Did Oligocene crustal thickening precede basin development in northern Thailand? A geochronological reassessment of Doi Inthanon and Doi Suthep

Nicholas J. Gardiner [a], 1 , Nick M.W. Roberts [b] , Christopher K. Morley [c,d] , Michael P. Searle [a] , Martin J. Whitehouse [e]

[a] Department of Earth Sciences, University of Oxford, Oxford OX1 3AN, United Kingdom

[b] NERC Isotope Geosciences Laboratory, British Geological Survey, Nottingham NG12 5GG, United Kingdom

[c] Department of Geological Sciences, Chiang Mai University, Thailand d PPT Exploration and Production, Vibhavadi-Rangsit Road, Soi 11, Bangkok 10900, Thailand

[e] Swedish Museum of Natural History, and Nordic Center for Earth Evolution, Box 50007, SE-104 05 Stockholm, Sweden

Abstract

The Doi Inthanon and Doi Suthep metamorphic core complexes in northern Thailand are comprised of amphibolite-grade migmatitic gneisses mantled by lower-grade mylonites and metasedimentary sequences, thought to represent Cordilleran-style core complexes exhumed through the mobilization of a low-angle detachment fault. Previous studies have interpreted two metamorphic events (Late Triassic and Late Cretaceous), followed by ductile extension between the late Eocene and late Oligocene, a model which infers movement on the detachment at ca. 40 Ma, and which culminates in a rapid unroofing of the complexes in the early Miocene. The Chiang Mai Basin, the largest such Cenozoic Basin in the region, lies immediately to the east. Its development is related to the extension observed at Doi Inthanon and Doi Suthep, however it is not definitively dated, and models for its development have difficulty reconciling Miocene cooling ages with Eocene detachment movement. Here we present new in-situ LA-ICP-MS and SIMS U–Pb age data of zircon and monazite grains from gneiss and leucogranite samples taken from Doi Inthanon and Doi Suthep. Our new zircon data exhibit an older age range of 221–210 Ma, with younger ages of ca. 72 Ma, and 32–26 Ma. Our monazite data imply an older age cluster at 83–67 Ma, and a younger age cluster of 34–24 Ma. While our data support the view of Indosinian basement being reworked in the Cretaceous, they also indicate a late Eocene–Oligocene tectonothermal event, resulting in prograde metamorphism and anatexis. We suggest that this later event is related to localized transpressional thickening associated with sinistral movement on the Mae Ping Fault, coupled with thickening at the restraining bend of the Mae Yuan Fault to the immediate west of Doi Inthanon. Further, this upper Oligocene age limit from our zircon and monazite data would imply a younger Miocene constraint on movement of the detachment, which, when combined with the previously recorded Miocene cooling ages, has implications for a model for the onset of extension and subsequent development of the Chiang Mai Basin in the early mid-Miocene.

Keywords

- Doi Inthanon;
- Migmatite leucogranite gneiss;
- U–Pb zircon monazite;
- Himalayan Orogeny;
- Thailand Cenozoic Basin

1. Introduction

In recent years, advances in high-precision in-situ U–Pb geochronological techniques have yielded enhanced information about the timing of significant magmatic and metamorphic events within Southeast Asia. These techniques are crucial tools for providing important age data to underpin regional Southeast Asian tectonic interpretations, since many study areas, such as Thailand and Myanmar, often present only limited outcrop exposure. Recent zircon and monazite in-situ U–Pb geochronology studies have provided discoveries of Eocene to Oligocene high-grade metamorphism and granite magmatism in both Myanmar (e.g. Mitchell et al., 2012 and Searle et al., 2007) and Thailand (e.g. Palin et al., 2013a and Searle et al., 2012), helping constrain models of regional orogenic evolution subsequent to the initial India–Asia collision.

Northern Thailand lies within a geologically complex domain (Fig. 1). Mesozoic–Cenozoic subduction, accretion, and collisional events gave way to late Cenozoic extension and basin development, all occurring within the framework of the continued northwards progression of the Indian plate and the subsequent clockwise rotation of accreted Asiatic terranes around the Eastern Himalayan Syntaxis. The development of a number of significant regional strike-slip faults and shear zones provided accommodation of strain associated with this rotational history. These faults together exhibit a temporal evolution that reflects the changing regional geometry during tectonic reconfiguration, controlling and focusing regions both of crustal extension and basin development, and of crustal thickening and coeval metamorphism and magmatism. Understanding the timing and evolution of faulting during the Cenozoic is of prime importance in constructing an evolutionary tectonic model for Southeast Asia, and in particular to better understand the onset and development of economically important Cenozoic basins within Thailand. Isotope geochronology can help constrain both the age of shear zones through the study of affected metamorphic rocks, and to date evidence of metamorphism and anatexis during crustal thickening, thereby providing age constraints for the onset of extension and basin development. In-situ U–(Th)–Pb geochronology is thus a powerful tool that can provide important and reliable data upon which any regional tectonic model needs to adhere and ultimately explain.

The Doi Inthanon metamorphic core complex (Barr et al., 1991 and Macdonald et al., 1993), sited in northern Thailand, comprises high-grade migmatitic gneisses mantled by lower-grade mylonites and metasedimentary sequences. It is part of the so-called “Chiang Mai–Lincang Belt” (Searle and Morley, 2011) which includes the similar Doi Suthep complex 40 km to the northeast near Chiang Mai, and the Lansang Gneiss further south. All three complexes have been the subject of a number of studies over the past 25 years (Section 2). A hypothesis for the formation of both Doi Inthanon and Doi Suthep is that together they represent extensional Cordilleran-style core complexes exhumed through the mobilization of a low angle detachment fault (Macdonald et al., 1993,Macdonald et al., 2010 and Rhodes et al., 2000), an extension assumed to underpin subsequent basin development. Understanding the relative timings of metamorphism, ductile shearing and assumed coeval uplift via detachment faulting can thereby provide key age constraints for the onset of extension and basin development within the regional Chiang Mai area.

We set out to revisit both Doi Inthanon and Doi Suthep given recent advances with in-situ microanalytical isotope techniques (here employed using both laser ablation and secondary ion mass spectrometry (LA-ICP-MS and SIMS respectively). Our aim was two-fold: (i) to ascertain whether higher resolution geochronology could uncover evidence for a more recent metamorphic event than previously reported, as has been observed further south in Lansang (Palin et al., 2013a) and further west in Myanmar (Searle et al., 2007); and (ii) to see if more age data could better constrain the development inception of the Chiang Mai Basin. Due to the limited exposure, an overlap in our sampling localities with those of previous workers was inevitable, however in certain instances this afforded the opportunity for employment of in-situ analytical techniques where whole-grain measurements had previously been made and therefore the potential for uncovering more complex growth histories.

Here, we detail our new zircon and monazite in-situ U–(Th)–Pb age data from both Doi Inthanon and Doi Suthep. In particular, we present evidence for what we interpret as a new late Eocene–Oligocene high-grade metamorphic event leading to partial melting occurring as recently as 24 Ma. We propose that these new data imply local crustal thickening occurred at least until the Oligocene, which would provide an important new geochronological constraint on the onset of extension in an area that was previously interpreted as having exhibited ductile extension between the late Eocene and late Oligocene (Macdonald et al., 2010). This study therefore potentially offers an important new upper age limit to the switch from a compressional regime to the onset of regional extension that was ultimately responsible for the development of the Chiang Mai Basin.

2. Geological framework

2.1. Chiang Mai–Lincang Belt

The Phanerozoic geology of Southeast Asia is dominated by the progressive closing of Tethys, resulting in the accretion of a series of continental plates that rifted off from Gondwana during the late Carboniferous–early Permian (Metcalfe, 2006), and collided with the South China craton. The late Triassic suturing of the Palaeo-Tethys leading to the Indosinian Orogeny (Metcalfe, 2000 and Sone and Metcalfe, 2008) was followed by the suturing of the Neo-Tethys, the collision of the Indian plate with Asia, and the onset of the Himalayan Orogeny at ca. 50 Ma (Green et al., 2008). The suturing of the Palaeo-Tethys resulted in the emplacement of two major granite belts: the *Main Range Province*and the *Eastern Province*, which together run broadly north–south through west–central Thailand into the Malay Peninsula (Cobbing et al., 1986, Cobbing et al., 1992,Hutchison, 1977 and Ng et al., 2015a). These belts delineate the Palaeo-Tethys suture in Malaysia, Thailand, and Myanmar (Fig. 2a: Barr and Macdonald, 1991, Gardiner et al., 2015a, Hutchison, 1975, Hutchison, 1973, Metcalfe, 2002, Metcalfe, 2000 and Mitchell, 1977). Within the Malay Peninsula, the Main Range Province outcrops as a single contiguous belt of undeformed granites. However in northern Thailand it exhibits a distinctive core of strongly deformed gneisses and migmatitic leucogranites some 400 km in length (Fig. 1A). This, termed the *North Thailand Migmatite Province* or *Chiang Mai–Lincang Belt* (Cobbing, 2011, Cobbing et al., 1986 and Searle and Morley, 2011), comprises the Doi Inthanon and Doi Suthep core complexes, the Lansang Gneiss west of Tak, and the Umphang Gneiss southwest of the Chainat Duplex (Searle and Morley, 2011).

The discovery of these gneisses initially led to interpretations that they represented the exposure of a deeper, Precambrian basement complex (Baum et al., 1970). However, the complexes at Doi Inthanon and Doi Suthep are overlain by a cover of lower-grade Palaeozoic metasedimentary rocks, and later work led to the interpretation that they represented Cordilleran-type metamorphic core complexes exposed through low angle detachment faulting during lateral extension (Barr and Macdonald, 1991, Dunning et al., 1995, Macdonald et al., 1993, Morley, 2009a and Rhodes et al., 2000). In this scenario they find a parallel within the core complexes of the Basin and Range province of southwestern North America (e.g., Wernicke, 1992).

The high-grade gneisses at Doi Inthanon are thus interpreted to be separated from the overlying lower-grade metasediments by an extensive detachment fault that runs across much of the northwest highlands of Thailand (Barr and Macdonald, 1991). The discontinuously exposed detachment forms a thick (10^2–10^3 m) zone of mylonite. The migmatitic gneisses exposed within the core are likely reworked Sibumasu basement (Barr and Macdonald, 1991, Dunning et al., 1995, Macdonald et al., 2010 and Rhodes et al., 2000), distinct from the surrounding Palaeozoic sediments exposed on the eastern margin of the belt, the western margin of the Chiang Mai Basin (Morley et al., 2011). The term *Inthanon Zone* (e.g. Macdonald et al., 1993) describes the broader Sibumasu continental crust, within which the Chiang Mai–Lincang Belt is exposed as crystalline basement.
Previous geochronological studies (Section 3) have interpreted Late Triassic ages from Doi Inthanon gneisses as magmatism associated with the Indosinian Orogeny, as well as evidence of an early Late Triassic metamorphic event. This was followed by evidence suggestive of a Cretaceous metamorphic overprint, and Eocene ages of mylonitization, and Oligocene magmatism.

