32 Ma*. Convergence following collision of India with Asia at about 59 Ma was initially about 100 mm a^{-1}; by 44 Ma this rate had slowed to about 60 mm a^{-1}.

(2) *32–23 Ma*. Continental extension was initiated in the North Sumatra–Mergui Basin (Polachan & Racey 1994; Andreason *et al.* 1997). Approximately 60 km of continental extension occurred in a 310° to 270° direction, at a rate of about 7 mm a^{-1} (Curray 2005). Accompanying the onset

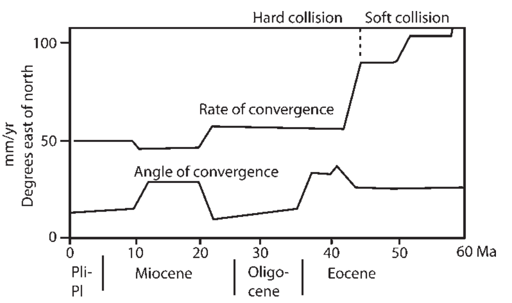

Fig. 5. Changes in direction and velocity of India–Eurasia plate convergence during the Cenozoic. Redrawn from Curray (2005).

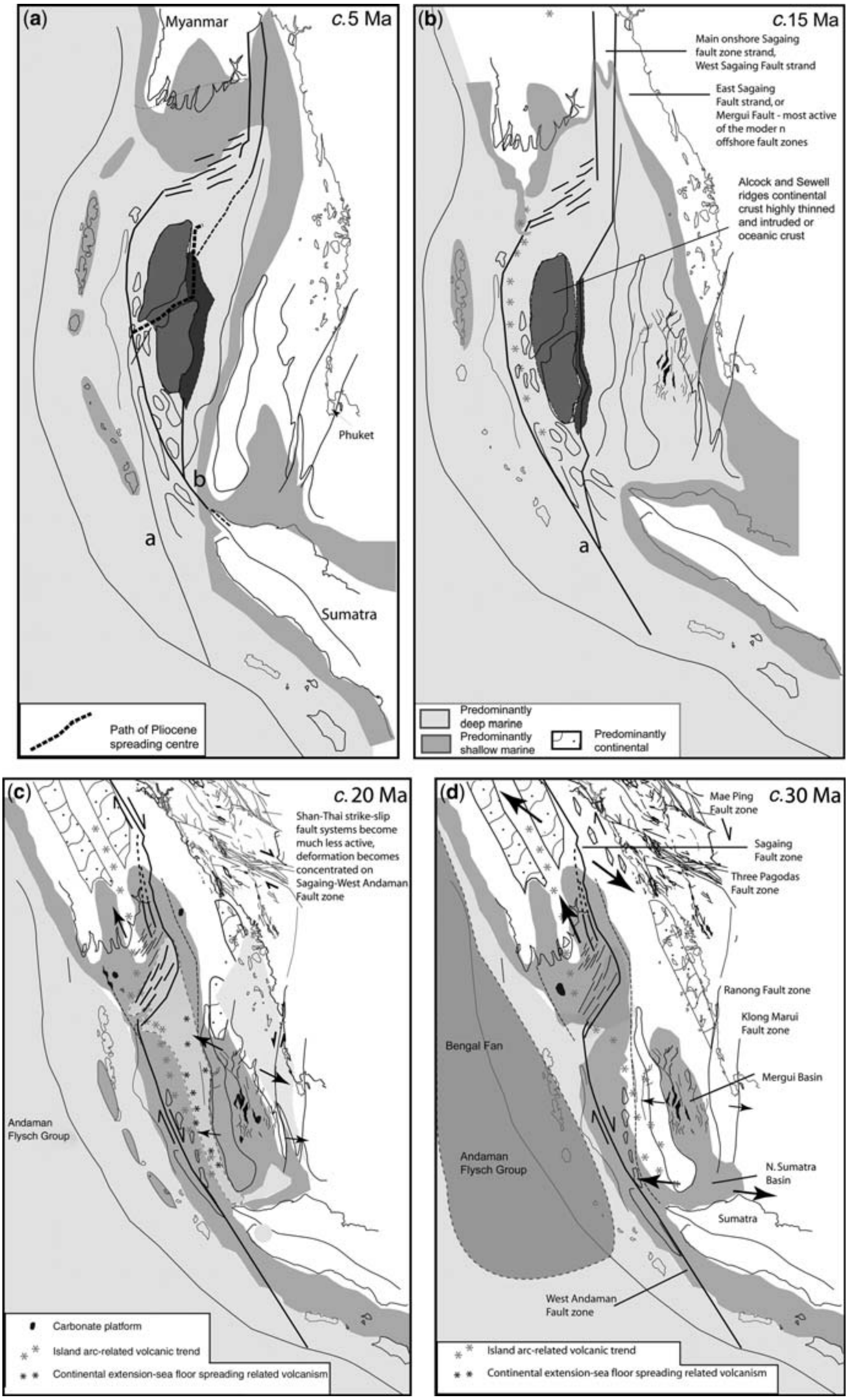

Fig. 6. Oligocene–Recent structural and tectonic evolution of the Andaman Sea area. Mostly based on data and maps of Hall (2002), Morley (2004) and Curray (2005). It should be noted that although the clockwise rotation of Thailand and Myanmar is show following Curray (2005), it is also possible that less rotation has occurred (e.g. Hall 2002).

of extensional and strike-slip deformation within the back-arc area there was decreasing activity along the Andaman–Nicobar part of the subduction zone. Recently there has been only one historically recorded volcanic eruption, and the subducted slab dips more steeply than in the Sumatran sector (Curray 2005; Shapiro *et al.* 2008). The onset of extension in the Mergui–north Sumatra basin marks the time when the margin evolved from an oblique Sumatra-like island arc margin to a more complex margin as the plate boundary. Accommodation of the differential motion between India and Sundaland broadened eastward from the Sumatra–Andaman subduction zone to more distributed dextral deformation within Myanmar and Thailand, particularly along the Sagaing Fault zone and Shan Plateau (Figs 4 and 6).

(3) *23–15 Ma*. The convergence rate of India with Eurasia dropped to less than 50 mm a^{-1}. The extension rate of the Andaman back-arc area was about 15 mm a^{-1}.

(4) *15–Ma*. The amount of extension along the NNE–SSW-striking Miocene spreading centre was *c*. 100 km in a 335° direction. The average opening rate was *c*. 9 mm a^{-1}.

(5) *4 Ma–present*. The present-day convergence rate of India with Asia is about 35 mm a^{-1} (Vigny *et al.* 2003). The present-day spreading centre, with dated magnetic anomalies, was initiated at *c*. 4 Ma, with an initial spreading rate of *c*. 16 mm a^{-1}, which increased to 38 mm a^{-1}, around 2.0–2.5 Ma (Kamesh Raju *et al.* 2004; Curray 2005; Fig. 5). The spreading direction was about 335°. Both Kamesh Raju *et al.* (2004) and Curray (2005) reached a similar conclusion that the Central Andaman Basin opened about 118 km in *c*. 4 Ma. The recent rate of dextral motion along the Sagaing Fault zone is of the order of 17–20 mm a^{-1}, suggesting that a further *c*. 15–18 mm a^{-1} is accommodated along other structures further west (Vigny *et al.* 2003; Sahu *et al.* 2006). Recent studies imaging shallow faults (Nielsen *et al.* 2004) and earthquakes coupled with modelling of global positioning system (GPS)-derived motions (Sahu *et al.* 2006) have identified major dextral faults in the Indo-Burma ranges and accretionary prism area that accommodated the dextral motion not taken up by the Sagaing–West Andaman fault system.

The Andaman Sea region records mostly extensional and strike-slip events in the trailing wake of the coupled India–Burma block region (Fig. 6). Towards the south the strike-slip faults, particularly the West Andaman Fault (Figs 1 and 6) connect the broad region of deformation in the Andaman Sea back to the more discrete plate boundary of Sumatra. Onshore in Myanmar and Thailand more complex orogenic effects related to the same plate-scale events are recorded.

Geological evidence for India coupling with the Burma block

In a highly simplified version of the structural style described by Curray (2005) the Indo-Burma Ranges–Andaman accretionary prism area can be characterized as an imbricate stack of predominantly eastward-dipping fault slices and folds (Fig. 7). Cretaceous ophiolites and older deep-sea sedimentary rocks generally lie at the top and on the eastward side of the prism. Progressively younger Neogene sedimentary rocks are found on the western side, and towards the base of the stack as well as draping the stack.

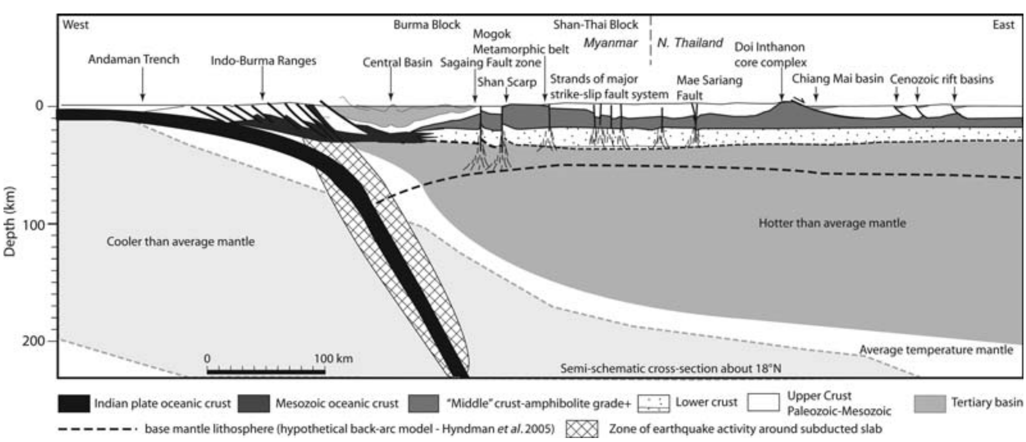

Fig. 7. A semi-schematic but true-scale cross-section across southern Myanmar and northern Thailand illustrating some of the main large-scale tectonic features of the area. The surface geology used is taken from *c*. 18°N. Mantle temperature distribution, and subduction zone geometry from Shapiro *et al.* (2008), their line 'A'.

