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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


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Abstract: Three principal granite provinces are defined across SE Asia, as follows. (1) The Western Thailand–Myanmar/Burma province consists of hornblende–biotite I-type granodiorite–granites and felsic biotite–K-feldspar (± garnet ± tourmaline) granites associated with abundant tin mineralization in greisen-type veins. New ion microprobe U–Pb dating results from Phuket Island show zircon core ages of 212 ± 2 and 214 ± 2 Ma and a thermal overprint with rims of 81.2 ± 1.2 and 85–75 Ma. (2) The North Thailand–West Malaya Main Range province has mainly S-type biotite granites and abundant tin mineralization resulting from crustal thickening following collision of the Sibumasu plate with Indochina during the Mid-Triassic. Biotite granites around Kuala Lumpur contain extremely U-rich zircons (up to 38000 ppm) that yield ages of 215 ± 7 and 210 ± 7 Ma. (3) The East Malaya province consists of dominantly Permian–Triassic I-type hornblende–biotite granites but with subordinate S-type plutons and A-type syenite–gabbros. Biotite–K-feldspar granites from Tioman Island off the east coast of Malaysia also yield a zircon age of 80 ± 1 Ma, showing Cretaceous magmatism in common with province 1. Geological and U–Pb geochronological data suggest that two east-dipping (in present-day coordinates) subduction zones are required during the Triassic, one along the Bentong–Raub Palaeo-Tethyan suture, and the other west of the Phuket–Burma province 1 belt.

Supplementary material: A full description of U–Pb analytical methods used and data tables are available at www.geolsoc.org.uk/SUP18523.

Granites in the SE Asian Tin Belt host the world’s most productive tin mineralized belt, with over 54% of global production in the past coming from Malaysia, Indonesia, Thailand and Burma; important tungsten, fluorite, gold, copper, and REE deposits also occur in the region (Scrivenor 1931; Hutchison 1973, 1977, 1983, 1989; Garson et al. 1975; Mitchell 1977; Mitchell & Garson 1981; Cobbing et al. 1986, 1992; Schwartz et al. 1995). In SE Asia mapping of granite provinces is extremely difficult owing to the extensive jungle cover, deep lateritic weathering profiles and poor exposure. Despite staring work over several decades, the delineation of tectonic, granitic and metallogenic province boundaries remains poorly constrained. Many of the boundaries of supposed Permain–Mesozoic granite provinces (Fig. 1) are now known to be Neogene strike-slip faults that clearly cannot be used to define Mesozoic tectonic units. Although an extensive database of whole-rock geochemistry and isotope data exists for granites from the Malay Peninsula (e.g. Cobbing et al. 1986, 1992; Krahenbuhl 1991; Ghani 2005, 2009; Hutchison & Tan 2009; and references therein) the region is characterized by a lack of chronological precision and incomplete coverage.

The geochemistry and isotope chemistry of granites have previously been interpreted using the I- and S-type classification of Chappell and White (1974). In essence, this scheme simply distinguishes granites that been derived from crustal melting of igneous sedimentary source rocks (I-types) from those derived from melting of sedimentary source rocks (S-types). In general terms, I-type granites are characterized by hornblende- and biotite-bearing cale-alkaline metaluminous granitoids (diorites–granodiorites–granites) withandesite–dacite–rhyolite extrusive rocks. They have meta-igneous enclaves and low initial 87Sr/86Sr ratios, are intrusive into high-level sedimentary country rocks, and frequently have low temperature contact metamorphic aureoles (andalusite hornfels). They are typically associated with porphyry style copper–molybdenum and epithermal Au, Ag, Pb and Zn ores (Robb 2004). Most I-type granites are related to magmatism above oceanic subduction zones in either an Andean-type setting or an advanced island-arc setting. The final magmatic phase of some calc-alkaline batholiths shows strong fractionation of a metaluminous magma resulting in peraluminous leucocratic melts (e.g. St-Onge et al. 2010).

S-type granites, on the other hand, are typically peraluminous granites containing muscovite, biotite, garnet, tourmaline, and occasional aluminium silicates (sillimanite or andalusite), have metasedimentary enclaves, and are associated with regional migmatite and high-grade metamorphic terranes. They have high SiO₂ contents and initial 87Sr/86Sr ratios, and apparently have not intruded far from their source region. S-type granites or leucogranites are typically associated with tin–tungsten mineralization in hydrothermal, greisen vein systems and are usually associated with high concentrations of U and Th. Ishihara (1977) and Ishihara et al. (1979) pointed to the overlap between S-type granites and his ‘ilmenite series’, and between I-type granites and his ‘magnetite series’. In reality, crustal melt I-type granites are variable, with the most fractionated end-members represented by Himalayan garnet, two-mica, tourmaline leucogranites (e.g.
Searle et al. (2009). Another class of granite is the anorogenic A-type granite category, which includes post-orogenic alkali gabbros, syenites and syenogranites related to isolated continental thermal anomalies. These granites are typically K-feldspar-, plagioclase-, quartz- and hornblende-bearing, have intruded from deep in the crust with mantle heat input and do not appear to be related to plate boundaries.

