Granitic magmatism, basement ages, and provenance indicators in the Malay Peninsula: Insights from detrital zircon U–Pb and Hf-isotope data

Inga Sevastjanova, Benjamin Clements, Robert Hall, Elena A. Belousova, William L. Griffin, Norman Pearson

Abstract

The Malay Peninsula lies on two continental blocks, Sibumasu and East Malaya, which are intruded by granitoids in two provinces: the Main Range and Eastern. Previous models propose that Permian–Triassic granitoids are subduction-related and syn-to post-collisional. We present 752 U–Pb analyses that were carried out on zircons from river sands in the Malay Peninsula; of these, 243 grains were selected for Hf-isotope analyses. Our data suggest a more complex Sibumasu–East Malaya collision history. \(^{176}\)Hf/\(^{177}\)Hf ratios reveal that Permian–Triassic zircons were sourced from three magmatic suites: (a) Permian crustally-derived granitoids, (b) Early-Middle Triassic granitoids with mixed mantle–crust sources, and (c) Late Triassic crustally-derived granitoids. This suggests three Permian–Triassic episodes ofmagmatism in the Malay Peninsula, two of which occurred in the Eastern Province. Although the exact timing of the Sibumasu–East Malaya collision remains unresolved, current data suggest that it occurred before the Late Triassic, probably in Late Permian–Early Triassic. Our data also indicate that Sibumasu and East Malaya basements are chronologically heterogeneous, but predominantly of Proterozoic age. Some basement may be Neoarchaean but there is no evidence for basement older than 2.8 Ga. Finally, we show that Hf-isotope signatures of Triassic zircons can be used as provenance indicators.

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1. Introduction

SE Asia is a composite region of continental crustal fragments and volcanic arcs, separated by sutures that represent remnant ocean basins (e.g. Metcalfe, 2006, 2010). These continental fragments are allochthonous to the Eurasian margin and separated from Gondwana in the Palaeozoic and Mesozoic (Audley-Charles, 1988; Metcalfe, 1988, 1996a,b). Palaeogeographic reconstructions show that these fragments arrived from NW Australia and NE Greater India (Hall, 2008; Hall et al., 2008; Metcalfe, 1988, 1996b, 2009).

In the SE Asian region, U–Pb detrital zircon geochronology has been successfully used for tracing sediment pathways (Clements and Hall, 2008; van Hattum, 2005; van Hattum et al., 2006), dating large Cenozoic eruptions (Smyth et al., 2008), and identifying fragments of unexposed basement (Smyth et al., 2007). Studies of Hf-isotope compositions in detrital zircons have resulted in detailed crustal evolution models for parts of Australia (Belousova et al., 2006; Griffin et al., 2004, 2006a; Murgulov et al., 2007) as well as for other parts of the world (e.g. Bahlburg et al., 2010; Bodet and Schärer, 2000; Kuznetsov et al., 2010; Matteini et al., 2010), and have also aided provenance interpretations (e.g. Belousova et al., 2009; Howard et al., 2009; Veevers et al., 2006). However, there are no Hf-isotope studies for the Sundaland region and few studies have addressed the age and nature of the basement fragments in the region. This is the first study to apply zircon U–Pb dating and Hf-isotope analyses to Sundaland.

In this paper we discuss U–Pb and Hf-isotope data in detrital zircons from modern rivers draining the Malay Peninsula. Current data suggest a complex multi-phase evolution of the volcanic arcs that developed in the Permian and Triassic on the western margin of SE Asia as a result of predominantly east-directed Palaeo-Tethys subduction. Crustal model ages reveal that the basement beneath the East Malaya and Sibumasu Blocks (Fig. 1) is Palaeoproterozoic, although of different age, and with probable Neoarchaean crust also present. The Sundaland basement is intruded by abundant Permian–Triassic, Jurassic, and Cretaceous granitoids. A significant overlap in U–Pb zircon ages from different Sundaland source areas makes provenance interpretations difficult. However, the different Hf-isotope compositions enable distinctions to be made between granitic provinces of similar age.

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2. Geological setting

2.1. Sundaland

Sundaland, the continental core of SE Asia (Hall, 2002; Hamilton, 1979; Hutchison, 1989), comprises Indochina, the Thai-Malay Peninsula, Sumatra, Java, Borneo and the shallow shelf between these landmasses (e.g. Hall and Morley, 2004). Amalgamation of the continental blocks that form Sundaland occurred during the Late Palaeozoic and Mesozoic as a result of separation of continental slivers from the Gondwana margin and successive opening and closure of Tethyan oceanic basins (e.g. Metcalfe, 1996b, 1998, 2009). Palaeozoic and Mesozoic reconstructions are based on multidisciplinary evidence that includes palaeomagnetism, lithofacies correlations, faunal provinces, magmatic episodes, and dating of tectonic events. These data are complex and difficult to interpret, especially with regard to the
Tethyan oceans, which have been destroyed by subduction (Hall et al., 2009). However, despite disagreements on the exact origin of the blocks, the timing of their departures and arrivals, it is now accepted that the core of Sundaland comprises the Indochina–East Malaya, West Burma, and West Sumatra Blocks that separated from Gondwana in the Devonian and together formed a composite Cathaysia Block in the Permian (Barber and Crow, 2009; Metcalfe, 2006, 2009). The Sundaland core also includes Sibumasu, which was accreted to Indochina–East Malaya, most likely in the Late Permian–Early Triassic (Barber and Crow, 2009; Metcalfe, 2009). The Sukhothai Volcanic Arc that lies between the Indochina–East Malaya and Sibumasu Blocks is interpreted to be a continental sliver that separated from the Indochina–East Malaya margin by back-arc spreading in the Permian (Metcalfe, 2009, 2010; Sone and Metcalfe, 2008) (Fig. 1). Another important episode of rifting around northern Australia occurred in the Jurassic and the blocks that separated from this area are now in Borneo, Java, and Sulawesi (Hall et al., 2009). The Banda and Argo Blocks collided with the SE Asian margin in Cretaceous time. Collision of the Woyla intra-oceanic arc with the Sumatra Block in the Late Cretaceous terminated subduction beneath Sundaland (Clements et al., in press; Hall et al., 2009) and it resumed only in the Eocene (Hall et al., 2009). West Sumatra and West Burma, that originally formed one block, became separated by the opening of the Andaman Sea in the Miocene (Barber and Crow, 2009).

