Evolution of deformation styles at a major restraining bend, constraints from cooling histories, Mae Ping fault zone, western Thailand

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Abstract: The c. 500-km-long Mae Ping fault zone trends NW–SE across Thailand into eastern Myanmar and has probably undergone in excess of 150 km sinistral motion during the Cenozoic. A large, c. 150-km-long, restraining bend in this fault zone lies on the western margin of the ChaiNat duplex. The duplex is a low-lying region dominated by north–south-trending ridges of Mesozoic and Palaeozoic sedimentary, metamorphic and igneous rocks, flanked by flat, post-rift basins of Pliocene–Recent age to the north and south. A review of published cooling-age data, plus new apatite and zircon fission-track results indicates that significant changes in patterns of exhumation occurred along the fault zone with time. Oldest uplift and erosion (Eocene) occurred in the Umphang Gneiss region, west of an inferred thrust-dominated restraining-bend setting. From 36 Ma to 30 Ma, exhumation was strongest north of the duplex, along the NW–SE-trending segment of the fault zone at the (northern) exiting bend of the ChaiNat duplex. This region of the fault zone is characterized by a mid-crustal level shear zone 5–6 km wide (La Sia Ngneisses), that passes to the NW into an apparent strike-slip duplex geometry. The deformation is interpreted to have occurred during passage around the northern restraining bend, which resulted in vertical thickening, uplift, erosion and extensional collapse of the northern side of the shear zone. This concentration of deformation at the bends at the ends of the restraining bend is thought to be a characteristic of strike-slip-dominated restraining bends. Following Late Oligocene–Early Miocene extension, there is apatite fission-track evidence for 22–18 Ma exhumation in the ChaiNat duplex, that coincides with a phase of inversion in the Phitsanulok Basin to the north. The Miocene–Recent history of the ChaiNat duplex is one of minor sinistral and dextral displacements, related to a rapidly evolving stress field, influenced by the numerous tectonic reorganizations that affected SE Asia during that time.

Restraining bends (cf. Crowell 1974) in strike-slip zones have been identified in many parts of the world (e.g. Anderson 1990; Corsini et al. 1996; Laney & Gates 1996; Curtis 1998), but in particular those in California, China and Mongolia have been the subject of numerous and diverse investigations (e.g. reviews in Cunningham et al. 1996, 2003; Cowgill et al. 2004; Wakabayashi et al. 2004). Typically, in these areas, major restraining bends form regions tens of kilometres up to several 100 km long. Models for restraining-bend behaviour have highlighted two end members: thrust dominated, and strike-slip dominated (e.g. Hauksson & Jones 1988; Cowgill et al. 2004). Restraining-bend structural evolution displays a range of trends, including synchronous movement on faults within a strike-slip duplex (McClay & Bonora 2001); progressive outward propagation of the active fault system within a duplex away from the original restraining bend (Wakabayashi et al. 2004), and complex rotations of faults during simple shear which causes changes in their sense of motion, and degree of activation (Cunningham et al. 2003). However, the number of well-documented examples of major restraining bends for developing and testing such models remains low.

Eastern Myanmar and western Thailand display an extensive network of Cenozoic strike-slip faults (e.g. Le Dain et al. 1984; Lacassin et al. 1997; Morley 2004; Fig. 1). One of the major faults within this system is the Mae Ping fault zone (also known as the Wang Chao fault zone). The

Mae Ping fault zone trends predominantly NW–SE, but displays important north–south-trending segments (Morley 2004; Figs 1, 2 & 3). From Myanmar to central Thailand, the Mae Ping fault zone is 500 km long; its continuation to the SE is uncertain. Some interpretations extend the Mae Ping fault zone over 1000 km further to the SE, to reach the Mekong Delta of southern Vietnam (Lacassin et al. 1997; Leloup et al. 2001). In regional restorations of SE Asian rigid-block motions during the Cenozoic, Replumaz & Tapponier (2003), building of a model published in Leloup et al. (2001) required the Mae Ping fault zone to extend to the NW Borneo margin. However, Morley (2002) viewed such an extensive Mae Ping fault zone as unsupported by available data, and contradictory to the known geological history of NW Borneo. There is actually no hard
evidence for even extending the Mae Ping fault zone through Cambodia and Vietnam to the Mekong Delta, except for the presence of convenient NW–SE-oriented linear features such as the lake, Ton Le Sap. It is even possible that the fault zone splays and ends in eastern Thailand/western Cambodia (Fig. 1).

The Mae Ping fault zone has undergone predominantly sinistral strike-slip motion (Lacassin et al. 1993, 1997) where the north–south segments would have acted as restraining bends within the overall NW–SE trend. Horizontal sinistral displacement is estimated at about 150 km (Lacassin et al. 1997). Hence, the restraining bends should have experienced considerable strain, uplift and erosion. Strongly entrenched in the literature is the idea of a later, simple reversal to dextral strike-slip motion along the major NW–SE-trending strike-slip faults of SE Asia during the Miocene or Pliocene (e.g. Huchon 1994; Leloup et al. 1995; Lacassin et al. 1997, 1998). Specifically for the Mae Ping fault zone, Lacassin et al. (1997) suggested that the switch occurred post-23 Ma. Smith et al. (2007) discuss the evidence for this dextral motion within the Chainat duplex area of the Mae Ping fault zone, and so the subject is not addressed in detail in this volume. However, the conclusions are that evidence for dextral motion can be found, but displacement is minor (a few kilometres of displacement). Dextral displacement increases in magnitude and importance, passing westward into Myanmar. In the Chainat duplex area, dextral motion has alternated with long periods of quiescence, and occasional left-lateral motion during the Miocene, and does not have the history of timing, displacement magnitude or correct detailed structural geometries.
to be the cause of rift basin development as pull-apart basins (Morley 2002; Smith et al. 2007, paper 11, this volume). The absence of large basins within the Chainat duplex area indicates that dextral motion reactivation of the area as a releasing bend must have been minor, and deep basins adjacent to the duplex were formed by extension, not by strike-slip (Morley 2002).

In this paper we show that the 33–30 Ma exhumation documented by Lacassin et al. (1997) is only seen locally in the Lan Sang area, and probably represents the results of transpression at the exiting bend of the Khlong Lhan restraining bend, with evolution from a thrust-dominated to strike-slip dominated type restraining bend. The structural evolution of the fault zone during the Cenozoic is defined by summarizing the existing thermochronology data from the region around the Mae Ping fault zone in western and central Thailand, and from new apatite (AFT) and zircon (ZFT) fission-track ages. This model is compared with existing models for restraining bend evolution.

Regional geological setting

The Mae Ping fault zone in western Thailand is clearly seen on satellite images to form a pronounced NW–SE-trending feature (Figs 1 & 2), with north–south-trending splay branching from it. The NW–SE trend of the fault zone slices through older Palaeozoic–Early Mesozoic terrane boundaries (as defined by Barr & Macdonald 1991), that trend predominantly north–south (Fig. 1). However, several of the splay are coincident with the terrane boundaries, hence the Mae Sariang splay (Fig. 1) coincide with the boundary between the Western Zone and the Inthanon Zone, whilst the major bend in the fault zone that is the focus of this study (here termed the Khlong Lhan bend, Fig. 1), lies between the Sukhothai Zone and the Inthanon Zone. Hence, the influence of major crustal pre-existing fabrics described for examples of large releasing or restraining bends elsewhere in the world (e.g. Corsini et al. 1996; Tommasi & Vauchez 1997; Curtis 1998), also appears to have influenced their location along the Mae Ping fault zone.