Mitchell (1979) proposed that the tin-bearing granites of SE Asia formed in three distinct tectonic settings: a Permian magmatic arc, a late Triassic foreland thrust belt following collision and a Cretaceous–Eocene back-arc thrust belt. Mitchell & Garson (1972, 1981) and Cobbing et al. (1986, 1992) classified the West Malaya Main Range granites as dominantly tin-bearing S-type granites of mainly Triassic age (Bignell & Snelling 1977; Liew & Page 1985) whereas the East Malaya province is dominantly I-type granite of Permian–Triassic age. The SW Thailand–Myanmar/Burma province (their ‘Western Province’) granites were classified as a mixture of tin-bearing S-type granites and I-type plutons of dominantly Cretaceous age. They also showed that tin mineralization (cassiterite) was generally related to the S-type granites and surrounding slates of the West Malaya Main Range province, although important tin mineralization does also occur in the SW Thailand province (e.g. Phuket Island) and in the East Malaya belt (e.g. Sungai Lembing, Kuantan). Of all tin mined in the region 95% is from alluvial sources, both offshore (e.g. Phuket) and onshore, with only a few exceptions of pre-1970s bedrock mining notably in Phuket (Thailand) and the Kinta Valley, Perak state and Sungai Lembing, Pahang state (Malaysia).

Fig. 1. Geological terrane map of SE Asia showing the three main granite provinces: (1) Western Thailand–Burma province including granites from Phuket Island and the Mogok belt, Myanmar/Burma; (2) North Thailand–Central Main Range West Malaya province including the Kuala Lumpur granites; (3) East Malaya province, including Tioman Island. U–Pb ages (in boxes) are from this paper and also from Barley et al. (2003) and Searle et al. (2007) from Myanmar/Burma, Dunning et al. (1995) from North Thailand, and Hotson et al. (2011) and Oliver et al. (2011) from Singapore.
The most important deficiency in interpreting the geology of SE Asia, and of the tin granite provinces in particular, is the lack of representative U–Pb dating across the region. Rb–Sr and K–Ar isotopic data for SE Asian granites (e.g. Cobbing et al. 1986, 1992; Krahenbuhl 1991; Kwan et al. 1992) are generally not as effective in determining igneous ages of crystallization because of the mobility of Rb and Sr during hydrothermal alteration, and because K–Ar data typically yield cooling ages through closure temperatures for hornblende (c. 520°C), muscovite and biotite (350–300°C). The lack of precise U–Pb geochronology has made it difficult to relate granite magmatism to specific tectonic events and also to relate the timing of hydrothermal activity and Sn–W mineralization to emplacement of granites. Hotson et al. (2011) recently dated gabbro, granodiorite and granite samples from Singapore Island using zircon U–Pb laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) as Late Permain–Early Triassic ranging between 253.5 ± 2 and 230.2 ± 6 Ma, although one granodiorite–diorite sample gave an anomalous mid-Cretaceous age of 94.6 ± 0.8 Ma.

In this paper we present new ion microprobe U–Pb zircon ages from five samples across the SE Asian Tin granite belt, two from Phuket Island, SW Thailand (SW Thailand–East Burma province), two from Kuala Lumpur, Malaysia (West Malaya Main Range province) and one from Tiongan Island off the east coast of Malaysia (East Malaya province). First we start by reviewing the geology and tectonic evolution of the region and then we describe the main characteristics of the three main granite provinces and the central Malaya Bentong–Raub zone, before presenting the new U–Pb age data.

**Geological setting**

The SE Asian granite provinces can be related to the subduction and accretion of a collage of plates and island arc terranes that have progressively accreted to the South China terrane during the closing of the Devonian to Middle Triassic Palaeo-Tethys (the Indosinian orogeny) and the Permain to Palaeo-Tethys Neo-Tethys oceans, with continuing northeastward subduction of the Indian Ocean plate beneath the currently active margin of the Burma–Andaman Islands–Indonesian subduction zone south of Sumatra and Java (Fig. 1). The Indochina terrane is defined as bounded by the poorly known Late Palaeozoic Song Ma suture in Vietnam to the NE and the Chiang Rai–Bentong–Raub suture to the west, with its continuation south to the East Malaya terrane (Metcalfe 2000; Sone & Metcalfe 2008; Hutchison & Tan 2009). The Sibumasu terrane (an acronym for China–Siam–Burma–Malaysia–Sumatra) terrane as defined by Metcalfe (2002) comprises the area west of the Palaeo-Tethyan suture zone in north and SW Thailand, and the Middle Triassic, from biogeographical (brachiopods and fusulinid foraminifera) and palaeomagnetic data. The Sibumasu terrane therefore links westwards with the Lhasa and Qiangtang terranes of Tibet and the various Cimmerian micro-continental blocks within the greater Tethys (Sengor 1984). The western boundary is the Neo-Tethyan suture that swings south from the Himalaya (Indus–Yarlung Tsangpo suture) through central Burma to the Andaman Islands and the Woyla suture zone in Sumatra (Barber 2000; Barber et al. 2005). This Mesozoic–Palaeogene plate margin has been thoroughly overprinted and cut by Neogene strike-slip faults such as the Sagaing Fault and its major splays the Three Pagodas and Mae Ping Faults in Thailand (Searle & Morley 2011).