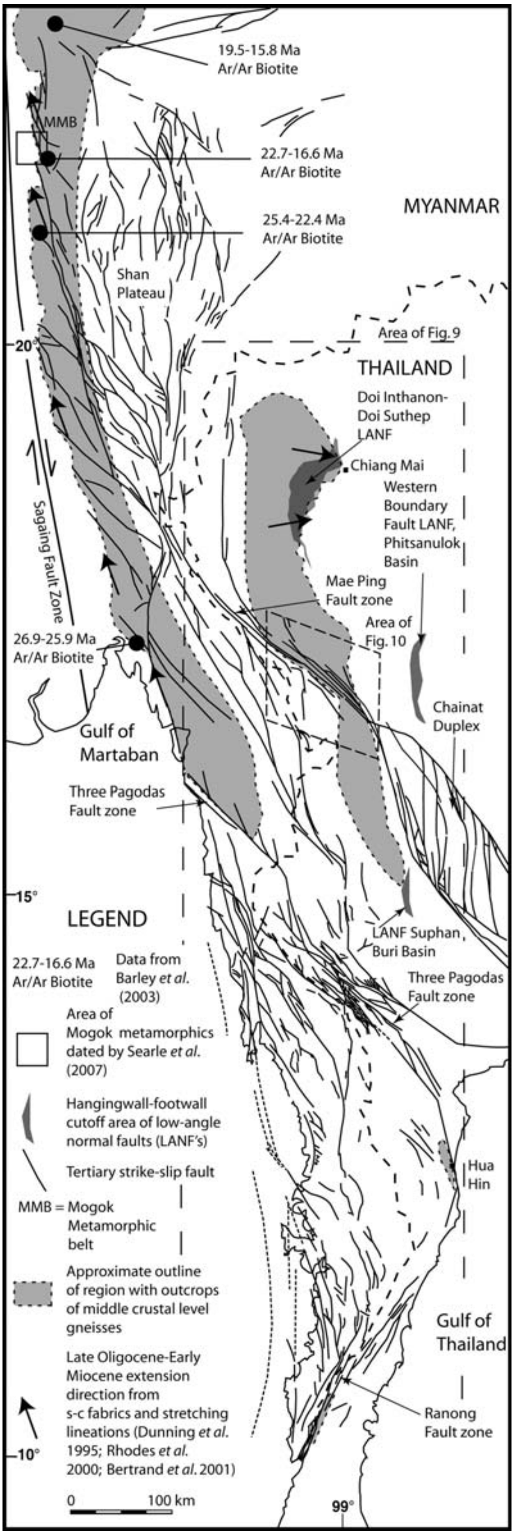

Fig. 8. Regional map of the Shan Plateau area. Fault patterns based on Landsat and digital elevation model (DEM) interpretation (revised from earlier interpretation by Morley 2004); the fault traces are inferred to be those associated with Cenozoic strike-slip faulting. The early sense of motion (Early Cenozoic to about 30 Ma) on these faults was sinistral; later fault movements were predominantly dextral. Biotite $^{40}Ar/^{39}Ar$ cooling ages along the Mogok metamorphic belt are from Bertrand *et al.* (1999, 2001).

Onshore, the Kabaw Fault separates the Late Cretaceous–Cenozoic clastic deposits of the Central Basin to the east from the Indo-Burma ranges to the west (Fig. 1). Although the Kabaw Fault has a reverse sense of motion, it probably also accommodates a considerable amount of dextral motion (Magung 1987, 1989; Zaw 1989). Offshore along approximately the same trend are the major dextral Diligent and West Andaman strike-slip fault trends (Curray 2005; Fig. 1).

Evidence for India coupling with Myanmar in the early Cenozoic has been found in a number of places. The Indo-Burman ranges were uplifted into a major subaerial mountain range during the Oligocene (Brunnschweiler 1974). Recent radiometric age dating has begun to reveal significant details about the response of the Mogok metamorphic belt to the coupling of the west Burma block with the Indian plate. Barley *et al.* (2003) reported *c.* 43–47 Ma rims to Jurassic zircons in orthogneiss and syenite interpreted as recrystallization during Eocene high-grade metamorphism. The magmatic age of a syntectonic syenite was determined as 30.9 ± 0.7 Ma and that of a late tectonic syenogranite as 22.6 ± 0.4 Ma (Barley *et al.* 2003). U–Pb and U–Pb–Th geochronology was conducted on the metamorphic belt by Searle *et al.* (2007). They combined their results with those of Barley *et al.* (2003) to conclude that a protracted period of sillimanite + muscovite grade, high-temperature metamorphism (*c.* 606–680 °C, 4.4–4.9 kbar), lasted from around 43 to 29 Ma and intermittent crustal melting occurred between 45.5 and 23 Ma (see Fig. 8 for location).

Although data are more restricted in Thailand there is evidence for similar magmatic events at around 45 Ma and younger in Thailand from granite–gneiss outcrops east (Chonburi) and west (Hua Hin) of Bangkok, as well as from the western highlands (Lan Sang, Doi Inthanon; Dunning *et al.* 1995; Charusiri 1989; S. Meffre, pers. comm.).

Shan Plateau: a Palaeogene sinistral transpressional strike-slip orogen

The most obvious structural features on satellite images of western Thailand and eastern Myanmar are the networks of sharp, curvilinear fault traces (Le Dain *et al.* 1984; Morley 2004; Fig. 9). These faults include major strike-slip faults (Mae Ping, Three Pagodas, Ranong faults; e.g. Tapponnier *et al.* 1986; Lacassin *et al.* 1997; Morley 2004, 2007) and occur in a north–south-trending belt, up to 250 km wide (east–west) and 1000 km long (north–south).

The best information on the timing and sense of motion of the strike-slip fault network comes from the Lan Sang National Park area of the NW–SE-striking Mae Ping Fault zone. Lacassin *et al.* (1993, 1997) determined a left-lateral sense of motion from an exhumed mid-crustal level, *c.* 5 km wide mylonitic shear zone (Figs 10 and 11). $^{40}Ar/^{39}Ar$ biotite cooling ages ranged between 33 and 30 Ma for the Mae Ping Fault zone and *c.* 36 and 33 Ma for the Three Pagodas Fault zone (Lacassin *et al.* 1997). The cooling ages were interpreted by Lacassin *et al.* (1997) as documenting the last increments of ductile sinistral deformation. At a restraining bend along the Mae Ping Fault zone the Umphang gneisses were sampled for zircon and apatite fission-track (AFT) dating (Upton

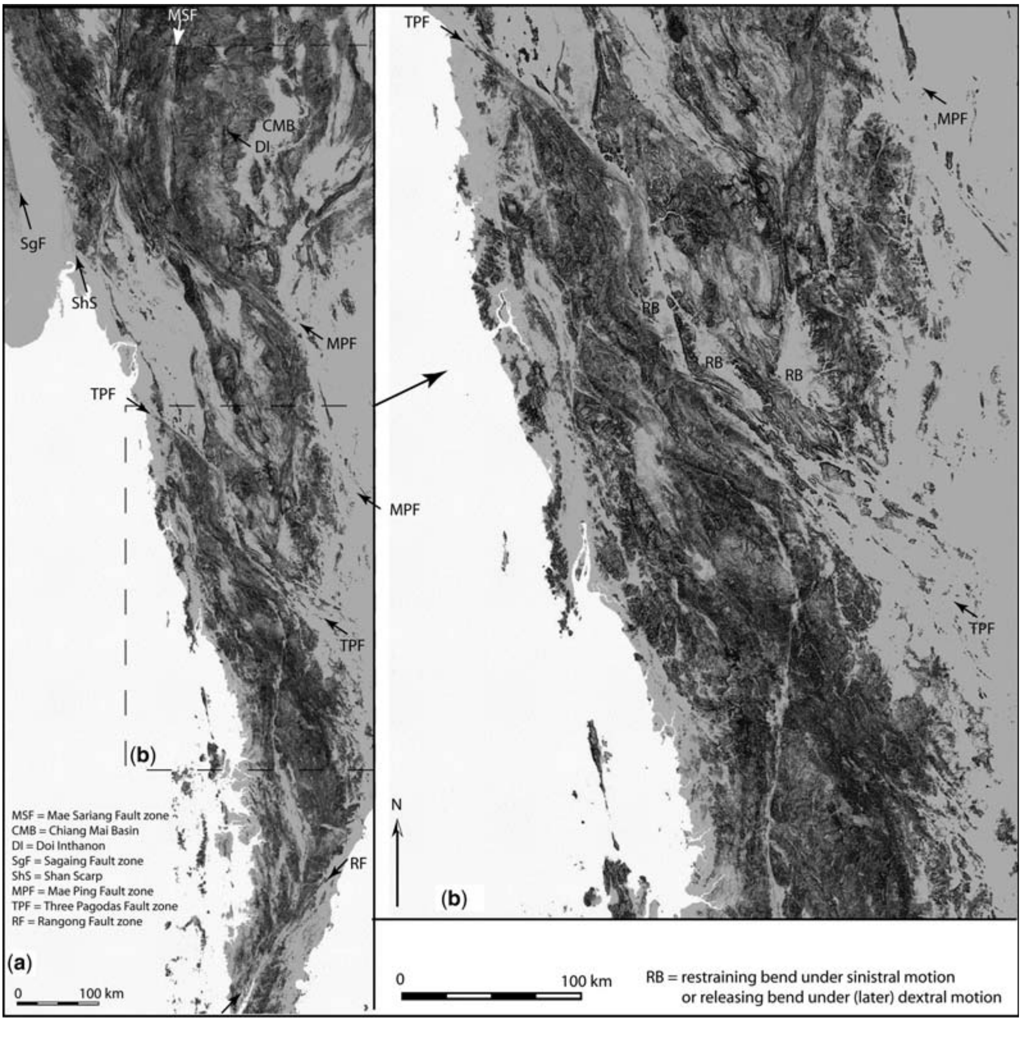

Fig. 9. Dip map of topography showing how clearly Cenozoic strike-slip faults show up as sharp linear features in the landscape. An interpretation of the fault patterns and location for the map are given in Figure 8. The strike-slip faults tend to form networks of north–south- and NW–SE-striking faults. The dense network of faults over a broad area suggests more of a transpressional fault style, compared with sharp, block-bounding strike-slip characteristic of escape tectonics.