2.2. Cenozoic Basin development

Over forty Cenozoic rift basins are found within northern and central Thailand (Morley, 2009b). These rifts exploited hot, weak crust created by subduction-related activity that subsequently migrated westwards in response to plate reconfiguration due to the India–Asian collision at 50 Ma (e.g. review in Hall and Morley, 2004). An Oligocene–Miocene regional age for the onset of basin development has been proposed on the basis of macro-fossils, magnetostratigraphy and palynology (e.g. Benammi et al., 2002, Morley, 2009b and Morley et al., 2001 and refs therein). The Chiang Mai Basin, sited immediately to the east of Doi Inthanon and Doi Suthep (Fig. 1B), is the largest Cenozoic Basin in northern Thailand, however no definitive date for its initiation has been realized from palynology despite a number of wells having been drilled.

The Doi Inthanon and Doi Suthep detachment is truncated by a younger low-angle boundary fault that developed on, and formed, the western margin of the Chiang Mai Basin, termed the Chiang Mai Low Angle Normal Fault (CMLANF) by Morley (2009b)(see cross-section in Fig. 7). $^{40}Ar/^{39}Ar$ muscovite cooling and apatite fission track ages of 21–16 Ma (Macdonald et al., 2010, Morley, 2007 and Upton et al., 1997) together imply rapid vertical exhumation of some 8 km in 4 My (Morley, 2009b). These Miocene ages are, however, too recent to identify the detachment as being responsible for the uplift of Doi Inthanon, since previous work infers the age of faulting at Eocene–Oligocene (e.g.Macdonald et al., 2010), and the logical conclusion would be that the CMLANF was therefore responsible for its exhumation. However, estimates for the displacement necessary on the CMLANF to exhume the Doi Inthanon complex are on the order of 35 km, a magnitude of throw expected to produce a much deeper basin than is observed with the Chiang Mai Basin.

To solve this conundrum, and to accommodate the exhumation of Doi Inthanon with the development of a relatively shallow basin, a hybrid model was proposed, based on initial limited independent exhumation of Doi Inthanon, and then subsequent movement on the CMLANF (Morley, 2009b). However, there remains uncertainty over the exact relationship between movement on the detachment, the exhumation of Doi Inthanon (and Doi Suthep), and movement on the CMLANF and concurrent development of the Chiang Mai Basin. Reappraisal of the timing of movement on the detachment fault would have implications for any model for formation of the Chiang Mai Basin.

3. Previous geochronological studies

Much of Northern Thailand was mapped by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in the 1970s as part of a German geological mission (Baum et al., 1970). The first geochronological measurements employed Rb–Sr whole-rock isotopic techniques, assigning a Triassic age to Main Range Province granites (e.g. Bignell and Snelling, 1977, Cobbing et al., 1992, Liew and Page, 1985 and von Braun et al., 1976).Charusiri et al. (1993) undertook a broad study of granite belts across Thailand using $^{40}Ar/^{39}Ar$ techniques, and yielded ages of 220–180 Ma for the Main Range Province.Ahrendt et al. (1997, 1992) reported an age of 197 ± 3 Ma from the Lansang Gneiss through zircon U–Pb age determinations.

Macdonald et al. (1993) undertook geological mapping of the Doi Inthanon area, distinguishing between an orthogneiss core and a mantling paragneiss and mylonitic gneiss, invoking comparison of Doi Inthanon with Cordilleran-type core complexes.Macdonald et al. (1993) further reported initial ID-TIMS whole-grain U–Pb zircon and monazite dating that suggested a Late Triassic protolith to the core orthogneiss, followed by a Late Cretaceous metamorphic event. They interpreted that this event marked the onset of regional extension and the development of the core complex occurred between the Cretaceous and Eocene.

Dunning et al. (1995) reported further ID-TIMS U–Pb analyses of both separated zircon and monazite grains taken from several localities around Doi Inthanon. Their orthogneiss samples gave zircon ages of 203 ± 4 Ma and 211 ± 4 Ma, which they interpreted as protolith ages, reflecting Indosinian-related magmatism. Further, they reported whole-grain monazite U–Pb analysis from the same orthogneiss yielding Cretaceous ages of 84 ± 2 and 71 ± 1 Ma (their samples WY90-63 and WY90-26 respectively). They interpreted these as representing ages of peak amphibolite-facies metamorphism. Two granite samples were also dated by Dunning et al. (1995). The Mae Cham granite (their sample WY90-119) gave a combined age of 203 ± 4 Ma from zircon and monazite fractions, assumed to be a protolith age. The Mae Klang granite (WY90-44) yielded Oligocene ages from both zircon and monazite analyses, averaging 26.8 ± 0.8 Ma, interpreted to reflect a granite crystallization age, and cited by Dunning et al. (1995) as evidence of Oligocene magmatism. Further, on the basis of textural evidence suggestive of granite emplacement prior to completion of mylonitization, Dunning et al. (1995)interpreted that the Mae Klang granite provided an upper age limit for mid-crustal extension, concluding that the age of mylonitization lay between a late Cretaceous thermal peak, and the early Miocene.

Rhodes et al. (2000), in a study of the neighbouring Doi Suthep complex, interpreted their structural observations as confirmation that a mid-Tertiary low-angle detachment fault extended through both complexes, and further that the detachment was subsequently domed. On the basis of kinematic indicators they observed within the mylonites, Rhodes et al. (2000) interpreted top-to-the-east simple shearing as evidence of eastwards-directed detachment faulting, noting that N–S-trending basin development implied E–W shortening. They further agreed with Dunning et al. (1995) that mylonitization occurred sometime after the Late Cretaceous, and that the latest movement came during and after the deposition of the Mae Rim Formation cover sequences.
Macdonald et al. (2010) reported U–Pb accessory mineral analyses from a calc-silicate gneiss located at Mae Wang, southwest of Chiang Mai (originally reported by Barr et al., 2002). Both titanite and zircon separates yielded Indosinian ages (213 ± 2.3 Ma and 210.1 ± 4.4 Ma respectively), which they interpreted as being representative of an early (their M1) metamorphic event. Further, they undertook

whole-grain monazite and U–Pb zircon geochronology from a granitic mylonite sampled from the Pa Ngerp Waterfall, west of Doi Suthep. A mean age of 40.0 ± 1.2 Ma was taken to be that of the syntectonic granite protolith (their sample BRC36), and interpreted by them as the upper age limit of mylonitization within the Doi Suthep area. Macdonald et al. (2010) also undertook laser-probe $^{40}Ar/^{39}Ar$ cooling age determination of muscovite and phlogopite grains from a number of samples in the Doi Inthanon complex. They reported an age range of 26–15 Ma, interpreted to represent rapid cooling through the 350 °C isotherm of the complex over this time period. Further, Macdonald et al. (2010) performed thermobarometric determinations of both gneiss and calc-silicate samples using independent mineral thermometers and barometers. They inferred a clockwise P–T–t path for the Doi Inthanon complex with a peak Cretaceous metamorphism at amphibolite facies conditions of 6–7 kbar and 700 °C, followed in the late Palaeogene by ductile shearing under retrograde lower amphibolite facies conditions. In particular, they invoked the $^{40}Ar/^{39}Ar$ cooling ages of 26–15 Ma to represent the rapid unroofing of the complex.

Apatite fission track ages performed by Upton et al. (1997), on samples from similar localities to Macdonald et al. (2010), yielded ages of 17 ± 1 Ma for Doi Inthanon, and 16 ± 1 Ma for the western margin — with a more regional range of 22–18 Ma. The conclusion from these results was rapid vertical exhumation of the Doi Inthanon massif over ca. 4 Ma, giving 8 km of uplift (Morley, 2009b).

4. Samples and results

Samples were collected from several localities around Doi Inthanon and one locality in Doi Suthep. Due to the limited exposure presented in the Doi Inthanon region, some sample localities are the same as those reported by Dunning et al. (1995). Further, our use of an in-situ analytical technique promised better spatial fidelity compared to previous whole-grain analyses leading to the possibility of distinguishing between growth zones. Table 1 summarizes samples, localities and measured zircon and monazite U–(Th)–Pb ages. Fig. 2a and b shows a geological map of northern Thailand, and of the Doi Inthanon area, respectively, with sample localities identified. Fig. 3 details selected outcrop photographs.

Sample T21 was taken from the Mae Klang Waterfall (Fig. 3d), and is a fine-grained granitic gneiss with quartz, plagioclase and K-feldspar and minor biotite. It is strongly foliated, and exhibits large (1–2 cm) K-feldspar augen.

Sample T25 is from the Huay Saai Leung Waterfall, the same locality as WY90-63 ofDunning et al. (1995). It is a strongly foliated gneiss with quartz, perthitic alkali feldspar, plagioclase feldspar, biotite and minor muscovite.

T29, the leucogranite boudin, was sampled from an outcrop on the Hot Road, 20 km west of Hot and south of the Doi Inthanon complex. It represents a medium-grained, alkali feldspar, plagioclase and quartz leucogranite with minor muscovite, and hosts small (5 mm) garnets. In outcrop it exhibits isoclinal folds, and boudinage on the 10 cm scale (Fig. 3b).
Sample T30 is a coarse-grained biotite augen gneiss from the Siribhume Waterfall, and represents the same locality as WY90-26.

T31 is a sample of K-feldspar augen gneiss from the Mae Ya Waterfall (Fig. 3a). It exhibits a strong fabric, and is comprised largely of alkali feldspar and quartz, with minor biotite, and large (1–2 cm) K-feldspar augen.

Sample T17 was taken from a locality near the summit of Doi Suthep, and is a foliated granite gneiss. It comprises muscovite with minor biotite, with quartz, K-feldspar and plagioclase. In outcrop it is intruded by a younger pegmatite.

4.1. U–(Th)–Pb geochronology

All samples from Doi Inthanon (i.e. except sample T17) were analyzed for in-situ zircon U–Pb geochronology and in-situ monazite U–Th–Pb geochronology by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Sample T17 from Doi Suthep underwent secondary ionization mass spectrometry (SIMS) zircon U–Pb geochronology. Methodologies and results are detailed below.

4.1.1. Zircon U–Pb geochronological method

Zircon grains were separated from crushed rock samples using a combination of Frantz magnetic and heavy liquid separation. Selected zircon grains were then mounted in epoxy. The mounts were imaged using the FEI Quanta 650 FEG Scanning Electron Microscope at the Department of Earth Sciences, University of Oxford. Zircon U–Pb geochronology was performed on all samples (except T17) using a Nu Instruments Attom single-collector ICP-MS at the NERC Isotope Geosciences Laboratory, Keyworth, UK (NIGL). The full method is described in Spencer et al. (2014). Laser ablation was performed with a New Wave Research 193UC excimer laser ablation system. Ablation parameters were a 25 µm static spot, a repetition rate of 5 Hz, a fluence of 2.2 j/cm^2, a 10 second washout period between analyses, and a 30 second ablation time. Tuning was adopted that gave a ThO of < 0.3%, and UO of < 0.1%. The Pb/Pb and U/Pb ratios were normalized to bracketing primary reference materials 91500 (1062 Ma; Wiedenbeck et al., 1995); Plešovice (337 Ma; Sláma et al., 2008); and GJ-1 (602 Ma; Jackson et al., 2004), on the basis of the average measured value of the reference materials compared with the ratio determined by ID-TIMS. Data processing used the time-resolved function on the Nu Instruments' software, and an in-house Excel spreadsheet for data reduction and uncertainty propagation.