In Malaysia the main Palaeo-Tethyan suture is thought to be the Bentong–Raub suture (Fig. 2; Hutchison 1973, 1975; Mitchell 1977; Metcalfe 2000, 2002; Sone & Metcalfe 2008) extending north to the Chiang Rai–Sra Kaeo suture (also called Chiang Mai or Inthanon suture; Sone & Metcalfe 2008), with the Nan-Uturaradit suture of north Thailand thought to be a back-arc basin (Barr & McDonald 1987; Metcalfe 2000; Sone & Metcalfe 2008). The Bentong–Raub suture zone contains only scattered and limited ophiolite occurrences, notably serpentinitized ultramafic rocks, but it does contain well-dated cherts and deep-sea sediments ranging from Middle Devonian to Middle Triassic in age (Hutchison 1975; Metcalfe 2000; Sone & Metcalfe 2008). In north Thailand and western Laos the suture zone has been cut and offset along numerous Tertiary strike-slip faults (e.g. Three Pagodas, Mae Ping faults) and becomes less well defined. The Bentong–Raub suture divides the differing granite provinces of East Malaya and West Malaya (see following section). Eastward subduction (present-day coordinates) of Palaeo-Tethyan oceanic crust is thought to have resulted in generation of the East Malaya I-type granite province, and ocean closure and crustal thickening is thought to have resulted in the Triassic dominantly ‘S’-type granites of the West Malaya Central Range granite province (Mitchell 1977; Cobbing et al. 1986, 1992). Another east-dipping subduction zone must have existed during the Triassic–Late Cretaceous west of the SW Thailand–Eastern Burma province to have generated similar subduction-related I-type granites along that zone from Phuket in the south to the Mogok belt of Burma in the north (Searle et al. 2007).

Traditionally the region has been divided into three major granite provinces (Fig. 1), after Hutchison (1973, 1977, 1983, 1989), Mitchell (1977), Cobbing et al. (1986, 1992) and Schwartz et al. (1995): (1) the Western province (SW Thailand–eastern Burma); (2) the Central Main Range province (central north Thailand–western Malaysia); (3) the Eastern province (Laos, eastern Thailand, eastern Malaysia). The Indonesian ‘Tin Islands’ (Riau, Bangka and Billiton Islands), south of Singapore and east of Sumatra, are grouped with the Eastern belt but show characteristics of both the Main Range and Eastern province granites (Cobbing et al. 1986, 1992). Those researchers characterized the West Malaya Main Range granites as dominantly S-type and the East Malaya province as dominantly subduction-related I-type granites, with the Western province a mixture of I- and S-types. Parts of the boundaries of these belts are in places coincidental with younger Tertiary strike-slip faults that have overprinted the earlier tectonic boundaries and are clearly not original boundaries of the Late Palaeozoic–Mesozoic granite provinces (Fig. 1).

Tectonic interpretation and the timing of granite magmatism have been hampered by a lack of accurate geochronology. Existing Rb–Sr, K–Ar and Ar–Ar ages suggested that SW Thailand–eastern Burma province granites were mainly Cretaceous, the West Malaya Main Range province mainly Triassic S-type granites and the East Malaya province mainly Permian to Triassic I-type granites with smaller Cretaceous plutons in peninsular Malaysia (Garson et al. 1975; Bignell & Snelling 1977; Mitchell 1977; Beckinsale 1979; Cobbing et al. 1986, 1992). Crow & van Leeuwen (2005) summarized previous age constraints on the mineralized granites of Sumatra and the Tin Islands. Granites of the Tin Islands of Indonesia range in age from 197 ± 12 to 252 ± 12 Ma with the majority c. 220 Ma (Cobbing et al. 1992).

**SE Asian granite provinces**

**SW Thailand–eastern Burma province**

The SW Thailand–eastern Burma province (‘Western Province’ of Cobbing et al. 1986) extends from Phuket Island in the south along the western Thailand border into the Mogok metamorphic belt of Burma (Barley et al. 2003; Searle et al. 2007). Cobbing et al. (1986, 1992) described an evolutionary series of granites from a parental mafic precursor, I-type equigranular hornblende and biotite granites
through leucocratic main phase granites to S-type composite batholiths of K-feldspar megacrystic and biotite-bearing granites. The S-type granites are particularly rich in tin and tungsten mineralization, mainly concentrated in pegmatite and greisen vein swarms and accompanied by a pervasive kaolinization (Garson et al. 1975). In the Phuket area these researchers described stanniferous lepidolite pegmatites and mica–tourmaline pegmatites also containing significant amounts of wolframite, monazite and other REE- and Y-bearing minerals in close association with cassiterite.