Recently, Morley (2004) has suggested that the Mae Ping fault zone first developed during a Late Cretaceous–Early Cenozoic transpressional event related to collision of the Burma Block with the western margin of Sundaland. This early transpression was a precursor to the main Indian–Eurasian collision when the fault zone underwent further (probably the greatest) sinistral motion during the
Oligocene (Lacassin et al. 1997). The best exposure of the mid-crustal levels of deformation associated with the Mae Ping fault zone is the 5–6 km-wide mylonitic to ultramylonitic shear zone in the Lan Sang national park (Lacassin et al. 1993, 1997; Fig. 2). North of this area is a north–south-trending region of gneisses and granites which form the highest ranges of hills in Thailand (Fig. 2). These ranges include the hills called Doi Inthanon and Doi Suthep, which have been interpreted as metamorphic core complexes exposed by top-to-the-east shear on low-angle east-dipping detachments (e.g. MacDonald et al. 1993; Rhodes et al. 1997). However, differences in ages between the dating of the detachment (Eocene) and the timing of exhumation (Early–Middle Miocene) mean that the history of metamorphic core complex is in doubt (e.g. Rhodes 2002).

The Lan Sang Gneisses within the Mae Ping fault zone NW of Lan Sang national park have a distinctive pattern to the trend of their foliation (Fig. 3). Although the main shear zone trends NW–SE, the foliations are curved and lie within a convex stretch of the NE northern boundary (Lacassin et al. 1997; Fig. 3). The pattern of foliations and shear zones suggests the strike-slip equivalent of an antiformal duplex geometry (e.g. Woodcock & Fischer 1986). The small Cenozoic sedimentary basin that opened up on the northernmost segment of the duplex suggests that one horse block moved independently from those to the south (Fig. 3). The minor road from Mae Ramat to Banli, which cuts the northern part of the duplex, reveals small outcrops of gneiss and augen gneiss that do not have an imposed sinistral mylonitic fabric, and a few strongly weathered outcrops with a subvertical foliation — a pattern consistent with horses within a duplex. However, the duplex (and the road) lies in remote, jungle-covered, hilly country, and detailed resolution of the structural geometry from outcrops is unlikely to be possible. If the foliation pattern on satellite images does represent an antiformal duplex, then the area would have evolved in a way similar to that illustrated in stages 1–4 of Figure 3. The first horse to move block 1 then ceased motion and became overridden by successive horses that each were transported further to the NW than previous ones. What was possibly the final motion on horse 4 set up a small releasing-bend geometry, resulting in the creation of a minor Cenozoic basin.

Southeast of Lan Sang national park and the western highlands are the broad Central Plains (Fig. 1). This region is a flat-lying area which represents a post-rift basin overlying several Late Oligocene–Miocene rift basins (e.g. Morley et al. 2001). The Mae Ping fault zone east of Lan Sang national park broadens and splay into the Central Plains area. In one large region of the Central Plains, some 200 km north–south and 100 km wide, Palaeozoic and Mesozoic sedimentary, metasedimentary and igneous rocks are exposed as isolated hills. These hills tend to trend either north–south or NW–SE. This area between the Cenozoic rift basins was called the Chaintak Ridge in O’Leary & Hill (1989). Morley (2002, 2004) interpreted the region as a strike-slip duplex and renamed it the Chaintak duplex. A detailed discussion of the evidence for strike-slip deformation in the Chaintak Ridge area is provided in a companion paper to this one (Smith et al. 2007). Adjacent to the Chaintak duplex are the Phitsanulok, Ayuthaya and Suphan Buri rift basins of Late Oligocene–Miocene age (O’Leary & Hill 1989). The timing and structural history of the basins are constrained by well and seismic reflection data gathered for hydrocarbon exploration (e.g. Flint et al. 1988; O’Leary & Hill 1989; Wongporphai 1997; Rong & Surarat 2002). The history of these basins helps to further constrain the activity of the Mae Ping fault zone. This paper focuses on the exhumation history of the region around the poorly exposed antiformal duplex in the NW illustrated in Figure 3, and the much better-constrained Chaintak duplex to the SE (Fig. 1).

Methods and results

This study is based on collating available published and unpublished cooling age data for NW Thailand, and providing additional ZFT and AFT data which infill key areas where there was little published information. The aim of the work is to determine whether the patterns of uplift are consistent with one or more mechanisms of uplift, and specifically to determine patterns of uplift that might be associated with motion along the Mae Ping fault zone.

A number of radiometric dating studies have been conducted in western Thailand, with a range of aims. The locations and cooling ages determined from these studies are shown in Figure 4. Several studies have focused on the uplift and erosion of gneisses in the Doi Suthep and Doi Inthanon areas, with regard to documenting the denudation history of putative metamorphic complexes associated with low-angle extensional detachments (Dunning et al. 1995; Rhodes 2002). Ahrendt et al. (1993, 1997) have regionally dated granites and gneisses in Thailand, and have related the ages to orogenic events. Charusiri (1989) obtained $^{40}$Ar/$^{39}$Ar radiometric age dates from micas and feldspars from parts of the Three Pagodas fault zone and the Mae Ping fault zone, in order to understand the timing and genesis of ore deposits (Fig. 4). Upton et al. (1997) and Upton (1999) collected samples for
Fig. 4. Regional map of NW Thailand, showing the location of cooling-age data used in this study.
apatic and zircon fission-track analysis in order to build a regional denudation history for Thailand, as well as focusing on more detailed local tectonic and exhumation problems in some areas (such as more concentrated sampling in the regions of the proposed metamorphic core complexes in the western highlands, and around the Mae Ping fault zone). Lacassin et al. (1997) specifically sampled the Mae Ping and Three Pagodas fault zones to determine the timing of strike-slip deformation; their results are discussed separately below.

For this study, samples were taken for apatite and zircon fission-track dating from the Lan Sang area into the Chainat Ridge area (Fig. 4) to determine whether any systematic change in ages occurred along the strike, and perpendicular to the Mae Ping fault zone passing away from the Lan Sang area (Table 1). The samples were analysed in the laboratories at the University College of London. The results of this work were partially successful; however, a systematic spread of data could not be obtained, due to unsuitable outcrop lithologies and insufficient apatite or zircon in some samples (UBDA-7, 8, 10, 11 and 12). New dates were obtained for two localities within the Chainat duplex (samples UBDA-9 and UBDA-13, Table 1, Fig. 4). Samples (UBDA-4, 5, and 6, Table 1, Fig. 4) within the Lan Sang area validated previous results and established similarity between biotite Ar/Ar and ZFT cooling ages (Table 2).

However, east and NE of the Mae Ping fault zone, around Tak, a cluster of cooling ages (samples UBDA-1, 2 and 3, Table 1, Fig. 4) showed AFT central ages around 19–20 Ma.

**Cooling-age studies in western Thailand**

The cooling ages available from the studies mentioned above are mostly from Ar/Ar biotite ages, zircon and apatite fission-tracks. Complications arising from mineral structure, grain size and previous cooling rates mean that the concept of ‘closure temperatures’ (Dodson 1979) for many mineral/isotopic systems (e.g. Ar/Ar) is an oversimplification. For example, chemical composition and the presence of large quantities of fluid inclusions can cause significant changes to standard closure temperatures form micas (e.g. McDougall & Harrison 1999; Dunlap 2003). However, the temperature range below which many of these systems effectively become stable can yield qualitative estimates of cooling rates experienced by a sample. In this context, stability means retention, within the crystal system, of some measurable product of various radioactive decay reactions. As an approximate guide, the temperature range below which the system is effectively stable is as follows (Carter 1999; McDougall & Harrison 1999; Dunlap 2003): Ar/Ar for muscovite = 400–250 °C; Ar/Ar for biotite 300 ± 50 °C, zircon fission-track 320–200°C, and apatite fission-track 110–60 °C. Consequently, for the high-temperature cooling age map (Fig. 5), dates for biotite Ar/Ar and zircon fission-track were combined. Whilst this is clearly a great approximation, where zircon fission-track and biotite Ar/Ar ages have been obtained from the same or nearby localities (e.g. Lan Sang, Fig. 4), the resulting cooling ages are very similar (Fig. 4; Tables 1 & 2). The low-temperature cooling-age map (Fig. 6) is entirely based on apatite fission-track ages from Upton (1999) and this study (Table 1).

