Middle Jurassic collision of an exotic microcontinental fragment: Implications for magmatism across the southeast China continental margin

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ABSTRACT

Thrusting, folding and metamorphism of late Paleozoic to middle Mesozoic sedimentary rocks, together with high precision U–Pb zircon ages from Middle to Late Jurassic volcanic and granitic rocks, reveals evidence for a major deformation event in northwestern Hong Kong between 164 and 161 Ma. This episode can be linked with collision of an exotic microcontinental fragment along the southeast China continental margin determined from contrasting detrital zircon provenance histories of late Paleozoic to middle Mesozoic sedimentary rocks either side of a NE-trending suture zone through central Hong Kong. The suture zone is also reflected by isotopic heterogeneities and geophysical anomalies in the crustal basement. Detrital zircon provenance of Early to Middle Jurassic rocks from the accreted terrane have little in common with the pre-Middle Jurassic rocks from southeast China. Instead, the zircon age spectra of the accreted terrane show close affinities to sources along the northern margin of east Gondwana. These data provide indisputable evidence for Mesozoic terrane accretion along the southeast China continental margin. In addition, collision of the exotic terrane, accompanied by subduction roll-back, is considered to have hastened foundering of the postulated flat-slab beneath southeast China leading to a widespread igneous flare-up event at 160 Ma.

1. **Introduction**

A major igneous event occurred in southeast China at about 160 Ma during which an enormous volume of dominantly I-type and subordinate A-type granitoids was emplaced over an area of 75,000 km^2 within a broad 400-km wide NE-trending belt (Li et al., 2007). Although various tectonic models have been proposed to account for this activity (e.g., Gilder et al., 1991; Zhou and Li, 2000; Li and Li, 2007), there is no consensus on its causal mechanism. Much of the debate has centred on the geochemistry of the granitoids with one school of thought preferring to interpret the I-type and A-type compositions as reflecting a within plate (i.e., anorogenic) tectonic setting (e.g., Gilder et al., 1991; Li et al., 2007), while another school argues for a mature continental arc tectonic setting (Sewell et al., 1992; Zhou and Li, 2000). An expression of the ca. 160 Ma igneous event is recorded in the Hong Kong Special Administrative Region (hereafter Hong Kong) by four precisely-dated I- and A-type granite plutons (Davis et al., 1997). These rocks have previously been interpreted to reflect a late orogenic to post orogenic setting (Sewell et al., 1992). The trace element abundances of these rocks relative to MORB (Sewell & Campbell, 1997) show enrichment in K, Rb, and Th and depletion of Nb, which are characteristic of subduction-related magmas (e.g., Thorpe et al., 1984). Unlike other pulses of magmatism in Hong Kong, these relatively weakly deformed granitoids do not have a recognizable volcanic equivalent (Sewell and Campbell, 1997). Furthermore, they intrude regionally folded and metamorphosed late Paleozoic to Middle Jurassic rocks, including volcanic and plutonic rocks that have been precisely dated by TIMS U–Pb zircon analysis at ca. 164 Ma (Davis et al., 1997). Thus, the period of deformation is constrained to between 164 and 161 Ma. In this paper, through highlighting the results of a structural, stratigraphic and geochronologic study of late Paleozoic to middle Mesozoic sedimentary rocks of Hong Kong, we propose a cause for this deformation and how it may be related to the widespread igneous event in southeast China at 160 Ma.

2. Geological Setting

South China comprises two continental blocks, Yangtze in the northwest and Cathaysia in the southeast. The latter block is further separated into eastern and western structural domains along a crustal scale discontinuity known as the Zhenghe–Dapu deep fault (Fig. 1). Although the precise trace of this structure in southeast China is poorly defined, it has been frequently depicted (e.g., Wang et al., 2013a; Li et al., 2014) to intersect the coast in the vicinity of the Hong Kong. Based on mantle and crustal isotope signatures reflected in magmatic rocks, some workers (e.g., Darbyshire and Sewell, 1997; Fletcher et al., 2004; Xu et al., 2007) have postulated that this fault may represent a basement terrane boundary.

Hong Kong is divided into two broad structural and stratigraphic domains by a NE-trending tectonic lineament, generally known as the Tolo Channel Fault (TCF) (Fig. 1). The TCF is exposed on the north side of Tolo Channel where it is character-

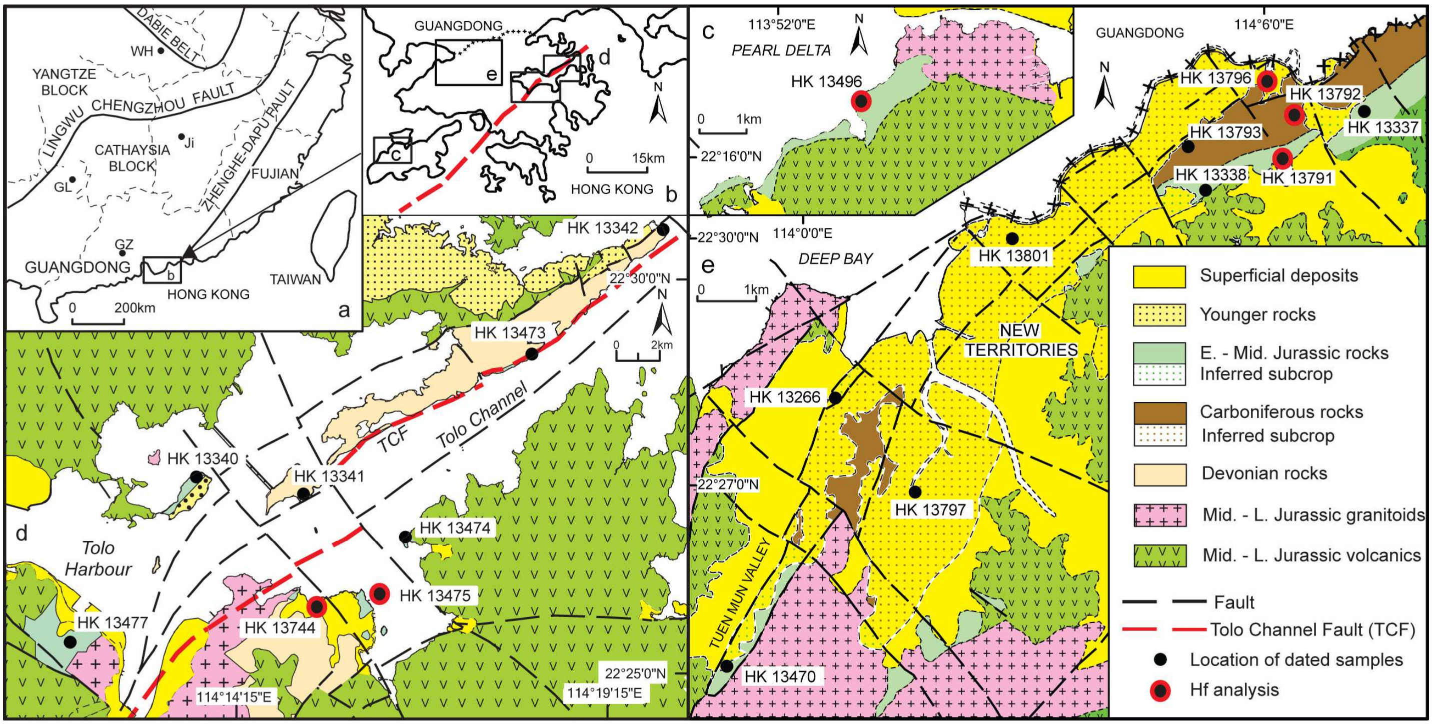

Fig. 1. Location map showing distribution of late Paleozoic and Early to Middle Jurassic sedimentary rocks on either side of the Tolo Channel Fault (TCF) in central and western Hong Kong. Inset map shows approximate trace of TCF through Hong Kong. Sample localities are also marked.

