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Detrital zircon U–Pb geochronology, Lu–Hf isotopes and REE geochemistry constrains on the provenance and tectonic setting of Indochina Block in the Paleozoic

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ABSTRACT

In situ U–Pb geochronology, Lu–Hf isotopes and REE geochemical analyses of detrital zircons from Cambrian–Devonian sandstones in the Truong Son Belt, central Vietnam, are used to provide the information of provenance and tectonic evolution of the Indochina Block. The combined detrital zircon age spectra of all of the samples ranges from 3699 Ma to 443 Ma and shows with dominant age peaks at ca. 445 Ma and 964 Ma, along with a number of age populations at 618–532 Ma, 1160–1076 Ma, 1454 Ma, 1728 Ma and 2516 Ma. The zircon age populations are similar to those from time equivalent sedimentary sequences in continental blocks disintegrated from the East Gondwana during the Phanerozoic. The younger zircon grains with age peaks at ca. 445 Ma were apparently derived from middle Ordovician–Silurian igneous and metamorphic rocks in Indochina. Zircons with ages older than about 600 Ma were derived from other Gondwana terrains or recycled from the Precambrian basement of the Indochina Block. Similarities in the detrital zircon U–Pb ages suggest that Paleozoic strata in the Indochina, Yangtze, Cathaysia and Tethyan Himalayas has similar provenance. This is consistent with other geological constrains indicating that the Indochina Block was located close to Tethyan Himalaya, northern margin of the India, and northwestern Australia in Gondwana.

1. Introduction

Clastic sedimentary rocks contain important information relating to their provenance and the sedimentary processes that took place during their original deposition (Oliveira et al., 2015). Detrital zircons of different ages are not fractionated in the sedimentary cycle and therefore provide information related to source terranes (Cawood and Nemchin, 2000; Cawood et al., 2003). In last decades, U–Pb dating of detrital zircon has been widely used in tectonic evolution studies, because of the stability of zircon in both weathering and diagenetic regimes (Morton et al., 2001; Fedo et al., 2003; Morton et al., 2009). In situ Lu–Hf isotopic data provide another dimension to the geochronology by adding information about crustal evolution of the sources (Corfu and Noble, 1992; Griffin et al., 2004; Zheng et al., 2007; Belousova et al., 2010). Trace element composition of zircons provides additional information on the composition of the igneous rocks in sedimentary source regions (Pearce et al., 1984; Hoskin and Ireland, 2000; Belousova et al., 2002; Yao et al., 2011).

Southeast Asia consists of allochthonous continental blocks derived from the northern margin of Gondwana at various times from the early Paleozoic to Jurassic (Metcalfe, 2006; Hall, 2009; Metcalfe, 2011), including the Indochina, South China, Sibumasu and West Burma blocks (Audley-Charles, 1983; Audley-Charles et al., 1988; Metcalfe, 1996; Metcalfe, 2011) (Fig. 1). The position of the Indochina Block in Gondwana has been of considerable controversy (Usuki et al., 2013). A number of studies suggest that Indochina Block was adjacent to the India–Australia margin of Gondwana, and most probably located close to north of India (Metcalfe, 1996, 2006; Wang et al., 2010; Usuki et al., 2013; Xu et al., 2014). Torsvik and Cocks (2009) and Cawood et al. (2013), however, plotted the Indochina Block as a discrete block in the paleo-Pacific, far away from the north margin of East Gondwana. In practice, the block was generally omitted in many paleogeographic reconstructions of the Gondwanaland (Li et al., 1995; Cawood and Buchan, 2007; Zhu et al., 2011; Xu et al., 2013). The uncertain paleogeography of the Indochina Block in Gondwana is due to the paucity of good quality of Paleozoic paleomagnetic and reliable geochronological