**Determination of the cooling history along the Three Pagodas and Mae Ping fault zones, by Lacassin et al. (1997)**

Evidence for dating motion on the Mae Ping (Wang Chao) and Three Pagodas fault zones relies considerably upon the work by Lacassin et al. (1997) who specifically dated synkinematic micas and feldspars from metasediments and orthogneisses within mylonitic shear zones, using the Ar/Ar technique. Biotite cooling ages for the Three Pagodas fault zone suggested that the dates of the onset and end of sinistral motion were ≥36 Ma to 33 Ma, and for the Mae Ping fault zone ≥33 Ma to 30 Ma (Figs 4 & 7). Lacassin et al. (1997) modelled the cooling histories of the Lan Sang samples, calibrated by Ar/Ar step-heating of a K-feldspar. The results indicate that cooling from 400 °C to 185 °C was rapid between 32.5 Ma and 31 Ma, in order to fit the last 16% of argon release. These authors also identified a second cooling step at about 23.5 Ma, before a final isothermal step (about 75 °C). Lacassin et al. also stressed that the 33 Ma to 30 Ma dates probably documented the last increments of ductile sinistral deformation. The authors also suggest that late-stage exhumation of the Lan Sang Gneisses might be explained by normal faulting within a transtensional setting. The onset of dextral strike-slip motion was placed at about 23 Ma, but was not constrained by any radiometric dating.

The work by Lacassin et al. (1997) also obtained biotite cooling ages between 29 Ma and 23 Ma in some gneisses away from the strike-slip fault zones, including the Bhumipol Dam to the north (Fig. 4). The gneisses at Bhumipol Dam show no evidence for Cenozoic shear, and hence are inferred to represent denudation between 29 Ma and 23 Ma, possibly related to a Cenozoic basin-bounding normal fault (Sam Ngao Fault) to the east (Lacassin et al. 1997).
Table 1. Results of apatite and fission-track dating conducted for this study

<table>
<thead>
<tr>
<th>Mineral</th>
<th>No. of crystals</th>
<th>Dosimeter</th>
<th>Spontaneous</th>
<th>Induced</th>
<th>Age dispersion</th>
<th>Central age (Ma) ± 1</th>
<th>Mean track length (µm)</th>
<th>SD</th>
<th>No. of tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ρd</td>
<td>N_d</td>
<td>ρs</td>
<td>N_s</td>
<td>ρi</td>
<td>N_i</td>
<td>P^2_E</td>
<td>RE%</td>
</tr>
<tr>
<td>UBDA-1</td>
<td>Apatite</td>
<td>19</td>
<td>1.060</td>
<td>3122</td>
<td>0.201</td>
<td>100</td>
<td>1.863</td>
<td>927</td>
<td>40</td>
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<tr>
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<td>20</td>
<td>1.066</td>
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<td>0.476</td>
<td>424</td>
<td>4.294</td>
<td>3821</td>
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<tr>
<td>UBDA-3</td>
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<td>233</td>
<td>4.076</td>
<td>2175</td>
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<tr>
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<td>0.243</td>
<td>401</td>
<td>2.146</td>
<td>3540</td>
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<tr>
<td></td>
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<td>0.409</td>
<td>2921</td>
<td>13.12</td>
<td>4709</td>
<td>9.388</td>
<td>3370</td>
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<tr>
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<td>303</td>
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<td>1.111</td>
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<td>UBDA-9</td>
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<td>2329</td>
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</table>

1. Track densities are (×10^6 tr cm^-2) numbers of tracks counted (N) shown in brackets.
2. Analyses by external detector method using 0.5 for the 4π/2π geometry correction factor.
4. P_X^2 is the probability of obtaining the χ^2 value for ν degrees of freedom, where ν = number of crystals – 1.
5. Central age is a modal age, weighted for different precisions of individual crystals.
Table 2. Comparison of high-temperature cooling ages determined for the Lan Sang Gneisses using zircon fission-track and $^{40}$Ar-$^{39}$Ar of biotite from three separate studies

<table>
<thead>
<tr>
<th>Sample</th>
<th>TL3 Biotite</th>
<th>TL7 Biotite</th>
<th>TL8 Biotite</th>
<th>TA34 Biotite</th>
<th>Upton (1999)</th>
<th>THI2264 zircon fission-track</th>
<th>UBDA-4 zircon fission-track</th>
<th>UBDA-5 zircon fission-track</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>33.1 ± 0.4</td>
<td>33.0 ± 0.2</td>
<td>31.3 ± 0.7</td>
<td>30.6 ± 0.3</td>
<td></td>
<td>28 ± 1 Ma</td>
<td>35.9 ± 1.3 Ma</td>
<td>29.7 ± 1.4 Ma</td>
</tr>
<tr>
<td>This study</td>
<td></td>
<td></td>
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Patterns of cooling ages in western Thailand

Introduction

The highest density of cooling-age data clusters around the Mae Ping fault zone and the area to the north. The area south of the Mae Ping fault zone, to the Three Pagodas fault zone, is much more sparsely sampled (Fig. 4). Therefore much of this discussion will focus on the northern half of western Thailand. To understand the uplift and erosion history of the Mae Ping fault zone, it is necessary to investigate not only the timing of exhumation around the fault zone, but also the regional pattern.

Upton (1999) sampled outcrops in western Thailand extensively for the purposes of apatite fission-track analysis, and produced composite cooling paths for a subset of those samples, using zircon fission-track and published K-Ar dates. For the apatite fission-track data, Upton et al. (1997) and Upton (1999) identified two sample suites that differ in both age and cooling history. The largest subset displayed results that mostly ranged between 24 Ma and 13 Ma. However, three samples with central ages of 40, 34 and 29 Ma were also included. These samples in the first set are characterized by narrow s.d. 1–1.5 μm, unimodal and long (>14 μm) mean track-length distributions, consistent with rapid cooling through the partial annealing zone. Upton (1999) estimated the average cooling rates as between 8.5 °C Ma and 25 °C Ma. The second subset ranged between 80 Ma and 37 Ma, and shows broad track-length distributions, with standard deviations between 2.03–2.49 μm. Mean track-length distributions are relatively short (12–13 μm), typical of samples exposed to short-lived, high temperatures, or prolonged residence in the partial annealing zone to reduce track length. The second suite of samples exhibited much slower average cooling rates, of about 1.85 ± 0.55 °C Ma. The young AFT ages of the first subset form an extensive north–south-trending region along the western highlands of Thailand (Fig. 6). On either side of this north–south trend, in central northern Thailand and along the Thailand–Myanmar border region, older ages of the second subset are found (Figs 6 & 7).

The variations in cooling-age history in the region are discussed in the context of three different provinces: the Chainat duplex; the Mae Ping fault zone; and the putative metamorphic core complex area between the Mae Sariang–Hot Highway and Chiang Mai. These provinces are exemplified in four cooling-age traverses (Fig. 7), and are discussed below.