ized by a zone of sheared and silicified rock that separates strongly indurated late Paleozoic conglomerates and sandstones to the NW from Early to Middle Jurassic sandstones and shales to the SE (Sewell et al., 2000). North of the TCF, late Paleozoic to early Middle Jurassic strata and Middle Jurassic volcanic–plutonic rocks are folded and regionally metamorphosed to greenschist facies (Allen and Stephens, 1971). Early workers (e.g., Lai, 1976; Langford et al., 1989) interpreted the overall structure to be a series of SW-plunging anticlines and synclines, plunging to the SW. South of the TCF, the late Paleozoic to early Middle Jurassic sedimentary strata are gently E-dipping (ca. 15°) and generally non-metamorphosed. Devonian rocks NW of the TCF contain an Early to Middle Devonian flora and marine fauna, and show paleocurrent directions toward the northwest (Jones et al., 1997). In contrast, Devonian rocks to the south have a Late Devonian flora and show paleocurrent directions toward the southeast (Jones et al., 1997). Jurassic sandstones and shales north of the TCF have an Early to Middle Jurassic terrestrial flora and marine fauna (Lee et al., 1997), whereas Jurassic sandstones and shales south of the TCF are exclusively marine (Lee et al., 1997).

Darbyshire and Sewell (1997) identified contrasting NE-trending Nd–Sr isotope domains in granitic rocks across Hong

Table 1. Description and location details of analysed samples.

Sample No.	Lithology	Fossil Age	Location	Lat.	Long.
HK13473	Sandstone	E.- Mid. Jurassic	Fung Wong Wat	22.29 08 36799	114.18 19 30843
HK13474	Sandstone	E.- Mid. Jurassic	Sham Chung	22.26 47 15967	114.16 29 92821
HK13475	Sandstone	E.- Mid. Jurassic	Three Fathoms Cove	22.26 04 74566	114.16 12 13474
HK13791	Metasandstone	E.- Mid. Jurassic	Ho Sheung Heung	22.30 49 39570	114.06 25 27388
HK13337	Metasandstone	E.- Mid. Jurassic	Sheung Shui	22.25 10 60966	114.14 08 84744
HK13338	Metasandstone	E.- Mid. Jurassic	San Tin	22.30 34 01848	114.05 15 34916
HK13496	Sandstone	E.- Mid. Jurassic	San Shek Wan	22.16 42 42363	113.53 16 28699
HK13470	Metasiltstone	E.- Mid. Jurassic	Fu Tei	22.24 33 01810	113.58 49 25029
HK13477	Siltstone	E.- Mid. Jurassic	CUHK	22.25 25 07572	114.11 55 24798
HK13340	Sandstone	E.- Mid. Jurassic	Ma Shi Chau	22.27 36 06205	114.13 49 21608
HK13266	Metasiltstone	E.- Mid. Jurassic	Tin Shui Wai Area 104	22.27 50 05301	114.00 07 18768
HK13801	Metasandstone	Carboniferous	Tam Kon Chau	22.29 40 38525	114.03 02 77880
HK13341	Sandstone	Devonian	Harbour Island	22.27 21 62562	114.15 17 27571
HK13342	Sandstone	Devonian	Bluff Head	22.30 37 35281	114.20 01 41391
HK13792	Metasandstone	Carboniferous	Tai Shek Mo	22.31 14 07380	114.06 33 51955
HK13793	Metasandstone	Carboniferous	Chau Tau	22.30 56 34152	114.04 59 22853
HK13796	Metasiltstone	Carboniferous	Sheung Ma Lei Yue	22.31 45 82458	114.06 09 00828
HK13797	Metasiltstone	Carboniferous	Yuen Long, A11	22.27 02 84089	114.01 42 23578
HK13744	Sandstone	Devonian	Sai Sha Road	22.25 48 20779	114.15 30 20861

Kong suggesting inherent differences in the source regions. They proposed a major crustal terrane boundary separating dominantly Archean and Mesoproterozoic protoliths in the northwest from dominantly Mesoproterozoic protoliths in the southeast. The peraluminous chemistry, strongly negative εNd(t) values (<-9), and radiogenic Sr–isotope chemistry (>0.71) of granites in the northwest indicated a major component of recycled crust in the source region. By contrast, the metaluminous chemistry, more enriched εNd(t) values (-4.2 to -7.2) and slightly less radiogenic Sr–isotope chemistry (0.7061 to 0.7102) of granites in the southeast suggested the involvement of juvenile (i.e. mantle-derived) components in the source region.

A steep SE-trending gradient in Bouguer gravity anomaly values along a NE-trending alignment through central Hong Kong was reported by Busby and Langford (1995). Modeling of the regional gravity data by Fletcher et al. (1997) revealed contrasting densities in the basement consistent with a felsic Archean crust in the northwest separating denser blocks of mafic Proterozoic crust in the southeast. The gravity map of the region around Hong Kong and neighbouring Guangdong Province compiled by Fletcher et al. (2004) shows a prominent NE-trending gradient in Bouguer anomaly values extending along the coast consistent with the pattern observed in Hong Kong. The boundary between both the isotope geochemistry domains and the regional gravity gradients in Hong Kong coincides with the trace of the TCF. Thus, the isotope geochemistry of the granites and regional gravity data provide strong circumstantial evidence for a deep crustal discontinuity through Hong Kong. We therefore conducted a detailed detrital zircon U–Pb dating and Hf isotope study to determine whether these differences were also expressed in sediment sources.

3. Analytical methods

Detrital zircon U – Pb dating was carried out on 19 samples (comprising 2630 single grain ages) from both sides of the TCF, with a subset of six samples selected for Hf isotope analysis (Fig. 1). Sample descriptions and location details are given in Table 1. Hf isotope data were obtained from the main age modes present in each tested sample. Descriptions and location details of analyzed samples are given in Table 1.

3.1 Zircon LA-ICPMS U-Pb analysis

Laser Ablation Inductively Coupled Mass Spectrometry (LA – ICPMS) U – Pb zircon analysis was carried out at the University College of London. Heavy minerals were separated from bulk sediment samples using standard density liquid and magnetic separation procedures. Zircon-enriched extracts were mounted in hard epoxy resin on glass slides and polished for analysis.

Polished grain mounts were CL imaged and the samples analyzed on an Agilent 7700 quadrupole-based inductively coupled plasma mass spectrometer (ICP–MS) coupled to a New Wave aperture-imaged frequency quintupled laser ablation system (213 nm) following the methodology of Jackson et al. (2004). Real time data were processed using GLITTER 4.5, data reduction software, developed by the ARC National Key Centre for Geochemical Evolution and Metallogeny of Continents (GEMOC) at Macquarie University and CSIRO Exploration and Mining. A 30 –55 µm laser spot size was used at 7–10 Hz repetition rate with 65% power. Background measurement before ablation lasted 40 seconds and laser ablation dwell time was 40 seconds. All analysed grains were numbered on a photomap to enable revisiting for Hf analysis.