Sample T17 was analyzed separately using a large geometry CAMECA IMS1280 ion microprobe at the NordSIM Facility housed at the Swedish Museum of Natural History, Stockholm, Sweden. Separated zircon grains from sample T17 were measured using methods similar to those described by Whitehouse and Kamber (2005) and Whitehouse et al. (1999).

All results used Isoplot for data presentation (Ludwig, 2003), and all calculated ages are $^{206}Pb/^{238}U$ ages presented at 2σ. Wetherill Concordia diagrams are presented in Fig. 4. Full zircon results are presented in the Supplementary tables.

4.1.2. Monazite geochronological method

Polished thin sections of samples were imaged using a FEI Quanta 650 FEG Scanning Electron Microscope at the Department of Earth Sciences, University of Oxford. Candidate monazite grains were then analyzed at NIGL following the methodology described in Palin et al. (2013b).

Instrumentation and parameters were the same as with zircon geochronology, except for a spot size of 10 µm. Ratios of Pb/Pb, Pb/U and Pb/Th were normalized to monazite reference materials Manangotry monazite (559 ± 1 Ma ID-TIMS age; Paquette et al., 1994); Stern (512.1 ± 1.9 Ma, ID-TIMS age; Palin et al., 2013b); and Moacyr (~ 515.6 ± 1.4 Ma, ID-TIMS age, Palin et al., 2013b).

Absolute uncertainties are provided only for regressed populations with a calculated MSWD value. All quoted uncertainties and ellipses on Tera–Wasserburg plots are at the 2σ confidence interval, and all calculations were performed using the Isoplot MS Excel add-in (Ludwig, 2003). Tera–Wasserburg diagrams are presented in Fig. 5. Full monazite results are presented in the Supplementary tables. All ages quoted are $^{206}Pb/^{238}U$ ages.

There is general concordance between those analyses where both Th/Pb and U/Pb ages were measured (Fig. 5), confirming the validity of the quoted age populations and ranges, and implying that older U/Pb ages due to excess ^{206}Pb have not posed a significant problem. Only one sample (T30) has scatter about a 1:1 line (Fig. 5f), with ages from some monazites falling to older U/Pb ages, but these are generally within 5 My and thus do not affect the interpretation.

4.2. Zircon and monazite U–(Th)–Pb results

Zircon U–Pb analyses from the six samples are presented using standard Concordia plots. The majority of zircon grains from most samples are conspicuously zoned, with identifiable cores and rims. Analyses from monazites from five samples are presented using Tera–Wasserburg plots to allow projection from common lead, and for this a common lead $^{207}Pb/^{206}Pb$ ratio of 0.83 ± 0.02 was used for anchoring. Additionally, U, Th and Pb were collected for 3 of the 5 samples (T25, T29 and T30), and therefore independent age determinations can be made using both the U–Pb and Th–Pb systems. Relevant plots of $^{208}Pb/^{232}U$ versus $^{206}Pb/^{238}U$ are presented in Fig. 5b,d and e. Table 1shows a summary of age data by sample.

Separated zircon grains from sample T17 are relatively euhedral, and are not conspicuously zoned. Six analyses from discrete zircon grains (Fig. 4a) yield a weighted mean age of 220 ± 8 Ma (MSWD = 3.4).

Zircon analyses from sample T21 yield two older ages, with a weighted mean of 217 ± 8 Ma (Fig. 4b). However, we also measured a population of much younger ages, with a range (n = 7) of 28–26 Ma. Monazite analysis from T21 yields an age range of 30–24 Ma, with the oldest and youngest intercept ages at 30.8 Ma and 24.8 Ma respectively (Fig. 5g). No satisfactory mean intercept age was calculable.

Zircon age data from sample T25 (Fig. 4d) show a dominant population from both cores and rims of ca. 220–200 Ma, with a spread of discordant data leading to an imprecise younger lower intercept at 7 ± 27 Ma. We interpret the spread of sub-concordant to concordant ages as being due to variable lead loss from a ca. 213 Ma age population, as opposed to multiple events leading to zircon growth. Monazite analyses from T25 yielded an age range of 83–69 Ma (upper intercept of 83.0 Ma, lower intercept at 69.4 Ma), with a mean intercept at 76.0 ± 2.1 Ma (Fig. 5a). The age of the younger event producing lead-loss in the zircons is likely the Cretaceous event as recorded by monazite analyses.

Sample T29 shows a spread of zircon-derived ages, with an oldest of ca. 215 Ma (Fig. 4d). There is also spread of age data from 90–45 Ma, with the oldest of these being Cretaceous ages. These ages may reflect either lead loss due to a younger event, zircon growth during the Cretaceous tectonothermal event recorded in other samples, or a combination of both. Monazite data from sample T29 showed the greatest age range of 73–22 Ma. The oldest intercept age is 73.3 Ma, and the lowest at 22.1 Ma. The data may reflect physical mixing between two age populations, at ca. 73 and ca. 22 Ma.

Data from sample T30 (Fig. 4e) shows a dominant Jurassic–Triassic population, and a single young zircon rim defining a lower intercept at 72 ± 15 Ma. Again, we interpret the spread of sub-concordant ages to reflect lead loss, and we interpret the upper intercept age of 221 ± 10 Ma (MSWD = 1.03) to reflect the crystallization age of the protolith. Monazite data from T30 showed a concentrated spread of data between 78–67 Ma, with an older intercept at 85.8 Ma and one anomalously young analysis defining a younger intercept at 50.0 Ma (Fig. 5e).

Sample T31 yields an oldest zircon age of ca. 210 Ma with a few variably younger zircon ages (Fig. 4f), falling to a large population (n = 19) of younger Oligocene ages ranging from 32–26 Ma. Monazite analyses from sample T31 yielded a late Eocene–Oligocene age range of 34.6 Ma–27.7 Ma, with a mean intercept of 31.47 ± 0.63 Ma (Fig. 5h).

In summary, our zircon data imply an older Late Triassic event (221–210 Ma), Cretaceous ages (90–45 Ma), and a spread of Oligocene ages (32–26 Ma). Our monazite age data imply an older Late Cretaceous event 83–67 Ma, and a younger late Eocene–Oligocene age cluster of 34–24 Ma.

5. Discussion

5.1. Implications of our new data

Fig. 6 details a time chart of all relevant age data both from this study and from others. Several age ranges are significant. Our zircon data of 221–210 Ma agree with an existing set of Late Triassic ages from both zircon and titanite, and which together imply events related to the Indosinian Orogeny. Further, both our zircon (ca. 72 Ma) and monazite (83–67 Ma) data concurs with existing data that indicates a Late Cretaceous tectonothermal event. However we also report evidence for what we believe is a new tectonothermal event during the late Palaeogene. Our zircon (32–26 Ma), monazite (34–24 Ma), and zircon lead-loss data all indicate a tectonothermal event during the late Eocene–Oligocene (34–24 Ma). The relevance of all these ages is discussed below.

5.1.1. Indosinian magmatic protolith

Late Triassic zircon U–Pb ages from Doi Inthanon reported by Dunning et al. (1995) were interpreted by them as representing the protolith age of the basement orthogneisses. Other geochronological studies using both Ar/Ar and U–Pb methodologies have assigned a general age range of 220–200 Ma for granites from the Main Range Province (e.g., Ahrendt et al., 1993, Charusiri et al., 1993, Gardiner et al., 2015a and Ng et al., 2015b), ages interpreted as reflecting magmatism related to the suturing of Palaeo-Tethys, and the subsequent onset of the Indosinian orogeny. Our zircon ages from both Doi Inthanon and Doi Suthep range from 221–210 Ma, and are in accord with these data.

Macdonald et al. (2010) analyzed accessory minerals from a calc-silicate gneiss from Mae Wang, southwest of Chiang Mai (their BRC146b). They reported an upper intercept from zircon and titanite U–Pb ages of 213 ± 2.3 and 210.1 ± 4.4 Ma respectively, with lower intercepts of 36.6 and 47 Ma respectively. They interpreted the older ages from the paragneiss as evidence for a tectonothermal event in the Late Triassic, which they ascribed as an early metamorphic event (their M1). Mickein (1997) also interpreted a Late Triassic/Early Jurassic metamorphic event in samples from both the Umphang Gneiss and Mae Sariang, suggesting a more regional footprint. While we see no strong evidence in our data for such an early Mesozoic metamorphic event, there is, however, overwhelming evidence of extensive Late Triassic magmatism across northern Thailand, which is a major thermal event. Therefore, given our data we concur with the interpretation of Dunning et al. (1995) that the protolith of the Doi Inthanon and Doi Suthep orthogneiss is Indosinian-related granite magmatism of the Main Range Province, and that yielded Late Triassic dates reflect protolith magmatic ages.

5.1.2. Cretaceous metamorphism

Our new monazite (83–67 Ma) and zircon (ca. 72 Ma) U–Pb ages are in agreement with Cretaceous monazite ages as reported by Dunning et al. (1995). We concur with their interpretation that these reflect Cretaceous reworking of the protolith Main Range Province Indosinian granites, and further date amphibolite facies peak metamorphism (Macdonald et al., 2010). Other studies have shown geochronological evidence of a regional Cretaceous-era tectono-magmatic overprint, with similar ages reported for granite magmatism in the Main Range Province in northern Thailand; from a dyke in Lansang; and from zircon and monazite dating of metamorphism also in Lansang (Cobbing, 2011, Cobbing et al., 1992, Gardiner et al., 2015a and Palin et al., 2013a).

More regionally, in Myanmar, the Western Province granite belt of Cobbing et al. (1986)hosts granitoids outcropping from Mandalay southwards. Measured samples of peraluminous crustal-melt granites have yielded Late Cretaceous–Eocene zircon U–Pb ages spanning 73–50 Ma (Barley et al., 2003 and Mitchell et al., 2012). Searle et al. (2012) reported composite zircon ages from granites in Phuket Island, the presumed southern extension of the Western Province. They measured zircon core ages of 214 ± 2 Ma and 212 ± 2 Ma, and Cretaceous zircon rim ages of 81.2 ± 2 Ma and 85–75 Ma respectively. Watkinson et al. (2011) also reported Cretaceous SHRIMP U–Pb zircon ages of 81 to 70 Ma from granites exposed along the Ranong Fault zone in southern Thailand.
We agree that Cretaceous ages measured at Doi Inthanon are part of a more regional magmatic and metamorphic overprint affecting Thailand and Myanmar, and further, we believe this is likely to be related to the eastwards subduction of Neo-Tethys under Sibumasu prior to the onset of the Himalayan Orogeny (e.g. Gardiner et al., 2015b,Mitchell, 1979 and Morley, 2012).