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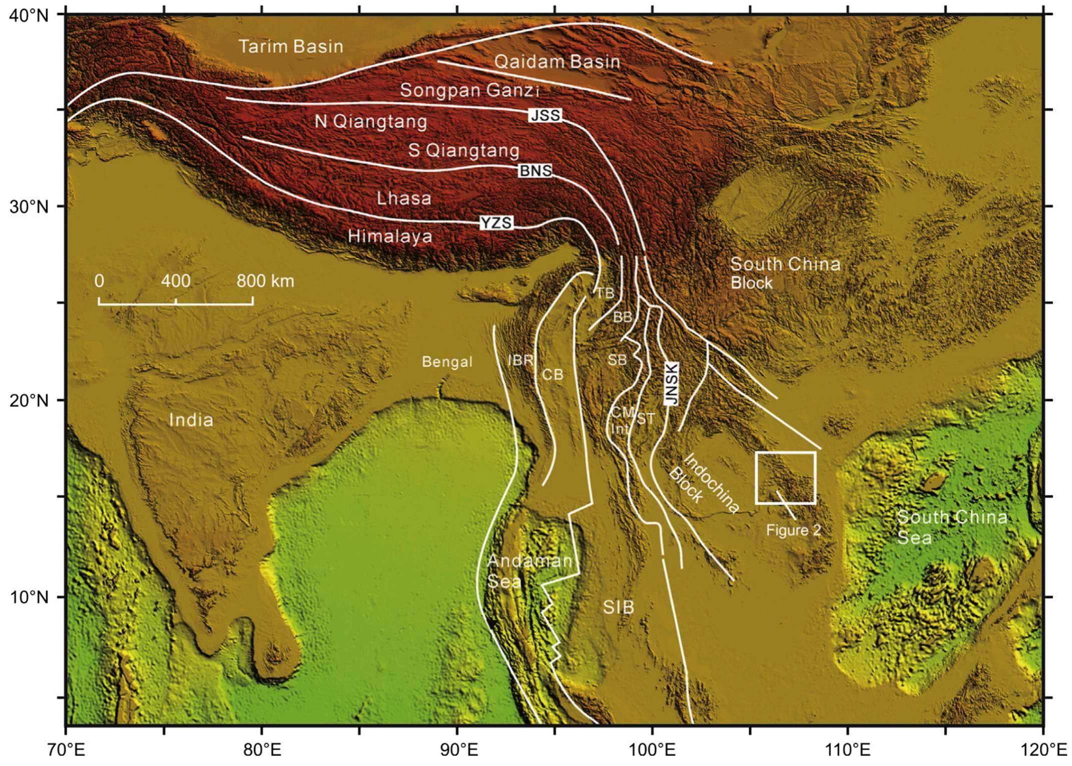

Fig. 1. Tectonic SE Asia, modified after Yin and Harrison (2000) and Cai et al. (in press). JSS = Jinsha Suture Zone, BNS: Bangong-Nujiang Suture Zone, YZS: Yarlung-Zangbo Suture Zone, JNSK: Jinghong-Nan-Sra Kaeo Suture Zone, TB: Tengchong Block, BB: Baoshan Block, SB: Simao Block, SIB: Sibumasu Block, CM-Int: Changning-Menglian and Inthanon Suture zones, ST: Sukhothai Terrane.