Repeated measurements of external zircon standard Plešovice which has a TIMS reference age 337.13 ± 0.37 Ma (Sláma et al., 2008) and NIST 612 silicate glass (Pearce et al., 1997) were used to correct for instrumental mass bias and depth-dependent interelement fractionation of Pb, Th and U.

3.2 Zircon Hafnium isotope analysis

Hafnium isotope analyses, carried out at the NERC Isotope Geosciences Laboratory (NIGL), used a Neptune Plus multi-collector ICP–MS coupled to a New Wave Research UP193FX 193 nm excimer laser ablation system.

Ablation data were acquired using the instrument software on the Neptune Plus but processed through an in-house calculation routine using a Microsoft Access database. A static spot ablation protocol was employed utilizing a 25µm beam and a 7 Hz laser pulse repetition rate. A fluence of 6.5 J/cm^2 and ablation time of 40 seconds resulted in total Hf signals for the Mud Tank reference zircon averaging 7V and combined uncertainties of 1.3 εHf units (2s) assuming an age uncertainty of 1 Ma (1s). All data were normalised to the ^{176}Hf/^{177}Hf of the Mud Tank zircon assuming a value of 0.282507. Zircon standard 91500 was used to normalize the ^{176}Lu/^{177}Hf ratio assuming a value of 0.000311 (Woodhead and Hergt, 2005). All uncertainty components, including those for age and normalisation, were factored into the uncertainty quoted.

Further details of data reduction and error propagation for U–Pb zircon and Hf isotope analysis are given in the supplementary data. Selected field photographs are given in Supplementary Figure 1. U–Pb zircon and Hf isotope analytical data are given in Supplementary Tables 1 and 2.

4. Results

Zircon age spectra for Early to Middle Jurassic rocks from either side of the TCF differ noticeably (Fig. 2). The maximum depositional age for rocks on the south side is 580 Ma, with strong population peaks at 790, 970 and 2490 Ma. By contrast, those from the north show a major population at 236 Ma, but with 24 grains of Early Jurassic age (Weighted Mean: 178 ± 5.6 Ma), and strong peaks at 436 Ma, 760–1200 Ma, 1860 Ma and 2500 Ma. Additionally, the rocks south of the TCF have a population of Archean age zircons ca. 3550 Ma. The tectonic setting for these rocks based on differences between zircon crystallization age and depositional age (Cawood et al., 2012) is an extensional basin or passive margin, whereas for the north side, the tectonic setting is a collisional basin.

Similar zircon spectra are observed among late Paleozoic rocks from either side of the TCF with principal age populations at 440 Ma, 760–1200 Ma, and 2500 Ma (Fig. 2), but with two important differences. The sample from south of the TCF shows a well-defined 790 Ma peak which is largely absent from samples on the north side. Additionally, the sample from the south shows a strong peak at 2470 Ma, whereas most samples from the north side show strong peaks at 2500 Ma. These differences in older age clusters for late Paleozoic rocks on either side

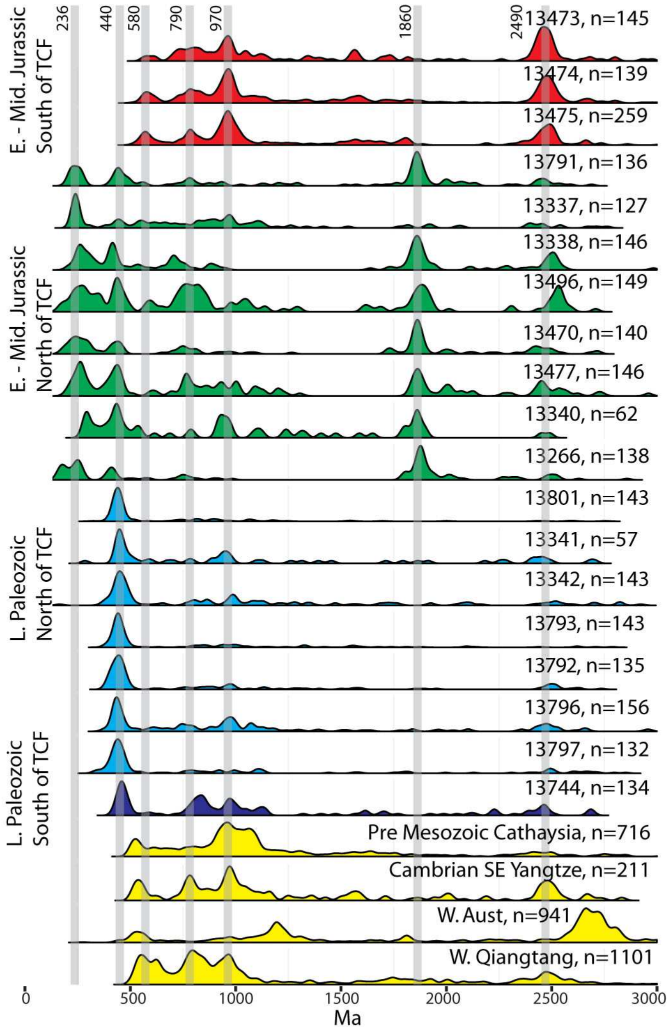

Fig. 2. Kernel density plots (Vermeesch, 2012) of detrital zircon U-Pb ages of analyzed samples compared with pre-Mesozoic rocks from Cathaysia (Yao et al., 2014; Wang et al., 2015), SE Yangtze (Wang et al., 2013b; Yao et al., 2015), West Australia (Cawood and Nemchin, 2000; Griffin et al., 2004; Veevers et al., 2005), and Western Qiangtang (Zhu et al., 2011; Dong et al., 2011; Pullen et al., 2008; Gehrels, et al., 2011). Differences among these samples are clearly seen on the Multidimensional Scaling (MDS) map (see Fig. 4).

of the TCF are similar to those shown by the Early to Middle Jurassic rocks.

Hf isotopes in zircons may be used to help characterize crustal source materials (Patchett et al., 1981; Griffin et al., 2004; Fig. 3). A negative $\varepsilon_{Nd}(t)$ value (parts per 10,000 deviation from the chondritic line at the time of zircon crystallization) suggests involvement of dominantly recycled materials in the crustal source region, whereas a positive $\varepsilon_{Nd}(t)$ value indicates a more juvenile (mantle-derived) source component.

Early to Middle Jurassic rocks north of the TCF have a large proportion of old zircons with age population peaks between 1800–1850 Ma and 2500 Ma, as well as input from granitoids of Indosinian, Wuyi–Yunkai, Rodinian and Jiangnan tectonothermal events. The source area for these rocks was mainly exposed Proterozoic basement. The youngest coherent zircon population (Fig. 2) indicates Early to Middle Jurassic sediments were sourced from exposed Triassic (ca. 236 Ma) granitoids. The strongly negative $\varepsilon_{Hf}(t)$ values (-20) for some zircons (Fig. 3a) reflect the involvement of ancient crustal sources, possibly Late Archean to Paleoproterozoic basement, and accords with the source area of Triassic S-type granite in Hong Kong (Davis et al., 1997) which is thought to have been derived from a Late Archean to Paleoproterozoic basement ($\varepsilon_{Nd}(t)$ = -13.9).