Chainat duplex area (Fig. 7 a–a’)

The southern traverse (Figs 4 & 7 a–a’) crosses the Khlong Lhan restraining bend and passes into the Chainat duplex. Location 1 is from the Umphang Gneiss area (Upton 1999; Fig. 4). The deepest crustal rocks exposed in the duplex, called the Umphang Gneiss, lie on the western side of the restraining bend. The U–Pb analysis of the Umphang Gneiss, indicates that the paragneiss underwent high-grade metamorphism during the Late Triassic (Mickey 1997). A ZFT central age of 47 ± 3 was obtained for the Umphang Gneiss by Upton (1999; Fig. 4). An apatite central age of 40 ± 2 Ma for the Umphang Gneiss (Upton 1999) suggests rapid exhumation on the western margin of the Chainat Ridge during the Eocene (Fig. 7 a–a’). At the NW corner of the duplex, where the Mae Ping fault zone splays to the SE, are the Khlong Lhan Gneissess. The U–Pb dating of zircon indicates a slightly younger age for high-grade metamorphism in the Khlong Lhan Gneiss compared with the Umphang Gneiss, of 174 ± 5–6 Ma, whilst a monazite age of 117 ± 3 Ma (Mickey 1997) indicates a subsequent high-temperature metamorphic event during the Cretaceous. ZFT and K-Ar analyses by Upton (1999) from both gneissess show overlap at the 2σ-error level, thus indicating that they had cooled below the 350–260 °C isotherm (Fig. 7) by the end of the Eocene (c. 40–43 Ma). However, the Khlong Lhan Gneiss has a 40 ± 1 Ma ZFT central age, and a 20 ± 1 AFT age, indicating either slower exhumation between 40 Ma and 20 Ma or a younger exhumation event imposed on the older Eocene one (Fig. 7 a–a’). Whatever the precise scenario, the cooling history is unlike the Umphang Gneiss, which just shows rapid cooling during the Eocene (Fig. 7).

Within the main part of the Chainat duplex there are only a few Triassic granitic outcrops. Five
Fig. 5. Map of high-temperature cooling ages for NW Thailand, mostly from zircon fission-track and $^{40}$Ar/$^{39}$Ar biotite cooling ages. Some of the older apatite fission-track dates are included because they provide minimum ages for high-temperature cooling.
Fig. 6. Map of low-temperature cooling ages for NW Thailand, from apatite fission-track data.
Fig. 7. Exhumation history for four transects through NW Thailand. See Figure 4 for locations of the transects and sources of the data. a–a' southernmost transect through the Umphang Gneiss area (1), Khlong Lhan Gneiss (2), and Chainat duplex area (3). Location 1 shows the rapid 50–40 Ma exhumation. A transect along the Mae Sot–Tak road is shown in b–b'. Along the western part of the road, cooling began early (locations 4 and 5) in the Late Cretaceous–Early Cenozoic and the Lan Sang Gneiss displays one phase of exhumation between about 35 Ma and 30 Ma (6) and a second phase around 25–19 Ma. Transect c–c' runs from a large north–south-trending splay of the Mae Ping fault zone in the west, to a putative metamorphic core complex in the east. In the west, exhumation is early (Late Cretaceous–Early Cenozoic) and relatively slow. There is no indication of rapid, strike-slip-related uplift. In the east (location 8) exhumation was extremely rapid at around 20–18 Ma. The northernmost transect (d–d') shows a similar pattern to c–c', except that the rapid exhumation in the east is younger, from about 16–13 Ma.

localities were sampled, and two yielded usable AFT data (Table 1). AFT central ages of 22.4 ± 2.8 and 18.2 ± 1.6 were obtained (Fig. 4). It is uncertain from these results alone whether the Early Miocene cooling ages represent regional uplift and erosion, or a specific structural event related to strike-slip deformation within the duplex. Seismic data from the Lahan graben of
the Phitsanulok Basin show that the basin ceased to be active in the latest Early Miocene, coincident with the AFT ages (Smith et al. 2007, paper 11, this volume). This uplift is not seen in the sedimentary section of the Ayuthaya or Suphan Buri basins on the southern margin of the duplex. Hence, the present available data suggest that uplift occurred in a NW–SE-trending belt, in the northern part of the duplex (Fig. 6).

**Mae Ping fault zone (Fig. 7 b–b’)**

Passing westward into Myanmar along the Mae Ping fault zone, the muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages increase — a similar trend to that established by the AFT ages further north (Figs 6 & 7 c–c’ and d–d’). Charusiri (1989) obtained $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages from micas in granites adjacent to the Mae Ping fault zone in westernmost Thailand (Fig. 4). The oldest ages obtained lie furthest to the west (69.5–72 Ma), and young eastward (69.5–65.7 Ma and 47.5 Ma). A sample of hydrothermal muscovite collected from a wolframite-bearing quartz vein (collected underground) yielded $^{40}\text{Ar}/^{39}\text{Ar}$ spectra with well-defined plateau ages of c. 69.5 ± 0.68 Ma and 70.6 Ma. Muscovite from younger, cross-cutting scheelite–fluorite–calcite–quartz and sphalerite–muscovite–quartz veins yielded fusion dates of c. 69.2 Ma and 71.9 Ma. The hydrothermal muscovite probably crystallized at temperatures between 300 and 425 °C, under maximum confining pressures of about 170 to 200 MPa (i.e. depths of 6–7 km).

Further ESE along the trend of the Mae Ping fault zone, Charusiri dated samples from the Mae Suri Mine. Hydrothermal muscovite from a tungsten-rich quartz vein was dated using total fusion and step-heating methods. The total fusion age is c. 45.2 Ma, and the integrated age c. 47.5 ± 0.51 Ma. The $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum displays a well-defined plateau of 46 Ma. The minimum at the first step (21.5 Ma) may be a result of thermal resetting. There was evidence of shearing within the mine that suggested emplacement of the veins during sinistral displacement of the Mae Ping fault zone.

The cooling ages obtained by Charusiri (1989) are not as directly linked to the Mae Ping fault zone as the Lan Sang ages (Lacassin et al. 1997). But they are close to the fault zone, and thus show that passing west, close to the fault zone, there is no evidence for large-scale Oligocene regional exhumation related to strike-slip faulting that would have obliterated the older ages. Hence, the exhumation of mid-crustal rocks at Lan Sang between 33 and 30 Ma (Fig. 7 b–b’ location 6) is an atypical and localized feature of the fault zone that requires specific explanation.

The pattern associated with high-temperature cooling (Fig. 6) is very consistent with the AFT results of Upton (1999). The contour patterns (Figs 5 & 6) suggest that, for much of the length of the Mae Ping fault zone, strike-slip motion does not equate with significant Oligocene uplift and erosion, and that if the exhumation is associated with the Mae Ping fault zone, then it is of Late Cretaceous–Palaeogene age (Fig. 7 b–b’). The overall cooling pattern indicates that the strike-slip deformation has not dominated the cooling history. The low-temperature cooling pattern shown in Figure 6 reveals a predominantly north–south-trending exhumation pattern. This pattern may represent both more local tectonic effects such as extensional or inversion related uplift and erosion, and more regional uplift and erosion at least partially related to climate change (Morley & Westaway 2006). For example, the syn-rift basins of northern Thailand show a switch from palynomorphs associated with a temperate climate to tropical forms in the Early Miocene (Songtham 2000; Ratanasathien 2002); this change is also seen in peninsular Malaysia (Morley 1998).

Exhumation of the Lan Sang area can either be interpreted as part of a regional Late Oligocene—Early Miocene north–south-trending event, or as a composite of strike-slip–related deformation superimposed on a north–south striking regional trend. We feel that there is sufficient evidence as presented by Lacassin et al. (1997) to justify much of the exhumation at Lan Sang as being related to strike-slip deformation.