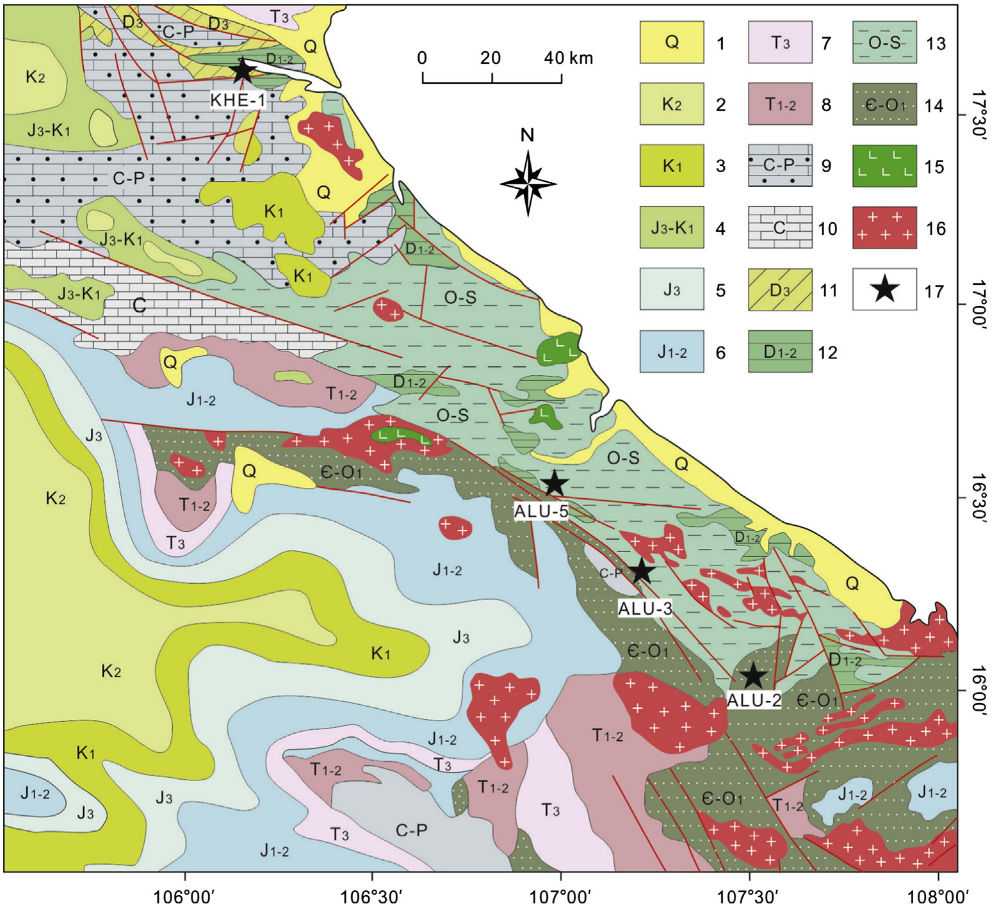

Fig. 2. Geologic sketch map and sample locations of this study. Legend 1–14 represent strata with geological time indicated, 15-Quaternary basalt, 16-early Paleozoic to Mesozoic granitoids, 17-Sample locations.

Table 1
Location and stratigraphic information of samples analyzed during this study.

Samples	Locations	Period of strata	Rock types
KHE-1	N 17°39′08.62″, E 106°10′02.43″	Lower Devonian	Sandstone
ALU-5	N 16°33′14.82″, E 106°57′27.68″	Upper Ordovician–Silurian	Sandstone
ALU-3	N 16°18′09.52″, E 107°12′22.90″	Upper Ordovician–Silurian	Pebbly sandstone
ALU-2	N 16°05′22.20″, E 107°27′32.42″	Cambrian–Lower Ordovician	Sandstone

The sample positions are shown in Fig. 1.

and isotopic data, which has strictly hindered understanding of the position of the block.

The Truong Son Belt is an important tectonic element within the Indochina Block, and therefore bears significant information for the evolution of the block. The belt was considered to have affinities to the Sino-Australian Province during the Silurian on the basis of brachiopods from central Vietnam (Rong et al., 1995). Recently, Usuki et al. (2013) used detrital zircon U–Pb ages and Hf isotopes collected from modern river sediments in the Truong Son Belt to estimate the early Paleozoic position of the block within Gondwana. However, the modern river sediments are not first-cycle sediments and might be influenced by detritus from other tectonic elements in SE Asia. In this study, we present new U–Pb age, Lu–Hf isotopes and REE elements for zircon grains directly extracted from Cambrian to Devonian sedimentary rocks across the Truong Son Belt. The results provide new insights into the paleogeographic setting of the Indochina Block.

2. Geological setting

The Indochina Block is bounded to the northeast by the Song Ma suture zone and to the west by the Uttaradit-Nan-Sra Kaeo sutures in Thailand and Malaysia, respectively (Metcalfe, 2006). The eastern part of the Indochina Block can be divided into two geological units: Truong Son Belt and Kontum Massif. The northern boundary of the Truong Son Belt is the Song Ma suture which can be considered as the boundary between the South China and Indochina blocks (Metcalfe, 1996; Hoa et al., 2008; Lepvrier et al., 2008; Liu et al., 2012). Nearly E-W trending fault zone (Tam Ky-Phuoc Son) separates the Truong Son Belt from the Kontum Massif to the south (Lepvrier et al., 2004; Tran et al., 2014). Truong Son Belt is dominated by a system of subparallel northwest-trending strike-slip faults (Fig. 2), and is mainly composed of Precambrian to Cenozoic sedimentary rocks, Paleozoic to Mesozoic igneous rocks and Quaternary basalt (Fig. 2).