By contrast, Early to Middle Jurassic rocks south of the TCF lack input from Wuyi – Yunkai or Indosinian granitoids, and instead have input from Pan–African orogeny (600 – 550 Ma) granitoids associated with Gondwana assembly. These rocks also lack input from Paleoproterozoic (1850 Ma) basement and have a larger proportion of very old zircons, including Eoarchaean. The sources of the majority of zircons are therefore quite distinct from the rest of Cathaysia. However, an abundant population of 970 Ma zircons suggests involvement of Jiangnan metamorphic basement (Fig. 3b), while other populations show a contribution from mainly Mesoproterozoic crustal sources, along with some very ancient crustal materials.

Among the late Paleozoic rocks, the 440 Ma and 760–1200 Ma age populations show the most prominent differences either side of the TCF. For example, 440 Ma zircons from north of the TCF (Fig. 3a) show a mixture of both juvenile and recycled

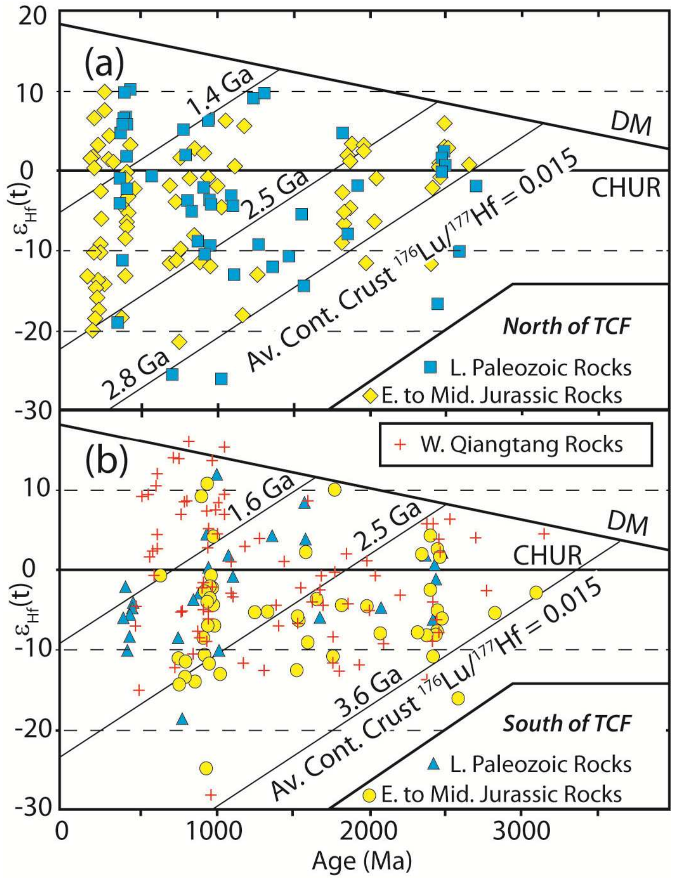

Fig. 3. $\varepsilon_{Hf}(t)$ vs. U-Pb zircon age for E. to Mid. Jurassic rocks, and late Paleozoic rocks. (a) north of the Tolo Channel Fault (TCF); (b) south of the TCF. West Qiangtang data from Dong et al. (2011). CHUR = Chondritic Uniform Reservoir. DM = Depleted Mantle.

crustal components (Fig. 3a), whereas 440 Ma zircons from south of the TCF (Fig. 3b) have a dominantly recycled crustal component.

Late Paleozoic rocks north of the TCF were derived from a terrain rich in granitoid rocks with key age populations at 440 Ma, 760–1200 Ma, and 2500 Ma. Such suites reflect tectonothermal events associated with collision of Yangtze and Cathaysia blocks at 1000–900 Ma (Jiangnan (or Sibao) Orogeny), and breakup of Rodinia at 830–750 Ma (Cawood et al., 2013). Granitoids were also emplaced across the southeast half of the South China block during a major intraplate orogenic event at ca. 460–420 Ma known as the Wuyi–Yunkai (or occasionally Kwangsian) Orogeny (Li et al., 2010).

Late Paleozoic rocks south of the TCF were derived from a terrain rich in both metasedimentary and granitoid rocks. Zircons in these rocks also reflect tectonothermal events associated with the Jiangnan Orogeny and breakup of Rodinia. However, the granitoids that were emplaced during the Wuyi–Yunkai Orogeny were derived principally from recycled crust (Wang et al., 2013c). This reflects contrasting basement source regions as indicated by Nd–Sr isotopes for Middle Jurassic to Early Cretaceous Hong Kong granitoids (Darbyshire and Sewell, 1997).

A simple explanation for the range of zircon ages seen in Early to Middle Jurassic rocks south of the TCF is that they were sourced from Precambrian basement in the southeastern Yangtze block (Fig. 2). However, the Yangtze block zircon spectra lack the strong 580 Ma peak shown by the Early to Middle Jurassic rocks, and also show marked age populations at 1560 Ma and 2020 Ma which are absent from the Jurassic rocks south of TCF. While it is possible that the zircons in Early to Middle Jurassic rocks south of the TCF could have been derived from exposed Cathaysia Precambrian basement, the zircon age peaks do not coincide (Fig. 2). It is also unlikely that sediments could have been transported across the southeast China during the Early to Middle Jurassic without any trace of contamination from Wuyi–Yunkai (460–420 Ma) or Indosinian (250–220 Ma) granitoids.

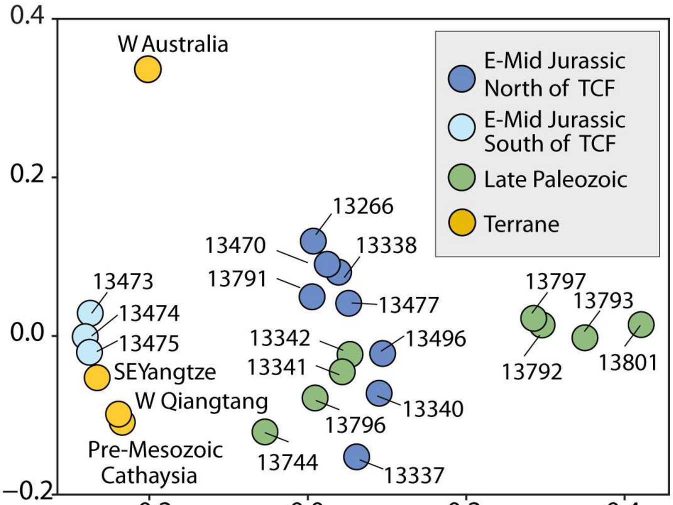

Fig. 4. MDS map of analyzed samples and other potential source terranes shown in Fig. 2 . The MDS map provides a visualization of Kolmogorov-Smirnov distances between samples and shows which samples are similar to each other (cluster together) and which are different (spaced apart).