Abundant subduction-related and syn- to post-collisional Permian–Triassic, Jurassic and Cretaceous granitoids are intruded into the core of Sundaland. The granitoids that extend from Thailand, through the Malay Peninsula and Indonesian Tin Islands are tin-bearing and are known as the SE Asian tin belt (e.g. Cobbing et al., 1992). These granitoids are probably a major source of detrital zircons in Sundaland. Few studies have attempted to date the basement in the SE Asian region. Hamilton (1979) mapped the extent of the Cretaceous continental crust from well data in the Java Sea and traced the Sundaland margin from West Java to SE Borneo. Based on U–Pb SHRIMP zircon dating of Cenozoic igneous and sedimentary rocks, Smyth et al. (2007) confirmed that there is a change in basement character from West to East Java. However, inherited Archaean, Proterozoic, and Palaeozoic zircons suggest that East Java is underlain by Gondwana-derived continental crust and not by Cretaceous accreted material as has been suggested previously (e.g. Hamilton, 1979). Previous Nd–Sr and U–Pb zircon dating of Permian–Triassic granitoids in the Malay Peninsula (Liew and McCulloch, 1985) suggested that the crust beneath the Sibumasu Block is 1500–1700 Ma old and the crust beneath the East Malaya Block is 1100–1400 Ma. Based on U–Pb dating and Hf-isotope analysis of detrital zircon and baublechite from large rivers draining mainland SE Asia – the West Burma, Sibumasu and Indochina Blocks – Bodet and Schärer (2000) identified five Proterozoic crustal growth events in the area at around 2.5 Ga, 2.3 Ga, 1.9 Ga, 1.1 Ga and 0.8 Ga. Based on radiogenic isotope analyses, radiometric age studies, and petrographic data from the Malino and Palu Metamorphic Complexes, van Leeuwen et al. (2007) suggested that Northwest Sulawesi is underlain by crust that was derived from the New Guinea–Australian margin of Gondwana.

2.2. The Malay Peninsula

The Malay Peninsula is situated in the heart of Sundaland and lies on the Sibumasu and East Malaya Blocks (Fig. 1). The Sibumasu Block extends from western Yunnan to Burma, Thailand, western Peninsular Malaysia, and northeast Sumatra. East Malaya is a southwards extension of the Indochina Block (Metcalfe, 2000). Lower Palaeozoic rocks of the Sibumasu Block show Gondwana biogeographic affinities. This and the presence of Lower Permian glaciomarine diamictites indicate that Sibumasu was part of Gondwana until the Early Permian (Metcalfe, 1988, 1996b, 1998, 2009; Schwartz et al., 1995). This is supported by general tectonostratigraphical similarities between Sibumasu and the Canning Basin of NW Australia (e.g. Metcalfe, 1996b, 2000). In East Malaya, only Orдовиан and Silurian but not younger faunas show Gondwanan affinities. It has therefore been suggested that East Malaya separated from Gondwana in the Devonian (e.g. Metcalfe, 2000). Sibumasu and East Malaya are separated by the Bentong–Raub Suture Zone, which includes a tectonic mélange with ribbon-bedded cherts, schists, and minor ophiolites that represent Palaeo-Tethys remnants (Hutchison, 1975, 1977, 2009; Metcalfe, 2000).

Late Palaeozoic and Early Mesozoic subduction of the Palaeo-Tethys oceanic crust and the collision of the Sibumasu and East Malaya Blocks resulted in active magmatism (Metcalfe, 2000). The products of this magmatism are Permian and Triassic granitoids of two provinces, the Main Range Province and the Eastern Province (which includes the Central and Eastern Belts) (Fig. 2). Predominantly I-type and rare S-type Permian and Triassic granitoids of the Eastern Province are considered to be subduction-related, produced in a volcanic arc that formed on the East Malaya Block (Metcalfe, 2000). Triassic S-type granitoids, intruded into the Sibumasu Block, are interpreted as syn- and post-collisional (Hutchison, 1977; Metcalfe, 2000). Triassic volcano-plutonic turbidites were sourced from the East Malaya Volcanic Arc and are now exposed near the Bentong–Raub Suture Zone (Metcalfe, 2000; Metcalfe et al., 1982; Roslan, 1989). Upper Cretaceous granitoids were emplaced locally in the Central Belt (Cobbing et al., 1992). Based on stratigraphical and structural differences the Malay Peninsula is divided into three geological zones (belts): the Eastern Zone, Central Zone, and Western Zone that are bounded by major fault zones (e.g. Hutchison, 1975, 1977; Khoo and Tan, 1983) (Fig. 2). The Western Zone lies on the Sibumasu Block and is intruded by the granitoids of the Main Range Province. The Central and Eastern Zones lie on the East Malaya Block and are intruded by Eastern Province granitoids.

Upper Mesozoic and Cenozoic rocks in the Malay Peninsula are continental. Alluvial and fluvial sequences of the Upper Jurassic–Lower Cretaceous Tembeling and Gagau Groups were deposited in the central part of the Malay Peninsula (Gobbett and Hutchison, 1973; Harbury et al., 1990; Racey, 2009; Rishworth, 1974). Palaeocurrent data from the Tembeling Group in the Malay Peninsula suggest sediment transport from the northwest (Harbury et al., 1990). The Tembeling Group and Khorat Group in NE Thailand are correlatable (Racey, 2009) and form a regionally extensive, laterally continuous stratigraphic sequence over much of the region (e.g. Racey, 2009). However, in the Malay Peninsula much of the Post-Triasic succession has been eroded as a result of prolonged emergence during the Late Cretaceous and Early Palaeogene (Clements et al., in press). Cenozoic coal-bearing lacustrine and fluvial basins have a very limited distribution on land (Stauffer, 1973).

3. Sample selection

Zircons from nine modern river samples draining the Malay Peninsula (Fig. 2) were dated using U–Pb techniques. Six of these samples were selected for Hf-isotope analyses based on the nature of source lithologies and catchment of the particular river, and on the composition of heavy mineral assemblages (Sevastjanova, 2007) with the aim of covering all potential source areas. Source lithologies were characterised based on the published literature, SRTM-derived digital elevation models (DEM), and geological and river maps (Gobbett and Hutchison, 1973; Hutchison and Tan, 2009 and references therein; Senathi Rajah et al., 1976) that were digitised using GIS software. Sample details are summarised in Table 1. Permian–Triassic zircons in samples IS37 and IS40 characterise detritus eroded from the Eastern Province granitoids. Samples IS14, IS18, IS19, IS31, and IS41 characterise various sedimentary, igneous and metamorphic source rocks common in the Central Zone, while samples IS2 and IS26 that
were collected from the first-order streams draining granitoids in the Western Zone are representative of the Main Range Province detritus.