Geochronological data from the Truong Son Belt and Kontum Massif reveal metamorphic events with grades up to granulite facies related to early Paleozoic and late Permian–middle Triassic orogenic events at around 450 Ma and 230 Ma, respectively (Lepvrier et al., 1997; Carter et al., 2001; Nagy et al., 2001; Nam et al., 2001; Roger et al., 2007, 2012). Early Paleozoic to Mesozoic magmatic rocks are widely distributed within the Truong Son Belt were emplaced during Ordovician–Silurian (470–420 Ma), late Carboniferous–early Permian (300–280 Ma), late Permian to middle Triassic (270–245 Ma) and middle-late Triassic (245–200 Ma) (Carter et al., 2001; Hoa et al., 2008; Usuki et al., 2009; Tran et al., 2014; Shi et al., 2015).

3. Sampling and analytical methods

Four Paleozoic sedimentary rock samples across the Truong Son Belt were collected for U–Pb geochronology, REE geochemistry and Lu–Hf isotopes analyses of detrital zircons. The samples are sandstones consisting of quartz, mica and plagioclase, with accessory zircon, epidote, rutile and apatite. The detailed location and stratigraphic information of samples are show in Table 1 and Fig. 3.

Zircons were separated using heavy liquids and Frantz magnetic separator methods. Zircon grains were randomly handpicked, mounted in epoxy and polished down to near half sections to reveal internal structures. Cathodoluminescence (CL) imaging of zircon grains was carried out using a MINI CL detector attached to an Electron Microprobe (JSM6510), to identify internal structure and to select target sites for laser ablation analyses.

Simultaneous determination of U–Pb ages and trace elements was conducted using a Agilent 7500a ICP-MS housed at the State Key Laboratory of Isotopic Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS). Sample mounts were placed in the two-volume sample cell flushed with Ar and He. Laser ablation was operated at a constant energy 80 mJ and at 8 Hz, with a spot diameter of 33 μm. Element corrections were made for mass bias drift, which was evaluated by reference to standard glass NIST SRM 610. Temora was used as the age standard ($^{206}Pb/^{238}U = 416.8$ Ma) (Black et al., 2003). The details of analytical procedure, precision and accuracy are described by Jackson et al. (2004), Yuan et al. (2004), Liu et al. (2008) and Liu et al. (2010). Isotopic ratios of U–Th–Pb were calculated using ICPMSDataCal (Version 7.2) (Liu et al., 2008, 2010). Common Pb was corrected by ComPbCorr#3_151 using the method of Andersen (2002). Ages which have more than ±10% discordance were rejected for statistical purposes in this study. The $^{206}Pb/^{238}U$ ages are used for zircons with concordant ages less than 1000 Ma, whereas $^{207}Pb/^{206}Pb$ ages are used for zircons with $^{206}Pb/^{238}U$ ages older than 1000 Ma. The concordia plots and relative age probability diagrams were made using ISOPLOT (Version 3.0) (Ludwig, 2003) and Probability Density Plots (PDPs) (Vermeesch, 2012), respectively. To show accuracy and