5.1.3. Palaeogene history

Macdonald et al. (2010) used U–Pb geochronology and Ar/Ar cooling ages to infer that peak amphibolite-grade metamorphism occurred within the Cretaceous, and that extension leading to exhumation was initiated by the late Eocene following this metamorphic peak. Their measured age of 40.0 ± 1.2 Ma for sample BRC36 (Barr et al., 2002 and Macdonald et al., 2010), taken as the crystallization of a syntectonic granite protolith, was interpreted as the upper age limit of mylonitization within the Doi Suthep area, and therefore interpreted as the initiation of detachment faulting. They further interpreted their $^{40}Ar/^{39}Ar$ cooling ages of 26–15 Ma as dating the rapid unroofing of the Doi Inthanon complex.

Here, we report new late Eocene–Oligocene zircon and monazite ages (32–26 Ma and 34–24 Ma respectively). We interpret these younger ages, observed both in the gneisses and in the leucogranite, as evidence of a single late Eocene–Oligocene prograde metamorphic event, of a sufficient grade to lead to partial melting and zircon and monazite resetting. This young thermo-metamorphic event is a scenario that would also explain the Oligocene crystallization age reported by Dunning et al. (1995) for the Mae Klang granite, although not interpreted by them as such. Implications of our new data are discussed below.

5.2. Synthesis

Macdonald et al. (2010) interpreted emplacement of the Mae Klang granite as occurring under retrograde amphibolite to greenschist facies conditions. In general, they described a retrogressing metamorphic trend during unroofing and exhumation of the core complex in the Eocene–Oligocene, accompanied by ductile shearing and mylonitization. However, we report here what we believe to be geochronological evidence for a prograde metamorphic event leading to anatexis during the late Eocene–Oligocene. One major driver for such a prograde event is crustal thickening, and below we explore an alternative tectonic scenario that could result in localized crustal thickening in the Doi Inthanon area during the late Eocene–Oligocene.

5.2.1. The Mae Yuan Thrust Zone

The Mae Yuan Fault (Fig. 2a) runs through Mae Sariang, forming a N–S trending valley that broadly separates thick sequences of predominantly Permo-Triassic rocks in the west, from the amphibolite grade para- and orthogneisses of the Doi Inthanon massif, and lower Palaeozoic sequences detached over, or intruded by Triassic granites to the east. In a narrow strip on the east side of the valley, lower Palaeozoic rocks are generally thrust over the Permo-Triassic sequence (Fig. 7). The cross section in Baum et al. (1981)is misleading in this respect, suggesting the lower Palaeozoic rocks dip under the Permo-Triassic rocks and are in normal fault contact. It is suggested here that the thrust zone, referred to here as the *Mae Sariang Thrust Zone* (Fig. 7), represents a major west-directed thrust and it is this thrust, and not the Mae Yuan Fault, that is responsible for the abrupt change in geology between the east and west sides of the valley. The later Mae Yuan Fault has caused the thrust relationships to be obscured in places and has complicated the fault and stratigraphic relationships. However, it is clear that deeper crustal levels are exposed in the hangingwall of the Mae Sariang Thrust Zone, compared with the western side, and are most easily explained by a major thrust (Fig. 7). While much of the contractional deformation is associated with the Indosinian Orogeny, it is also possible that some is also of Late Cretaceous and Palaeogene age, and is associated with crustal thickening, metamorphism and generation of granites.

Upton (1999) sampled both a granite and a metatuff in the hangingwall of the thrust (his samples THI9578 and THI9580) for apatite fission track analysis. Sample THI9578 (Fig. 7b) lies immediately east of the Mae Sariang Fault, and 30 km north of the line of section in Fig. 7. It is modelled as having been on a slow burial path since the Late Cretaceous, never exiting the partial annealing zone. Then, around 56 Ma, cooling from around 100 °C began, and around 46 Ma the sample exited the partial annealing zone (60 °C), with rapid cooling ending around 40 Ma (Upton, 1999). Sample THI9580 (the Mae Sariang Pluton) entered the partial annealing zone at around 46 Ma, and exited it around 8.5 Ma (Fig. 7a). It exhibits slow cooling, and relatively short tracks. The data suggests that although much of the displacement on the Mae Sariang Thrust was Indosinian in age, a possible reactivation of the thrust, and the subsequent development of the Mae Yuan Fault, resulted in initiation of exhumation during the Palaeogene, although this exhumation was relatively slow.

5.2.2. The Mae Ping Fault

The left-lateral Mae Ping Fault lies immediately to the south of Doi Inthanon (Fig. 1). Transpressional thickening associated with movement on this fault, coupled with thickening at the restraining bend of the dextral Mae Yuan Fault, may be responsible for localized crustal thickening in the vicinity of Doi Inthanon. Geochronological studies dating movement along the Mae Ping Fault (also known as the Wang Chao Fault) imply Eocene–Oligocene shearing; Lacassin et al. (1997) measured movement up to 30.5 Ma, while Palin et al. (2013a) measured ages of 45–37 Ma, assumed as the age of metamorphism due to ductile shearing on the fault. These ages imply movement on the Mae Ping Fault occurred at a similar time to the late Eocene–Oligocene crustal thickening event at Doi Inthanon proposed here.

We therefore suggest that movement on the Mae Ping Fault, and the compounding effects of the Mae Yuan Fault as a restraining bend, was responsible for this late Eocene–Oligocene period of metamorphism and magmatism. Further, cessation of movement on the fault pre-dated or perhaps helped initiate subsequent regional extension.

5.2.3. Onset of extension and development of the Chiang Mai Basin

The Chiang Mai Basin, sited directly to the east of Doi Inthanon and Doi Suthep, is the largest Cenozoic Basin in northern Thailand. Although several exploration wells have been drilled, its age is not well established. At the southeast margin of the Chiang Mai Basin is the small Li Basin, where palynology has dated the oldest section as being late Oligocene (Morley et al., 2000 and Morley et al., 2001). Given the regional trends in ages of rift basins (Morley and Racey, 2011 and Morley et al., 2001) it seems reasonable to infer that the Chiang Mai Basin is of late Oligocene–Miocene age. Consequently, the early Miocene cooling ages determined for Doi Inthanon, and the early to middle Miocene cooling ages for Doi Suthep, indicate that at least the later stages of exhumation of these two domes were associated with extensional motion on the western bounding fault of the Chiang Mai Basin. On seismic reflection data this bounding fault is imaged as prominent broad, low-angled (20°–30°) reflection (CMLANF) (Morley, 2009b). The up-dip location of the reflection correlates well with the occurrence of the Palaeozoic units that are sandwiched between the shallow brittle western basin bounding fault, and the underlying thick, low-angled mylonite zone, with a top-to-the-east sense of shear. The mylonites are present in many outcrops along the entire western margin of the Chiang Mai Basin.

Morley (2009b) related the mylonites to large, Miocene displacement. Dunning et al. (1995), on the basis of textural evidence suggestive of granite emplacement prior to completion of mylonitization, interpreted that their Oligocene age (26.8 ± 0.8 Ma) from the weakly foliated Mae Klang granite provided an upper age limit for mid-crustal extension. They concluded that the age of mylonitization lay between a Late Cretaceous thermal peak, and the early Miocene. Rhodes et al. (2000) concurred that mylonitization occurred sometime after the Late Cretaceous.

The 40 Ma age determined for monazites from the mylonites at Doi Suthep (Macdonald et al., 2010) was proposed by them as dating the age of extensional mylonite formation. Further, Macdonald et al. (2010) interpreted “the granitic mylonite from Doi Suthep and mylonitized granite from Mae Klang on Doi Inthanon (27 Ma) as the respective syn-tectonic and late-tectonic products of extensional shearing”; they noted that the 40 Ma age represents the upper age limit for shearing.

Our study finds new late Eocene–Oligocene ages for metamorphism and anatexis that need to be accommodated in any model of development for the Chiang Mai Basin. We propose that there was a period of crustal thickening between 34 and 24 Ma, and in this interpretation the gneiss domes developed initially under compression during the Palaeogene, and it was only during the late Oligocene that extension contributed to movement on the detachment and the unroofing of the complex. However, only samples from the mantling paragneiss exhibit this younger metamorphic event, and further this scenario needs to be reconciled with the interpretation of onset of detachment during the Eocene (Macdonald et al., 2010).

Previous models for the formation of the Chiang Mai Basin had difficulty in reconciling the Miocene cooling ages of Macdonald et al. (2010) and Upton et al. (1997), with inferred Eocene movement on the detachment by (Macdonald et al., 2010). The late Oligocene–Miocene age Chiang Mai Basin is bound on its western side by a low-angle east-dipping fault (CMLANF), resulting in the assumption that this was largely responsible for development of the basin. However the improbable displacement that would then be necessary on the CMLANF gave rise to a hybrid model for the formation of the Chiang Mai Basin (Morley, 2009b).

Macdonald et al. (2010) envisage a prolonged episode of ductile detachment faulting between 40 Ma and 27 Ma followed by progressive retrogressional deformation with extensional mylonite shearing under lower amphibolite to greenschist conditions. In this model the extension phase is highly protracted (~ 25 My), and overlaps with a period of regional transpressional deformation and high-grade metamorphism. Morley, 2009a and Morley, 2009b suggested as an alternative that the early top to the east shear could be related to thrusting. Reassigning an early Miocene age to movement on the detachment, as implied by a late Eocene–Oligocene metamorphic event, has obvious implications for any model for the development of the Chiang Mai Basin.

5.2.4. Regional overview

It is suggested here that moderate Eocene–Oligocene shortening and crustal thickening east of the Mae Yuan Fault was a consequence of an Andean-type margin on the edge of Neo-Tethys to the west (see review in Gardiner et al., 2015b), and the subsequent Himalayan Orogeny. This crustal thickening caused the generation of granitic magma, which was emplaced largely as small intrusions, and manifested as localized anatexis, up to as late as the early Oligocene (Fig. 6). Much of the middle crust that is exposed today at Doi Inthanon and Doi Suthep began to be exhumed as a consequence of uplift and erosion during this thrusting and folding, and hence we see a mixture of evidence both for a Cretaceous prograde metamorphic event, and another prograde metamorphic event during the late Eocene–Oligocene. Transpressional thickening associated with movement on the Mae Ping Fault, coupled with thickening at the restraining bend of the dextral Mae Yuan Fault, may be responsible for localized crustal thickening in the vicinity of Doi Inthanon. The gneiss domes of Doi Inthanon and Doi Suthep were probably initiated as compressional, or transpressional features during the Palaeogene, and enhanced by extensional exhumation during the early Miocene. The rapid uplift of the Doi Inthanon area through about 300 °C to less than 60 °C is seen in the biotite and muscovite Ar/Ar ages, and zircon and apatite fission track ages that all cluster in the early Miocene (Dunning et al., 1995, Macdonald et al., 2010 and Upton, 1999). Initiation of detachment faulting in the early Miocene leads into development of the Chiang Mai Basin.