4. Analytical techniques

4.1. Sample preparation

Heavy minerals were separated from the 63 to 250 μm grain-size fraction following a standard procedure described by Mange and Maurer (1992). The heavy mineral fraction was separated using sodium polytungstate (SPT) solution (density 2.89 g/cm³) and run through a Franz Magnetic separator at 20° tilt angle, and 0.1, 0.4, and 1.7 μA voltages. Non-magnetic fractions (>1.7 μA) were separated in diiodomethane (DIM) with a density 3.3 g/cm³. Zircons were hand-picked from the residual DIM heavy fraction, mounted in araldite resin on labelled glass slides or resin discs, and polished. Samples IS2, IS18, IS37, IS40 and IS41 were imaged with CL-SEM prior to Hf-isotope analyses.
Table 1

<table>
<thead>
<tr>
<th>Geological zone</th>
<th>Sample</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Drainage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern</td>
<td>IS40</td>
<td>102.49112</td>
<td>5.73761</td>
<td>Eastern Province granitoids, Carboniferous schists and phyllites and recent coastal sediments</td>
</tr>
<tr>
<td></td>
<td>IS37</td>
<td>103.43609</td>
<td>4.64011</td>
<td>Eastern Province granitoids, Carboniferous schists and phyllites, recent coastal sediments and minor Mesoarctic clastic rocks.</td>
</tr>
<tr>
<td>Central</td>
<td>IS41</td>
<td>101.69095</td>
<td>5.66084</td>
<td>The Cretaceous Stong Migmatic Complex</td>
</tr>
<tr>
<td></td>
<td>IS14</td>
<td>102.11230</td>
<td>5.53565</td>
<td>Eastern Province granitoids, the Stong Migmatic Complex, Mesoarctic and Permian clastic and volcanoclastic rocks, minor basic volcanics and limestones</td>
</tr>
<tr>
<td></td>
<td>IS19</td>
<td>102.01583</td>
<td>4.09164</td>
<td>Mesoarctic and Permian clastic and volcanoclastic rocks, Eastern (the Central Belt), and Main Range Province granitoids, and Permian limestones</td>
</tr>
<tr>
<td></td>
<td>IS18</td>
<td>102.19065</td>
<td>4.04281</td>
<td>Mesoarctic and Permian clastic and volcanoclastic rocks, minor basic volcanics, Eastern (including the Central Belt), and Main Range Province granitoids, and Permian limestones</td>
</tr>
<tr>
<td>Western</td>
<td>IS31</td>
<td>102.68436</td>
<td>3.55614</td>
<td>Jurassic-Cretaceous fluvial-alluvial rocks (the Tembeling Gp)</td>
</tr>
<tr>
<td></td>
<td>IS2</td>
<td>101.34138</td>
<td>4.42584</td>
<td>Main Range Province granitoids</td>
</tr>
<tr>
<td></td>
<td>IS26</td>
<td>101.89650</td>
<td>3.44557</td>
<td>Main Range Province granitoids</td>
</tr>
</tbody>
</table>

4.2. LA-ICP-MS U–Pb dating

U–Pb dating was performed at University College London using a New Wave 213 aperture-imaged frequency-quintupled laser ablation system (213 nm) coupled to an Agilent 7500 quadrupole-based ICP-MS. Grains typically were ablated with 55 μm laser spot and a 30 μm laser spot was used for finer-grained samples. Background was measured for 30 s, followed by 30 s of data collection, and a 30 s purge cycle after each run. Real-time data were processed using the GLITTER® software package (Griffin et al., 2002). Real-time data were processed using the GLITTER® software package (Griffin et al., 2002). PLESOVIC zircon (TIMS reference age 337.13 ± 0.37 Ma; (Sláma et al., 2008)) and NIST SRM 612 silicate glass (Pearce et al., 1997) were used as external standards for correcting mass fractionation and instrumental bias. At least 60 grains were analysed in each sample. 204Pb could not be measured for common lead correction because of interference from 204Hg in the carrier gas. The correction of Andersen (2002), which assumes that measured 206Pb/238U, 207Pb/235U and 208Pb/232Th ratios are discordant due to a combination of common lead contamination and lead loss at defined time, was used instead. A 10% cutoff was adopted to reject discordant data. 238U/206Pb ages are used for zircons <1000 Ma and the 207Pb/206Pb ages were used for older zircons.

4.3. Hf-isotope analyses

Hf-isotope analyses were performed at GEMOC ARC National Key Centre at Macquarie University, Australia. 176Hf/177Hf ratios in zircons were measured with a New Wave Research 213 nm laser-ablation microprobe attached to a Nu Plasma multicollector ICPMS. The analytical procedure is described in detail by Griffin et al. (2000, 2006a). Time-resolved analyses were processed using Nu Plasma software. Analyses were carried out at 5 Hz frequency with a beam diameter of 55 μm and energies around 0.1 mJ per pulse. Background was measured for 60 s. The length of the analysis varied between 30 s and 140 s depending on the thickness of the grains.

Repeated analyses of Mud Tank (long-term running average 176Hf/177Hf value 0.282523 ± 0.000321, (Griffin et al., 2006b)) and 91,500 (5-year running average 176Hf/177Hf value 0.282307 ± 0.0027, (Griffin et al., 2006b)) zircon standards were used to monitor data quality (Table 2).

The 176Lu decay constant (1.865 × 10⁻¹¹) calculated by Scherer et al. (2001) from terrestrial samples, the chondritic values of 176Hf/177Hf = 0.0332 and 176Lu/177Hf = 0.282772 (Blichert-Toft and Albarède, 1997), and zircon ages determined by U–Pb dating techniques were used for further calculations.

Epsilon Hf (εHf) describes the deviation of the initial 176Hf/177Hf ratio from the evolution line defined by chondritic meteorites (CHUR) (Faure and Mensing, 2004). In the granitoid magmas high 176Hf/177Hf (εHf ≫ 0) indicates mantle-derived input and low 176Hf/177Hf (εHf ≪ 0) suggests crustal reworking (Belousova et al., 2006). Hf model ages (TDM) represent a minimum age for the source material of the zircon parental magma. Crustal model ages (TDM) assume that zircon parental magma was produced from an average continental crust (176Lu/177Hf = 0.015), that originally was derived from the depleted mantle (Belousova et al., 2006), and provides a more realistic estimate of its source age.