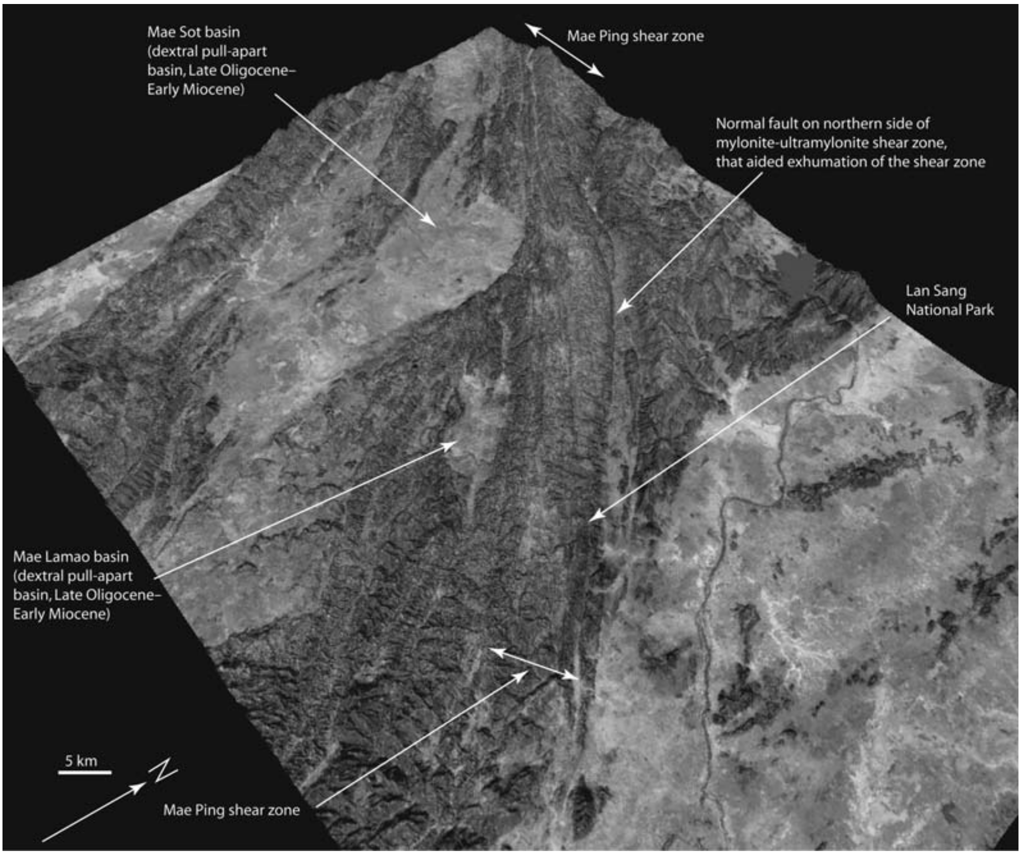

Fig. 10. A 3D perspective of a satellite image draped over a 90 m DEM with a view to the NW along the Mae Ping fault zone. The linear ridge formed by the fault zone comprises sheared middle-crustal level rocks, about 5 km wide, within which are zones of mylonites and ultramylonites of hundreds of metres to *c*. 1 km wide (Lacassin *et al.* 1997); the shear zone is best exposed in Lan Sang National Park. The shear zones are indicative of sinistral motion (Fig. 12), and associated $^{39}Ar/^{40}Ar$ biotite cooling ages range between 33 and 30 Ma (Lacassin *et al.* 1997). Exhumation of the shear zone appears to have been aided by the presence of a normal fault on the northern side of the shear zone (Lacassin *et al.* 1997). The geometry of the Mae Sot Basin indicates that the Mae Ping fault zone reversed its sense of motion during the Late Oligocene–Early Miocene, undergoing (minor, probably $<$10 km) dextral motion. (See Fig. 8 for location.)

1999; Fig. 10). The results of the dating indicated exhumation between *c*. 50 and 40 Ma, which Morley *et al.* (2007*b*) interpreted as representing the timing of early sinistral transpressional faulting.

The geometry of the broad fault network is very different from the long, single straight strike-slip faults that accommodated rigid block movement in the region (Sagaing Fault zone, Fig. 1, Red River Fault zone; e.g. Leloup *et al.* 1995). The sinistral sense of motion on NW–SE-oriented fault strands requires an approximately east–west maximum horizontal stress direction (Huchon *et al.* 1994; Figs 4 and 12). On the basis of fault geometry, Morley (2004, 2007) inferred that the region of strike-slip faulting was characteristic of a transpressional orogenic belt related to India–Burma coupling.

If there once was a more classic fold and thrust belt associated with the transpressional orogenic belt, it is not immediately obvious from the mapped geology of Thailand. With the exception of the Late Triassic–Cretaceous Khorat Group, the remainder of the rocks cropping out in Thailand were those previously caught up in the Indosinian orogeny, then intruded by Triassic and Cretaceous granites. Hence the highly heterogeneous nature of the upper crust means that a regular fold and thrust belt exploiting a simple layer cake stratigraphy did not develop. Instead, the early Cenozoic deformation that is detectable in the Palaeozoic rocks is the transpressional sinistral system (Figs 8, 9 and 12).

The thick, extensive Late Triassic–Cretaceous Khorat Group sedimentary rocks preserved in the

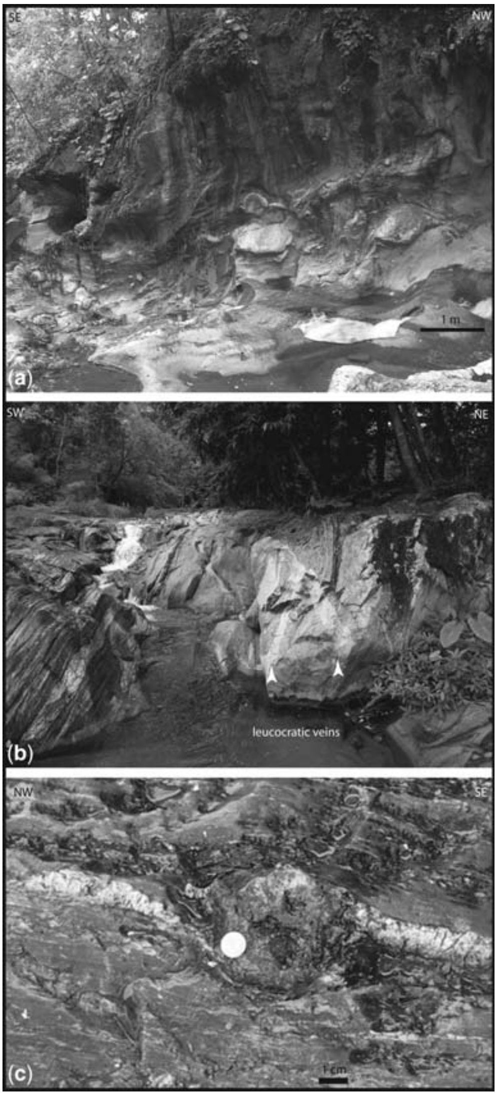

Fig. 11. Mid-crustal level Oligocene deformation: shear zones in the Mae Ping fault zone at Lan Sang National Park (see Fig. 10 for location). (**a**) High-strain zone within paragneiss, boudinaged more resistant units within marble; (**b**) typical steeply dipping mylonitic fabric (striking NW–SE) with some cross-cutting leucocratic veins that have been rotated to a low angle with respect to the shear zone; (**c**) downward view onto flat-lying surface showing δ structure in boudinaged leucocratic vein indicative of sinistral displacement.

Khorat Plateau of eastern Thailand display a number of broad folds (Cooper *et al.* 1989; Kozar *et al.* 1992; Booth 1998; Fig. 12). The Khorat Group is up to 4000 m thick (Racey *et al.* 1996) and thins only gradually towards the western margin of the plateau. Isolated remnants of Khorat Group are found scattered in synclines in central Thailand, southern peninsular Thailand and the Gulf of Thailand (Fig. 12). Beneath the Late Oligocene–Miocene sediments of the Phitsanulok basin the folded and imbricated Khorat Group is visible on seismic reflection data (Morley *et al.* 2007*a*; Fig. 12). Hence widespread folding and thrusting seems to have occurred but uplift and erosion of the Khorat Group across Thailand removed much of the evidence. AFT dating of the western edge of the Khorat Plateau (Fig. 12) indicates that the samples experienced near total annealing between 70 and 50 Ma (Upton 1999). The age range is later than the *c*. 110 Ma age for the upper part of the sequence (Racey *et al.* 1996), hence there is the possibility that an orogenic-related thermal event resulted in the annealing, not simple burial. Samples left the partial annealing zone between 49 and 11 Ma, with those nearest the strongly deformed areas uplifted between *c*. 49 and 30 Ma (Upton 1999). This dating suggests that the timing of folding in the Khorat Plateau was coincident with sinistral displacement on the sinistral transpressional zone to the west.

Oligocene–Recent dextral transtensional strike-slip system: unroofing of the orogen

After 30 Ma the strike-slip faults of the Shan Plateau reversed their sense of motion, with the dominant NW–SE to north–south trend undergoing dextral motion. Evidence for dextral motion comes from fault shear-sense indicators (Bertrand *et al.* 1999; Morley *et al.* 2007*b*), pull-apart basins developed along large-scale releasing bends as seen on geological maps and satellite images (e.g. Lacassin *et al.* 1998; Morley 2001, 2007; Figs 9 and 10), and from earthquake focal mechanisms (Bott *et al.* 1997). Morley (2007) contended that the late dextral strike-slip motion was largely confined to the Shan Plateau area and died out eastward, so that the north–south-trending Oligocene–Miocene rift basins east of the plateau (Fig. 1) are largely extensional in origin. The extensional basins appear to overlie the more external parts of the older sinistral transpressional belt, and may be associated with orogenic collapse.

The sinistral motion is inferred to be a result of strain partitioning and transpression caused by India–west Burma coupling, whereas the change to dextral motion is related to the subsequent northward movement of the coupled India–west Burma block. At the southern part of the system the Andaman Sea underwent extension–transtension during the Oligocene, probably commencing around 32 Ma (Polachan *et al.* 1994). To the north