In the Mogok belt of eastern Burma both granite types coexist with younger Palaeogene metamorphic rocks and crustal melt leucogranites. Barley et al. (2003) reported Late Triassic and Early Jurassic U–Pb sensitive high-resolution ion microprobe zircon ages of 209 ± 7 and 171–170.1 ± 1.1 Ma from the Kyanikan gneisses and Mandalay granite and a Cretaceous age (121 ± 1.3 Ma) from the yebokson granodiorite. Searle et al. (2007) reported U–Th–Pb thermal ionization mass spectrometry and LA-ICP-MS ages to support two metamorphic events in this region, the first a Palaeocene metamorphism that ended with intrusion of cross-cutting biotite granite dykes at c. 59 Ma, and the second a high-temperature sillimanite-grade Eocene–Oligocene event spanning 47–29 Ma. Synmetamorphic crustal melting produced garnet- and tourmaline-bearing leucogranites at 45.5 ± 0.6 and 25.5 ± 0.7 Ma. This zone appears to have been a long-lasting magmatic province with Jurassic and Cretaceous subduction-related granites emplaced above a Neo-Tethyan east-dipping (in present coordinates) subduction zone, followed by post-collision (Burma microplate–Sibumasu collision) regional high-grade metamorphism and crustal melting producing more S-type granites. The southern area around Phuket is strongly Sn–W mineralized (Garson et al. 1975; Mitchell 1977) and the northern part in Burma has Sn and W mines at Hermyingi, Mawchi and Padakchaung (Mitchell & Garson 1981; Hutchison 1989). The lack of tin in Burma is made up for by the abundance of gem-quality rubies and sapphires in the Mogok belt and epithermal gold in eastern Burma (Mitchell et al. 2007).

North Thailand–West Malaya Main Range province

The north Thailand granite province is continuous south into the Main Range province of west Malaysia. Cobbing et al. (1986, 1992) drew the western boundary along the later Tertiary Klong Marui strike-slip fault, drawing into question the division of this belt with the SW Thailand–West Malaya belt. SW of Bangkok S-type
granites occur on both sides of Cobbing et al.’s (1986) boundary and in north Thailand granite lithologies in the Doi Inthanon and Doi Suthep massifs to the east are similar to those in the Mogok belt to the west. The province extends south across the Gulf of Thailand to the far south of Thailand and the Main Range of peninsular Malaya (Fig. 2). The granites in this province are dominantly biotite–K-feldspar megacrystic–plagioclase granites (some with tourmaline and rarely with garnet and secondary muscovite) of Triassic age intruded into Ordovician to Devonian sedimentary rocks (Fig. 3a). Geochemically the granites are S-type peraluminous and potassic, alkaline–calcic associations showing high levels of incompatible and high field strength elements with high initial 87Sr/86Sr ratios (0.7105–0.7310) indicative of a crustal source (Cobbing et al. 1992). Liew & Page (1985) described a range of compositions from biotite adamellite to muscovite leucogranite cropping out near the Bentong–Raub suture in central Malaysia (Fig. 2). The gabbros and syenites are genetically linked with xenoliths of gabbro entrained in the syenite and vice versa, suggesting two immiscible liquids. Both gabbros and syenites have been intruded by dolerite dykes. Magmatic foliation in the syenites is defined by euhedral K-feldspar megacrysts. The alkaline rocks are intrusive into the I-type biotite- and hornblende-bearing Benom batholith to the east. Rare alcali series syenites and hornblende-bearing granites have been described from the Perhentian Islands offshore Terengganu on the NE coast of Malaysia (Ghani & Khoo 1998; Ghani 2001, 2003b). The existence of inclusions of the syenite facies within the granite shows that the granite intruded after the syenite (Fig. 4e). The Perhentian syenites and granites together with all the east coast Malaya granites have been cut by a prominent set of plagioclase, clinopyroxene and amphibole phric dolerite dykes (Ghani et al. 2002).

In northern Malaya in the Penjom gold mine, Late Permian calcareous shales and mudstones have been intruded by a series of felsite (trachyte, microgranite) dykes (Fig. 4f and g) that cross-cut the regional bedding. Quartz, ankerite and calcite veins are abundant and the felsite dykes are associated with gold, arsenopyrite and base metal mineralization (Fig. 4h). Biotite–K-feldspar and hornblende-bearing granite plutons (Benom and Noring) have been emplaced into metametamorphic country rocks including sillimanite–garnet gneisses (Fig. 5a) and calc-silicates (Hutchison 1971; Ghani 2007). Garnet–biotite–sillimanite-bearing gabbrotites, banded calc-silicate marbles and other regional metamorphic rocks make up much of the northern part of the central Malaya highlands. At the Renyok River waterfall locality mylonitic fabrics indicate very high strain, possibly associated with a major ductile shear zone cutting this part of the East Malaya province. At least three sets of leucogranite dykes intrude mylonites at this locality, with at least two early sets of deformed and boudinaged sills or dykes (Fig. 5b and c) parallel to the foliation and a later set cross-cutting the metamorphic fabric (Fig. 5d), as well as the early leucogranite dykes (Abdullah & Sethiawan 2003).

Pulau Tioman off the east coast of Malaysia is the easternmost exposure of the peninsular Malaysia granite province and is composed of gabbros, diorites and biotite- and hornblende-bearing granites. Bignell & Snelling (1977) published a K–Ar age of 74±2 Ma and suggested this was a Cretaceous emplacement age. Ghani et al. (1999) found evidence for an older garnet-bearing granite series on Tioman Island. Also present are felsic to intermediate volcanic rocks,

**East Malaya province**

The East Malaya province consists mainly of I-type subduction-related, calc-alkaline biotite–hornblende- and K-feldspar megacrystic granodiorites, granites and tonalites collectively known as the Kapal batholith in the east and the Boundary Range batholith in NE Malaysia (Hutchison 1977; Cobbing et al. 1986, 1992; Ghani 2005, 2009). These granites are dominated by K-feldspar, plagioclase and quartz with hornblende and biotite as the mafic components (Fig. 4a). They have igneous dioritic enclaves and the plutons occasionally show narrow contact metamorphic aureoles. The occurrence of some peraluminous ignimbrites and high-K orthopyroxene-bearing dacites (Sempah volcanic complex; Ghani & Singh 2002, 2005) shows that some of these granites do have a volcanic component (Fig. 4b).