5.2.5. Late Eocene–Oligocene metamorphism

Is there evidence for more widespread regional late Eocene–Oligocene metamorphism? Late Palaeogene metamorphism has been observed elsewhere in Southeast Asia: in the Mogok Metamorphic Belt in Myanmar (e.g. Searle et al., 2007), and in the Lansang Gneiss region south of Doi Inthanon (e.g. Palin et al., 2013a). Late Palaeocene–Eocene ages of ca. 57–51 Ma have been reported further south from exhumed high-grade gneisses of the Thabsila Complex along the Three Pagodas Fault in western Thailand (Nantasin et al., 2012).

However, south of the Mae Ping Fault zone within the Umphang Gneiss at Khlong Lang National Park, Upton (1999) measured a zircon fission track age of 47 Ma, and an apatite fission track age of 40 Ma. Together, these data imply that south of the Mae Ping Fault, Indosinian basement was perhaps not undergoing the same high-grade metamorphism as seen at Doi Inthanon. Hence late Eocene–Oligocene metamorphism does not appear to be a regional event (although earlier Eocene metamorphism does seem to be more widespread) — an expected outcome if the late Eocene–Oligocene event at Doi Inthanon was caused by a combination of movement on the Mae Ping Fault and concurrent thickening at the restraining bend.

6. Summary

Here, we report new in-situ zircon and monazite U–Pb age data from Doi Inthanon and Doi Suthep. We show monazite and zircon rim data of 34–24 Ma and 32–26 Ma respectively, with zircon lead loss. These together imply a new late Eocene–Oligocene prograde metamorphic event, which has implications for age constraints of crustal thickening and the onset of regional extension.

Models for the formation of the Chiang Mai Basin have thus far struggled to accommodate measured Miocene cooling ages with an interpreted Eocene movement on the regional detachment fault. Our new late Eocene–Oligocene metamorphic event implies a later period of crustal thickening, which may be due to transpression on the Mae Ping Fault coupled with the Mae Yuan Fault restraining bend. This later event suggests that extension and concurrent detachment did not commence until the late Oligocene–early Miocene, although this needs to be reconciled with an inferred Eocene age of mylonitization. Reassigning a Miocene age to the detachment responsible for the unroofing of both Doi Inthanon and Doi Suthep, allows reevaluation of the structural processes involved in the formation of the Chiang Mai Basin, with concomitant reassignment of the role of the CMLANF.

Acknowledgments

We thank the Oxford University Fell Fund (Ref. DGD07260) for financial support of both NJG and Thailand fieldwork. Dave Sansom is thanked for help with drafting figures. NJG thanks Al Sloan for helpful discussions. We thank Adrian Wood at NIGL for help with the sample preparation, and Jeremy Hyde is acknowledged for thin section preparation. The NordSIM facility is operated under an agreement between the research funding agencies of Denmark, Iceland, Norway and Sweden, the Geological Survey of Finland and the Swedish Museum of Natural History, and we are indebted to Kerstin Lindén and Lev Ilyinsky for technical support whilst at NordSIM. We thank Marco Scambelluri for careful editorial handling, and Michael Crow and an anonymous reviewer for their constructive comments that have greatly improved the manuscript. This is NordSIM publication 424.

References

Ahrendt, H., Chonglalmani, C., Hansen, B.T., Helmecke, D., 1993. Geochronological cross section through northern Thailand. Journal of Southeast Asian Earth Sciences 7, 262.

Ahrendt, H., Hansen, B., Lumhuan, A., Mickein, A., Wemmer, K., 1997. Tectonometamorphic evolution fo NW-Thailand deduced from U/Pb-, Rb/Sr-, Sm/Nd- and K/Ar-isotope investigations. International Conference Stratigraphy Tectonic Evolution Southeast Asia South Pacific 314–319.

Barley, M.E., Pickard, A.L., Khin Zaw, Rak, P., Doyle, M.G., 2003. Jurassic to Miocene magmatism and metamorphism in the Mogok metamorphic belt and the India-Eurasia collision in Myanmar. Tectonics 22, 1–11. http://dx.doi.org/10.1029/2002TC001398.

Barr, S.M., Macdonald, A.S., 1991. Toward a late Paleozoic–early Mesozoic tectonic model for Thailand. Thailand Journal of Geosciences 1, 11–22.

Barr, S.M., Macdonald, A.S., Dunning, G.R., Yaowanoiyothin, W., 1991. The Doi Inthanon metamorphic core complex in NW Thailand: age and tectonic significance. GEOSEA VII.

Barr, S.M., Macdonald, A.S., Miller, B.V., Reynolds, P.H., Rhodes, B.P., Yokart, B., 2002. New U–Pb and 40Ar/39Ar ages from the Doi Inthanon and Doi Suthep metamorphic core complexes, northwestern Thailand. Proceedings of the Symposium on Geology of Thailand. Department of Mineral Resources, Bangkok, pp. 284–294.

Baum, F., von Braun, E., Hahn, L., Hess, A., Kock, K.-L., Kruse, G., Quarch, H., Siebenhüner, M., 1970. On the geology of Northern Thailand. Beihefte zum Geologisches Jahrbuch 102, 1–23.

Baum, F., Braun, E.V., Hess, A., Kock, K.E., 1981. Geologic map of northern Thailand. Benammi, M.J., Urrutia-Fucugauchi, L., Alva-Valdiva, Y., Chaimanee, S., 2002. Magnetostratigraphy of the Middle Miocene continental sedimentary sequences of the Mae Moh Basin in northern Thailand: evidence for counterclockwise block rotation. Earth and Planetary Science Letters 204, 373–383.

Bignell, J.D., Snelling, N.J., 1977. The geochronology of Malayan granites. 47 pp. 1–72.

Charusiri, P., Clark, A.H., Farrar, E., Archibald, D., Charusiri, B., 1993. Granite belts in Thailand: evidence from the 40Ar/39Ar geochronological and geological synthesis. Journal of Southeast Asian Earth Sciences 8, 127–136.

Cobbing, E.J., 2011. Granitic Rocks. In: Ridd, M.F., Barber, A.J., Crow, M.J. (Eds.), The Geology of Thailand. Geological Society, London, pp. 442–457.

Cobbing, E.J., Mallick, D.I.J., Pitfield, P.E.J., Teoh, L.H., 1986. The granites of the Southeast Asian Tin Belt. Journal of the Geological Society of London 143, 537–550. http://dx.doi.org/10.1144/gsjgs.143.3.0537.

Cobbing, E.J., Pitfield, P.E.J., Darbyshire, D., Mallick, D.I., 1992. The Granites of the Southeast Asian Tin Belt. 10th ed. Overseas Memoirs of the British Geological Survey, London. Department of Mineral Resources (DMR), 1999. Geological map of Thailand, scale 1: 1,000,000. Geological Survey Division, Department of Mineral Resources, Bangkok, Thailand

Dunning, G.R., Macdonald, A.S., Barr, S.M., 1995. Zircon and monazite U–Pb dating of the Doi Inthanon core complex, northern Thailand: implications for extension within the Indosinian Orogen. Tectonophysics 251, 197–213. http://dx.doi.org/10.1016/0040- 1951(95)00037-2.

Gardiner, N.J., Searle, M.P., Robb, L.J., Morley, C.K., 2015a. Neo-Tethyan magmatism and metallogeny in Myanmar — an Andean analogue? Journal of Asian Earth Sciences http://dx.doi.org/10.1016/j.jseaes.2015.03.015.

Gardiner, N.J., Searle, M.P., Morley, C.K., Whitehouse, M.P., Spencer, C.J., Robb, L.J., 2015b. The closure of Palaeo-Tethys in eastern Myanmar and northern Thailand: new insights from zircon U–Pb and Hf isotope data. Gondwana Research http://dx.doi.org/ 10.1016/j.gr.2015.03.001.

Green, O.R., Searle, M.P., Corfield, R.I., Corfield, R.M., 2008. Cretaceous–Tertiary carbonate platform evolution and the age of the India-Asia collision along the Ladakh Himalaya (northwest India). Journal of Geology 116, 331–353. http://dx.doi.org/10.1086/ 588831.

Hall, R., Morley, C.K., 2004. Sundaland basins. In: Clift, P., Kuhnt, W., Wang, P., Hayes, D. (Eds.), Continent–ocean interactions within East Asian marginal seas. AGU, Washington, DC, pp. 55–85.

Hogan, J.P., Gilbert, C., Price, J.D., 2000. Crystallisation of fine-and coarse grained A-type granite sheets of the Southern Oklahoma aulacogen, USA. Transactions of the Royal Society of Edinburgh: Earth Sciences 91, 139–150.

Hutchison, C.S., 1973. Tectonic evolution of Sundaland: a Phanerozoic synthesis. Bulletin. Geological Society of Malaysia 6, 61–86.

Hutchison, C.S., 1975. Ophiolite in Southeast Asia. Bulletin Geological Society of America 86, 797–806. http://dx.doi.org/10.1130/0016-7606(1975)86b797:OISAN2.0.CO;2.

Hutchison, C.S., 1977. Granite emplacement and tectonic subdivision in Peninsular Malaysia. Geological Society of Malaysia Bulletin 9, 187–207.

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. Chemical Geology 211, 47–69. http://dx.doi.org/10.1016/j.chemgeo. 2004.06.017.

Lacassin, R., Maluski, H., Leloup, P.H., Tapponnier, P., Hinthong, C., Siribhakdi, K., Chuaviroj, S., Charoenravat, A., 1997. Tertiary diachronic extrusion and deformation of western Indochina: structural and 40Ar/39Ar evidence from NW Thailand. Journal of Geophysical Research 102, 10013–10037.

Liew, T.C., Page, R.W., 1985. U–Pb zircon dating of granitoid plutons from the west coast province of Peninsular Malaysia. Journal of the Geological Society of London 142, 515–526.

Ludwig, K.R., 1998. On the treatment of concordant uranium-lead ages. Geochimica et Cosmochimica Acta 62, 665–676. http://dx.doi.org/10.1016/S0016-7037(98)00059-3. 82

N.J. Gardiner et al. / Lithos 240–243 (2016) 69–83

Ludwig, K.R., 2003. User's Manual for Isoplot 3.00: A Geo-chronological Toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication, Berkeley, USA.

Macdonald, A.S., Barr, S.M., Dunning, G.R., Yaowanoiyothin, W., 1993. The Doi Inthanon metamorphic core complex in NW Thailand: age and tectonic significance. Journal of Southeast Asian Earth Sciences 8.