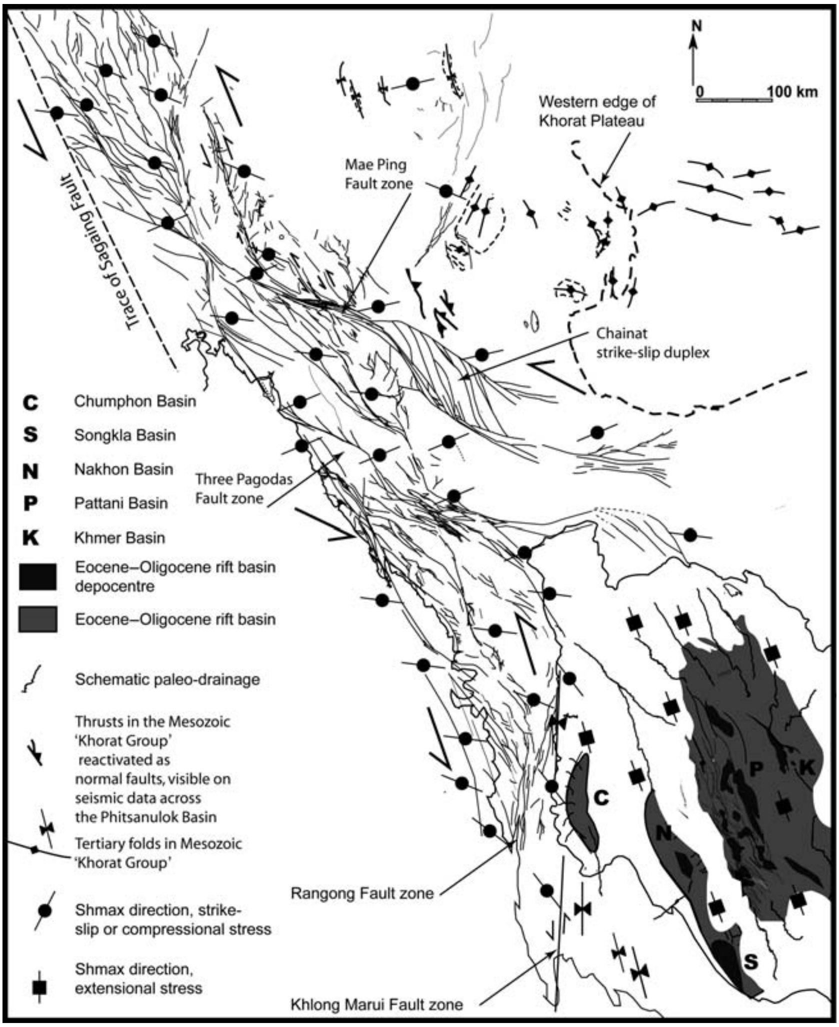

Fig. 12. Illustration of the Eocene–Early Oligocene deformation that affects Thailand and eastern Myanmar. The orientation of the structures has been rotated 20° anticlockwise from the present day to reflect Eocene orientations (e.g. Curray 2005). Strike-slip fault patterns from interpretation of surface geology and satellite geology (revised from Morley 2004, 2007). Offshore the rift basins may have developed on an earlier Cenozoic transpressional belt. Rift basin configuration from Morley & Westaway (2006). Palaeostress orientations are based on Andersonian assumptions of S_{hmax} direction to faults, with north–south- to NW–SE-trending faults on the western side of the map having sinistral displacement (Lacassin *et al.* 1997). Fold patterns in the Khorat area have a range of orientations that probably does not directly reflect palaeostress directions, but instead represents the influence of pre-existing fabrics, particularly inverted Triassic rift basins.

the Mogok metamorphic belt displays NNW–SSE extensional stretching lineations on low-angle faults, and mica cooling ages young from south (*c.* 25–27 Ma) to north (22.7–16.6 Ma; Bertrand *et al.* 1999). NNW–SSE-oriented transtension is also indicated from data in the Central Basin to the west (Pivnik *et al.* 1998).

The peak metamorphic ages between 37 and 29 Ma obtained by Searle *et al.* (2007) came from the same region of the Mogok gneisses where Bertrand *et al.* (1999) determined 22.7–16.6 Ma biotite cooling ages (Fig. 8). Hence the transition from transpression, and peak metamorphism, to transtensional exhumation in one area probably occurred in about 7 Ma. However, along the entire system dextral transtension in the south probably occurred at the same time as sinistral transpression occurred further north, which may suggest a clockwise rotational pivoting of the Indian continent. The northward motion of India appears to have caused progressively younger transtensional activation of the Sagaing–Mergui Fault zone passing northward (Bertrand *et al.* 1999).

For the Mogok metamorphic belt Torres *et al.* (1997) reported a similar cooling history to Bertrand *et al.* (1999), supplemented with AFT dating that yielded central ages between 14.6 and 18.7 Ma. These Late Oligocene–early Miocene cooling ages fit well with the duration of the large pull-apart basins formed during strike-slip deformation in Thailand; in particular, the youngest ages of the Mae Sot, Mae Lamao (Fig. 10) and Nong-y-Plong (Three Pagodas Fault zone, Fig. 1) basins are Early Miocene. The timing of these strike-slip related basins differs from the larger, extensional basins of the central plains to the east, which continued to develop during the Middle and Late Miocene (Fig. 4; Gibling *et al.* 1985; Ratanasthien 1989, 2002; Watanasak 1990; Morley *et al.* 2001).

Today north–south dextral motion is no longer so widely distributed, but instead has become focused on the linear Sagaing Fault zone (Bertrand *et al.* 1999; Vigny *et al.* 2005) and the Indo-Burma ranges and Andaman–Nicobar Islands (Nielsen *et al.* 2004; Sahu *et al.* 2006). The eastern side of the Shan Plateau has only a low level of recorded earthquake activity (Bott *et al.* 1997).

Oligocene–Miocene central Thailand extensional province

Central Thailand is occupied by a string of large and small Oligocene–Miocene rift basins that lie immediately east of the Shan Plateau (Fig. 1). These basins display a northward transition to a more strike-slip dominated province passing into Laos (Fig. 1; Lacassin *et al.* 1998; Morley 2007). The basins have also undergone episodic inversion during the Miocene, indicating fluctuations in the stress state with time (e.g. Morley *et al.* 2000, 2001, 2007*b*; Morley 2007). Four unusual characteristics of the extensional province are discussed below: (1) episodes of basin inversion; (2) post-rift basin thickness in the eastern Gulf of Thailand; (3) the diachroneity of rift basin onset and termination; and (4) the presence of Oligocene–Middle Miocene low-angle normal faults (LANFs).

Basin inversion. Worldwide many rift basins are characterized by episodes of inversion; with the exception of long-lived basins there is usually only one significant phase, such as the post-rift inversion found in the central Sumatran basin (e.g. Pertamina BPPKA 1996). In the rifts of Thailand inversion is highly variable; some basins do not exhibit evidence for any inversion, whereas others display multiple events and alternate periods of extension with phases of inversion over a period of 15–20 Ma (Morley *et al.* 2001, 2007; Morley 2007). Inversion is generally poorly developed in the Gulf of Thailand, and becomes more important northward, particularly from the Phitsanulok Basin. Seismic reflection data from the southern Phitsanulok Basin display a strong inversion event during the early Miocene. At least four Miocene inversion events were identified from coal mines in the Li Basin, and many of the rift basins in northern and central Thailand terminated in the Late Miocene or early Pliocene with an inversion event (Morley *et al.* 2001). The episodic inversion appears to require considerable changes in the stress state during the Miocene, Figure 13 illustrates some of the likely permutations of the stress field during the late Cenozoic. Probably most of the time the rifts developed under extension (Fig. 13c) but for short periods were subject to stresses appropriate for inversion (Fig. 13b). Figure 13d shows the present-day stress state, which may be appropriate as far back as the latest Miocene. The current stress state is largely determined from earthquake focal mechanisms, but is supplemented by borehole breakout data in some areas (Morley 2007).

Post-rift basin thickness in the Gulf of Thailand. As reviewed by Morley & Westaway (2006), the Miocene–Recent post-rift thickness of the Pattani and Malay basins in the Gulf of Thailand exceeds 6–7 km in places. The post-rift basins are synformal in cross-section and subsidence is clearly not strongly fault controlled. The problem of understanding the rapid post-rift subsidence was discussed in detail by Morley & Westaway (2006). They concluded that conventional post-rift thermal subsidence models annot explain such subsidence, and consequently proposed that sediment loading initiated flow of hot lower crust away from the basin, thereby creating accommodation space (Fig. 14). The basin centre heat flows of around $100\ \mathrm{mW\ m^{-2}}$ and geothermal gradients of $6\ ^{\circ}\mathrm{C}$ per 100 m (Pigott & Sattayarak 1993) indicate that hot, ductile crust is present beneath the basin. For ductile flow away from the basin to operate, a pressure head at the top of the ductile crust had to be established. The pressure head is achieved in the model by erosion causing the brittle–ductile transition zone under the sediment source area (Shan Plateau) to be uplifted higher than the transition zone under the sedimentary basin. The sediment flux moved to the SE, in the opposite direction to the flow of ductile crust (Fig. 14b–d; Morley & Westaway 2006).

The schematic evolution of the Pattani Basin – Shan Plateau source area shown in Figure 14 is explained below. During the initial stage (Fig. 14a)

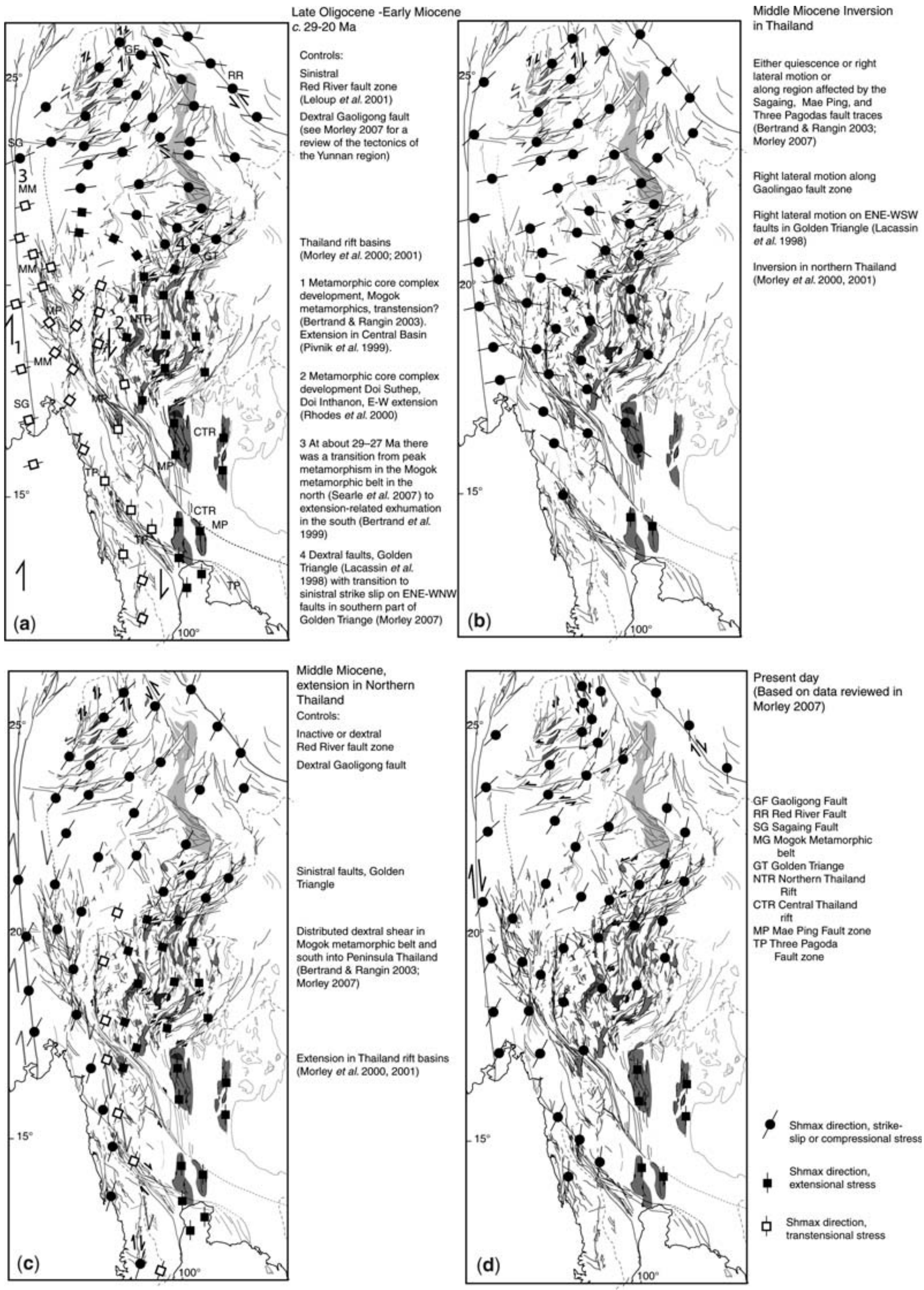

Fig. 13. Illustrations of the likely range of stresses that have affected the Yunnan–Myanmar–Laos–northern Thailand region from the Late Oligocene onwards. Stresses are inferred from Andersonian assumptions of S_{hmax} direction to faults, palaeostress studies (Morley *et al.* 2000; Bertrand & Rangin 2003; Morley 2007) and modern stresses (see review by Morley 2007).