The Kenerong biotite granite between the Berangkat tonalite and Noring granite exhibits magmatic textures that appear to relate to assimilation of metametamorphic country rocks (Fig. 4c). All three plutons have been included in the Stong Complex (Ghani 2009). One anomalous pluton, the Maras-Jong pluton in Terengganu state, NE Malaya, is a K-feldspar phric monzogranite, but shows several S-type characteristics, notably the presence of garnet and tourmaline (Fig. 4d). Based on petrological and geochemical data, Ghani (2003b) interpreted this as a highly fractionated felsic I-type pluton rather than an S-type.

One rather anomalous sequence of rocks is the alkaline gabbros, pyroxenites, syenites and monzonites of the Benom Complex (bin Ahmad 1979; Yong et al. 2004; Umor et al. 2008; Ghani 2009) cropping out near the Bentong–Raub suture in central Malaysia (Fig. 2). The gabbros and syenites are genetically linked with xenoliths of gabbro entrained in the syenite and vice versa, suggesting two immiscible liquids. Both gabbros and syenites have been intruded by dolerite dykes. Magmatic foliation in the syenites is defined by euhedral K-feldspar megacrysts. The alkaline rocks are intrusive into the I-type biotite- and hornblende-bearing Benom batholith to the east. Rare alcali series syenites and hornblende-bearing granites have been described from the Perhentian Islands offshore Terengganu on the NE coast of Malaysia (Ghani & Khoo 1998; Ghani 2001, 2003b, 2009). The existence of inclusions of the syenite facies within the granite shows that the granite intruded after the syenite (Fig. 4e). The Perhentian syenites and granites together with all the east coast Malaya granites have been cut by a prominent set of plagioclase, clinopyroxene and amphibole phric dolerite dykes (Ghani et al. 2002).
both lavas and tuffs. Liew (1983) and Liew & McCulloch (1985) obtained U–Pb zircon ages of 264 ± 2 Ma for the Kuantan granite and 257 ± 4 Ma for the Tinggi granite, with U–Pb discordia and εNd ages suggesting a Neoproterozoic crustal source. 87Sr/86Sr ratios of Eastern Province granites are 0.7070–0.7122. Volcanic components include calc-alkaline andesites, dacites, rhyolites and tuffs.

**U–Pb geochronology**

Zircon was separated using standard rock disaggregation and heavy mineral separation procedures. Separated grains were hand-picked, mounted in epoxy, polished to reveal grain interiors and imaged using a Robinson CL detector on an Hitachi S4300 scanning electron microscope. U–Pb zircon geochronology was determined using a large geometry Cameca IMS1270 ion microprobe at the Swedish Museum of Natural History, Stockholm, Sweden (Nordsims facility) using methods described by Whitehouse et al. (1999) and Whitehouse et al. (2005).

**Phuket Island, Thailand, Western Thailand–Burma province (1)**

Granites from Phuket Island include both hornblende- and biotite-bearing I-type granites and muscovite-bearing S-type granites. Field evidence from Phuket suggests that early calc-alkaline, more mafic hornblende-bearing granites have been subsequently affected by a weak deformation fabric and then intruded by a later more peralkaline leucocratic facies (Cobbing et al. 1992). The samples are coarse K-feldspar–biotite granites containing small mafic enclaves that are sometimes flattened in a weak foliation plane.

**Sample Phuket-1.** Zircons from sample Phuket-1 are generally well-faceted prisms with aspect ratios of 1.5–4. All grains exhibit core and rim structures. The cores comprise both oscillatory zoned and unzoned, CL-medium to CL-bright zircon with a rounded and occasionally embayed interface to uniformly CL-dark unzoned to weakly zoned rims (Fig. 6a). Thirteen grains were analysed by secondary ionization mass spectrometry (SIMS), with separate core and rim analyses performed on five grains (Fig. 6b). The five rim analyses have high U contents between 2400 and 6200 ppm with consistently low Th/U ratios (<0.09), which may be consistent with a metamorphic and/or anatexic origin, an interpretation further supported by the rounding and occasional embayment of the cores. These analyses yield a concordia age of 81.2 ± 0.95 Ma (95% conf., MSWD of concordance and equivalence = 1.1). Cores in polyphase grains and single grain analyses yield a spread in ages up to >1530 Ma (a minimum 207Pb/206Pb age on a discordant grain), with a group of six concordant grains yielding a concordia age of 214.4 ± 2.4 Ma (95% conf., MSWD of concordance and equivalence = 1.0); U contents for these six grains range from 260 to 2600 ppm with Th/U ratios ranging from 0.25 to 1.0. Five grains with ages between the two concordant clusters most probably represent variable amounts of Pb.

**Phuket Island, Thailand, Western Thailand–Burma province (2)**

Granites from Phuket Island include both hornblende- and biotite-bearing I-type granites and muscovite-bearing S-type granites. Field evidence from Phuket suggests that early calc-alkaline, more mafic hornblende-bearing granites have been subsequently affected by a weak deformation fabric and then intruded by a later more peralkaline leucocratic facies (Cobbing et al. 1992). The samples are coarse K-feldspar–biotite granites containing small mafic enclaves that are sometimes flattened in a weak foliation plane.