5. Discussion

5.1 Late Mesozoic tectonic model for SE China

Major differences in stratigraphy, structure, and zircon provenance among late Paleozoic to Middle Mesozoic strata on either side of the TCF strongly suggest that rocks south of the TCF were isolated from Mesozoic Cathaysia and therefore belong to a discrete terrane (here termed the "Tolo Terrane"). Either the Tolo Terrane represents an exotic terrane, or one that has been juxtaposed as a result of large-scale strike-slip movement from elsewhere within the same convergent margin complex. A strike-slip juxtaposition cannot easily account for the passive margin tectonic setting inferred for Early to Middle Jurassic rocks from the zircon spectra. Passive margins are dominated by subdued relief with low zircon production (Cawood et al., 2012), quite unlike any other known settings in southeast China. Neither could strike-slip juxtaposition involving sliver-plate tectonics, similar to the modern-day highly oblique subduction of the Indian Ocean plate beneath Sundaland in Sumatra, western Indonesia (e.g. McCaffrey, 2009), be easily accommodated. It is most unlikely that two sedimentary basins sliding past each other could preserve no record of detrital cross-contamination. An exotic terrane would have originated from Gondwana and therefore it is useful to examine the zircon age signatures for the main blocks considered to be in the proximity of South China prior to break-up. There is as yet no consensus on the precise location of the South China craton within Gondwana but there is a general agreement that it was a part of East Gondwana and occupied a position near West Australia and the Lhasa and Qiangtang terranes adjacent to northern Greater India (Cawood et al., 2013; Cocks and Torsvig, 2013; Duan et al., 2011). Basement zircon ages for the Lhasa and Qiangtang terranes lie between ca. 1000 and 500 Ma (Leier et al., 2007; Pullen et al., 2008; Gehrels et al., 2011). Kolmogorov–Smirnov distances (Vermeesch, 2013) for sample age spectra and other potential pre-Mesozoic sources were fed into a multidimensional scaling (MDS) algorithm to convert the data into a 'map' (Fig. 4) to display the relative distances (similarities) between the data. Comparing other potential Precambrian sources

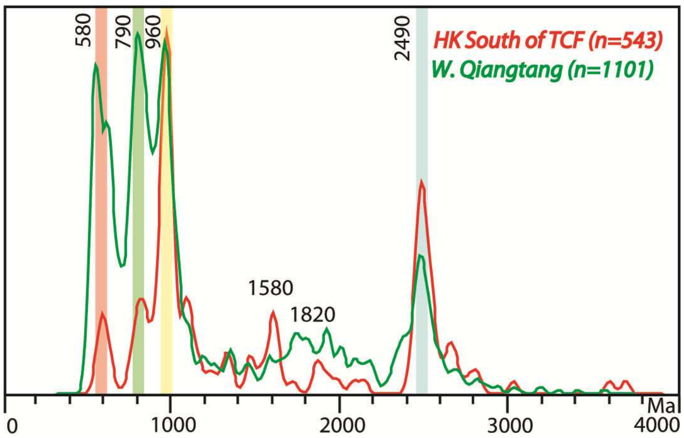

Fig. 5. Kernel Density Estimate plots for representative U-Pb detrital zircon ages from the Western Qiangtang terrane compared with Early to Middle Jurassic rocks south of the TCF. Data sources from Zhu et al., (2011), Dong et al., (2011), Pullen et al., (2008), and Gehrels et al., (2011). (n = no. of grains analyzed)

for Early to Middle Jurassic rocks from the Tolo Terrane, the zircon age spectra do not easily match with signatures from West Australia. Importantly, however, the zircon age spectra have a close match with the Qiangtang Terrane (Fig. 5). The Hf isotopes for the Qiangtang Terrane (Dong et al., 2011) also match with those of the Early to Middle Jurassic strata from the Tolo Terrane (Fig. 3b).

5.2 Origin of the Tolo Terrane and link to the Qiangtang Terrane

Yao et al. (2014) have suggested that Cambrian sedimentary rocks from SW Cathaysia preserve a NW Indian Himalaya provenance. They propose that after breakup of Rodinia, the South China Block (SCB) drifted toward NW India in the Ediacaran during Gondwana assembly, with SW Cathaysia as the leading edge. The Qiangtang Terrane was partly sandwiched between NW India and the SCB at this time, with western Qiangtang and SW Cathaysia receiving detritus dominantly from the East African Orogen (Fig. 6a). Collision with the NW India is thought to have occurred diachronously as the SCB rotated clockwise with the closure of a V-shaped ocean basin (Yao et al., 2014). We suggest that during this collision, a portion of western Qiangtang may have calved off and become isolated by strike-slip faulting (Fig. 6b). While the isolated Qiangtang microfragment ceased receiving detritus in the Ediacaran, SW Cathaysia and the main part of Qiangtang continued to receive sediments from the NW margin of the Indian continent during the Cambrian. Collision of the SCB with the India craton is thought to have triggered a Cambro-Ordovician mountain-building event called the North India Orogen. Uplift and erosion of rocks supplied detritus to depositional basins in Cathaysia and Qiangtang (Fig. 6b). During opening of Tethys in the Late Paleozoic, the isolated Qiangtang microfragment may have drifted north along with the SCB (Fig. 6c). By the Early Triassic, it was repositioned adjacent to East Cathaysia, and as the SCB drifted north to collide with the North China Block (Fig. 6d), a new SE China active continental margin developed.

Therefore, we propose that an isolated continental fragment (Tolo Terrane) derived from the Greater India portion of east Gondwana, possibly western Qiangtang, approached the SCB along an active continental margin during Early to Middle Jurassic. Accretion took place in the late Middle Jurassic. High precision U–Pb zircon dating of Middle and early Late Jurassic volcanic rocks, plutons and dykes (Davis et al., 1997) constrain the timing of terrane amalgamation to between approximately 164 and 161 Ma followed shortly afterward by a pulse of plutonism. The Tolo Terrane coincides with isotopically distinct basement sources of Hong Kong granitoids which are reflected by regional gravity models (Fletcher et al., 1997).

The event is consistent with deformation and regional metamorphism recorded in Hong Kong but also may provide a plausible mechanism to explain the presence of a broad regional scale magmatic event in SE China at ca. 160 Ma.

5.3 Implications for the 160 Ma magmatic event across the SE China continental margin

A number of tectonic models have been proposed to explain the enormous volume of fractionated I-type and subordinate A-type granitoids that were emplaced over an area of 75,000 km^2 within broad 400-km wide NE-trending belt in SE China at ca. 160 Ma. These include basin and range extensional tectonics (Gilder et al., 1991), low-angle subduction of the Paleo-pacific plate beneath southeast China (Zhou and Li, 2000), slab-foundering (Li et al., 2007), and post-orogenic extension (Chen et al., 2008). These models are based almost exclusively on the interpretation of major and trace element geochemistry, and isotope geochemistry of igneous rocks and have little supporting tectonic evidence.