5. Results

5.1. U–Pb dating

752 U–Pb zircon ages were collected from nine modern river-sand samples from the Malay Peninsula. Results are illustrated in Figs. 3 and 4. Sample locations were chosen with the aim of covering zircon age variations in all three geological zones.

5.1.1. The Eastern Zone

Two samples (IS37 and IS40) were analysed from the Eastern Zone. There are two major Phanerozoic zircon populations: Late Permian–Late Triassic (199 to 260 Ma) and Early-Middle Permian (266 to 296 Ma). A Late Permian–Late Triassic population is present in both samples. An Early-Middle Permian population is prominent only in sample IS37, collected from the southern part of the zone.

5.1.2. The Central Zone

Five samples, IS14, IS18, IS19, IS31, and IS41, were analysed from the Central Zone. There are five Phanerozoic zircon populations in the Central Zone samples: Late Cretaceous (70 to 84 Ma), Jurassic (162 to
190 Ma), Late Permian–Late Triassic (224 to 258 Ma), Early-Middle Permian (267 to 299 Ma), and Ordovician–Silurian (423 to 458 Ma). A Late Cretaceous population is prominent in samples IS14 and IS41, collected from rivers draining the Stong Migmatite Complex. Jurassic grains form a small population in sample IS31, collected from a river draining Mesozoic alluvial sedimentary rocks. A significant Late Permian–Late Triassic population is present in all samples. An Early-Middle Permian population is present only in sample IS18 collected from the southern part of this zone. A minor Ordovician–Silurian population is found only in sample IS31.

5.1.3. The Western Zone
Two samples (IS2 and IS26) were analysed from the Western Zone. Two major Phanerozoic zircon populations can be identified: Late Triassic (221 to 228 Ma) and Middle Permian–Middle Triassic (229 to 270 Ma). The Late Triassic population is dominant in both samples IS14 and IS41. A Middle Permian–Middle Triassic population is prominent only in sample IS26, which was collected in the southern part of this zone. Devonian–Carboniferous grains are present in all zones, but do not form major populations (Fig. 4). Small numbers of Late Archaean–Late Proterozoic grains are consistently present in all samples analysed. Sample IS31 contains minor latest Neoproterozoic (598 to 646 Ma), Meso-Neoproterozoic (793 to 1171 Ma), late Palaeoproterozoic (1732 to 1888 Ma) and Neoarchaean–early Palaeoproterozoic populations (2196 to 2722 Ma). There is one Eoarchaean (3750 ± 56 Ma) zircon in sample IS37.

5.2. Hf-isotope composition
During this study 243 of the dated zircon grains were analysed for Hf-isotope composition. Results are summarised in Figs. 6 and 7.

5.2.1. The Eastern Zone
Samples IS37 and IS40 were analysed from the Eastern Zone. Late Permian–Late Triassic grains yield $^{176}\text{Hf}/^{177}\text{Hf}$ values that are higher than those in zircons of similar age from the Western Zone. $^{176}\text{Hf}/^{177}\text{Hf}$ values of these grains plot both above and below CHUR ($\epsilon_{\text{Hf}}$ range from $-4$ to $+8$) (Figs. 6 and 7). This suggests a mixed crustal and mantle-derived source. Low $^{176}\text{Hf}/^{177}\text{Hf}$ values of Early-Middle Permian zircon grains suggest a crustally-derived source and those of Precambrian plot both above and below CHUR.

5.2.2. The Central Zone
Samples IS18, IS31, and IS41 were analysed from the Central Zone. Late Cretaceous grains yield low $^{176}\text{Hf}/^{177}\text{Hf}$ values that plot below CHUR (Figs. 6 and 7). This suggests a crustal source and is consistent with the detrital zircon U–Pb age data.
with a provenance from granitoids within the Strong Migmatite Complex. $^{176}\text{Hf}/^{177}\text{Hf}$ values for Jurassic grains suggest a mixed source. $^{176}\text{Hf}/^{177}\text{Hf}$ values for Triassic and Permian grains have $^{176}\text{Hf}/^{177}\text{Hf}$ values that plot both above and below CHUR and are comparable to zircons of similar age from the Eastern Zone. Early Palaeozoic grains yield predominantly low $^{176}\text{Hf}/^{177}\text{Hf}$ values that suggest crustally-derived source rocks, while $^{176}\text{Hf}/^{177}\text{Hf}$ values of Precambrian zircons plot both above and below CHUR.

5.2.3. The Western Zone

Sample IS2 was analysed from the Western Zone. Late Triassic grains in this sample yield $^{176}\text{Hf}/^{177}\text{Hf}$ ratios lower than CHUR ($\varepsilon\text{Hf}<0$). This suggests a crustal source for the parental granitoids of these zircons. The high $^{176}\text{Hf}/^{177}\text{Hf}$ values of Mesoproterozoic grains suggest minor ‘juvenile’ crust production around 1.1–1.2 Ga and 1.6 Ga. The low $^{176}\text{Hf}/^{177}\text{Hf}$ values of Palaeoproterozoic grains suggest a crust-derived source for these grains.
6. Discussion

6.1. Late Palaeozoic–Early Mesozoic granitic magmatism in the Malay Peninsula

Morphology, oscillatory growth-zoning, and ages of Permian and Triassic zircons in the river sediments indicate that they were derived predominantly from local granitoids. Therefore, U–Pb ages for these zircons constrain the timing of magmatism throughout the Malay Peninsula. Detrital zircon is resistant to tropical weathering and therefore we suggest that these ages are more robust than the previous K–Ar and Rb–Sr ages (e.g. Ahmad and Yap, 1976; Bignell and Snelling, 1977; Cobbing et al., 1992; Gobbett, 1973; Krähenbuhl, 1991; Schwartz et al., 1995; Seong, 1990; Yap, 1986) reported for the Malay Peninsula granitoids. K–Ar ages need to be treated with caution in tropical settings (e.g. Macpherson and Hall, 2002) such as those that prevailed in the Malay Peninsula through the Mesozoic and Cenozoic (e.g. Morley, 1998). Rb–Sr ages can also be problematical as these isochrones date hydration events that are often difficult to interpret.

A summary of previously published data (Fig. 8A) suggests that granitoids of the Malay Peninsula range in age from 65 ± 2 Ma to 406 ± 12 Ma, and that Permian and Triassic granitoids are most abundant. Most published datasets indicate that the Main Range Province granitoids are 200–230 Ma old (Fig. 8G). However, some ages are Jurassic and some are as young as Cretaceous. There are a few Main Range granitoids that are older than 230 Ma in the Langkawi Islands (242 Ma (Krähenbuhl, 1991)) and in Melaka (253–305 Ma (Gobbett, 1973; Krähenbuhl, 1991)).