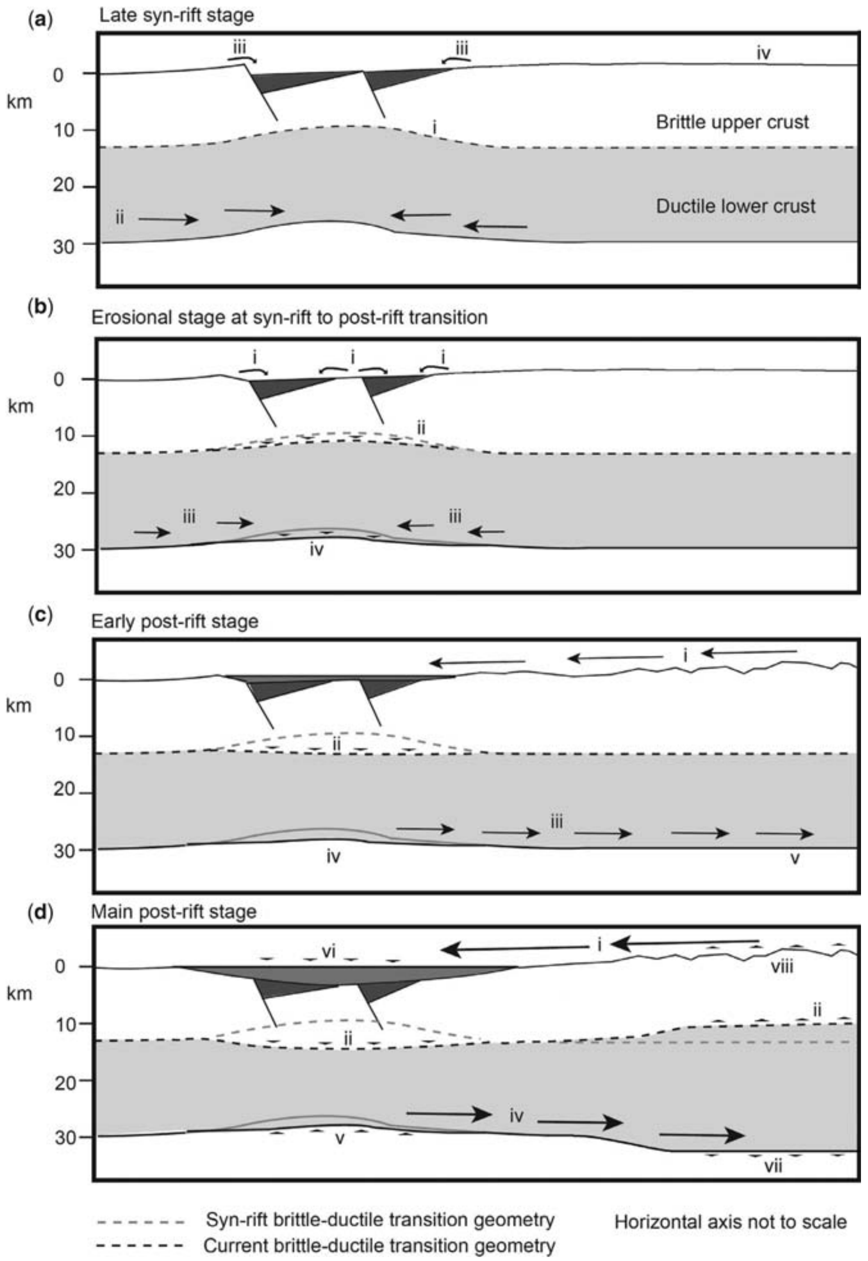

Fig. 14. Schematic summary of the Morley & Westaway (2006) model for the evolution, from synrift to post rift conditions, of the sedimentary basins in the Gulf of Thailand. Inferred senses of lower crustal flow are indicated at each stage. (**a**) Late synrift stage (Early Oligocene). (**b**) Erosional stage at the synrift to post-rift transition (Late Oligocene). (**c**) Early post-rift stage (?Early Miocene). (**d**) Main post-rift stage (post-(?)Early Miocene).

moderate crustal extension ($b \sim 1.3$) occurred, accompanied by sedimentation at a low rate (estimated as typically *c*. 1 km in *c*. 10 Ma, or *c*. 0.1 mm^{-1} a^{-1}). The sediment was mainly of local provenance (iii, Fig. 14a) (Lockhart *et al.* 1997; Jardine 1997). When extension ended during the late Oligocene the lithosphere cooled and the base of the brittle layer thus adjusted to progressively deeper levels (ii, Fig. 14b). The sense of any contemporaneous lower crustal flow was probably still inward, but weak. During the Early Miocene the post-rift basin was increasingly supplied by sediments derived from the Shan Plateau. Return lower crustal flow from under the basin towards the sediment source area began (iii, Fig. 14c), as a result of both sediment loading in the basin and erosion from the sediment source area. Following a change of climate and tectonics (including extension and dextal transtension), erosion in the sediment source area greatly increased (i, Fig. 14d) and resulted in much faster sedimentation rates in the basin. The faster sedimentation caused the base of the brittle upper crust to advect downwards beneath the basin (ii, Fig. 14d), and the faster erosion caused upward advection beneath the sediment source (iii). These changes increased the lateral pressure gradient and consequently increased lower crustal flow (iv, Fig. 14d).

Diachroneity of rift onset and termination. The onset of rifting in the Gulf of Thailand tends to young from east (Eocene–Early Oligocene) to west (Late Oligocene) except in the southern gulf where the Chumphon, Songkla and Nakhon basins all appear to have a Palaeogene history (Fig. 12; Morley *et al.* 2001; Hall & Morley 2004; Morley & Westaway 2006). With possibly one or two exceptions, the oldest age for rift basin initiation onshore in central and northern Thailand is Late Oligocene. Younging of the synrift to post-rift transition is from east (Late Oligocene) to west (Middle Miocene–Late Miocene) in the Gulf of Thailand, and south (Late Miocene) to north (Pliocene) passing onshore. Some basins in northern Thailand are bounded by faults that have remained active until the present day (Fenton *et al.* 1997, 2003). The northward younging of the synrift to post-rift transition suggests a link between rifting and the northward passage of India.

Low-angle normal faults. The Cenozoic rifts of Thailand are bounded by high-angle normal faults, and form classic half-graben type geometries (e.g. Flint *et al.* 1988; O'Leary & Hill 1989; Pradidtan & Dook 1992; Jardine *et al.* 1997; Lockhart *et al.* 1997; Morley *et al.* 2001; Chantraprasert 2003). Extension generally appears to be low ($b < 1.3$) within the basins (e.g. Watcharanantakul & Morley 2000). However, on the eastern edge of the Shan Plateau, two putative metamorphic core complexes (Doi Inthanon, Doi Suthep) have been identified adjacent to the Chiang Mai Basin (Fig. 3; Macdonald *et al.* 1993; Dunning *et al.* 1995; Rhodes *et al.* 2000, 2005; Barr *et al.* 2002). Other low-angle rift-bounding faults have been identified from seismic reflection data across the Suphan Buri and Phitsanulok basins, in the Mergui Basin and in the Gulf of Thailand (Chumphon, Songkla, north Malay basins) but the footwalls to the faults display Palaeozoic sedimentary, metasedimetary and igneous rocks, not mid-crustal level amphibolites. The large LANFs seen on seismic reflection data (Fig. 15) display heaves >2 km (more typically between 5 and 15 km), and dips less than 30°, typically about 20°. Based on published data, and unpublished seismic lines across the Chiang Mai Basin, the evolution of the Doi Inthanon core complex is presented in Figure 15 and is discussed below.

The temperature scale for Figure 16 is derived from Macdonald *et al.* (1993), who determined high-temperature (600–700 °C), low-pressure (280 $\pm$ 60 MPa) conditions of formation from mineral assemblages for the orthogneiss and paragneiss in the Doi Inthanon area. These conditions indicate a high geothermal gradient of about 5 °C per 100 m in the upper crust (Fig. 17). The presence of numerous hot springs in the area today and geothermal gradients of up to 7 °C per 100 m in some sedimentary basins (e.g. Fang Basin, Pradidtan & Tongtaow 1984), demonstrate that high temperatures are still present in northern Thailand.

One indication of high temperatures lasting into the Late Oligocene–Early Miocene is the grade of coal in Mae Cham mine. The coal mine lies in a very small basin, which has only about 200 m of section preserved, yet the grade of the coal (vitrinite reflectance value (Ro) = 0.65%) is considerably higher than those of the other Cenozoic coals mined in the region (Ro $\sim$ 0.40–0.45%) (Morley *et al.* 2001). The high grade of the coal probably indicates both relatively high geothermal gradient and that the basin was much deeper (probably at least 1.5 km deep) and more extensive than it is today. One possible scenario is that the Mae Cham Basin was part of the Chiang Mai Basin left behind in the footwall of the LANF (Fig. 16d and e).

The stages of the Doi Inthanon LANF development are outlined below (see Fig. 16). They provide a summary of the key Cenozoic orogenic events that affected the eastern Shan Plateau.

85–70 Ma. This period represents the time of peak metamorphism (Dunning *et al.* 1995), marked by the emplacement of S-type granites (Charusiri *et al.* 1993) and possible transpressional thickening of the crust (Charusiri *et al.* 1993; Morley 2004; Watkinson *et al.* 2009). Evidence for transpressional or contractional structures related to this event are not well established in the Western Highlands. However, to preserve the extensive detachment geometry between the amphibolite gneisses and the overlying Palaeozoic rocks would seem to require that earlier deformation did not extensively warp or offset the contact. Hence the simplest solution is to have the Palaeozoic section thrust along a décollement above the paragneiss.