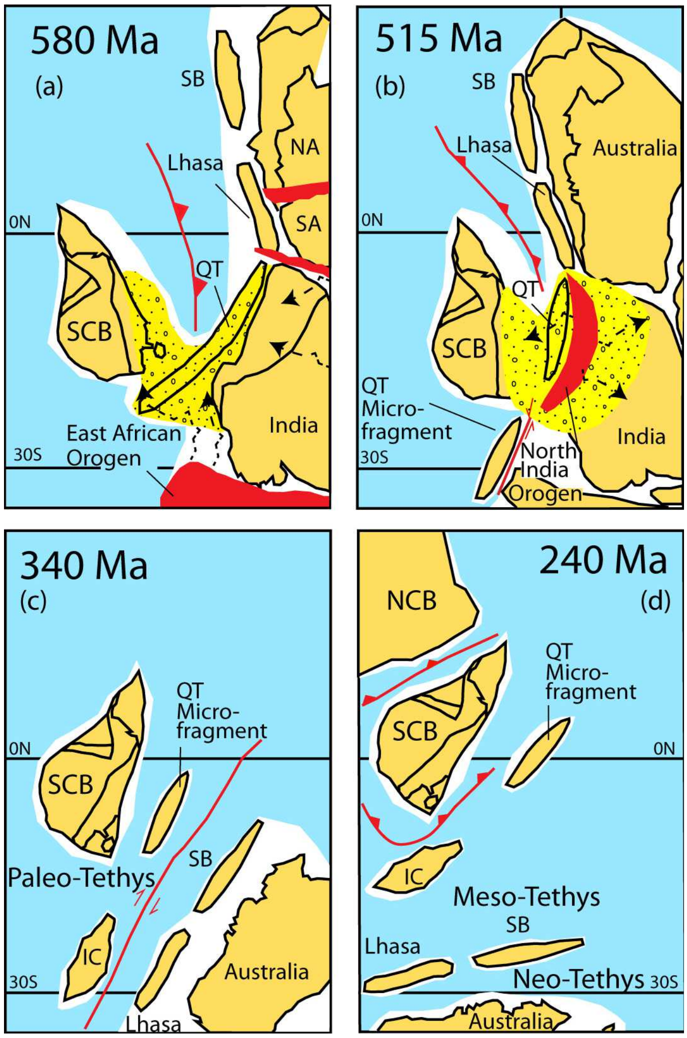

Fig. 6. Paleogeographic reconstructions for the position of the South China Block (SCB) and Qiangtang Terrane (QT) relative to northern India during assembly of Gondwana. (a) Ediacaran, and (b) Cambrian (modified after Yao et al. 2014). (c) Suggested position of the QT microfragment during opening of Tethys, (d) Suggested position of QT microfragment prior to collision of the SCB with the North China Block (NCB) in the Triassic. SB = Sibumasu, IC = Indochina.

U–Pb zircon, geochemical and Sr–Nd–Hf isotope studies on the 160 Ma granites of SE Guangdong (e.g., Li et al., 2007; Huang et al., 2012) have suggested that the high-K calcalkaline I-type and aluminous A-type granites were emplaced in a dominantly within-plate tectonic setting. It is argued that the geochemistry of the I-type granites shows no evidence of a subduction

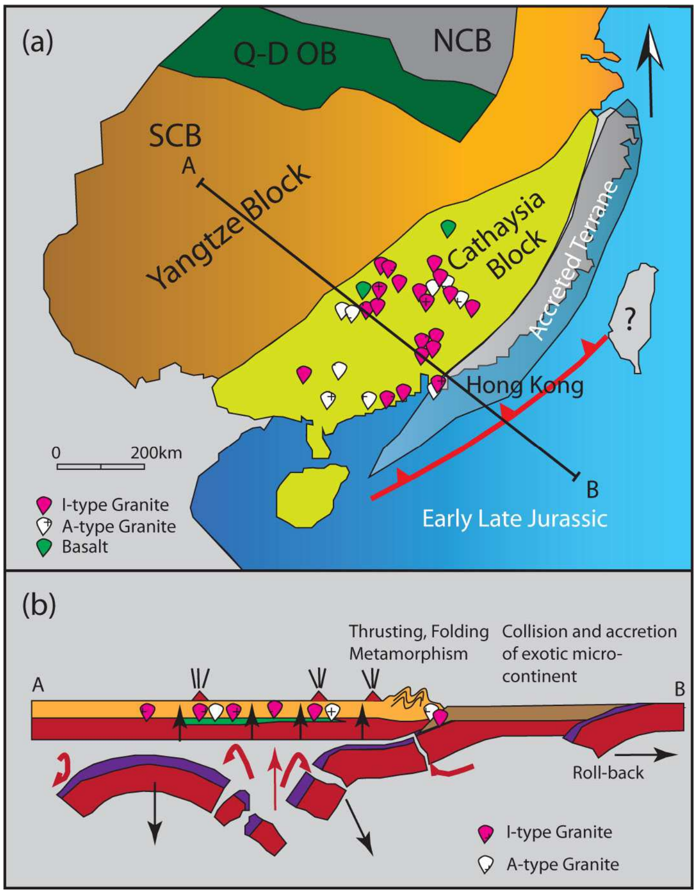

Fig. 7. (a) Distribution of granitoids and related intrusions following collision and roll-back of subduction zone at 160 Ma. (Modified after Li et al., 2007). (b) Schematic cross section along the line A-B showing main magmatic event at 160 Ma in response to foundering of a flat-slab hastened by collision of an exotic microcontinental fragment with the southeast China continental margin, and subsequent roll-back of the subduction zone. (Modified after Li et al., 2007). SCB = South China Block, NCB = North China Block, Q-D OB = Qingling-Dabie Orogenic Belt.

influence and that granite magmas were derived principally from partial melting of ancient mafic to intermediate igneous materials. On the other hand, the aluminous A-type granites are thought to have been generated from extensive crystal fractionation from an OIB-like mantle-derived source that had also assimilated some crustal components.

Direct evidence of a syn-orogenic setting for the SE China continental margin during the Middle Jurassic is provided by exposures of subduction-related andesitic rocks in Hong Kong (Sewell and Campbell, 1997) which have returned a U–Pb zircon age of ca. 170 Ma (GEO, unpublished data). Additionally, the 164 Ma volcanic and plutonic rocks in Hong Kong preserve a strong subduction signature in their major and trace element geochemistry (Sewell and Campbell, 1997). By contrast, field observations and whole-rock geochemistry suggest that the 160 Ma I-type and A-type granites in Hong Kong were most likely generated in a late orogenic to post-orogenic setting (Sewell et al., 1992). The Nd and Sr isotope geochemistry of the 160 Ma A-type granites suggests an origin from partial melting of a Paleoproterozoic tonalitic to granodioritic crustal protolith with minimal contribution from mantle-derived sources (Darbyshire and Sewell, 1997). Such a scenario is consistent with post-collisional settings where peraluminous granites are known to be associated with melting of overthickened crust (Sylvester, 1998).

Among the various tectonic models proposed for the origin the 160 Ma igneous event in SE China, the slab-foundering model (Li et al., 2007) has gained considerable support (e.g., Meng et al., 2012, Huang et al., 2012). This is considered to be consistent with the basin and range-type extensional setting proposed by Gilder et al., (1991). However, neither model provides an adequate causal mechanism for the sudden pulse of magmatism at 160 Ma, nor satisfactorily explains the subduction-related signature observed in the 160 Ma Hong Kong granitoids. Detachment and foundering of the subducted flat-slab is thought to have commenced as early as 190 Ma with the appearance of the first A-type granites in SE China (Li and Li, 2007). However, this Early Jurassic anorogenic magmatism in South China was relatively sparse, and the region is thought to have been dominated by marine and terrestrial sedimentation due to crustal down-warping (Li and Li, 2007). This is reflected by the remarkable paucity of Early Jurassic magmatic zircons in these sediments as shown by the Hong Kong zircon age spectra and those from central SE China (Meng et al., 2015). Basin and range extensional tectonics in SE China is indicated by an influx of Triassic age zircons (ca. 236 Ma) from unroofing of Indosinian granitoids in the earliest Middle Jurassic sediments (Meng et al., 2015). Andesitic magmatism in the Hong Kong region at about 170 Ma provides the most direct evidence for coastward re-positioning of the subduction zone following Early Jurassic roll-back. However, there was still no sign of large-scale anorogenic magmatism in central SE China at this time. Subduction-related intermediate to silicic magmatism recorded in the Hong Kong region at 164 Ma (Sewell and Campbell, 1997) indicates that the continental arc was developing and maturing. At about 160 Ma, there was an abrupt change of events marked by a surge of widespread I-type and A-type magmatism across a large part of SE China.