U–Pb zircon data presented in this study reveal two distinct episodes of magmatism (Fig. 8D and F) in the Eastern Province during the Permian and Triassic. This bimodal age distribution has not been identified in previous studies. Zircons sourced from the Main Range Province granitoids are predominantly Late Triassic (Fig. 8H). One sample in the Western Zone (IS26) contains a small number of Late Permian–Middle Triassic grains (Fig. 4), although it is not clear whether these grains were sourced from Main Range Province granitoids or from granitic clasts in the Bentong–Raub Suture Zone. Our new data do not support the hypothesis that Jurassic granitoids are present in the Malay Peninsula (Fig. 8B). Although samples IS31 and IS14 from the Central Zone (Fig. 4) have a small number of Jurassic grains (n = 5 and 2 respectively) and there is one Jurassic core in sample IS41, we suggest these grains were most likely reworked from Upper Jurassic alluvial–fluvial ‘redbeds’ that are exposed over...
large areas of Central and SE Laos, Cambodia, NE Thailand, and the Malay Peninsula (Harbury et al., 1990; Racey, 2009). Provenance studies of these ‘redbeds’ in Thailand, referred to as the Khorat Group and lateral equivalents (e.g. Carter and Bristow, 2003; Racey, 2009), suggest that they were sourced from the Qinling Orogenic Belt immediately to the north and deposited in a foreland basin setting. A northerly provenance is supported by palaeocurrent data from the Malay Peninsula (Harbury et al., 1990). Five U–Pb zircon age populations are recognised from the Khorat Group in Thailand (Carter and Bristow, 2003; Carter and Moss, 1999): Jurassic (161 to 170 Ma), Permian–Triassic (242 to 261), Ordovician–Silurian (433 to 467 Ma), late Palaeoproterozoic (1799 to 1839 Ma), and early Palaeoproterozoic (2450 to 2500 Ma). Presence of Jurassic zircons in the Khorat Group supports our interpretation that its equivalents are the most likely sources for the Jurassic zircons in river sands from the Malay Peninsula. There is therefore no firm evidence for major magmatism in the area between the Late Triassic and Cretaceous.

6.2. Magma sources for Permian–Triassic granitoids in the Malay Peninsula

Compositions of magma sources are governed by the tectonic processes by which they are produced and therefore may be matched to individual geodynamic settings. Granitoids can be produced in a range of settings that include mid-ocean ridges, intraplate settings (oceanic islands, continental rifts and hotspots), subduction zones (continental margin arcs, and island arcs), and continent–continent collision zones. Mantle-derived sources are commonly associated with mid-ocean ridges, oceanic island arcs, and hotspot settings, whereas crustal reworking is the primary source for magma generation in continental collision zones. Sources for subduction-related magmas may be complex, since many processes such as partial melting of subducted sediments and oceanic lithosphere, melting of the mantle wedge, mantle flow, magma mixing, and crustal contamination can all contribute to subduction-related melts. Most
subduction-related magmas are produced by a combination of several of these processes (e.g. Condie, 1989; Pearce and Peate, 1995). Some authors have emphasised that newly generated crust has a different preservation potential in different tectonic settings. For instance, Hawkesworth et al. (2010) suggested in subduction zones the volume of the continental crust that can be recycled back into the mantle may be comparable with the volume of crust that is generated in these settings.

Permian–Triassic granitoids of the Malay Peninsula are commonly interpreted as subduction-related and syn-to post-collisional (e.g. Metcalfe, 2000). Hf-isotope data obtained for Permian and Triassic zircons allow the recognition of three major magmatic suites: (a) Permian crustally-derived granitoids, (b) Early-Middle Triassic granitoids with a mixed mantle–crust source, and (c) Late Triassic crustally-derived granitoids. This suggests three major Permian–Triassic episodes of magmatism in the Malay Peninsula. Two of these episodes (a and b) occurred in the Eastern Province.

Evolved Hf-isotope compositions (εHf values vary from −8 to −13) of Triassic zircons from the Sibumasu Block (Western Zone of the Malay Peninsula) indicate a reworked crustal source and a syn- to post-collisional setting for their parental granitoids. The older crystallisation ages of Permian–Triassic zircons from the East Malaya Block (Western and Central Zones of the Malay Peninsula) support a subduction-related setting for their parental granitoids. Abundant crustally-derived granitoids are unusual in a subduction-related setting and their presence may indicate derivation from old continental basement beneath the East Malaya Block.

6.3. Different tectonic models

There are several tectonic models for the Permian and Triassic evolution of the Thai–Malay Peninsula. Most of these models acknowledge that tin belt granitoids were produced during the closure of Palaeo-Tethys and the resulting collision between Sibumasu and East Malaya–Indochina (e.g. Barber and Crow, 2009; Hutchison, 1977; Metcalfe, 2000, 2009). However, the exact timing of this collision remains contentious, and is the focus of this section. Three main ages have been suggested for the Sibumasu–East Malaya collision: 1) Late Triassic–Jurassic (Hirsch et al., 2006; Kamata et al., 2002; Sashida et al., 1995), 2) Middle-Late Triassic (Sone and Metcalfe, 2008), and 3) Late Permian–Early Triassic (Barber and Crow, 2009; Metcalfe, 2009) (Table 3).

6.3.1. Late Triassic–Jurassic collision

Proposals for a Late Triassic–Jurassic collision between Sibumasu and East Malaya are based on radiolarian biostratigraphy from cherts in the Semanggol Formation of northwestern Malay Peninsula and its equivalents in Thailand. Hirsch et al. (2006) suggest that the Sibumasu–East Malaya collision occurred in the latest Triassic–Early Jurassic, Kamata et al. (2002) argued for the collision after the Early Carnian (early Late Triassic), and Sashida et al. (1995) suggest collision occurred after the Middle Triassic. These studies base the timing of collision on the assumption that radiolaria from cherts represent pelagic open-ocean sedimentation and therefore must be older than collision. Metcalfe (2000) however suggests that Triassic Semanggol Formation cherts were deposited in a foredeep basin and therefore do not represent true Palaeo-Tethyan oceanic deposits. Furthermore, Metcalfe (2000) draws attention to a major structural discontinuity between Palaeozoic and Mesozoic rocks in the Peninsula as evidence for collision at this time and Metcalfe (2003) provides additional conodont colour and textural alteration data that support collision at the end Permian. Barber and Crow (2009) also point out that in many occurrences the studied radiolarian cherts were deposited in intracratonic basins on the Sibumasu continental crust and not on Palaeo-Tethyan oceanic crust. Therefore, the timing of collision between Sibumasu and East Malaya–Indochina, and the
destruction of Palaeo-Tethys, cannot be determined by these radiolarian ages. Furthermore, collision in the Late Triassic is not supported by other lines of evidence. Our new detrital zircon U–Pb ages presented here indicate unequivocally that collision occurred prior to the Late Triassic.