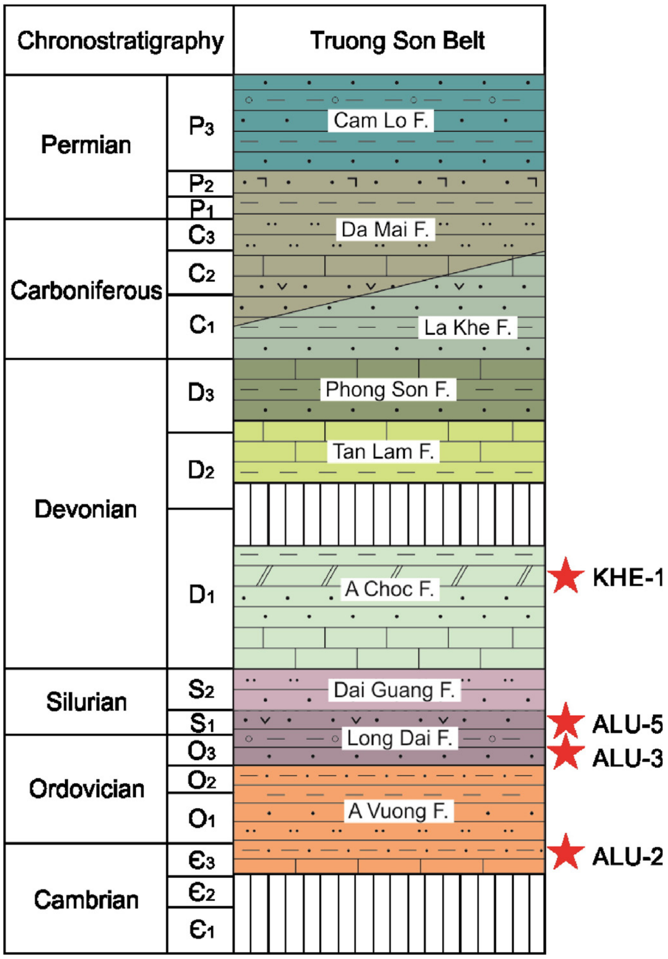

Fig. 3. Paleozoic stratigraphic units of the Truong Son Belt, modified after Khuc (2011).