**Hot–Mae Sariang highway-region west of Chiang Mai (Fig. 7 c–c’ & d–d’)**

The two northernmost traverses (Fig. 7 c–c’, d–d’) are through the putative metamorphic core complex area (MacDonald et al. 1993; Rhodes et al. 1997, 2002). Traverse c–c’ is along the Hot–Mae Sariang highway (Figs 6 & 7). The pattern of cooling was defined by Upton (1999) using AFT, ZFT and K–Ar biotite cooling ages. Passing westward, four AFT ages progressively become older, ranging from 19 ± 2 Ma and 18 ± 1 Ma, through 22 ± 1 Ma in the east to 37 ± 2 Ma in the west (Fig. 7). For the 18 ± 1 Ma sample, Upton (1999) also obtained a 19 ± 1 ZFT age, and nearby a concordant K–Ar biotite cooling age of 20 ± 1 Ma, was reported. For the 22 ± 1 Ma sample, Upton (1999) obtained a ZFT age of 52 ± 4 Ma, and a K–Ar biotite cooling age of 67 ± 2 Ma, indicating a much slower and more prolonged cooling history toward the west. Using isotopic dating, Mickein (1997) also identified a younging-to-the-east pattern along the Hot to Mae Sariang highway.
On the northernmost line (Fig. 7 d–d') a similar pattern of cooling ages is seen, with slow, prolonged exhumation in the west (AFT central age of 80 ± 6 Ma) and rapid exhumation in the east. The timing of the eastern rapid exhumation becomes younger passing north, along line c–c' (Fig. 7) with the AFT central ages being Early Miocene. Along line d–d', the AFT central ages are Middle Miocene, with the nearest biotite $^{40}$Ar/$^{39}$Ar age being 16 ± 0.2 Ma. The rapid Early and Middle Miocene cooling occurs in the region identified as the metamorphic-core-complex area. However, one problem with a simple core-complex story is that the rapid exhumation is young, compared with the age of the shearing defined by dating of biotite within the detachment zone, which is of Eocene age (Rhodes 2002).

One possible explanation of the cooling-age pattern lies in the model for basin subsidence in response to sediment loading, a model proposed by Morley & Westaway (2006). There, erosion of the sediment source area and deposition in the sedimentary basin triggers a return flow in the lower crust, from beneath the basin toward the sediment source area. Applied to Thailand, the model predicts lower-crustal flow from beneath the basins of the Gulf of Thailand toward the sediment source areas of the western highlands (Morley & Westaway 2006). If the pattern of erosion and lower-crustal flow shifted northward with time then this may explain the pattern of young, rapid cooling on the eastern side of the highlands.

Before discussing a model for the structural history of the Mae Ping fault zone, other constraints on timing of deformation and exhumation associated with the Mae Ping fault zone from adjacent sedimentary basins and the Chainat duplex area are reviewed.

**Significance of Cenozoic basins for exhumation history**

Sedimentary basins that were sites of subsidence synchronous with the areas of exhumation provide important constraints for the location and origin of exhumation. Here the basins within the western highlands are discussed.

**Mae Lamoao**

The main exposures of the Mae Lamoao basin are coarse conglomerates and sandstones along the main Tak–Mae Sot road, and deeper levels of the basin exposed in a very small coal mine that lies north of the main Tak–Mae Sot road (Fig. 3). The main coal seam is mined from the footwall of a normal fault. This fault strikes 325° and dips 60°. It displays pure dip-slip striations that plunge 60° 238° SW. Bedding dips range between 306°-20° SW and 330°-24° WSW. The mine lies very close to the Mae Ping fault zone, just a kilometre or two south of one of the main fault strands (Fig. 3). There is little evidence in the outcrop for strike-slip deformation. Instead, the main normal fault and two secondary faults show almost pure dip-slip motions.

In the Mae Lamoao Basin, deposits over 500 m thick comprise conglomeratic claystone and sandstone at the base, overlain by shales, oil shales, coal, and sandstone. The palynology indicates a Late Oligocene–Early Miocene age (Ratanasinthien 1989), which is presumably also the age of the normal faulting. The coal seams pass abruptly laterally into thick conglomeratic sequences, indicating that the sediment from an adjacent uplifted area was dumped into the basin. There is little post-Miocene deposition except for fluvial deposits, indicating Early Miocene or later uplift and erosion. Vitritine reflectance values from the coals average 0.45 (Ratanasinthien 1989), i.e. the rocks experienced maximum temperatures of about 120 °C. If a 30 °C surface temperature is assumed, then, for a geothermal gradient of 3 °C/100 m, burial to 3 km is indicated. If a much higher rift-type geothermal gradient of 6 °C/100 m is assumed, then burial to 1.5 km is indicated. These numbers suggest that a considerably thicker, more extensive basin existed in the past and was removed by Early Miocene or later uplift and erosion. The basin geometry appears to be that of a simple uplifted and eroded rift. Hence, it is uncertain whether strike-slip motion was responsible for basin uplift, or whether it was just part of the more regional uplift and erosion event.

**Mae Sot Basin**

The Mae Sot Basin is one of the larger rift basins in northern Thailand, and lies just south of the Mae Ping Fault (Figs 2 & 3); hence, its evolution is of great interest for understanding the activity of the Mae Ping Fault. Unfortunately, there is little information in the public domain about the basin. Gibling et al. (1985) show a Bouguer gravity map for the Mae Sot Basin which comprises two en échelon NNW–SSE-trending gravity lows, which are 10–20 milligals less in magnitude than the areas of outcropping pre-Cenozoic basement. The largest anomaly indicates a Cenozoic basin centred around Mae Sot about 20 km long and 10 km wide. They also report on a drill-hole (DDH 3-5) made by the Department of Mineral Resources (DMR). The drill-hole penetrated 833 m of Cenozoic strata, dominated by carbonate...
Mae Tuen coalfield

The Mae Tuen coalfield is located in a small basin that lies along the northern trend of the Mae Ping fault zone, north of Lan Sang national park (Fig. 3). Ratanasthien (1990) describes the Mae Tuen coalfield as having early coals (Late Eocene–Early Oligocene, i.e. probably in the range of 36–32 Ma) unconformably overlain by Late Oligocene–Early Miocene strata. Vitritine reflectance values from the coals are high (about 0.66% \( R_o \), Ratanasthien, pers. comm., 2005). These values suggest uplift in the order of 2 km if a high (6 °C/100 m) geothermal gradient is assumed. Modern geothermal gradients associated with Thailand rift basins range between about 3 °C and 7 °C (see Morley et al. 2001 for a review). The modern values occur at a time when rifting has largely ceased or is very minor, yet they are high, and would seem to indicate a range of gradients appropriate for syn-rift times as well.

The relatively old age of the Mae Tuen Basin is unusual considering that other coal mines in northern Thailand exploit the reserves in basins of Late Oligocene–Miocene age (e.g. Ratanasthien 2002). The Eocene–Early Oligocene age is concomitant with biotite \(^{40}\text{Ar}/^{39}\text{Ar} \) and zircon fission-track cooling ages in the Lan Sang area (Fig. 5). Hence, there is a strong indication that extensional collapse and basin formation occurred on the northern side of the Lan Sang Gneiss region during strike-slip deformation. Widening of the Tak–Mae Sot road just south of the Lan Sang national park has cut

![Fig. 8. Line drawing of a seismic line through the Mae Sot Basin, on website http://www.ccop.or.th/epf/thailand/thailand_petroleum.html](http://www.ccop.or.th/epf/thailand/thailand_petroleum.html)
into sediments of the Mae Tuen Basin. The road cutting has revealed a poorly sorted conglomerate, including boulder-sized clasts composed of metamorphic rocks typical of the Lan Sang area, cut by minor normal faults. There are no shales present that could be used for dating. However, the coarse, immature deposits of metamorphic rock clasts are consistent with deposition adjacent to a rapidly uplifted and eroded region.