6.3.2. Middle-Late Triassic collision

Sone and Metcalfe (2008) interpret the Eastern Province granitoids as remnants of the Sukhothai Arc (including the Linchang, Sukhothai, and Chanthaburi Blocks). According to Sone and Metcalfe (2008) this arc developed on an elongate fragment of continental crust in the Permian that collided with Indochina (East Malaya) by the Early Triassic – a model that places the major continent–continent collision (Sibumasu–East Malaya) later than initial collision and prior to the Middle Triassic–early Late Triassic. It is likely that the Eastern Province granitoids represent the southerly continuation of the Sukhothai Arc into the Malay Peninsula and Sumatra. However, this proposed continuation of the Sukhothai Arc (Chanthaburi Block) southward into the Malay Peninsula (Metcalfe, 2009) requires the presence of a second suture zone (between the Sukhothai Arc and East Malaya Block) east of the Bentong–Raub suture zone. This inference is supported by a zone of sheared diamicrite along the eastern margin of the Central Belt of the Malay Peninsula (referred to as the Lebir Fault Zone), that is interpreted by Metcalfe and Chakraborty (1988) as either olistostromes that formed along the fault scarps of a developing graben or as a suture zone mélangé. Although there are no reports of ophiolitic-type rocks or radiolarian cherts within the sheared diamicrites of the Lebir Fault Zone, we prefer to interpret these mélanges as tectonic in origin, and representative of a major suture. This interpretation fits very well with observations further north, where the Chanthaburi and Sukhothai Blocks are separated from Indochina by the Sra Kaeo and Nan Sutures respectively. These sutures both contain ophiolitic rocks, melange and radiolarian cherts of Permian age and are interpreted as a remnant back-arc basin by Sone and Metcalfe (2008).

Our new detrital zircon data do not contradict the model that assumes Permian–Triassic collision of East Malaya with the Sukhothai Arc was followed by Sibumasu–East Malaya collision (the major continent–continent collision) in the Middle–Late Triassic. A Late Permian–Early Triassic gap in magmatism and a subsequent change of zircon Hf-isotope compositions could be explained by the collision between the Sukhothai Arc and East Malaya. The predominantly Late Triassic ages of zircons sourced from the Main Range Province and their crustally-derived Hf-isotope signatures are consistent with the Middle Triassic–early Late Triassic major continent–continent collision. However, this timing is not supported by structural evidence (Barber and Crow, 2009).

6.3.3. Late Permian–Early Triassic collision

Several authors (Barber and Crow, 2009; Harbury et al., 1990; Metcalfe, 2009) support Late Permian–Early Triassic collision between the Sibumasu and East Malaya Blocks. These arguments are based mainly on the different structural deformation styles of Late Palaeozoic and Triassic rocks in the Malay Peninsula and Sumatra (Barber and Crow, 2009; Harbury et al., 1990). Late Palaeozoic, and especially Carboniferous rocks show multiphase folding and regional metamorphism (Harbury et al., 1990). Permian rocks show intensive internal deformation, whereas Triassic rocks are only tilted and gently folded (Barber and Crow, 2009). In Sumatra end-Permian collision is supported by the absence of uppermost Permian and lowermost Triassic fossils (representing an unconformity) within a sequence of Permian–Triassic limestones (Barber and Crow, 2009).

In the new interpretation for Thailand (Sone and Metcalfe, 2008), this tectonic event corresponds to the collision of the Sukhothai Arc...
with the East Malaya Block and not collision between Sibumasu and East Malaya. An alternative interpretation is that Sibumasu–East Malaya collision occurred in the Late Permian–Early Triassic, shortly after, or contemporaneously with, the collision of East Malaya and the Sukhothai Arc. The Lebir Fault Zone therefore marks the boundary between the Sukhothai Arc and East Malaya (and represents a remnant oceanic basin – as suggested by Sone and Metcalfe (2008) further north), whereas the Bentong–Raub suture zone separates Sibumasu from the Sukhothai Arc and East Malaya and represents the main Palaeo-Tethys Suture. Two issues require explanation for this model to be valid: (a) the tectonic setting of the Eastern Province granitoids and (b) the time lag between Sibumasu–East Malaya collision (Late Permian–Early Triassic, ~250–254 Ma) and the major phase of post-collisional magmatism in the Main Range Province (200–230 Ma). In this model, collision between the Sukhothai Arc and East Malaya was shortly followed by Sibumasu collision and the Permian Eastern Province granitoids are interpreted as subduction-related despite their crustal \(^{176}\text{Hf}/^{177}\text{Hf}\) values that are unusual for Permian Eastern Province granitoids are interpreted as subduction-related despite their crustal \(^{176}\text{Hf}/^{177}\text{Hf}\) values. We therefore prefer to interpret the Sukhothai Arc as intra-oceanic and not the result of slab rollback and back-arc basin formation processes. The arc developed on a sliver of continental crust that was then accreted to the Indochina margin at the end Permian. Sone and Metcalfe (2008) point out that Permian marine faunas associated with this continental sliver are of warm water Tethyan type and support the interpretation of a back arc origin. These observations however, do not require the Sukhothai Arc to have been attached to the East Malaya Block before the Permian, although these warm water Tethyan marine faunas do suggest a Cathaysian affinity. Therefore, this evidence cannot be used to argue for the back-arc tectonic history of the Sukhothai Arc and does not contradict our interpretation.

The Triassic Eastern Province granitoids may be post-collisional, despite their mixed ‘crustal’ and ‘juvenile mantle’ \(^{176}\text{Hf}/^{177}\text{Hf}\) values. Using the example of the Woyla Arc collision, Barber (2000) has shown that in the case of oblique subduction granitic rocks can be intruded into an active shear zone that developed as the result of collision. Examples of foliated granitoids intruded into the (Inthanon) suture zone in northern Thailand (Baum et al. (1970) support such arguments. We suggest that it is likely that the Triassic Eastern Province granitoids were emplaced along the Lebir Fault Zone in a similar fashion to that described by Barber (2000); these granites were sourced from the upper mantle and crustal melts.