Macdonald, A.S., Barr, S.M., Miller, B.V., Reynolds, P.H., Rhodes, B.P., Yokart, B., 2010. P–T–t constraints on the development of the Doi Inthanon metamorphic core complex domain and implications for the evolution of the western gneiss belt, northern Thailand. Journal of Asian Earth Sciences 37, 82–104. http://dx.doi.org/10.1016/j.jseaes.2009. 07.010.

Metcalfe, I., 2000. The Bentong–Raub Suture Zone. Journal of Asian Earth Sciences 18, 691–712.
Metcalfe, I., 2002. Permian tectonic framework and palaeogeography of SE Asia. Journal of Asian Earth Sciences 20, 551–566. http://dx.doi.org/10.1016/S1367-9120(02)00022-6.

Metcalfe, I., 2006. Palaeozoic and Mesozoic tectonic evolution and palaeogeography of East Asian crustal fragments: the Korean Peninsula in context. Gondwana Research 9, 24–46. http://dx.doi.org/10.1016/j.gr.2005.04.002.

Mickein, A., 1997. U/Pb-, Rb/Sr- und K/Ar-Untersuchungen zur metamorphen Entwicklung und Altersstellung des "Prakambriums" in NW Thailand. Gottinger Arbeitin zur Geologie und Palaontologie 73, 1–83.

Miller, R.B., Paterson, S.R., 2001. Construction of mid-crustal sheeted plutons: examples from the North Cascades, Washington. Geological Society of America Bulletin 113, 1423–1442.

Miller, C.F., Furbish, D.J., Walker, B.A., Claiborne, L., Koteas, G.C., Bleick, H.A., Miller, J.S., 2011. Growth of plutons by incremental emplacement of sheets in crystal-rich host: evidence from Miocene intrusions of the Colorado River region, Nevada, USA. Tectonophysics 500, 66–77.

Mitchell, A.H.G., 1977. Tectonic settings for the emplacement of Southeast Asian tin granites. Geological Society of Malaysia Bulletin 9, 123–140.

Mitchell, A.H.G., 1979. Rift-, subduction- and collision-related tin belts. Geological Society of Malaysia Bulletin 11, 81–102.

Mitchell, A.H.G., Chung, S.-L., Thura Oo, Lin, T.H., Hung, C.H., 2012. Zircon U–Pb ages in Myanmar: Magmatic-metamorphic events and the closure of a neo-Tethys ocean? Journal of Asian Earth Sciences 56, 1–23. http://dx.doi.org/10.1016/j.jseaes.2012.04. 019.

Morley, C.K., 2007. Variations in late Cenozoic–Recent strike-slip and oblique-extensional geometries, within Indochina: the influence of pre-existing fabrics. Journal of Structural Geology 29, 36–58. http://dx.doi.org/10.1016/j.jsg.2006.07.003.

Morley, C.K., 2009a. Geometry and evolution of low-angle normal faults (LANF) within a Cenozoic high-angle rift system, Thailand: implications for sedimentology and the mechanisms of LANF development. Tectonics 28, 1–30. http://dx.doi.org/10.1029/ 2007TC002202.

Morley, C.K., 2009b. Evolution from an oblique subduction back-arc mobile belt to a highly oblique collisional margin: the Cenozoic tectonic development of Thailand and eastern Myanmar. Geological Society of London, Special Publication 318, 373–403. http://dx.doi.org/10.1144/SP318.1.

Morley, C.K., 2012. Late Cretaceous–Early Palaeogene tectonic development of SE Asia. Earth-Science Reviews 115, 37–75. http://dx.doi.org/10.1016/j.earscirev.2012.08.002.

Morley, C.K., Racey, A., 2011. Tertiary stratigraphy. In: Ridd, M.F., Barber, A.J., Crow, M.J. (Eds.), The Geology of Thailand. The Geological Society, London, pp. 223–272.

Morley, C.K., Sangkumarn, N., Hoon, T.B., Chonglakmani, C., Lambiase, J., 2000. Structural evolution of the Li Basin, northern Thailand. Journal of the Geological Society of London 157, 483–492.

Morley, C.K., Woganan, N., Sankumarn, N., Hoon, T.B., Alief, A., Simmons, M., 2001. Late Oligocene–Recent stress evolution in rift basins of northern and central Thailand: implications for escape tectonics. Tectonophysics 334, 115–150. http://dx.doi.org/10. 1016/S0040-1951(00)00300-0.

Morley, C.K., Charusiri, P., Watkinson, I., 2011. Structural geology during the Cenozoic. In: Ridd, M.F., Barber, A.J., Crow, M.J. (Eds.), The Geology of Thailand. The Geological Society, London, pp. 273–333.

Nantasin, P., Hauzenberger, C., Liu, X., Krenn, K., Dong, Y., Thöni, M., Wathanakul, P., 2012. Occurrence of the high grade Thabsila metamorphic complex within the low grade Three Pagodas shear zone, Kanchanaburi Province, western Thailand: petrology and geochronology. Journal of Asian Earth Sciences 60, 68–87. http://dx.doi.org/10. 1016/j.jseaes.2012.07.025.

Ng, S.W.P., Chung, S.-L., Robb, L.J., Searle, M.P., Ghani, A.A., Whitehouse, M.J., Oliver, G.J.H., Sone, M., Gardiner, N.J., Roselee, M.H., 2015a. Petrogenesis of Malaysian granitoids in the Southeast Asian tin belt: part 1. Geochemical and Sr-Nd isotopic characteristics. Geological Society of America Bulletin 1–29 http://dx.doi.org/10.1130/B31213.1.

Ng, S.W.P., Whitehouse, M.J., Searle, M.P., Robb, L.J., Ghani, A.A., Chung, S.-L., Oliver, G.J.H., Sone, M., Gardiner, N.J., Roselee, M.H., 2015b. Petrogenesis of Malaysian granitoids in the Southeast Asian tin belt: part 2. U–Pb zircon geochronology and tectonic model. Geological Society of America Bulletin 1–21 http://dx.doi.org/10.1130/B31214.1.

Palin, R.M., Searle, M.P., Morley, C.K., Charusiri, P., Horstwood, M.S.A., Roberts, N.M.W., 2013a. Timing of metamorphism of the Lansang gneiss and implications for leftlateral motion along the Mae Ping (Wang Chao) strike-slip fault, Thailand. Journal of Asian Earth Sciences 76, 120–136. http://dx.doi.org/10.1016/j.jseaes.2013.01.021.

Palin, R.M., Searle, M.P., Waters, D.J., Parrish, R.R., Roberts, N.M.W., Horstwood, M.S.A, Yeh, M.W., Chung, S.L., Anh, T.T., 2013b. A geochronological and petrological study of anatectic paragneiss and associated granite dykes from the Day Nui Con Voi metamorphic core complex, North Vietnam: constraints on the timing of metamorphism within the Red River shear zone. Journal of Metamorphic Geology 31, 359–387. http://dx.doi.org/10.1111/jmg.12025.

Paquette, J., Nédélec, A., Moine, B., Rakotondrazafy, M., 1994. U–Pb, single zircon Pb-evaporation, and Sm–Nd isotopic study of a granulite domain in SE Madagascar. Journal of Geology 102, 523–538.

Rhodes, B.P., Blum, J., Devine, T., 2000. Structural development of the Mid-Tertiary Doi Suthep Metamorphic Complex and Western Chiang Mai Basin, Northern Thailand. Journal of Asian Earth Sciences 18, 97–108. http://dx.doi.org/10.1016/S1367- 9120(99)00019-X.

Searle, M.P., Morley, C.K., 2011. Tectonics and thermal evolution of Thailand in the regional context of Southeast Asia. In: Ridd, M.F., Barber, A.J., Crow, M.J. (Eds.), The Geology of Thailand. The Geological Society, London, pp. 539–572.

Searle, M.P., Noble, S.R., Cottle, J.M., Waters, D.J., Mitchell, A.H.G., Tin Hlaing, Horstwood, M.S.A., 2007. Tectonic evolution of the Mogok metamorphic belt, Burma (Myanmar) constrained by U–Th–

Pb dating of metamorphic and magmatic rocks. Tectonics 26. http://dx.doi.org/10.1029/2006TC002083.

Searle, M.P., Whitehouse, M.J., Robb, L.J., Ghani, A.A., Hutchison, C.S., Sone, M., Ng, S.W.-P., Roselee, M.H., Chung, S.-L., Oliver, G.J.H., 2012. Tectonic evolution of the Sibumasu– Indochina terrane collision zone in Thailand and Malaysia: constraints from new U–Pb zircon chronology of SE Asian tin granitoids. Journal of the Geological Society of London 169, 489–500. http://dx.doi.org/10.1144/0016-76492011-107.

Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., Whitehouse, M.J., 2008. Plešovice zircon — a new natural reference material for U– Pb and Hf isotopic microanalysis. Chemical Geology 249, 1–35. http://dx.doi.org/10. 1016/j.chemgeo.2007.11.005.

Sone, M., Metcalfe, I., 2008. Parallel Tethyan sutures in mainland Southeast Asia: new insights for Palaeo-Tethys closure and implications for the Indosinian orogeny. Comptes Rendus - Geosciences 340, 166–179. http://dx.doi.org/10.1016/j.crte.2007. 09.008.

Spencer, C.J., Roberts, N.M.W., Cawood, P.A., Hawkesworth, C.J., Prave, A.R., Antonini, A.S.M., Horstwood, M.S.A., 2014. Intermontane basins and bimodal volcanism at the onset of the Sveconorwegian orogeny, southern Norway. Precambrian Research 252, 107–118. http://dx.doi.org/10.1016/j.precamres.2014.07.008.

Trzebski, R., Lennox, P., Palmer, D., 1999. Contrasts in morphogenesis and tectonic setting during contemporaneous emplacement of S- and I-type granitoids in the Eastern Lachlan Fold Belt, southeastern Australia. In: Castro, A., Fernandez, C., Vigneresse, J.L. (Eds.), Understanding Granites: Integrating New and Classical Techniques. Geological Society, London, pp. 123–140.

Upton, D.R., 1999. A regional fission track study of Thailand: implications for thermal history and denudation. University of London (PhD Thesis).

Upton, D.R., Bristow, C.S., Hurford, A.J., Carter, A., 1997. Tertiary tectonic denudation in northwestern Thailand: provisional results from apatite fission-track analysis. Proceedings of the International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific, pp. 421–431.

von Braun, E., Besang, C., Eberle, W., Harre, W., Kreuzer, H., Lenz, H., Müller, D., Wendt, I., 1976. Radiometric age determinations of granites in northern Thailand. Geologisches Jahrbuch 21, 171–204.

Watkinson, I., Elders, C., Batt, G., Jourdan, F., Hall, R., McNaughton, N.J., 2011. The timing of strike-slip shear along the Ranong and Khlong Marui faults, Thailand. Journal of Geophysical Research — Solid Earth 116, 1–26. http://dx.doi.org/10.1029/2011JB008379.