**Structural evolution of the Mae Ping fault zone**

The still limited, but more regional, data review undertaken in this study shows that the region of the Lan Sang Gneisses where the Oligocene mica cooling ages have been obtained (Lacassin et al. 1997) is very limited geographically (Fig. 5). The Oligocene ages from Lan Sang are bracketed to the NW and SE by Eocene–Late Cretaceous biotite, ZFT and AFT cooling ages (Figs 4, 5 & 7). Hence, the area with the highest number of cooling ages from the fault zone is not really representative of the history of exhumation along the entire fault zone. This is a demonstrably large fault zone in outcrop and on satellite images, a zone which extends hundreds of kilometres into Myanmar (Lacassin et al. 1997; Morley 2004). However, accurate quantification of the displacement has not yet been achieved: Lacassin et al. (1993) estimated a minimum 40 km of sinistral displacement based on shear-zone geometries. Using the offset of the regional geological markers, Lacassin et al. (1997) estimate about 150 km sinistral displacement, whilst the regional rigid-plate reconstructions of Replumaz & Tapponnier (2003) require up to 240 km of 40–30 Ma sinistral motion. The Replumaz & Tapponnier (2003) estimate is model-driven and is not constrained by geological markers, whereas the 150 km estimate is based on a generalized, but reasonable, offset of granitic outcrops, and is the preferred estimate here. However, detailed geochemical typing of offset granites is really necessary to demonstrate offset of the same granite body and to obtain a reasonably constrained offset estimate. Despite the probable large displacements, the exhumation history along the fault zone is highly variable and certainly not consistently in the range of the 33–30 Ma ages determined by Lacassin et al. (1997) (Fig. 5). This section discusses how the available cooling ages can be used to explain the structural evolution of the Mae Ping fault zone.

The early history of a Mae Ping fault zone as part of a transpressional orogen spanning the Late Cretaceous–Palaeogene, related to collision of the Burma Block with the Shan Thai Block, has been discussed by Morley (2004), and is not discussed in detail here. The oldest cooling ages in westernmost Thailand (Figs 4 & 5) are part of the evidence for that orogenic event. The starting point for this discussion is the Eocene–Oligocene history of the fault zone. Within the Chaimat Ridge area the Umphang Gneiss to the west shows rapid exhumation within the time span of 50 Ma to 40 Ma (Figs 7 & 9). Cooling-age data south of the Umphang Gneisses are sparse (Fig. 4), but regionally appear to fit a north–south trend of Late Oligocene–Early Miocene AFT ages that extend from peninsular Thailand up to northern Thailand (Morley 2004). Hence, the Umphang Gneisses appear to be a patch of locally older exhumation, on the western margin of the Mae Ping fault zone, consistent with exhumation at the restraining bend of a sinistral strike-slip fault system (Fig. 9). However, the subsequent history of the Mae Ping fault zone in the area does not follow such a simple interpretation.

The outcropping geology in the Lan Sang area shows that the deepest crustal levels exposed along the Mae Ping fault zone are not in the restraining-bend area to the SE, but along a NW–SE segment of the fault. This uplift occurred from 36 Ma to 30 Ma (Lacassin et al. 1997; Upton 1999; Figs 4, 5, 9 & Table 1), with the ages younging from the NW to the SE. The most intensely deformed part of the fault zone is a belt of gneisses and mylonite metasediments about 6 km wide, within which are more highly deformed zones of ultramylonite (particularly calc-silicates and marbles) typically about 1 km wide (Lacassin et al. 1993). Assuming simple shear, Lacassin et al. (1993) estimated lower bounds of 7 to 9 ± 3 for the shear strain (γ)% within the mylonite zones. The strain estimate implies a minimum of 35–45 km sinistral displacement within a c. 5-km-wide shear zone (Lacassin et al. 1993). The latest sinistral shear occurred along a retrograde P/T path, and progressed from ductile deformation to below the brittle–ductile transition (Lacassin et al. 1993; 1997). Commonly, small-scale conjugate brittle faults cross-cut the ductile shear zone fabrics. They tend to strike east–west (sinistral shear sense) and NNE–SSW (dextral shear sense). Displacements are typically in the order of centimetres to metres, although a few may display tens of metres of displacement. The conjugate brittle faults indicate that the horizontal principal stress was (at least locally) approximately perpendicular to the strike of the gneissic foliation during their formation. In Figure 10b, the sheared mid-crustal rocks seen in Lan Sang are restored to a position east of the Umphang Gneiss. In this position they would have occupied the first Chaimat duplex area. During progressive simple shear, the
Fig. 9 Proposed evolution of the Mae Ping fault zone to fit the cooling ages and outcrop patterns discussed in this study. Note: motions during the later stages of deformation (30 Ma–present) were probably small (a few kilometres at most), and hence appear insignificant on the maps.
Fig. 10. Schematic cross-section illustrating the structural evolution of the Mae Ping fault zone. The eastern half (ii) of the cross-section is kept in a constant location, equivalent to the location of the Lan Sang Gneisses today, whereas the western half (i) of the cross-section changes with time as section (ii) moves north to NW during sinistral displacement. Hence, for section (c), (i) is through the Umphang Gneiss area, whilst, for section (a), (i) is through the Mae Sot and Mae Lamao basins. Section a shows the present-day configuration; however, most of the uplift of the Lan Sang Gneiss was completed by the Late Oligocene, and apart from some erosion and minor strike-slip motion, and development of the Mae Sot and Mae Lamao basins, the geometry of the strike-slip fault zone is likely to have been similar from the Late Oligocene onward. The near-surface Lan Sang Gneiss geometry is based on the cross-section in Lacassin et al. (1997). Section (b) represents c. 34 Ma to 32 Ma ago. Since the Lan Sang Gneiss had to undergo vertical thickening and uplift to be exposed today, restoration of the gneisses through the bend requires that the region of strike-slip deformation becomes broader, with the amalgamated shear zones
duplex was translated, became subject to horizontal simple shear, and became narrower. Vertical thickening is required to produce exhumation of the Palaeozoic–Mesozoic cover and retrograde P/T conditions within the Lan Sang Gneisses.

Whilst some erosion of the Chainat duplex has occurred, it is noticeable that the area of the duplex is dominated by Palaeozoic–Mesozoic sedimentary, metasedimentary and igneous rocks. Deeper crustal levels are exposed only where the Khlong Lhan Gneisses crop out in the NW corner of the duplex. The Khlong Lhan Gneisses show a cooling history (ZFT = 40 ± 1 Ma, AFT = 20 ± 1 Ma) different from the adjacent Umphang Gneiss (ZFT = 47 ± 3 Ma, AFT = 40 ± 2 Ma) (Fig. 7). In Figure 9, the history of the Khlong Lhan Gneiss is explained as early exhumation occurring during entry into the restraining-bend area in the south of the duplex, and later exhumation where the gneisses entered the northern bend of the duplex. This interpretation of the history of the Khlong Lhan Gneiss implies that the main exhumation of the Lan Sang Gneisses did not occur at the obvious restraining-bend geometry, but as the rocks entered and turned the corner of the bend, passing from a north–south to NNW–SSE-striking fault segment to the NE–SW-striking segment. The cooling-age data are consistent with this interpretation, the oldest (36–33 Ma) ZFT and biotite cooling ages in the Lan Sang Gneisses come from the NW area, whilst the youngest (30 Ma) come from the SE. Whilst the data-set is not sufficient to be definitive, these data fit with rocks entering the bend and then being uplifted and eroded. Probably the exhumed, cooled, and thus relatively strong, region of the Umphang Gneiss acted as a hard anvil or buttress at the bend in the Mae Ping fault trace, and served to focus stresses, as rocks to the NE were translated, uplifted and flattened when passing through the bend.