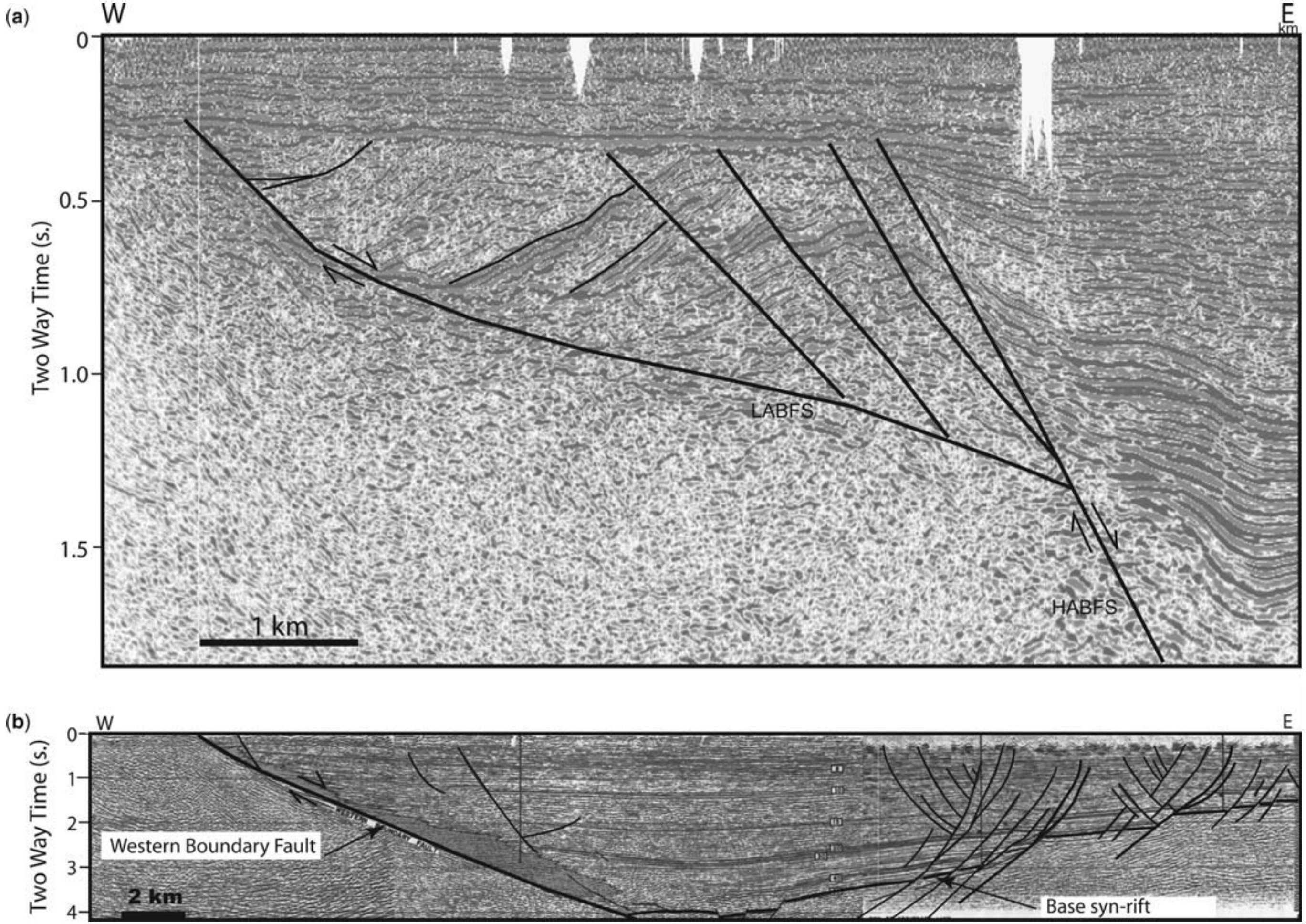

Fig. 15. Seismic lines illustrating east-dipping low-angle normal faults (LANFs) bounding (**a**) the Phitsanulok Basin (Western Boundary Fault, Morley *et al.* 2007; Fig. 3) and (**b**) the Suphan Buri Basin. The Phitsanulok Basin LANF has maximum heave of around 10–15 km; the Suphan Buri LANF has about 5 km maximum heave. (See Fig. 8 for locations.)

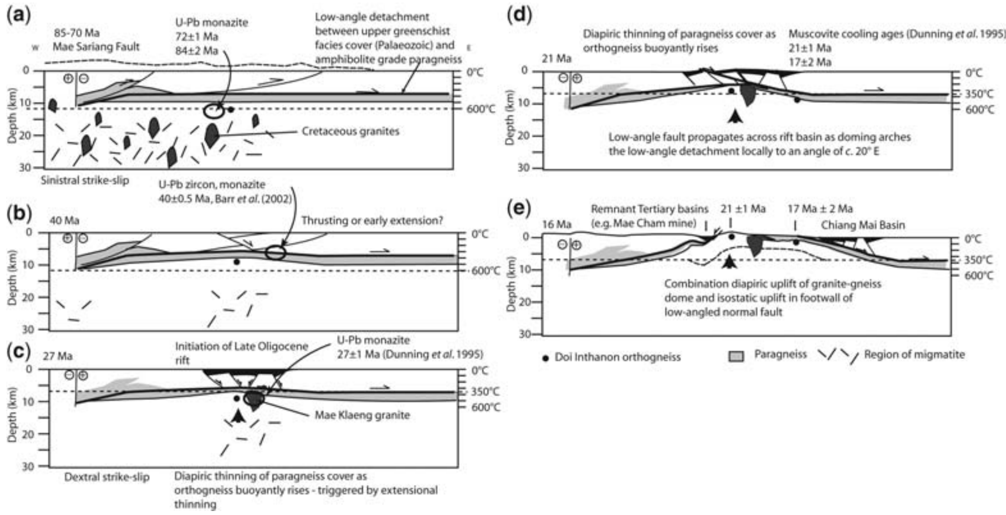

Fig. 16. Regional evolution of the Chiang Mai Basin and Western Highlands illustrating the key tectonic events affecting the eastern Shan Plateau during the Late Cretaceous–Miocene. Based on data of Macdonald *et al.* (1993), Dunning *et al.* (1995), Upton (1999), Morley *et al.* (2001) and Barr *et al.* (2002), and unpublished seismic reflection data.

40–27 Ma. Monazite and zircon grains from mylonitic gneiss in the Doi Suthep area yielded $^{235}U-^{207}Pb$ ages of 40 ± 0.5 Ma (Barr *et al.* 2002), which Barr *et al.* interpreted to define the upper age limit for mylonitization. The *c*. 27 Ma Mae Klaeng granite intrudes across a mylonitic fabric and is thought to constrain the upper age of mylonitization (Barr *et al.* 2002). Extensional collapse of the transpressional belt along the mylonitic detachment sometime between *c*. 40 and 27 Ma is a possible scenario (Barr *et al.* 2002). However, no sedimentary basins of this age are documented in the area, so the Eocene extensional event must be regarded as poorly established. One other possibility is that the detachment records a top-to-the-east compressional décollement around the brittle–ductile transition; the timing coincides with development of peak metamorphism (*c*. 40–29 Ma) in the Mogok metamorphic belt on the western side of the Shan Plateau (Searle *et al.* 2007) and sinistral transpression along the Mae Ping and Three Pagodas fault zones of Thailand and Myanmar (Lacassin *et al.* 1997; Morley 2004). An Eocene–early Oligocene transpressional thickening event followed by extensional collapse in the early Miocene is the scenario favoured here.

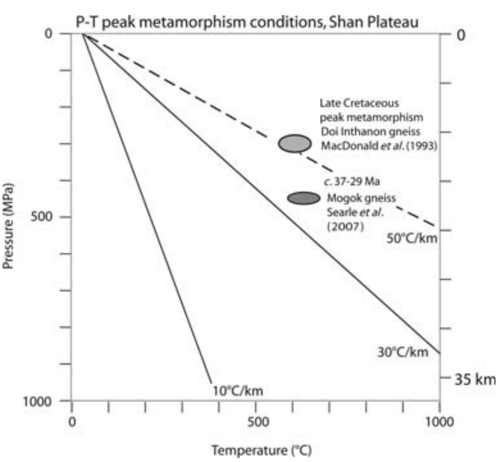

Fig. 17. Two estimates of pressure and temperature from metamorphic assemblages on the eastern and western side of the Shan Plateau. The data suggest prolonged high temperatures in the Shan Plateau area consistent with a back-arc model (Figs 7 and 18).

27 Ma. Late Oligocene–early Miocene rifts are widespread onshore in Thailand (e.g. Morley *et al.* 2001). From the seismic reflection data across the Chiang Mai Basin, the low-angle fault appears to have truncated an older high-angle rift system. Hence a high-angle rift system is shown for the Late Oligocene–Early Miocene, together with development of a gneiss dome. The Himalayan orogen provides models for contractional deformation triggering anatexis and migmatitic gneiss dome development as a result of large-scale release of fluids by overthrusting of low-grade, fluid-rich sedimentary rocks (Le Fort 1986; Le Fort *et al.* 1987), or by shear heating along major thrusts (Harrison *et al.* 1997). Once gneiss domes are initiated, a positive feedback between decompression and partial melting helps fuel further buoyant uplift and more melting (Teyssier & Whitney

2002). The partial melting of crust can help initiate subsequent orogenic collapse and crustal thinning. Hence, although it can be argued that purely extensional processes drive gneiss dome development, in orogenic belts it may more often be the case that gneiss domes are initiated during contraction, and enhancement of the process occurs subsequently during extension (e.g. Lee *et al.* 2004); the latter is the preferred evolution for the northern Thailand core complexes (Fig. 16).

21–16 Ma. During the Early Miocene the low-angle detachment developed and sliced through the existing Late Oligocene–Early Miocene high-angle fault rift basin, transporting it up to 35 km to the east. The Doi Inthanon gneisses were exhumed from temperatures of about 350 °C to about 50 °C; that is, from depths of *c*. ≥8 km to *c*. 1 km (Macdonald *et al.* 1993; Dunning *et al.* 1995). Exhumation was probably driven both by diapiric uplift of the granite gneiss dome and by isostatic footwall uplift caused by low-angle fault motion. Late Early Miocene cooling ages limited between muscovite ^{40}Ar–^{39}Ar cooling ages of 21 Ma and AFT ages as young as 14 ± 1 Ma (Dunning *et al.* 1995; Upton *et al.* 1997; Upton 1999; Barr *et al.* 2002) indicate the duration of LANF and core complex development. Two-dimensional seismic reflection data suggest that a high-angle fault-bounded rift basin of probable Oligocene age was truncated by the younger, early Miocene LANF activity.

Central Basin

The Central Basin in Myanmar (Fig. 7) accommodated a tremendous thickness (up to about 12 km) of Palaeogene sedimentary rock, in particular Eocene–Oligocene fluvio-deltaic to shallow marine deposits (Pivnik *et al.* 1998), yet these sediments appear to have been deposited in a broad synformal basin, with little internal deformation. Adjacent areas to the west (Indo-Burma ranges) and the east (Shan Plateau) were undergoing considerable uplift and deformation during the Eocene–Oligocene, whereas the intervening Central Basin shows virtually no compressional deformation until the Miocene (Pivnik *et al.* 1998). The Central Basin was apparently a region of relatively strong crust between two areas of much weaker crust. The western part of the Central Basin has accumulated a much greater thickness of sediment than the eastern half (Fig. 7), which can be explained by the western basin being floored by strong, dense oceanic crust, passing eastward into less dense continental crust (Pivnik *et al.* 1998).