Wernicke, B., 1992. Cenozoic extensional tectonics of the U.S. Cordillera. In: Burchfiel, B.C., Lipman, P.W., Zoback, M.L. (Eds.), The Cordilleran orogen: conterminous U.S. Geological Society of America, pp. 553–582

Whitehouse, M.J., Kamber, B.S., 2005. Assigning dates to thin gneissic veins in high-grade metamorphic terranes: a cautionary tale from Akilia, southwest Greenland. Journal of Petrology 46, 291–318. http://dx.doi.org/10.1093/petrology/egh075.

Whitehouse, M.J., Kamber, B.S., Moorbath, S., 1999. Age significance of U–Th–Pb zircon data from early Archaean rocks of west Greenland—a reassessment based on combined ion-microprobe and imaging studies. Chemical Geology 160, 201–224. http://dx.doi.org/10.1016/S0009-2541(99)00066-2.

Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., von Quadt, A., Roddick, J.C., Spiegel, W., 1995. Three natural zircon standards for U–Th–Pb, Lu–Hf, trace element and REE analyses. Geostandards Newsletter 19, 1–23.

Fig. 1.
a (left): simplified map showing the granite belts of the study area (inset: of Southeast Asia), with major sutures and faults. DI = Doi Inthanon; CM = Chiang Mai. After Cobbing et al. (1986) and Sone and Metcalfe (2008). b (right): geological map of Southern Myanmar and Northern Thailand. Box shows locality of Doi Inthanon Map (Fig. 2). X–X′ shows line of cross-section in Fig. 7.

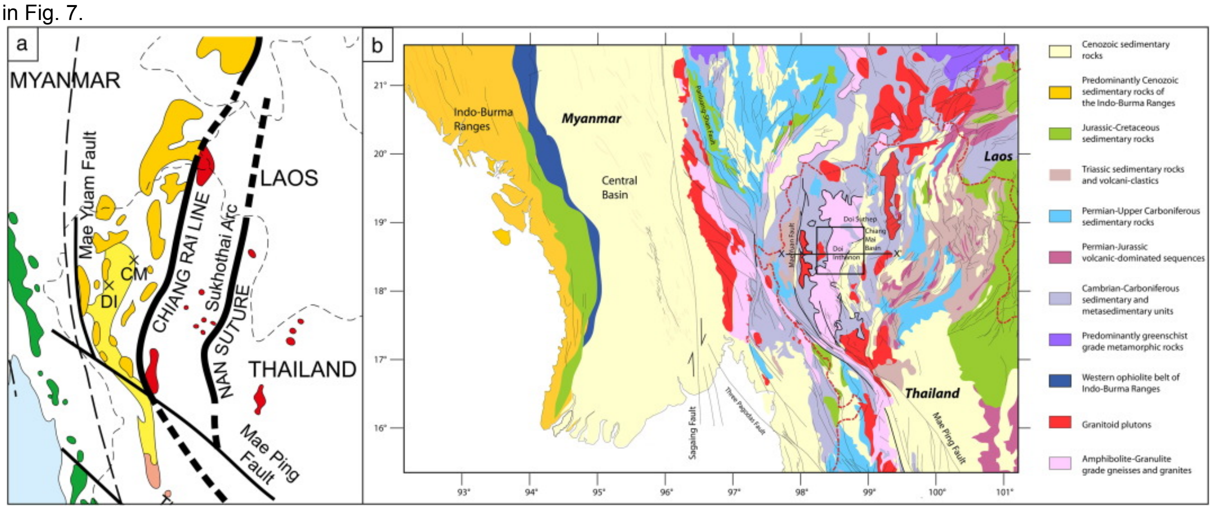

Fig. 2.
a: geological map of northern Thailand showing the locality of sample T17, Doi Suthep and the Doi Inthanon massif. The outline of map 2B is marked. Red line with red triangles = basal thrust to Palaeo-Tethyian units over units of Sibumasu origin, i.e. basal thrust of the Inthanon Zone. After Baum et al. (1981) and DMR (1999). b: geological map of the Doi Inthanon area detailing main sample localities; after Baum et al. (1981) and Macdonald et al. (1993).

a

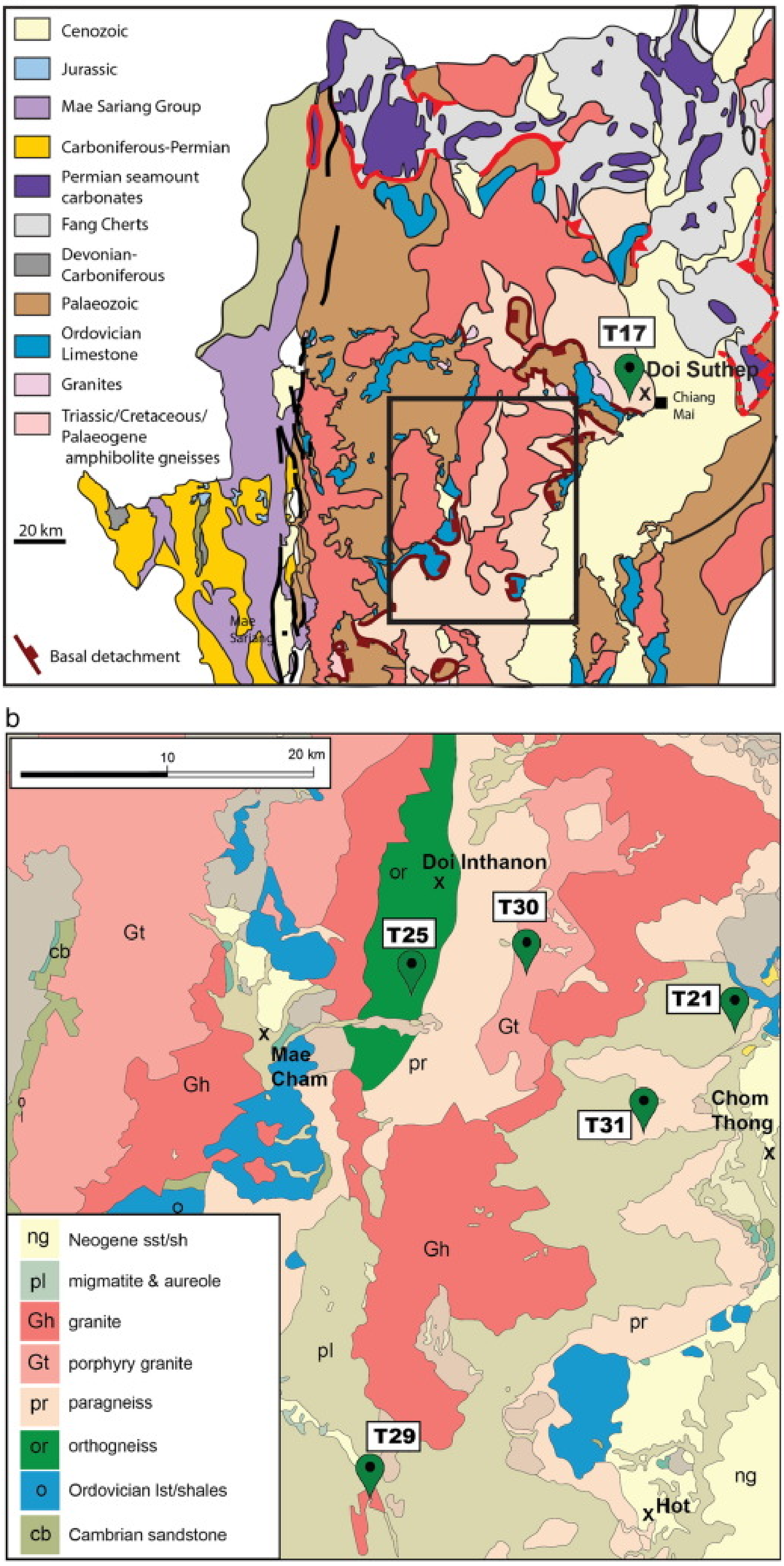

Fig. 3.
Outcrop photographs from around Doi Inthanon. a: augen gneiss at the Mae Ya Waterfall (Sample T31). b: the leucogranite boudin (Sample T29) enclosed within migmatitic gneiss, 20 km west of Hot. c: mylonites outcropping at Pa Ngerp Waterfall, west of Doi Suthep, same locality as sample BRC36 of Macdonald et al. (2010). d: augen gneiss with felsic pod (Sample T21), Mae Klang Waterfall. All photos taken by NJG.

Fig. 4.

Wetherill Concordia diagrams showing common Pb-corrected zircon U–Pb analyses for all samples selected for calculation of Concordia ages. All uncertainty ellipses are 2 sigma.

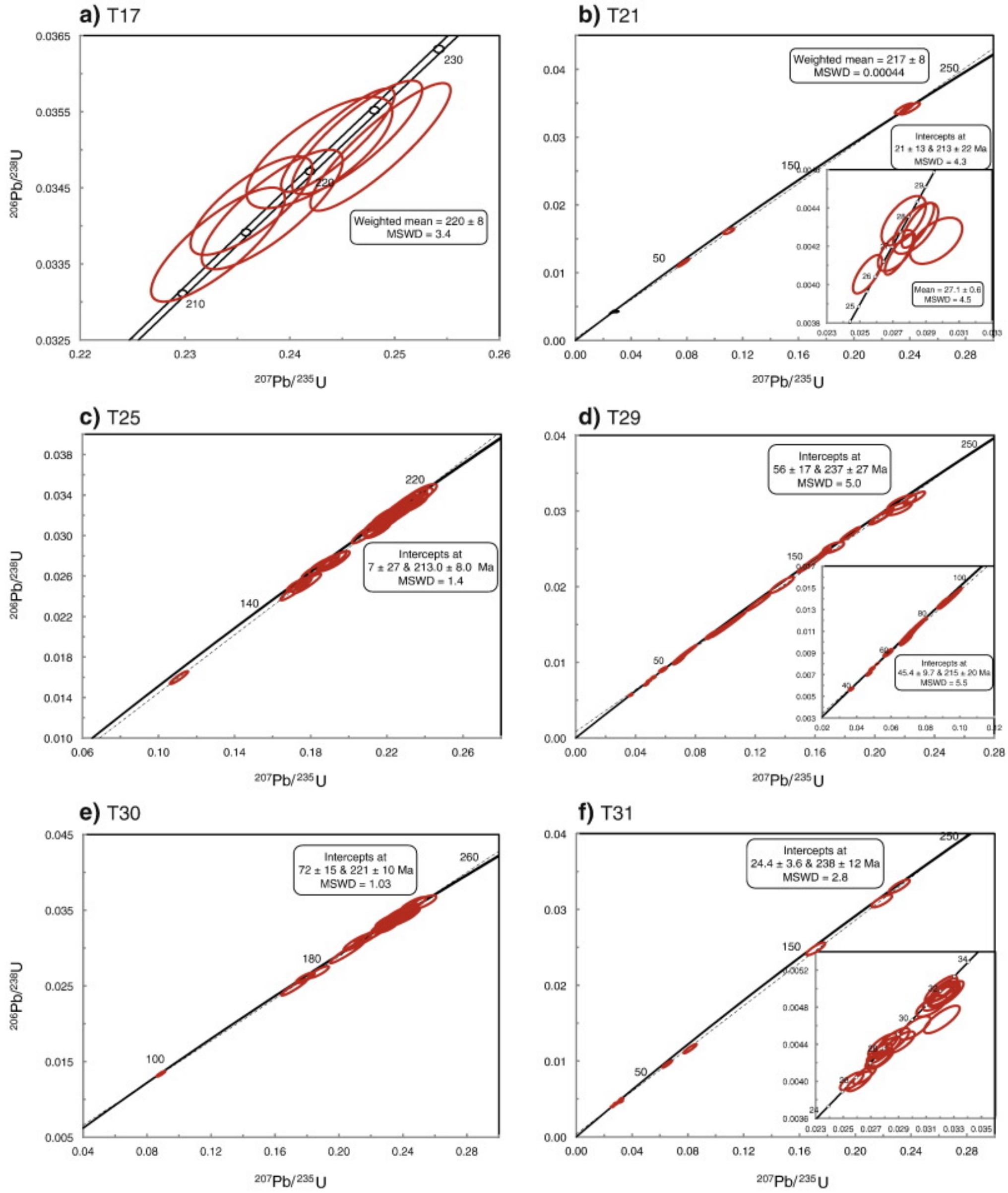

Fig. 5.