Metcalfe (2000) states that the age of melting of the Sibumasu continent probably occurred tens of millions of years prior to the Main Range Province granitoid emplacement. Such a time lag between the collision and post-collisional magmatism is not unlikely. Some studies (e.g. England and Thompson, 1984; Thompson and England, 1984) suggest that it may take several tens of millions of years to generate melts in a thickened crust. Syn-collisional plutons are expected, but may not be abundant. This is consistent with the presence of rare Late Permian–Middle Triassic Main Range Province granitoids in Melaka (Krähenbuhl, 1991), the Langkawi Islands, and Bangka (Barber and Crow, 2009).

6.3.4. Collision timing supported in this study

Our data do not contradict the interpretation that the Sukhothai Arc collided with East Malaya at the end of the Permian and was then followed by the main collision between Sibumasu and the newly accreted Sukhothai Arc and East Malaya in the Middle to Late Triassic (e.g. Sone and Metcalfe, 2008). However, other lines of evidence (e.g. gently deformed Triassic deposits overlying intensely deformed Palaeozoic rocks (Barber and Crow, 2009; Harbury et al., 1990) and missing latest Permian to earliest Triassic fauna from within Permo-Triassic limestones (Barber and Crow, 2009) – discussed above) support major collision at the end of the Permian/earliest Triassic. We favour this interpretation and suggest that Sibumasu was accreted to the Indochina margin at the end Permian and that this collision was broadly contemporaneous with the collision between the Sukhothai Arc and East Malaya (Fig. 9).

6.4. Ages of Sundaland basement

The parental magmas of many granitoids are produced from mixed sources or incorporate a significant proportion of inherited material. Crustal model ages calculated for zircons produced from a mixed source give only an average age of the source material and should not be treated as crustal-formation ages (Arndt and Goldstein, 1987; Kemp et al., 2006). However, when crustal model ages are supported by other lines of evidence, such as U–Pb zircon ages, they can be used as an indicator of the true age of the basement rocks.

6.4.1. The Eastern Zone

Late Permian-Late Triassic zircons from the Eastern Zone have both positive and negative \(\varepsilon^{187}\text{Hf}\) values and a spread of crustal model ages from 0.72 to 1.55 Ga. The spread in \(\varepsilon^{187}\text{Hf}\) and age discrepancies between crustal model ages and U–Pb ages suggest a mixed source. Therefore, the crustal model ages of these grains may not provide a meaningful estimate of the basement ages.

\(T_{\text{DM}}\) of Early-Middle Permian zircon grains indicate that their parent granitoids were produced from a 1.97 Ga old source. Six U–Pb ages between 1.7 and 2.1 Ga confirm a Palaeoproterozoic age for the basement. \(T_{\text{DM}}\) suggest a 2.17 Ga source for Devonian–Carboniferous zircons, but the U–Pb ages do not support a 2.17 Ga age for the basement. These grains are not abundant and may have been sampled from Palaeozoic sediments overlying the basement. \(T_{\text{DM}}\) of Palaeoproterozoic grains around 2.73 Ga and one 2.5 Ga U–Pb for a zircon core may indicate a minor Neoarchaean basement contribution.

6.4.2. The Central Zone

River sediments in the Central Zone of the Malay Peninsula contain zircons from local granitoids and Mesozoic siliciclastic rocks, and some of these zircon grains are likely to be sourced from outside the Malay Peninsula. \(T_{\text{DM}}\) from Permian–Triassic zircons are similar to those of the Eastern Zone and are likely to have been produced from the same mixed source. \(T_{\text{DM}}\) of Early Palaeozoic detrital zircons indicate the presence of Mesoproterozoic (1.88 Ga) crust beneath the East Malaya Block. This is supported by nine U–Pb zircon ages ranging from 1.7 to 1.9 Ga.

Several small Mesozoic detrital zircon populations (Fig. 7) suggest numerous minor episodes of magmatism. Some of these zircon grains are rounded with frosted surfaces (Fig. 5) and therefore are likely to have been recycled from Mesozoic and Palaeozoic sedimentary rocks. The majority of these grains have \(T_{\text{DM}}\) around 2.5 Ga (Fig. 6), similar to \(T_{\text{DM}}\) in the Eastern Zone. This may indicate the contribution of Neoarchaean basement in the East Malaya–Indochina Block. Nine U–Pb zircon ages that range from 2.3 to 2.7 Ga support this suggestion.
Late Cretaceous zircons present in the river sediments are most likely derived from the Stong Migmatite Complex. The origin of the Jurassic zircons in river sands is less clear and we interpret these to be recycled from the Mesozoic fluvial–alluvial ‘red-beds’. Palaeocurrent data suggest that these ‘red-beds’ are derived from the north–north-east (Harbury et al., 1990). However, there is no firm evidence for abundant acid igneous rocks of Jurassic age in this region that could have been a primary source for Jurassic zircons in the sedimentary rocks. Although Jurassic granitoids are common in Sumatra (Cobbing, 2005; McCourt et al., 1996), there is no other evidence to support provenance of the Mesozoic ‘red-beds’ from this region. The most likely primary source rocks for the Jurassic zircons in the Mesozoic fluvial–alluvial sedimentary rocks and, hence in river sands recycled from them, are minor rhyolites that are locally interbedded with these ‘red-beds’ (e.g. Hutchison, 1989; Racey, 2009). Nevertheless, because of the lack of isotopic dating of these rhyolites firm conclusions cannot be drawn at present.

6.4.3. The Western Zone

$T_{DM}$ and $\varepsilon_{Hf} < 0$ in Triassic detrital zircons from the Western Zone suggest that the Main Range Province granitoids (the source rocks of these grains) were produced by remelting 1.9–2.0 Ga old crust. This is supported by the presence of Palaeoproterozoic cores in younger euhedral/subhedral zircons (Figs. 5 and 6). Triassic zircons have a spread of $\varepsilon_{Hf}$ values that can be produced either by the introduction of ‘juvenile’ material into the melt (e.g. Belousova et al., 2006) or by melting of inhomogeneous basement (e.g. Howard et al., 2009). However, there is no evidence of juvenile component in this zone and the presence of the old zircon cores supports the latter mechanism. $T_{DM}$ and $\varepsilon_{Hf} > 0$ in Mesoproterozoic cores suggest a minor mantle-
derived input at around 1.1–1.2 and 1.6 Ga (Fig. 7). However, there are few zircons of these ages in the samples analysed, which may indicate that Mesoproterozoic granitoids are not abundant. \( T_{DM} \) of three Palaeoproterozoic grains between 2.64 and 2.97 Ga suggest a minor contribution from Neoarchaean basement beneath the Sibumasu Block. This is supported by the observation of two zircon cores with ages of 2.5 and 2.8 Ga.