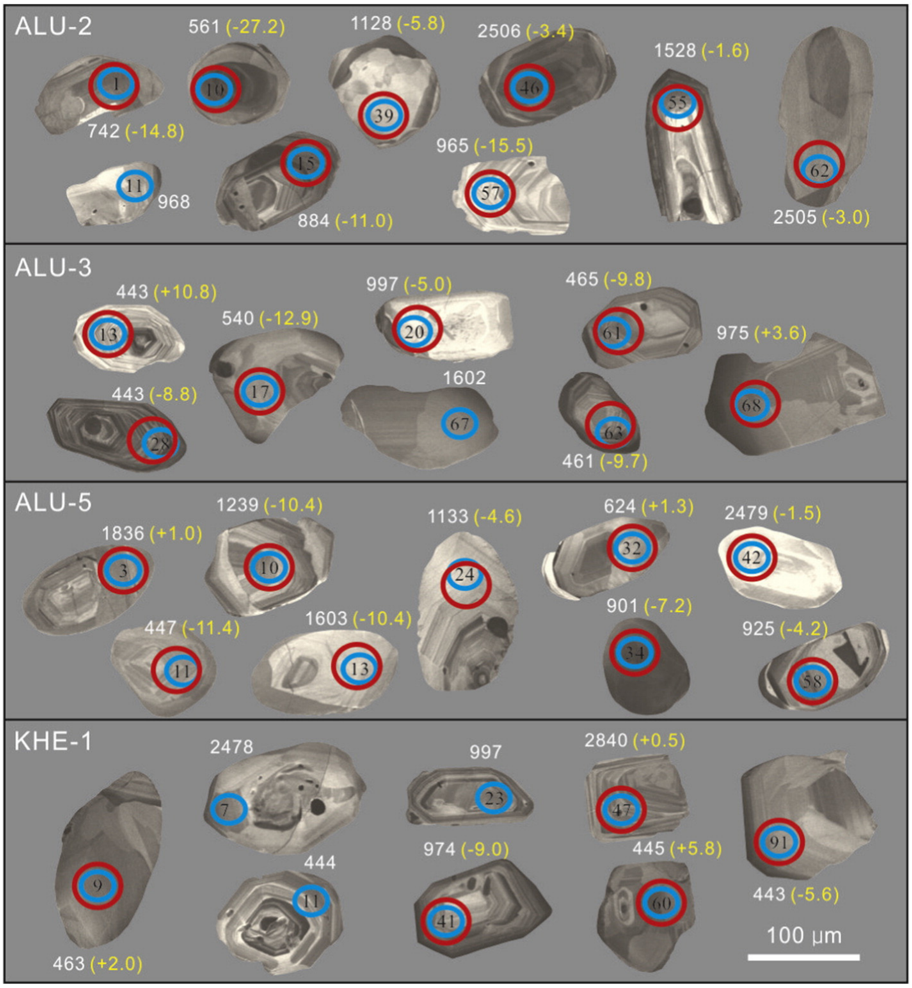

Fig. 4. CL images of representative detrital zircons analyzed in this study. The small circle (33 μm in diameter) and big circle (45 μm in diameter) denote the LA-(MC)-ICP-MS analytical spots for U–Pb ages and Lu–Hf isotopes, respectively. Numbers near the circles are the U–Pb age and ε_{Hf} (t) value (within parentheses). Numbers within the small circle are analyses numbers of each sample.

analytical precision, data points are displayed on concordia plots as filled error ellipses, with all errors reported at the 1 sigma confidence level.

In situ zircon Lu–Hf isotopic analyses were carried out on a Neptune Plus multi-collector ICP-MS equipped with a RESOlution M-50 laser-ablation system at the same laboratory. The Lu–Hf isotopic measurements were made on the same spots previously analyzed for U–Pb. The laser parameters were as follows: spot size, 45 μm; repetition rate, 8 Hz; energy, 80 mJ. Helium was used as carrier gas and a small flow of nitrogen was added in gas line to enhance the sample signal. A normal single spot analysis consists of 30 s gas blank collection and 30 s laser ablation. The integration time was 0.131 s and about 200 cycles of data were collected. ^{173}Yb and ^{175}Lu were used to correct the isobaric interference of ^{176}Yb and ^{176}Lu on ^{176}Hf. The ^{176}Hf/^{177}Hf was normalized to ^{179}Hf/^{177}Hf 0.7325 using an exponential law for mass bias correction. Penglai sample was used as the reference standard (Li et al., 2010). The analytical procedures were same as those described by Wu et al. (2006) and Yuan et al. (2008). The initial Hf isotope ratios are denoted as $\varepsilon_{Hf}(t)$ values that were calculated with the Chondritic Uniform Reservoir (CHUR) at the time of zircon crystallization, and the present-day ^{176}Hf/^{177}Hf and ^{176}Lu/^{177}Hf ratios of chondrite and depleted mantle are at 0.28277 and 0.0332, 0.28325 and 0.0384, respectively (Blichert-Toft and Albarède, 1997). Initial ^{176}Hf/^{177}Hf values were calculated based on ^{176}Lu decay constant of 1.865×10^{-11} year^{-1} (Scherer et al., 2001). The single-stage model Hf ages (T_{DM1}) were computed with reference to the depleted mantle with a present-day ^{176}Lu/^{177}Hf ratio of 0.28325 and ^{176}Lu/^{177}Hf ratio of 0.0384 (Griffin et al., 2000). Two-stage model Hf ages (T_{DM2}) were computed using a ^{176}Lu/^{177}Hf value of 0.015 for average continental crust (Griffin et al., 2002). The rephrase are described by (Li et al., 2012). During the analyses, the ^{176}Hf/^{177}Hf and ^{176}Lu/^{177}Hf ratios of standard zircon (Penglai) were 0.282902 ± 0.000017 (2σ, $n = 32$) and 0.000303, respectively. These values agree with the recommended ^{176}Hf/^{177}Hf values for Penglai (0.282906 ± 0.000016, 2σ, $n = 117$) (Li et al., 2010).

4. Results

4.1. Zircon U–Pb ages

The CL images of representative zircons together with spots ages are shown on Fig. 4. U–Pb data for these samples are shown on concordia plots and relative age probability diagrams (Fig. 5), and presented in detail in Appendix A.