The Central Basin has long been recognized as a *c*. 1000 km long Cenozoic palaeo-gulf that was filled primarily by a north to south prograding major delta system (e.g. Chhibber 1934; Pivnik *et al.* 1998). For much of the Eocene and Oligocene the delta remained in the northern half of the basin, with the boundary between freshwater and marine conditions fluctuating between about 20° and 23°N. Then from the late Oligocene onward dominantly alluvial plain redbeds (Irrawadian) prograded southward, reaching the Salin sub-basin at about 20°N (Fig. 1) during the Pliocene. Hence it appears that at least until the latest Miocene the Central Basin accommodated the great majority of the sediment transported by the Irrawaddy River.

In the Salin sub-basin the Miocene section shows expansion into active normal faults (Pivnik *et al.* 1998). Then sometime in the Late Miocene–Early Pliocene a tectonic reorganization occurred, and the basin was affected by inversion, accompanied by folding and thrusting (Pivnik *et al.* 1998). Deformation in the Salin sub-basin matches the change in deformation style along the Sagaing Fault proposed by Bertrand & Rangin (2003), who described a switch from transtensional strike-slip deformation to transpressional strike-slip deformation around the Miocene–Pliocene boundary. Inversion effectively halted large-scale basin subsidence and forced rapid progradation of the Irrawaddy Delta southward into the Gulf of Martaban.

Information on crustal temperature from Myanmar is not well established; however, in the Gulf of Martaban geothermal gradients from hydrocarbon exploration wells are in the range of 3–3.5 °C per 100 m; onshore the Central Basin is thought to have been cool in the past because of the depth of maturation of hydrocarbon source rocks, and geothermal gradients from the onshore fields are around 2 °C per 100 m. Hence the available data suggests that the Central Basin was indeed a stronger, cooler region of crust than the Shan Plateau area during the Cenozoic. Probably only after the Shan Plateau area had effectively strain-hardened during the Miocene did deformation start to extensively affect the Central Basin.

Discussion

The aim of this discussion is to suggest a plate-scale scenario that explains the metamorphic, igneous and structural characteristics of the study region. The discussion considers a number of themes.

Application of the back-arc mobile belt model to eastern Myanmar and Thailand

In the 1990s Thailand and the Shan Plateau of Myanmar were largely viewed as one of the peripheral regions to the Himalayas that underwent escape tectonics, where rigid continental blocks were squeezed out laterally away from the orogenic belt by tens to hundreds of kilometres along large bounding strike-slip faults (Le Dain *et al.* 1984; Tapponnier *et al.* 1986; Polachan *et al.* 1991; Lacassin *et al.* 1993, 1997; Replumaz & Tapponnier 2003). The escape tectonic model required the rigid blocks to be composed of cold crust, and little deformed internally during the Cenozoic. The deep sedimentary basins of Thailand could also be explained by the strike-slip setting (Tapponnier *et al.* 1986; Polachan *et al.* 1991). More recently, modern regional displacement patterns based on GPS data have been used to constrain a numerical model of the Himalayan orogen that treats the crust as a continuously deforming solid (not a rigid plate) under the influence of gravity (England & Molnar 1997*a*, *b*, 2005). This model predicts little impact of Himalayan deformation on Indochina. The view that little of orogenic significance affected eastern Myanmar and Thailand during the Cenozoic is implicit in the topographic ooze model of Clark & Royden (2000). This model explained the decreasing topography passing from the Tibetan Plateau into northern Myanmar and Thailand as being created by a wedge of ductile lower crust that flowed southwards from Tibet in the Late Miocene. This focus on imposing Tibetan Plateau-related processes on the region is understandable, but ignores the role played by the other plate-scale feature of the region: the Sumatra–Andaman subduction zone. Here it is contended that the structural development of NW Sundaland is best understood in the context of a back-arc mobile belt related to the evolution of the Andaman Sea section of the Java–Sumatra–Andaman arc, plus the effects of highly oblique continent–continent collision, rather than *ad hoc* models related to only the India–Eurasia collision.

Hyndman *et al.* (2005) and Currie & Hyndman (2006) reviewed and described the characteristics of back-arc mobile belts as follows: most mobile belts arise in a back-arc situation as a result of shallow asthenosphere convection, facilitated by water derived from the underlying slab driving vigorous flow rates (Fig. 18). Heat flow is typically of the order of 70–90 mW m^{-2}. Former back-arc regions are likely to remain hot, weak areas where orogenic shortening is concentrated. The high temperatures also aid widespread orogenic plutonism and ductile crustal deformation, in particular facilitating detachments within the lithosphere and lower crustal flow. High surface elevations may also be associated with little or no crustal thickening, and instead rely on dynamic mantle support. Mobile belts can be persistently weak regions for long periods (hundreds of millions of years) of geological time (Hyndman *et al.* 2005).

NW Sundaland fits many of the back-arc mobile belt criteria above: it has been the site of subduction and terrane accretion since the Permo-Triassic Indosinian orogeny began at around 260 Ma (e.g. Metcalfe 1998). Two pronounced phases of tin-bearing, two-mica, granite intrusion occurred during the Triassic and Late Cretaceous–Palaeogene, which appear to link with collisional events or an Andean margin setting (Charusiri *et al.* 1993; Barley *et al.* 2003).

Many of Thailand's sedimentary basins have high present-day geothermal gradients (3–7 °C per 100 m), and high heat flows. For example, the Pattani Basin in the Gulf of Thailand has heat flows in the range of 70–100 mW m^{-2} (Pigott & Sattayarak 1993) despite being at the post-rift stage of development for the last 25 Ma (Morley & Westaway 2006; Fig. 14). U–Pb dating of monazites and zircons and analysis of mineral assemblages from the Shan Plateau have revealed high palaeo-temperatures of *c.* 4–6 °C per 100 m in the upper crust during the Eocene–Oligocene in the Mogok metamorphic belt (Searle *et al.* 2007) and Late Cretaceous around Doi Inthanon (Macdonald *et al.* 1993; Dunning *et al.* 1995; Figs 8 and 17). Seismic tomography indicates that the upper mantle is anomalously hot under Indochina (Fig. 7), and SE Asia as a whole, in a broad region overlying the subduction zones that ring SE Asia (Hall & Morley 2004; Shapiro *et al.* 2008). The Shan Plateau forms a high topographic region with many peaks at around 1500 m. Regional seismic tomography suggests that crustal thickness in northern Thailand and most of Myanmar, including the Shan Plateau, ranges between 40 and 50 km (Engdahl & Ritzwoller 2001).

Other manifestations of the high geothermal gradient are Cenozoic basic mantle-derived igneous activity, small basins with mature oil source rocks (Fang Basin) or relatively high-grade coal (Mae Chaem Basin), extensive occurrences of hot springs, super-deep post-rift Miocene sedimentary basins that may be indicative of lower crustal flow (Morley & Westaway 2006), and LANFs and putative metamorphic core complexes on the western and eastern side of the Shan Plateau and LANFs in many of the rift basins (Figs 7, 8 and 15).

Hyndman *et al.* (2005) noted that 'the high temperatures of current mobile belts are also indicated by widespread sporadic Cenozoic basaltic volcanism'. This feature is seen in Thailand, where despite being 500 km east of the active volcanic arc Cenozoic basic igneous activity occurs extensively (Putthapiban 2002). Although most of the surface volcanic rocks are of Miocene–Pliocene age (Barr & Macdonald 1981), some basic intrusions encountered in wells in the Gulf of Thailand are as old as Eocene. A number of seismic lines across rift

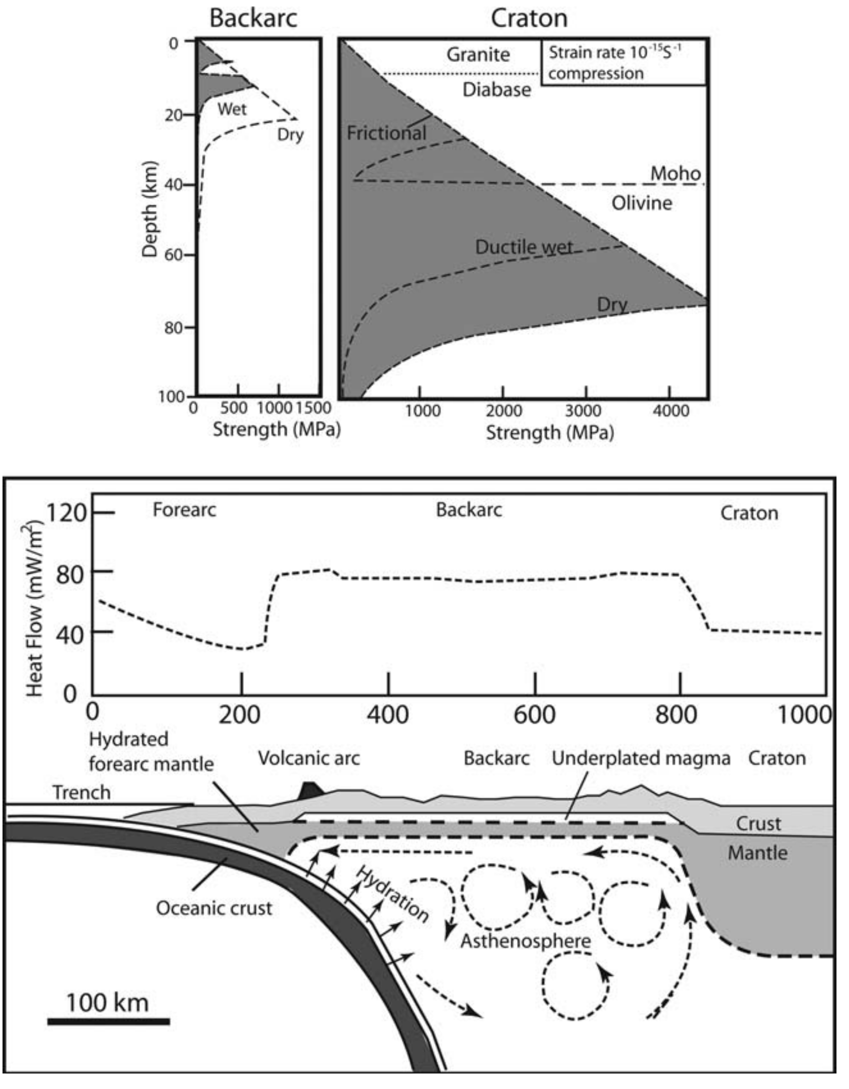

Fig. 18. Model for back-arc mobile belt modified from Hyndman *et al.* (2005).

basins clearly show the presence of igneous intrusions and flows. Wells have penetrated basic Cenozoic igneous bodies in the Suphan Buri, Kamphaeng Saeng, Phitsanulok and Phetchabun basins (Remus *et al.* 1993). The geochemistry of the volcanic rocks indicates that they were derived from the mantle with little crustal contamination (Barr & Macdonald 1981).