**Sample Phuket-1.** Zircons from sample Phuket-1 are generally well-faceted prisms with aspect ratios of 1.5–4. All grains exhibit core and rim structures. The cores comprise both oscillatory zoned and unzoned, CL-medium to CL-bright zircon with a rounded and occasionally embayed interface to uniformly CL-dark unzoned to weakly zoned rims (Fig. 6a). Thirteen grains were analysed by secondary ionization mass spectrometry (SIMS), with separate core and rim analyses performed on five grains (Fig. 6b). The five rim analyses have high U contents between 2400 and 6200 ppm with consistently low Th/U ratios (<0.09), which may be consistent with a metamorphic and/or anatexic origin, an interpretation further supported by the rounding and occasional embayment of the cores. These analyses yield a concordia age of 81.2 ± 0.95 Ma (95% conf., MSWD of concordance and equivalence = 1.1). Cores in polyphase grains and single grain analyses yield a spread in ages up to >1530 Ma (a minimum 207Pb/206Pb age on a discordant grain), with a group of six concordant grains yielding a concordia age of 214.4 ± 2.4 Ma (95% conf., MSWD of concordance and equivalence = 1.0); U contents for these six grains range from 260 to 2600 ppm with Th/U ratios ranging from 0.25 to 1.0. Five grains with ages between the two concordant clusters most probably represent variable amounts of Pb.
loss during the younger event. With one exception, these grains have similarly moderate U contents and Th/U ratios to the older group; the outlier grain has high U (8400 ppm) and low Th/U (0.04), suggesting that it belongs in the 81 Ma age group and that, instead of Pb loss, its slightly older age is an analytical artefact of its high U, a relatively common occurrence in SIMS analysis of high-U zircon (e.g. McLaren et al. 1994; Butera et al. 2001), which will be discussed below in relation to the Kuala Lumpur samples.

**Sample Phuket-2.** Zircons from sample Phuket-2 have very similar CL characteristics to those from Phuket-1. U–Th–Pb data are considerably scattered presumably as a result of at least one period of recent Pb loss, and no significant age populations can be calculated from concordant analyses. Despite this, the same age populations at c. 80 and c. 210 Ma are clearly represented in this sample, with 207-corrected ages from four core analyses yielding a weighted average age of 211.5 ± 3.0 Ma (95% conf., MSWD = 0.33) that corresponds well to the core age from Phuket-1.

**Kuala Lumpur granite, West Malaya Main Range province (2)**

The Central Main Range granites are thought to be mostly Triassic in age from previous Rb–Sr (Cobbing et al. 1992) and U–Pb dating (Liew & Page 1985). Our samples from the Kuala Lumpur granite are composed of K-feldspar megacrysts and bluish ...

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**Fig. 4.** Field photographs from the East Malaya granite province. (a) Typical hornblende + biotite granite from Kuantan pluton. (b) Orthopyroxene-bearing dacites from Sempah volcanic unit, east of Kuala Lumpur. (c) Migmatites in the Kenerong biotite granite, part of the Stong complex. (d) Large tourmaline crystal in the leucocratic Maras-Jong pluton. (e) Hornblende-bearing alkali granite intruding syenite, Perhentian Island. (f, g) Felsite microgranite dykes intruding Late Permian calcareous shales and mudstones, Penjon gold mine. (h) Gold, arseno-pyrite and base metal mineralization associated with the felsite intrusions, Penjon gold mine.
quartz xenocrysts in a quartz-feldspathic matrix that also contains muscovite and biotite. This granite is strongly peraluminous, and also highly siliceous (SiO₂ in the range 73.6–76.6 wt%), and potassic (K₂O/Na₂O ratios >1.8) (Cobbing et al. 1992). Although interpreted as an anatectic granite, it forms a large batholith emplaced into low-grade metasedimentary rocks of Silurian–Devonian age. Alluvial tin deposits are widespread around Kuala Lumpur and all the granites show extensive tin mineralization. Liew & Page (1985) obtained U–Pb zircon ages of 215 ± 4 Ma for the western margin and 211 ± 8 Ma for the eastern margin of the pluton.

Sample KL1. Zircons from sample KL1 are well faceted and prismatic with aspect ratios of 3–6. Generally these grains are CL-dark, with barely discernible oscillatory zoning; a few grains contain CL-bright, rounded cores that exhibit faint zoning (Fig. 6a). The outer CL-dark parts of seven grains analysed by SIMS all contained extremely high contents of U ranging from 8900 to 40000 ppm and have low Th/U ratios from 0.02 to 0.07. On an inverse concordia diagram, the samples apparently range in 206Pb/238U age from c. 230 to 270 Ma but are mostly reversely discordant (Fig. 6c, inset). This is interpreted as an analytical artefact of the very high U contents, which renders the U/Pb calibration unreliable (e.g. McLaren et al. 1994; Butera et al. 2001). In such high-U zircon the 207Pb/206Pb ratios may, however, be measured by SIMS with a sufficient degree of precision to yield a meaningful age in such relatively young zircon (e.g. Lee & Whitehouse 2007). For sample KL1, the weighted mean 207Pb/206Pb age of 210 ± 7 Ma (95% conf., MSWD = 0.34; Fig. 6c) is therefore considered as the best estimate of the intrusion age of the granite.