Collision of a microcontinental fragment with the SE China continental margin accompanied by subduction zone roll-back between 164 and 161 Ma provides an effective tectonic solution to the abrupt change of events in the late Middle Jurassic. Such a model (a) provides a mechanism to hasten the final stages of flat-slab foundering and trigger the widespread magmatism at 160 Ma (Fig. 7), (b) explains the coeval distribution of late orogenic I-type to post orogenic A-type magmatism on the continental margin and within-plate I-type and A-type magmatism in the continental interior, and (c) provides a suitable explanation for the overall change in tectonic setting in Hong Kong during the Late Jurassic from subduction to transtension as reflected by the change in style of magmatism from a continental intra-arc environment to a back-arc environment (Campbell and Sewell, 1997). We therefore consider that a terrane collision model can accommodate both a continental-arc setting and a within plate setting proposed to explain the broad 160 Ma magmatic event in SE China.

6. Conclusions

A major tectonomagmatic event occurred in SE China around the end of the Middle Jurassic. In the Hong Kong region, the event was characterized by regional thrusting, folding and metamorphism. This episode may have been triggered by the collision of an exotic microcontinental fragment with the eastern Cathaysia margin. Subsequent intrusion of fractionated I-type and A-type granites in Hong Kong at ca. 160 Ma stitched the suture zone and signaled the onset of extensional tectonics in the region following roll-back of the subduction zone. The collision may have hastened the final stages of fracturing and foundering of a subducted flat slab beneath SE China. The origin of the microcontinental fragment fits with the Greater India part of east Gondwana. The suture zone approximates a NE-trending basement terrane boundary previously identified from Nd–Sr isotope studies of Late Mesozoic granites. The suture zone has been severely overprinted by later Mesozoic igneous activity but an exposed remnant is preserved in Hong Kong.

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References

Allen, P.M., Stephens, E.A., 1971. Report on the Geological Survey of Hong Kong. Hong Kong Government Printer, 107 p.

Burrett, C., Zaw, K., Meffre, S., Lai, C.K., Khositanont, S., Chaodumrong, P., Udchachon, M., Ekins, S., Halpin, J., 2014. The configuration of Great Gondwana-Evidence from LA ICPMS, U-Pb geochrnonology of detrital zircons from the Palaeozoic and Mesozoic of Southeast Asia and China. Gondwana Res. 26, 31–51.

Busby, J.P., Langford, R.L., 1995. Interpretation of the regional gravity survey of Hong Kong. Hong Kong Geol. 1, p. 52–66.

Campbell, S.D.G., Sewell, R.J., 1997. Structural control and tectonic setting of Mesozoic volcanism in Hong Kong. J.Geol. Soc. Lond. 154, 1039–1052.

Cawood, P.A., Hawkesworth, C.J., Dhuime, B., 2012. Detrital zircon record and tectonic setting. Geology 40, p. 875–878.

Cawood, P.A., Nemchin, A.A., 2000. Provenance record of a rift basin: U/Pb ages of detrital zircons from the Perth Basin, Western Australia. Sediment. Geol. 134, 209–234.

Cawood, P.A., Wang, Y., Xu, Y., Zhao, G., 2013. Locating South China in Rodinia and Gondwana: A fragment of greater India lithosphere. Geology 41, 903–906.

Chen, C.H., Lee, C.Y., Shinjo, R., 2008. Was there Jurassic paleo -pacific subduction in South China?: Constraints from $^{40}Ar/^{39}Ar$ dating, elemental and Sr-Nd-Pb isotopic geochemistry of the Mesozoic basalts. Lithos 106, 83–92.

Cocks, L.R.M., Torsvig, T.H., 2013. The dynamic evolution of the Palaeozoic geography of eastern Asia. Earth Sci. Rev. 117, 40–79.

Darbyshire, D.P.F., Sewell, R.J., 1997. Nd and Sr isotope geochemistry of plutonic rocks from Hong Kong: Implications for granite petrogenesis, regional structure and crustal evolution. Chem. Geol. 143, 81–93.

Davis, D.W., Sewell, R.J., Campbell, S.D.G., 1997. U–Pb dating of Mesozoic igneous rocks from Hong Kong. J. Geol. Soc. Lond. 154, 1067–1076.

Dong, C.Y., Li, C., Wan, Y.S., Wang, W., Wu, Y.W., Xie, H.Q., Liu, D.Y., 2011. Detrital zircon age model of Ordovician Wenquan quartzite south of Lungmuco-Shuanghu suture in the Qiangtang area, Tibet: Constraint on tectonic affinity and source regions. Sci. China Earth Sci. 54, 1034–1042.

Duan, L., Meng, Q.R., Zhang, C.L., Liu, X.M., 2011. Tracing the position of the South China block in Gondwana: U-Pb ages and Hf isotopes of Devonian detrital zircons. Gondwana Res. 19, 141–149.

Fletcher, C.J.N., Campbell, S.D.G., Busby, J.P., Carruthers, R.M., Lai, K.W., 1997. Regional tectonic setting of Hong Kong: implications of new gravity models. J. Geol. Soc. Lond. 154, 1021–1030.

Fletcher, C.J.N., Chan, L.S., Sewell, R.J., Campbell, S.D.G., Davis, D.W., Zhu, J.C., 2004. Basement heterogeneity in the Cathaysia crustal block, southeast China. In: Malpas, J., Fletcher, C.J.N., Ali, J.R., Aitchison, J.C., (Eds.), Aspects of the Tectonic Evolution of China. The Geological Society of London Special Publication, 226, pp. 145–156.

Gehrels, G., Kapp, P., DeCelles, P., Pullen, A., Blakey, R., Weislogel, A., Ding, L., Guynn, J., Martin, A., McQuarrie, N., Yin, A., 2011. Detrital zircon geochronology of pre-Tertiary strata in the Tibetan-Himalaya orogen. Tectonics 30, TC5016.

Gilder, S.A., Keller, G.R., Luo, M., Goodell, P.C., 1991. Timing and spatial distribution of rifting in China. Tectono. 197, 225 –243.

Griffin, W.L., Belousova, E.A., Shee, S.R., Pearson, N.J., O'Reilly, S.Y., 2004. Archean crustal evolution in the northern Yilgarn Craton: U-Pb and Hf-isotope evidence from detrital zircons. Precamb. Res. 131, 231–282.

Huang, H.Q., Li, X.H., Li, Z.X., Li, W.X., 2012. Intraplate crustal remelting as the genesis of Jurassic high-K granites in the coastal region of the Guangdong Province, SE China. J. Asian Earth Sci. 74, 280-302.

Jackson S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U-Pb zircon geochronology. Chem. Geol. 211, 47–69.

Jones, N.S., Fyfe, J.A., Sewell, R.J., Lai, K.W., Lee, C.M., 1997. Devonian fluviodeltaic sedimentation in Hong Kong. J. Asian Earth Sci. 15, 533–545.

Lai, K.W., 1976. Research on the structural system and Mesozoic stratigraphy of Hong Kong. Geography Journal of Chinese University of Hong Kong. 1, 3–12.

Langford, R.L., Lai, K.W., Arthurton, R.S., Shaw, R., 1989. Geology of the Western New Territories. Hong Kong Geological Survey Memoir No. 3, Geotechnical Control Office, Hong Kong Government, 140 p.