The Shan Plateau is a cryptic orogenic belt in many ways. There is no obvious Cenozoic fold and thrust belt, although remnants can be found (Fig. 12), and with the exception of the 2500 m high Doi Inthanon (caused by LANF activity) the height of the plateau is limited to about 1500 m. Therefore it is not surprising that the escape tectonics and topographic ooze models have been imposed upon it. However, the characteristics of tectonics affecting the Shan Plateau seem to owe much to the subduction history. The low height of the plateau is characteristic of the back-arc mobile belt model (Hyndman *et al.* 2005), the crust has been weakened thermally from below by hot mantle, and internally by the heat from high-radioactivity I-type and S-type granitoid intrusions, both mechanisms being ultimately related to subduction.

Characteristics of the transition from back-arc to oblique collisional deformation

During the Eocene Thailand and Myanmar underwent the transition from a margin dominated by subduction-related processes to one where a highly oblique collision with India focused deformation in the Shan–Thai block. It might be expected that the linkage with India would have focused deformation to a much greater extent in western Myanmar than appears to be the case. A fold and thrust belt did continue to develop in the old accretionary prism area of the Indo-Burma ranges, yet immediately to the east the Central Basin continued to accumulate sediment apparently undisturbed by compressional deformation. The surface of the basin remained at approximately sea level during the Oligocene and received fluvio-deltaic sediments in a broad synformal trough (Pivnik *et al.* 1998; Fig. 7). This is not a geometry typical of Andean-type margins. The location of the sinistral transpressional belt in the Shan Plateau suggests that the lithosphere was much weaker in comparison with the Central Basin. The key explanation for this strength difference lies in the much lower temperatures typically found in the forearc area compared with the back-arc (Hyndman *et al.* 2005; Fig. 18).

Origin of the distributed deformation accommodating India–Indochina relative motion

During the Oligocene the Sumatra–Andaman Trench ceased to be the primary site accommodating the differential motion of India and Indochina, and the zone broadened eastwards by about 300 km to the Shan Plateau (Figs 4 and 13). The reason for the shift may lie in (1) the presence of hot weak crust in eastern Myanmar and western Thailand, and (2) the abandoned, north–south-striking Indian plate subduction zone hanging down in the mantle below Myanmar, which would have acted as a giant sheet anchor exerting drag against the overall northward motion of the lithosphere. If the mantle on both sides of the slab were part of the same plate moving in the same direction less drag would occur than when the slab formed the interface between two plates undergoing predominantly strike-slip relative motions. An eastward relocation of the region that accommodated relative motion between India and Indochina would have had the effect of keeping the slab within one plate and hence may explain the location of the dextral strike-slip zone in the Shan Plateau.

The present-day intraplate position of the subduction zone is supported by the seismicity study of Guzman-Speziale & Ni (1996), which suggested the absence of interplate earthquakes in western Myanmar. They favoured interpreting the earthquake data in terms of the overriding plate being coupled with India, a conclusion supported in studies by Radha Krishna & Sanu (2000) and Rao & Kalpna (2005).

From about 40 Ma western Indochina has rotated clockwise, and the Andaman segment of the subduction zone has rotated from a roughly NW–SE strike to a north–south strike (e.g. Lee & Lawver 1995; Curray 2005; Fig. 4), hence the sheet anchor effect would have become increasingly important with time as the slab became more oblique to the northward motion of India. The (local) jump or broadening of the plate boundary was manifest during the Oligocene when the Mogok metamorphic complex became unroofed on the western side of the Shan Plateau (Bertrand *et al.* 1999). The transtensional component of the dextral strike-slip motion and western ranges uplift and erosion had the effect of exhuming the hottest parts of the Shan Plateau. Exhumation of the Shan Plateau provided a large sediment source for basins in the Gulf of Thailand (Morley & Westaway 2006) and Gulf of Martaban in the Early and Middle Miocene. A consequence of exhumation was cooling and effectively strain-hardening of the Shan Plateau, which may have facilitated concentration of deformation onto the Sagaing Fault zone and Indo-Burma ranges from the Middle Miocene onwards.

Extension in Thailand

Crustal thickening of the Shan–Thai block led to anatexis in the Doi Inthanon area and the intrusion of the Late Oligocene Mae Klaeng granite migmatites within a gneiss dome. However, the development of the metamorphic core complexes west of Chiang Mai from *c.* 21–15 Ma does not appear to coincide with the unroofing of the adjacent segment of Mogok metamorphic belt to the west, which dates predominantly from *c.* 27–25 Ma (but is possibly as young as 22.4 Ma) according to data of Bertrand *et al.* (2001; Fig. 8). Nor are the low-angle fault-related stretching directions (NNW–SSE and east–west) in the two provinces similar (Fig. 8). Although there appears to be no direct kinematic linkage between the two provinces, they may mark different stages in the northward passage of India. The NNW–SSE unroofing of the Mogok metamorphic belt directly records the northward movement (Bertrand & Rangin 2003), whereas stress relaxation in the Shan Plateau, and gravity spreading in the trailing wake of the Indian plate, is marked by development of the Doi Suthep and Doi Inthanon metamorphic core complexes, and Late Oligocene–Miocene extension in the western

Gulf of Thailand and onshore. This broad extensional province with mixed high-angle and low-angle extensional faults shifted westward and northward from the focus of earlier (Eocene–Oligocene) extension.

Extensive rifting affected SE Asia during the Cenozoic, and most of the basins had passed into post-rift subsidence by the end of the Oligocene (Hall & Morley 2004; Fig. 4). The continuation of rifting in Thailand during the Miocene is regionally anomalous. This observation, coupled with the progressive northward younging of the onset of post-rift subsidence in Thailand, strongly suggests that the northward passage of India had a strong influence on the continuation of rifting (e.g. Huchon *et al.* 1994). However, another influence on the strain pattern in Thailand is the Sumatra–Andaman subduction zone, as indicated by the pattern and magnitude of co-seismic deformation resulting from the 2004 Sumatra–Andaman earthquake. Southern peninsular Thailand (Phuket), was displaced to the WSW *c.* 27 cm (40–45 cm including post-seismic motions), Bangkok *c.* 8 cm, and Chiang Mai *c.* 2.6 cm (Vigny *et al.* 2005). How such differential movements translate to strain within Thailand is less certain, but GPS stations south, east and NE of Thailand showed considerably less displacement than those in Thailand (Vigny *et al.* 2005). Assuming a mega-earthquake every 500 years, and differential motion was focused on the Thailand rifts over a period of 25 Ma, then Phuket-magnitude displacements could account for *c.* 13–20 km WSW displacement relative to Vietnam, whereas displacement in Chiang Mai would be *c.* 1.3 km. Consequently, it seems reasonable to speculate that a considerable portion of the Late Cenozoic extension in the Gulf of Thailand could be related to events associated with the subduction zone, not only the Himalayan collision.

Conclusions

The application of the Himalayan-dominated tectonic models of escape tectonics (Tapponnier *et al.* 1986) and topographic ooze (Clark & Royden 2000) to Thailand and Myanmar involves an assumption of relatively cold crust in the region, prior to the imposition of Himalayan-dominated orogenic effects. However, the eastern Myanmar–western Thailand orogenic belt discussed in this paper displays a range of evidence that indicates it has been a high-temperature but low-relief orogenic belt, characterized by ductile lower crust and episodic deformation during much of the Cenozoic. The orogenic belt characteristics are atypical for Cordilleran-type, Andean-type or Himalayan-type orogenic belts, but fit well with a back-arc mobile belt setting (Hyndman *et al.* 2005; Currie & Hyndman 2006) modified by the effects of highly oblique continent–continent collision. Some key characteristics are as follows:

(1) The region of most intense deformation (eastern Myanmar–western Thailand orogenic belt) begins about 300–350 km inland from the subduction zone. A low-relief, weakly deformed sedimentary basin (Central Basin) separates the accretionary prism compressional–transpressional region (Indo-Burma ranges) from the main 'orogenic' belt. This is explained by the Central Basin occupying a region of stronger crust (oceanic crust with relatively low lithospheric temperatures) whereas the Myanmar–western Thailand orogenic belt was a hot and weak former back-arc area heavily intruded by I-type and S-type granites during the Triassic, Cretaceous and Palaeogene. High-temperature, low-pressure metamorphic or thermal events occurred during the Late Cretaceous–earliest Cenozoic and the Eocene–Oligocene (Barr *et al.* 2002; Barley *et al.* 2003; Searle *et al.* 2007).

(2) A clearly defined foreland fold and thrust belt is absent. A broad belt of sinistral transpression and later dextral transtension forms the clearest evidence of deformation in the Myanmar–western Thailand orogenic belt. However, folds and thrusts formed during the Palaeogene are extensively exposed in the Khorat Plateau, and glimpsed elsewhere in the highly eroded Khorat Group remnants seen in a few outcrops between rift basins, and as patchy remnants in seismic reflection data beneath basins.

(3) Extensional collapse of thickened continental crust is suggested by the widepread development of low-angle normal faults with and without putative metamorphic core complexes on the eastern and western margins of the orogenic belt and concomitant high-angle rifting in Thailand. On the eastern margin of the Shan Plateau extension was approximately perpendicular (east–west) to the north–south trend of the orogenic belt, whereas on the western margin it was subparallel (NNW–SSE) to the relative movement direction of India with respect to Sundaland.

(4) Exhumation of the eastern side of the present-day Shan Plateau area during the Early Miocene produced a great flux of sediment into the Gulf of Thailand, which during the post-rift stage loaded the Pattani Basin and caused the lower crust to flow away from under the post-rift basin to accommodate the load (Morley & Westaway 2006).

(5) A possible sheet-anchor effect from the steeply dipping subducted oceanic slab beneath Myanmar resulted from increasingly oblique convergence of India and Sundaland. The effect could have influenced the broad accommodation of India–Sundaland relative motion along strike-slip

zones in the upper crust distributed between the Andaman Trench and the Shan Plateau.

(6) The origin of the forces giving rise to Late Cenozoic extension and episodic inversion in the Thailand rift basins appears to be complex. Local buoyancy forces may play a role, and the Himalayan collision has strongly influenced stress patterns (e.g. Huchon *et al.* 1994), but events along the Sumatra–Andaman subduction zone also appear to be important, as indicated by GPS-defined displacements in Thailand associated with the 2004 Sumatra–Andaman earthquake (Vigny *et al.* 2005).

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