Sample KL2. This sample contains zircons similar in appearance to those from KL1 and these also are very U rich (range 3600–37000 ppm) with low Th/U ratios (range 0.02–0.09 with one outlier at 0.44). SIMS U–Pb ages range from c. 53 to 273 Ma and are again considered unreliable owing to the effects of very high U contents, in this case with some Pb loss to younger ages clearly superimposed on the high-U matrix effect that yields ages that are apparently too old. The magnitude of the high-U matrix-induced increase in Pb/U ratios for both KL1 and KL2 averages 1.1 ± 0.5% per 1000 ppm U, slightly lower than the c. 2% estimated by Butera et al. (2001) but likely to be a minimum because of superimposed Pb loss. The 207Pb/206Pb age for this sample, omitting two grains with high common Pb, is 215 ± 7 Ma (95% conf., MSWD = 0.99; Fig. 6c), and is interpreted as the intrusion age of the granite.

Tioman Island, East Malaya province (3)

Granites of the Eastern Province of Cobbing et al. (1986) extend from eastern Malaysia to NE Thailand and into Laos (Fig. 1) and include numerous plutons of dominantly I-type monzogranite related to oceanic subduction during Permo-Triassic time. Several islands off the east coast of Malaysia are also composed of granites but whereas the northern islands are probably part of the Eastern Province, the granites from Tioman Island have very different U–Pb ages. Our samples from Tioman Island are undeformed biotite granites with large K-feldspar megacrysts.

Zircons from the Tioman sample are well faceted and prismatic, ranging in size from <100 to >300 µm, and have aspect ratios of 3–5. Internal structures revealed by CL imaging vary between fine-scale oscillatory zoning and homogeneous–unzoned, sometimes with the latter forming the central portion of grains that have a zoned outer part. Eighteen SIMS analyses were performed on 17 grains, with two analyses placed on apparently distinct ‘core’ and ‘rim’ domains of one of these grains. Contents of U are relatively low, ranging from 62 to 730 ppm, with typically magmatic Th/U ratios from 0.6 to 1.4. On an inverse concordia diagram (Fig. 6d), most of the analyses are concordant at c. 80 Ma with a limited spread in U/Pb ages, although a single younger analysis suggests that some post-crystallization Pb loss has occurred, which also probably affects the other analyses to some degree. Omission of the youngest analysis as well as two analyses with high common Pb yields a concordia age of 79.1 ± 1.0 Ma (95% conf., MSWD = 2.0). Assuming that the relatively high MSWD reflects slight Pb loss.
affecting the population, omission of a further four analyses results in a statistically more robust concordia age of 80.1 ± 0.8 Ma (95% conf., MSWD = 1.0), which is interpreted as the preferred crystalization age of the Tioman sample.

Discussion and conclusions

Previous divisions of the main SE Asian granite provinces, into a (1) Western province of mixed I- and S-type granites, (2) Central province (Thailand–West Malaya Main Range) showing S-type granites and (3) Eastern province dominated by I-type granites (Cobbing et al. 1986, 1992), are regarded as being too generalized and inconsistent with some mineralogical and geochemical data (e.g. Ghani 2000, 2001, 2005). The Western province extending from Phuket Island northwards to eastern Myanmar (Burma) includes both Triassic I-type subduction-related biotite–hornblende-bearing granodiorites and granites (Barley et al. 2003) as well as more S-type crustal melt granites of Palaeogene age in the Mogok belt, Burma (Searle et al. 2007), and with U–Pb zircon rim ages indicating Cretaceous magmatism (this paper). The nature of the boundary between the Western province and the Central province (West Malaya Main Range) is not clear as the Cobbing et al. (1986, 1992) boundary is the late Tertiary Klong Marui fault. S-type granites occur on both sides of this line and there is no suture zone.

The Central province extending from West Malaya north to the Doi Inthanon range of North Thailand is composed dominantly of S-type granites of batholithic proportions and includes migmatites (e.g. Doi Inthanon, Thailand; Stong complex, Malaya). Although most granites in the West Malaya Main Range batholith are reported to be S-types (Cobbing et al. 1986, 1992) there are subordinate hornblende–biotite granites with I-type affinities. In addition, both I-type and S-type granites with apparently similar age ranges (c. 220–200 Ma; Rb/Sr ages) formed across the Indonesian ‘Tin Islands’ SE of Singapore (Cobbing et al. 1992). It is suggested that I-type subduction-related granites in the Western province...
became more felsic with increasing crustal influence and the large-scale batholiths of biotite granite in both the western and central provinces hosted tin mineralization during the later stages of plutonism along large greisen-type pegmatite vein networks.

The ‘S-type granites’ of Cobbing et al. (1992) in the West Malaya Main Range province are dominantly composed of biotite- and K-feldspar, but in a few places the more fractionated magmas contain garnet and tourmaline. They are more likely to be evolved felsic I-types rather than S-type granites like the Himalayan leucogranites for example (Searle et al. 2009). The large scale of the batholiths along the Main Range of peninsular Malaysia suggests that an extra heat source is required during the late Triassic and this can only come from a mantle source. This granite province may be comparable with the Baltoro granite batholith in the Pakistan Karakoram, which is a large-scale post-collision S-type crustal melt granite but has earlier pre-collision subduction-related I-type components as well (Searle et al. 2010). The mixture of Main Range S-type granites and East Malaya province granites on the Indonesian Tin Islands also suggests that there is no distinct boundary between the two.