6.4. Summary

U–Pb and Hf-isotope data presented in this study support previous interpretations that NW Sundaland lies on chronologically heterogeneous basement (Fig. 10). The basement of the Sibumasu Block is mostly Palaeoproterozoic, around 1.9–2.0 Ga old. There are also probably minor Mesoproterozoic (1.6 Ga) and Neoarchaean (2.8 Ga) crustal components. The basement of the East Malaya Block is also Palaeoproterozoic, around 1.7–2.0 Ga, but younger than that of the Sibumasu Block. Late Archaean to Early Proterozoic crustal components, ranging from 2.3 to 2.7 Ga, are also present in the East Malaya Block.

Data presented in this study are broadly consistent with the three Palaeoproterozoic crust-formation episodes identified in mainland SE Asia by Bodet and Schärer (2000), taking place at 2.5 Ga, 2.2–2.3 Ga and 1.9–2.0 Ga. A number of Mesoproterozoic–Early Palaeozoic episodes of granitoid production can also be recognised in detrital zircon populations from the Sibumasu and East Malaya Blocks. Some of these zircons show rounded morphologies and frosted surfaces and are therefore best interpreted as recycled from sedimentary rocks. These grains may therefore represent magmatic episodes outside the area of Sibumasu and East Malaya.

The lack of Mesoarchaean and Palaeoarchaean grains is a striking feature of both blocks. Ten Precambrian grains have \( T_{DM} \) between 3.21 and 4.18 Ga, but there is only one 3.34 Ga detrital zircon core in the Malay Peninsula samples. These grains are most likely recycled from areas outside the SE Asian region.

6.5. Detrital zircon as an indicator of the tin belt provenance

Sundaland has been emergent or submerged to very shallow water depths since the Early Mesozoic (Hall, 2009a). Throughout this period local landmasses have shed large volumes of detrital material to nearby areas. Different Phanerozoic histories of the Sundaland basement fragments have generated provenance-diagnostic detritus, specific to particular source provinces.

Previous provenance studies in Sundaland (Clements, 2008; van Hattum, 2005; van Hattum et al., 2006) have shown that the tin belt granitoids, including the Malay Peninsula, were an important source of siliciclastic detritus in the region. Despite this, almost no studies have attempted to characterise material derived from this significant SE Asian source area. The purpose of this section is therefore to identify detrital zircon signatures characteristic to different source provinces in the Malay Peninsula.

It is difficult to distinguish between the Main Range and Eastern Province based on U–Pb dating alone, as there is an overlap in the zircon ages. However, distinctively different \( 176^{\text{Hf}}/177^{\text{Pb}} \) values of Triassic zircons derived from the Eastern and Main Range Provinces can be used to refine provenance interpretations based on U–Pb methods. Negative \( \epsilon_{\text{Hf}} \) values are typically zircons of crustally-derived Triassic Main Range Province granitoids, whereas Late Permian–Late Triassic zircons sourced from the mixed crust- and mantle-derived Eastern Province granitoids have \( \epsilon_{\text{Hf}} \) around –4.5 and +9.2. This difference can be used as a provenance indicator.

Cretaceous granitoids are only locally common in the Malay Peninsula and their erosional products are not expected to be consistently abundant in the material derived from this area. However, if present, zircons from the Stong Migmatite Complex can be distinguished from those of other Cretaceous sources in Sundaland by their 70–85 Ma age. Most Cretaceous granitoids in Sundaland are older than 80 Ma (Hall, 2009b).

Small amounts of Precambrian zircons are expected in detritus derived from the tin belt, but their similar U–Pb and Hf-isotopic compositions do not allow more precise provenance identification. Some of the material from the Malay Peninsula is likely to be recycled from the Mesozoic and Palaeozoic siliciclastic sedimentary rocks that overlie the basement in places. Therefore, the presence of the Early Palaeozoic and Precambrian zircons is also expected in the detrital material derived from such pre-existing sediments.

We suggest that our method of assessing the provenance characteristics of the Malay Peninsula by the sampling of river sediments is arguably more robust than U–Pb and Hf investigations of the granitoids themselves, since Condie et al. (2009) point out that there may be instances when detrital rocks contain zircons from basement lithologies that have been completely removed by erosion, or are hidden beneath younger sedimentary/volcanic cover. By sampling river sands in close proximity to the granitoids we are also confident that these ages reflect a granitoid signature typical to each region rather than to a restricted sampling locality that perhaps represents only an individual magmatic event in the complex development of the pluton as a whole.

7. Conclusions

1. U–Pb detrital zircon ages reveal that magmatism in the Eastern Province of the Malay Peninsula occurred in two distinct episodes: Permian and Early-Middle Triassic. Hf-isotope data identify different magma sources for these zircon populations, suggesting a complex history for the Palaeo-Tethyan subduction of oceanic
crust and the Sibumasu–East Malaya collision and destruction of Palaeo–Tethys.

2. The data presented here do not resolve the argument as to whether the Sibumasu–East Malaya collision occurred in the Late Permian–Early Triassic or in Middle Triassic–Late Triassic time. However, detrital zircon ages do not support tectonic models that argue for collision after the Late Triassic.

3. The basement of the Malay Peninsula is chronologically heterogeneous. The basement of the Sibumasu Block is ~1.9–2.0 Ga old including some components around 2.8 Ga. The basement of the East Malaya Block is ~1.7–2.0 Ga old with some older (2.7 Ga) components. There is no firm evidence of Archaean basement older than 2.8 Ga beneath the Malay Peninsula.

4. U–Pb ages and Hf-isotope compositions in detrital zircons from the Malay Peninsula suggest that juvenile magmatic input increases eastwards. The major feature of the Western Zone is reworking of pre-existing Proterozoic crust and the lack of firm evidence for juvenile magmatism. The Central Zone has a significant contribution of both Proterozoic and Archaean crustal components with a minor juvenile contribution. The Eastern Zone has the most significant juvenile input during the Triassic magmatism, mixed with Proterozoic and Archaean crustal components.

5. U–Pb and Hf-isotope signatures of Permian, Triassic and Cretaceous zircons are useful indicators of provenance from different granitoid provinces within the SE Asian tin belt. Triassic zircons derived from the Main Range Province granitoids can be distinguished from similar-age zircons shed from the Eastern Province granitoids by their "crustal" Hf-isotope signatures.

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