Lee, C.M., Chan, K.W., Ho, K.H., 1997. Palaeontology and stratigraphy of Hong Kong. Volume 1: Science Press, Beijing, 206 p.

Li, Z.X., Li, X.H., 2007. Formation of the 1300-km-wide intracontinental orogen and postorogenic magmatic province in Mesozoic South China. A flat-slab subduction model: Geology 35, 179–182.

Li, X.H., Li, Z.X., Li, W.X., Liu, Y., Yuan, C., Wei, G., Qi, C., 2007. U-Pb zircon, geochemical and Sr-Nd-Hf isotopic constraints on age and origin of Jurassic I- and A-type granites from central Guangdong, SE China: A major igneous event

in response to foundering of a subducted flat-slab? Lithos 96, 86–204.
Li, Z.X., Li, X.H., Wartho, J.A., Clark, C., Li, W.X., Zhang, C.L., Bao, C., 2010. Magmatic and metamorphic events during the early Paleozoic Wuyi-Yunkai orogeny, southeastern South China: New age constraints and pressure-temperature conditions. Geol. Soc. Amer. Bull. 122, 772–793.
Li, J., Zhang, Y., Dong, Z., Johnston, S.T., 2014. Cretaceous tectonic evolution of South China: A preliminary synthesis. Earth Sci. Rev. 134, 98–136.
Leier, A.L., Kapp, P., Gehrels, G.E., DeCelles, P.G., 2007. Detrital zircon geochronology of Carboniferous-Cretaceous strata in the Lhasa terrane, southern Tibet. Basin Res. 19, p. 361–378.
McCaffrey, R., 2009, The tectonic framework of the Sumatran subduction zone. Ann. Rev. Earth Planet. Sci. 37, 345–366.
Meng, L., Li, Z.-X., Chen, H., Li, X.-H., Wang, X.-C., 2012. Geochronological and geochemical results from Mesozoic basalts in southern South China support the flat-slab subduction model. Lithos 45, 1-28.
Meng, L., Li, Z.-X., Chen, H., Li, X.-H., Zhu, C., 2015, Detrital zircon U-Pb geochronology, Hf isotopes and geochemistry constraints on crustal growth and Mesozoic tectonics of southeastern China. J. Asian Earth Sci. 105, 286-299.
Patchett, P.J., Kouvo, O., Hedge, C.E., Tatsumoto, M., 1981. Evolution of continental crust and mantle heterogeneity: evidence from Hf isotopes. Contrib. Mineral. Petrol. 78, 279–297.
Pearce, N.J.G. et al., 1997. A compilation of new and published major and trace element data for NIST SRM 610 and NIST SRM 612 glass reference materials. Geostand. Newslett. 21, 115–144.
Pullen, A., Kapp, P., Gehrels, G.E., Vervoot, J.D., Ding, L., 2008. Triassic continental subduction in central Tibet and Mediterranean-style closure of the Paleo-Tethys Ocean. Geology 36, 351 –354.
Sewell, R.J., Campbell, S.D.G., 1997. Geochemistry of coeval Mesozoic plutonic and volcanic suites of Hong Kong. J. Geol. Soc. Lond. 154, 1053–1066.
Sewell, R.J., Campbell, S.D.G., Fletcher, C.J.N., Lai, K.W., Kirk, P.A., 2000. The Pre-Quaternary Geology of Hong Kong, Geotechnical Engineering Office. The Government of the Hong Kong Special Administrative Region, 181 p.
Sewell, R.J., Darbyshire, D.P.F., Langford, R.L., Strange, P. J., 1992. Geochemistry and Rb-Sr geochronology of Mesozoic granites from Hong Kong. Trans. Roy. Soc. Edin. Earth Sci. 83, 269–280.
Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, J.M., Hanchar, A., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., Whitehouse, M.J., 2008. Plešovice zircon - A new natural reference material for U-Pb and Hf isotopic microanalysis. Chem. Geol. 249, 1–35.
Sylvester, P.J., 1998. Post-collisional strongly peraluminous granites. Lithos 45, 29–44.
Thorpe, R.S., Francis, P.W., O'Callaghan, L., 1984. Relative roles of source composition, fractional crystallisation and crustal contamination in the petrogenesis of Andean volcanic rocks. Phil. Trans. Roy. Soc. Lond. A310, 675–692.
Veevers, J.J., Saeed, A., Belousova, E.A., Griffin, W.L., 2005. U-Pb ages and source compositon by Hf-isotope and trace element analysis of detrital zircons in Permian sandstones and modern sand from southwestern Australia and a review of the paleogeographical and denudational history of the Yilgarn Craton. Earth Sci. Rev. 68, 245–279.
Vermeesch, P., 2012. On the visualization of detrital age distributions: Chem. Geol. 312–313, 190–194.
Vermeesch, P., 2013. Multisample comparison of detrital age distributions. Chem. Geol. 341, 140–146.
Wang, Y., Fan, W., Zhang, G., Zhang, Y., 2013a. Phanerozoic tectonics of the South China Block: Key observations and controversies. Gondwana Res. 23, 1273–1305.
Wang, P.M., Yu, J.H., Sun, T., Shi, Y., Chen, P.R., Zhao, K.D., Chen, W.F., Liu, Q., 2013b. Composition variations of the Sinian-Cambrian sedimentary rocks in Hunan and Guangxi and their tectonic significance. Sci. China Earth Sci. 56, 1899–1917.
Wang, D., Zheng, J., Ma, M., Griffin, W.L., Zhao, H., Wong, J., 2013c. Early Paleozoic crustal anatexis in the intraplate Wuyi-Yunkai orogen, South China. Lithos 175–176, 124–145.
Wang, J.Q., Shu, L.S., Santosh, M., Xu, Z.Q., 2015. The Pre-Mesozoic crustal evolution of the Cathaysia Block, South China: Insights from geological investigation, zircon U-Pb geochronology, Hf isotope and REE geochemistry from the Wugongshan complex. Gondwana Res. 28, 225–245.
Woodhead, J.D., Hergt, J.M., 2005. A preliminary appraisal of seven natural zircon reference materials for in situ Hf isotope determination. Geostand. Geoanalyt. Res. 29, 183–195.
Xu, X., O'Reilly, S.Y., Griffin, W.L., Wang, X., Pearson, N.J., He, Z., 2007. The crust of Cathaysia: Age, assembly and reworking of two terranes. Precamb. Res. 158, 51–78.
Yao, W.H., Li, Z.X., Li, W.X., 2015. Was there a Cambrian ocean in South China? – Insight from detrital zircon provenance analyses. Geol. Mag. 152, 184–191.
Yao, W.H., Li, Z.X., Li, W.X., Li, X.H., Yang, J.H., 2014. From Rodinia to Gondwanaland: A tale of detrital zircon provenance analyses from the southern Nanhua Basin, South China. Amer. Jour. Sci. 314, 278–313.
Zhou, X.M., Li, W.X., 2000. Origin of late Mesozoic igneous rocks in Southeastern China: Implications for lithosphere subduction and underplating of mafic magmas. Tecton. 326, 269–287.
Zhu, D.C., Zhao, Z.D., Niu, Y., Dilek, Y., Mo, X.X., 2011. Lhasa terrane in southern Tibet came from Australia. Geology 39, 727 –730.