The West Malaya Main Range granites are highly radioactive with zircon U contents up to 37000 ppm. They are also associated with hydrothermal activity that was responsible for the widespread tin mineralization (Mitchell 1977, 1979, 1981; Hutchison 1989).

These granites are unlike the classic Himalayan crustal melt granites, which are formed by muscovite dehydration melting, are associated with migmatite zones and do not contain tin mineralization. The Main Range peraluminous granites have batholithic dimensions suggesting an origin by crustal anatexis, possibly associated with extra heat input from the mantle and possible injection of mantle-derived melts at the base of the crust.

The East Malaya province from Singapore Island north to Kota Bharu does indeed show dominant I-type subduction-related hornblende and biotite granite magmatism with some dacitic–rhyolitic volcanism preserved in places (e.g. Sempah volcanic series). However, there are several anomalous syenite–gabbro intrusions including the Benom Complex in central Malaya and the Perhentian Islands syenite intrusions off the east coast, both of which are more akin to within-plate magmatism. Another anomalous pluton in the East Malaya province is the garnet- and tourmaline-bearing Maras-Jong pluton, which shows several S-type characteristics.

Our new U–Pb age data from the Phuket and Kuala Lumpur granites together with U–Pb age data from the Eastern belt granites in Singapore (Hotson et al. 2011; Oliver et al. 2011) show that Latest Permian–Triassic subduction-related calc-alkaline plutonism occurred in both the Western and Eastern granite provinces. We suggest that two east-dipping subduction zones (in present-day coordinates) must have been active during the Permo-Triassic to

Fig. 7. Tectonic evolution of SE Asia region illustrated with two sections: (a) shows two east-dipping subduction zones (in present-day coordinates) beneath the East Burma–SW Thailand province and subduction of the Palaeo-Tethys beneath the East Malaya terrane; (b) illustrates the Late Triassic closure of Palaeo-Tethys along the Bentong–Raub suture, and crustal thickening of the West Malaya province associated with intrusion of the Triassic S-type granites in the Main Range of Malaya.

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generate these suprasubduction-zone granites, one along the Bentong–Raú–Chiang Rai Palaeo–Tethyan suture and the other to the west of Phuket and the Mogok belt in Burma (Fig. 7). Collision of the Sibumasu plate with the Indochina terrane closed the Palaeo-Tethyan Ocean during the Late Triassic and generated crustal thickening, regional metamorphism and ‘S-type’ tin-bearing granites along the North Thailand–West Malaya Central Range province. The subduction influence continued into the Middle Cretaceous when both the late-stage Phuket granites in the west and the Tioman Islands granite in the east were emplaced. Our new Cretaceous U–Pb zircon age from the Tioman granite may be part of the same igneous episode as the Late Cretaceous granodiorite that has a zircon age of 95 ± 1 Ma from Pulau Ubin, Singapore (Hotson et al. 2011; Oliver et al. 2011). It might be possible that the Late Cretaceous Tioman granites are the western extension of the Sunda shelf arc granites that crop out in southern Borneo (Carlisle & Mitchell 1994) and are, therefore, related to west-dipping subduction of palaeo-Pacific oceanic crust beneath the eastern margin of Asia. Alternatively, the Cretaceous plutons could be the far-field effects of Neo-Tethyan subduction similar to some of the Tibetan plutons (Chung et al. 2005; Chu et al. 2006).

Our work has highlighted several unresolved problems with SE Asia–Malaysian granite mineralization provinces. One is the occurrence of tin mineralization across the SE Asian region (Taylor 1986; Hutchison 1996; Hutchinson & Tan 2009). Tin mineralization is not restricted to the peraluminous crustal melt granites of the West Malaya Main Range province, although this is where the majority of tin deposits are hosted. Important tin mineralization also occurs in the other granite provinces. Tin mineralization occurs mainly in greisen vein pegmatites along the roof zones of the granite plutons. Most tin is mined from Quaternary placer alluvial deposits both offshore (Phuket) and onshore (e.g. Kinta Valley region). Tin deposits occur in all three provinces, the SW Thailand–East Myanmar/Burma province (e.g. Phuket), the major deposits in the West Malaya Main Range province (e.g. Kinta valley) and subordinately in the East Malaya province (e.g. Sungei Lembing lodes (Hutchison 1996, 2009) and the Tin Islands (Cobbing et al. 1992)). Although the Bentong–Raú suture zone separates two continental blocks from opposite sides of the Palaeo-Tethys Ocean, tin mineralization occurs in both continental blocks, albeit far more in the West Malaya Main Range province.

A second major problem is the source of the tin enrichment. Tin is unlikely to have been derived from a mantle source and the mineralization is more probably related to crustal hydrothermal redistribution during extreme fractionation or more S-type crustal reworking processes. Clearly, more detailed mapping of the Sn, W, Cu, Mo and Au mineralized zones is required, to match the style and timing of mineralization to granite petrogenesis. Further U–Pb dating of granites across all three provinces is clearly required before the plate-tectonic history of this complex region is thoroughly understood.

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