a, c, e, g & h: Tera–Wasserburg diagrams showing common Pb-corrected monazite U–Pb analyses for all samples selected for calculation of Concordia ages. Dashed lines indicate regressions from a common-lead ratio of $^{207}Pb/^{206}Pb = 0.83 \pm 0.02$. All ages represent intersections with Concordia. All uncertainty ellipses are 2 sigma. b, d & f: plots of $^{208}Pb/^{232}U$ versus $^{206}Pb/^{238}U$ for three samples.

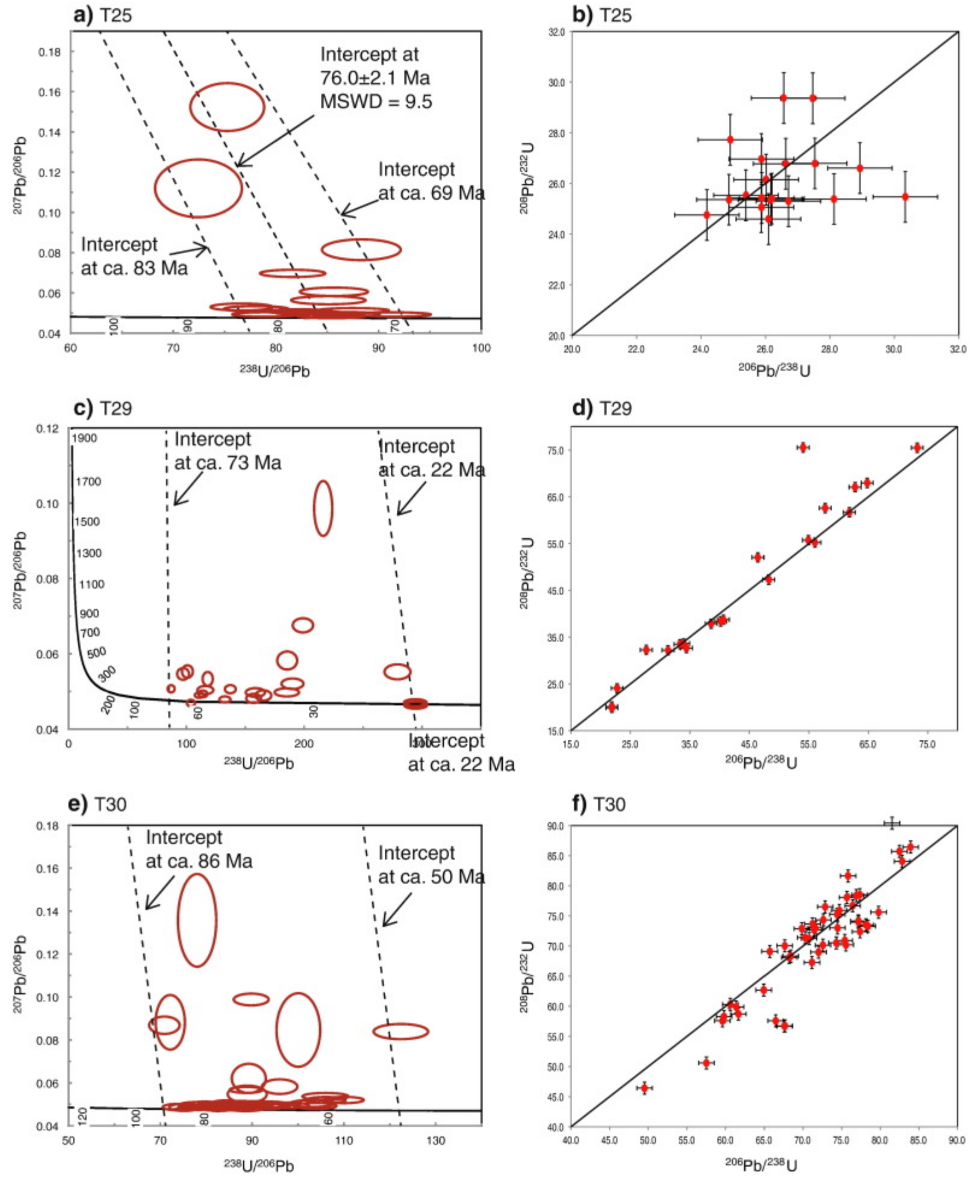

Fig. 6.

Timechart showing ages from Doi Inthanon and Doi Suthep, and inferred tectonic events. MPF = Mae Ping Fault. Ages from (1) Dunning et al., 1995; (2) this study; (3) Macdonald et al., 2010 and Barr et al. (2002); and (4) Upton (1999). Inferred suturing ages from Green et al. (2008) and Gardiner et al. (2015b). Mae Ping Fault movement ages from Lacassin et al. (1997) and Palin et al. (2013a). Epoch ages based on the International Chronostratigraphic Chart v 2014/02.

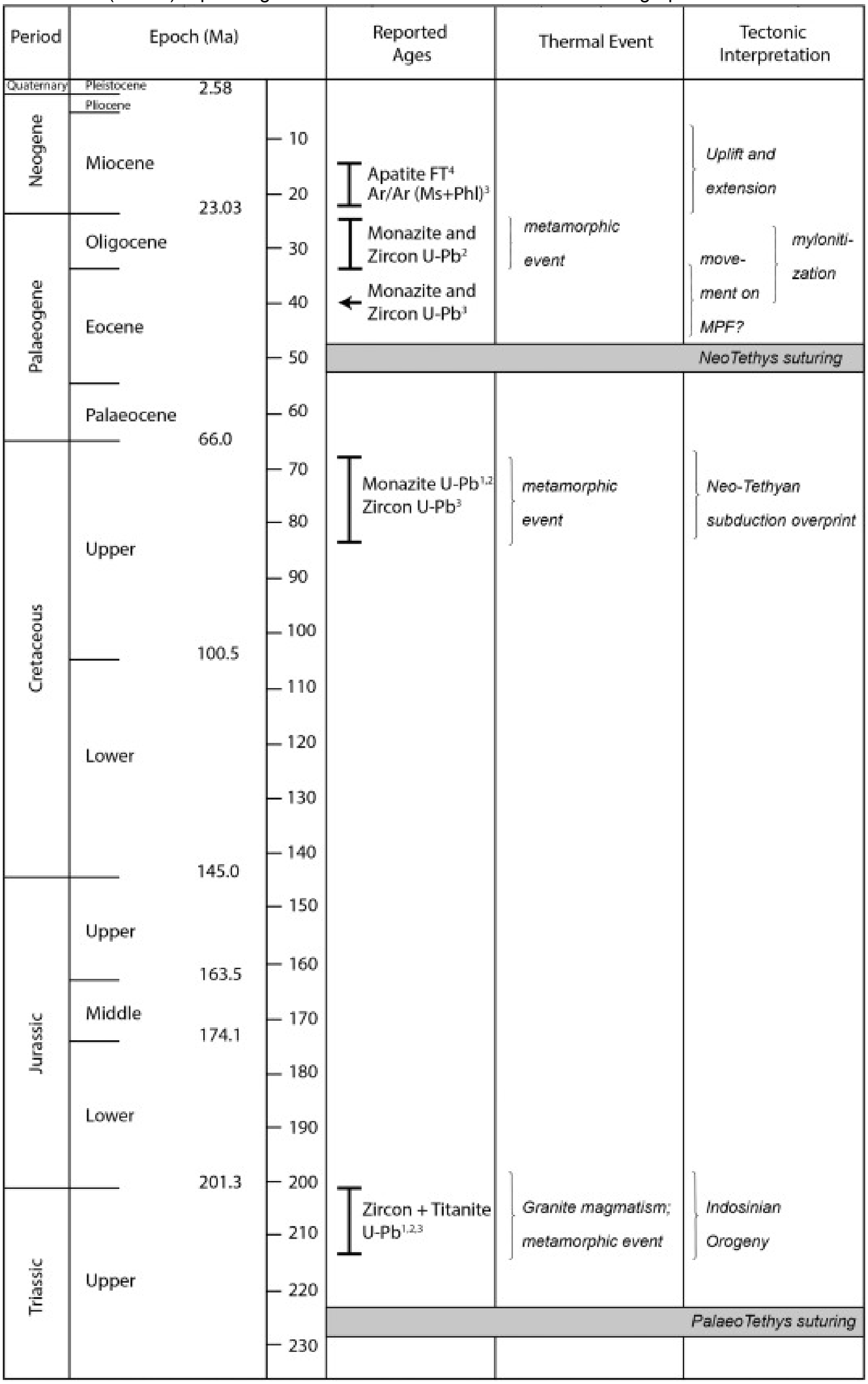

Figure 7. Schematic cross-section across NW Thailand, based on the geological map of Baum et al. (1981). See Fig. 1 for location. The deep structure has no subsurface control, except around the Chiang Mai Basin in the east. Granites are assumed to be sheet-like intrusions fed by dykes at depth (e.g. Hogan et al., 2000 and Miller and Paterson, 2001), but other geometries are also possible (e.g. Trzebski et al., 1999; see review in Miller et al., 2011). a, b and c are modelled apatite fission track cooling trajectories from Upton (1999). M = muscovite $^{40}Ar/^{39}Ar$ cooling ages from Macdonald et al. (2010), Mo = Monazite U–Pb ages, this study. AFT = apatite fission track central age (Upton, 1999). Z = zircon U–Pb age from Macdonald et al. (2010).