One of the key questions arising from the model for exhumation of the Lan Sang Gneiss is why was the Umphang Gneiss area exhumed first, then failed to continue reactivating, but instead acted as the hard, resistant buttress against which the Lan Sang Gneisses were flattened and sheared? The answer may lie in the granite intrusions prevalent in western Thailand. Malaysia, Myanmar and Thailand are famous for their extensive suites of granitic rocks, in particular those formed during Triassic and Cretaceous orogenic events (e.g. Beckinsale et al. 1979; Charusiri et al. 1993). The Umphang Gneiss region is a mixture of para- and ortho-gneisses intruded by granites. Formation of granite melts depletes the lower crust of radiogenic materials and concentrates them in the granites (for example, see the discussion by Sandiford & McLaren 2002). Granite intrusion then transfers those radiogenic materials to higher levels of the crust. Uplift and erosion such as that seen in the Umphang Gneiss region would then remove much of the radiogenic granite to sedimentary basins, and elevate the remaining granite to very high levels in the crust. Consequently, the underlying area of gneiss is likely to be depleted in radiogenic material; have lower geothermal gradients than the surrounding regions; and thus be relatively cold and strong. Hence, the exhumation to the highest levels of the crust of the Umphang Gneiss would have brought the stronger granitic rocks west of the Khlong Lhan restraining bend into contact with weaker sedimentary and metasedimentary rocks east of the Khlong Lhan restraining bend. Deeper in the upper and middle crust, once the depleted, less-radioactive crust cooled, the Umphang Gneiss area would have been colder than the adjacent radioactive granitic Khlong Lhan gneiss region east of the Khlong Lhan restraining bend. Thus, the buttressing effect of the Umphang Gneiss would have developed, due to both mechanical and thermal variations in the upper crust, west and east of the Khlong Lhan restraining bend.

One feature of the northern boundary of the Lan Sang Gneisses is a sharp contact with an adjacent Cenozoic basin, mapped as a northward dipping normal fault by Lacassin et al. (1997) (Fig. 3). This Cenozoic basin contains the Mae Tuen coalfield with its Late Eocene–Early Oligocene coals unconformably overlain by a Oligocene–Early Miocene section (Rathanasethi 1990). Lacassin et al. (1997) interpreted the normal fault as a Late Oligocene feature. However, the coalfield data indicate that the normal fault probably operated during
sinistral displacement as well. Hence, the inference is made here that whilst passing through the bend the sheared and uplifted, hot and thickened area of Lan Sang Gneisses underwent extensional collapse on the northern side, whilst being overthrust to the SW on the southern side of the shear zone (Fig. 10). The evidence from the modelled cooling histories using K-feldspar (Lacassin et al. 1997) indicates rapid cooling from 400 to 185 °C between 32.5 Ma and 31 Ma, which is consistent with exhumation occurring in a short burst, and not progressively throughout the strike-slip history of the fault zone. Movement through the bend, uplift, and concomitant extensional unroofing are interpreted here to be the reason for the narrow range of cooling ages.

During the Late Oligocene–Early Miocene (i.e. c. 28–22 Ma) there was a period of extensive rift-basin formation, from the Gulf of Thailand, all the way up to northern Thailand (as reviewed by Morley et al. 2001). Adjacent to the Mae Ping fault zone, several rift basins developed (the Mae Sot, Mae Lamao, Phitsanulok, Suphan Buri and Ayutthaya basins). The regional extent of these basins suggests a major change in regional stress, probably from an approximately east–west S$_{Hmax}$ direction favourable for sinistral strike-slip deformation, to a north–south S$_{Hmax}$ direction appropriate for east–west extension (e.g. Huchon et al. 1994; Morley 2002).

The Chainat duplex area is a region of uplift, but, east of the Umphang Gneiss, deep levels of the crust are not exposed, despite having a restraining-bend geometry under sinistral motion. Relatively young uplift is supported by the 22–18 Ma range of three AFT central ages from the duplex area. As discussed in Smith et al. (2007) uplift within the duplex approximately coincides with the cessation of extension in the Lahan graben immediately north of the duplex, and a phase of inversion within the southern Phitsanulok Basin (Bal et al. 1992). The interpretation therefore implies a short-lived phase of minor (in the order of kilometres of horizontal displacement) sinistral motion occurred along the Mae Ping fault zone in the Early Miocene and contributed to the present duplex geometry.

The Mae Lamao and Mae Sot basins may have opened under dextral motion on the Mae Ping fault zone, but an oblique extensional origin is also possible. Satellite images show fault strands branching off the Mae Ping fault zone and linking with basin-bounding faults. However, whether the basins are just reactivating older strike-slip trends or are kinematically linked remains uncertain. In the basins the youngest rift fill is of Early Miocene to early Middle Miocene age; there are inversion structures in the Mae Sot Basin; and coal maturity points to removal of somewhere between 1.5 and 3 km of section from the Mae Lamao Basin. These data point to an uplift event of Middle Miocene or younger age. A known Late Miocene inversion event associated with sinistral deformation on NW–SE-trending faults affects the Phitsanulok and Ayutthaya basins (Bal et al. 1992; Smith et al. 2007, this volume), and hence may also fit with the Mae Sot and Mae Lamao uplift history.

**Vertical extent of strike-slip shear zones**

There are two main models for the way that the large escape tectonics related shear zones might be behaving in SE Asia. In one model the shear zones penetrate the entire crust and upper mantle, and a broadening – but comparatively narrow and discrete – zone of simple shear (e.g. the Red River fault zone model of Leloup et al. 1995). The alternative model considers the fault zones to be essentially upper-crustal features that die out into broadly distributed shear within the middle or lower crust (e.g. England & Houseman 1989). The model in Figure 10 shows the Mae Ping fault zone as dying out within the lower crust. This is not because there is definitive evidence for either model, but because on balance it is the model most favoured by the data at present. First, there are no melts along the Mae Ping fault zone that indicate that magma of mantle origin was being tapped, unlike the model for the Red River fault zone (Leloup et al. 1995). Second, in Yunnan, where there are numerous important strike-slip zones, there does appear to be evidence for strike-slip faults dying out in the middle to lower crust – both from magneto-telluric data which indicate the presence of a middle-crustal detachment layer (e.g. Bai & Meju 2003) and from seismic tomography which shows no evidence for any deep perturbation of layers vertically beneath the major strike-slip fault zones (Liu et al. 2000). In the case of the Red River fault zone, it may follow a major suture zone at the surface, but tomography indicates that a relict Tethyan subduction zone at lower-crustal and mantle levels lies fifty or more kilometres west of the Red River fault zone (Liu et al. 2000). Hence, the upper-crustal zone of weakness does not appear to extend downward vertically throughout the crust to favour the development of a deep-penetrating strike-slip fault zone.

**Comparison with other models of restraining-bend development**

Cowgill et al. (2004) describe large restraining bends in terms of thrust- and strike-slip-dominated
types. Thrust-dominated restraining bends display maximum uplift along the main length of the restraining bend, producing restraining-bend ‘pop-ups’ (e.g. Wakabayashi et al. 2004). Thrust-dominated earthquake focal mechanisms from restraining bends in California, such as the Santa Cruz bend, indicate that the vertical principal stress is the minimum principal stress (Hauksson & Jones 1988; Cowgill et al. 2004). In strike-slip-dominated restraining bends, the vertical principal stress is the intermediate principal stress. Strain and uplift are focused on the areas of changing fault orientation entering and leaving the restraining bend (Cowgill et al. 2004). There is also a tendency for the strike-slip fault to undergo vertical-axis rotation to reduce the bend angle (Cowgill et al. 2004). The Akato Tagh bend along the Alty Tagh Fault in China, is cited by Cowgill et al. (2004) as such an example.

The Mae Ping fault zone does not appear to show a simple or constant pattern of deformation associated with the restraining-bend geometry of the Chainat duplex area. The oldest documented uplift began in the Umphang Gneiss region on the western margin of the duplex (Fig. 2), and may have spanned the time from about 50 Ma to 40 Ma (Fig. 9). This uplift suggests a thrust-dominated Santa Cruz-type restraining-bend setting (e.g. Hauksson & Jones 1988; Cowgill et al. 2004), where uplift of the gneisses occurred along the restraining bend in the hanging wall of a steeply inclined, west-dipping transpressional fault zone.

The next phase of deformation, during the Oligocene, appears to be very different in character, and involved extensive shearing and translation of the Lan Sang Gneiss around the northern bend in the fault zone just west of Tak (Fig. 9). The Klong Lhan Gneiss underwent uplift moving into the restraining bend at about 40 Ma, and then appears to have been translated with only moderate cooling until a second uplift event occurred at 20 Ma at the exiting bend of the Chainat duplex. Conversely, the Lan Sang Gneisses moving around the exiting bend display rapid Late Eocene–Early Oligocene cooling ages (Figs 5 & 7). This concentration of uplift at the entering and exiting bends is consistent with the strike-slip-dominated restraining-bend model (Cowgill et al. 2004), with transpressional deformation just being locally concentrated at the exiting bend. The two styles are also consistent with the regional tectonics, where early fault development occurred within a Late Cretaceous–Palaeogene transpressional orogen (Morley 2004), whilst Oligocene reactivation occurred during Himalayan escape tectonics (Lacassin et al. 1997).

McCay & Bonora (2001) presented analogue models for restraining-bend duplex geometries, and they thus generated a range of deformation styles that changed according to: the amount of displacement; the angle between the restraining bend and the main strike-slip trend; and the width of the restraining bend. The last major stage of the Chainat restraining-bend development is the formation of the present-day Chainat duplex, and its geometry appears to be quite appropriate for comparison with the McCay & Bonora (2001) analogue models. In the Chainat duplex, the angle made by the restraining bend with respect to the main fault trend is about 35°, hence the 30° stepover model shown in McCay and Bonora (their fig. 3) is the most appropriate. In this model, the duplex is dominated by internal faults striking subparallel to the restraining bend, unlike higher stepover angles, where a wider range of fault angles is developed. The model pattern is reminiscent of the dominant NNW–SSE to north–south strike of ridges within the Chainat duplex, bounded by NW–SE-striking faults to the north and south (Fig. 2). It is quite apparent from analogue models and descriptions of natural examples of strike-slip duplexes (e.g. Laney & Gates 1996; McCay & Bonora 2001; Cunningham et al. 2003) that the relatively simple, classic strike-slip duplex geometry becomes complicated by a wide range of fault trends, rotation of faults, and variable fault kinematics once large displacements become imposed. Whilst the comparative simplicity of the Chainat duplex geometry might be misleading (and a function of exposure), the lack of strong uplift (and exposure of higher metamorphic-grade rocks) within the duplex; the long, linear, unimpaired trend of the Jurassic ridge on the west side of the duplex (Smith et al. 2007, paper 11, this volume); and the 22 Ma to 18 Ma AFT ages, all indicate that it is a comparatively young feature that developed late in the history of the fault zone. It appears to represent the third incarnation of uplift at the restraining bend.

During the Late Oligocene to Pliocene, the rift basins of central and northern Thailand document a series of extensional phases punctuated by periods of inversion (e.g. Morley et al. 2000, 2001), and testify to a rapidly evolving stress regime. Two episodes of inversion during the Early Miocene and the latest Miocene to Early Pliocene appear to be quite widespread (Morley et al. 2000; 2001), but at least four episodes of inversion have been recorded in some basins (Bal et al. 1992; Morley et al. 2000). Probably the most prominent stress regime was extensional, with $S_{max}$ oriented approximately north–south, as it is today (Bott et al. 1997). The orientations of inversion-related folds, inverted normal faults, and episodically
active strike-slip faults indicate that during episodes of inversion the stress regime may have ranged from strike-slip to compression, and the $S_{\text{max}}$ direction ranged between north—south and east—west (Morley et al. 2000, 2001). This brief summary of regional data indicates that the latest history of the Chainat duplex was characterized by short episodes of activity during phases of basin inversion, and there is clear structural evidence for sinistral motion within the duplex, from folded Mesozoic rocks and fault kinematic data (Smith et al. 2007).

The NW–SE trending Three Pagodas Fault to the south has Late Cenozoic basins developed at north—south releasing-bend geometries (Morley 2002). The low-level earthquake activity that affects northern and western Thailand today is dominated by dextral strike-slip fault-plane mechanisms on NW–SE-striking faults and sinistral focal mechanisms for NE–SW-striking faults; the $S_{\text{max}}$ direction is approximately north—south (e.g. Bott et al. 1997; Morley 2004). From these two lines of evidence and the observed dextral slickensides within the duplex, it is concluded that the Chainat duplex was also reactivated episodically under minor dextral motion.

Conclusions

The study by Lacassin et al. (1997) remains vitally important to our understanding of the Mae Ping fault zone, but highlights the problem of drawing conclusions from a geographically limited area of the fault zone. Other parts of the fault do not show the same cooling-age histories. Both to the SE (Umphang and Khlong Lhan Gneisses, Fig. 7) and the NW (Fig. 5) of the Lan Sang Gneisses cooling ages become older. The rapid cooling ages of the Lan Sang area do not appear to be representative of the entire fault zone, or even a long segment of it, but instead record an unusual exhumation event, interpreted here to be a passage around the exiting restraining bend. In addition, the regional north—south trend of cooling-age patterns seen for biotite, ZFT and AFT data (Figs 5 & 6) indicates that, at least in part, exposure of the Lan Sang Gneisses is related to more regional exhumation patterns than strike-slip specific uplift and erosion.

Given the available range of major structures in the area (large rift basins, pull-apart basins, low-angle extensional detachments, major strike-slip faults, strike-slip duplexes, the ‘extensional collapse’ normal fault north of Lan Sang) and the available range of cooling ages (and associated data such as sedimentary-basin history), our ability to construct the structural model remains limited, and numerous questions remain outstanding. Considerably more supplementary data is required to test the models presented in this paper and to develop a good understanding of the relationships between different structural styles. For example, the way that the region of ‘metamorphic core complexes’ west of Chiang Mai, down to the Mae Sariang–Hot highway (between arrows c–c’, Fig. 4) connects with the Mae Ping fault zone is uncertain. The Umphang Gneiss appears to be an island of Eocene exhumation in the western ranges, surrounded by Oligocene–Miocene cooling ages, but again data south and west of the gneisses are very sparse and additional information is required to fill in the gaps in our knowledge.

Despite the caveats associated with the interpretation of the data and its limitations, a fairly detailed model for the evolution of the fault zone has been proposed in this paper, and can be tested in future studies. The Cenozoic history of the predominantly sinistral Mae Ping strike-slip fault zone shows considerable strain in the vicinity of the Khlong Lhan restraining bend. This deformation can be understood in terms of models proposed for other restraining beds (strike-slip v. thrust-dominated restraining bends Cowgill et al. 2004) and analogue modes of early restraining-bend deformation (McClay & Bonora 2001). Initial uplift and erosion on the western side of the restraining bend unroofed the Umphang Gneisses during the Eocene, probably in a thrust-dominated restraining-bend context. Later, as regional deformation evolved from a transpressional orogen related to terrane collision, to escape tectonics associated with the main India–Eurasia collision (Morley 2004) the restraining bend shows strike-slip-dominated characteristics (Cowgill et al. 2004). Passing through the northern (exiting) bend in the restraining bend, the northern side of the fault zone was subject to extensive simple shear and vertical thickening, resulting in uplift, erosion and extensional unroofing during passage through the bend. The resulting 5–6-km-wide mid-crustal shear zone exposed at Lan Sang records cooling ages consistent with this passage through the bend. Possibly prior to flattening and simple shear passing through the bend, this zone was originally some 40–50 km wide. The final phase of restraining-bend deformation (Late Oligocene–Recent) occurred under a complexly evolving stress field when episodically relatively small displacements (probably totalling a few kilometres of motion) with both sinistral and dextral sense of motion affected the Chainat duplex area.

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References


MAE PING FAULT ZONE, WESTERN THAILAND