More than 200 zircon grains were separated from each sample. The morphologies of these zircon grains are colorless to light pink and transparent, and show a wide range from prismatic crystals to oval shapes with mostly rounded corners (Fig. 4), suggestive of a long transport before deposition or multi-cycle deposition. Some zircon grains are incomplete, and they might have been damaged during transport or processing. The zircon grains are up to 300 μm in length, but mainly about 80–110 μm. Most grains show oscillatory growth zoning under

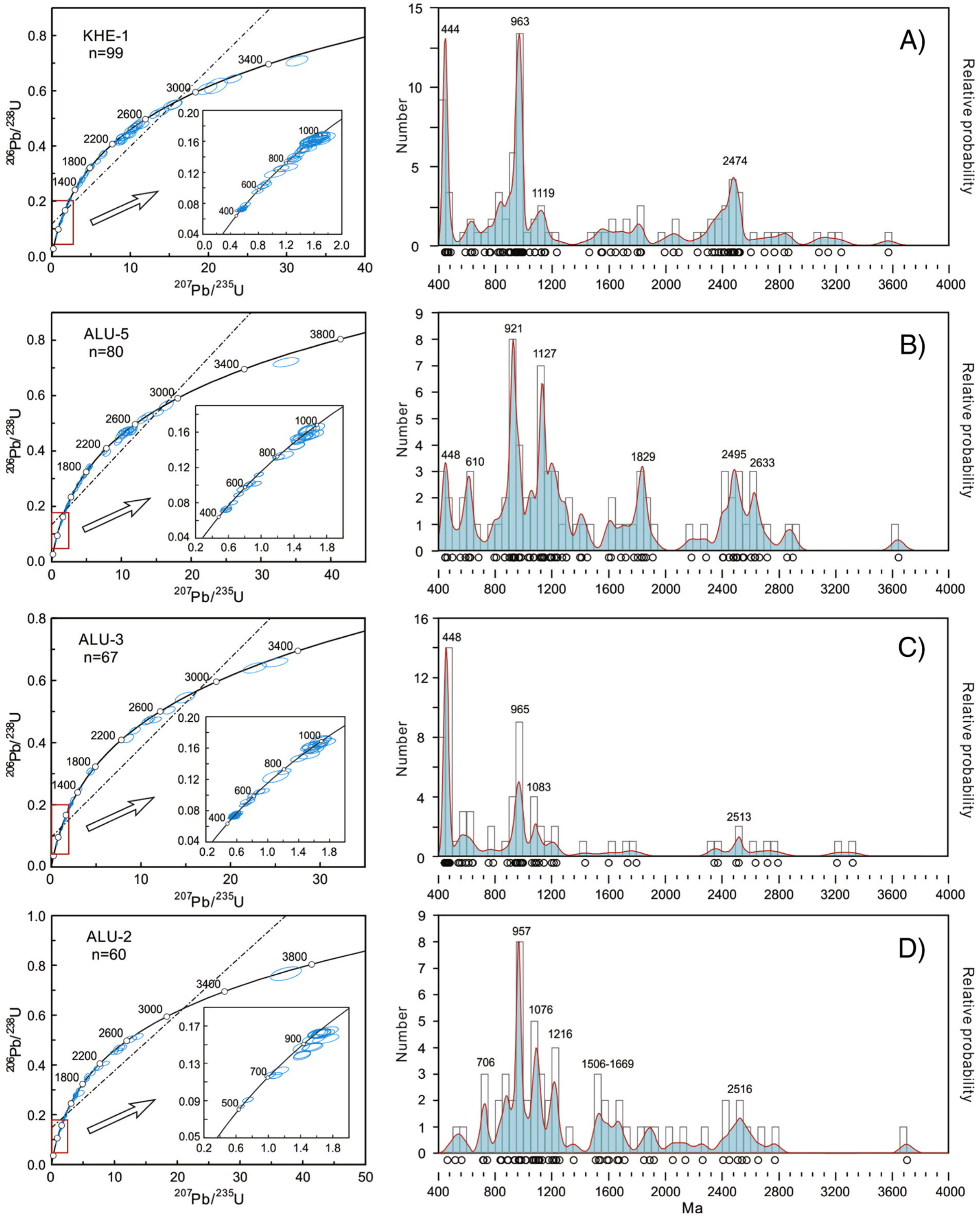

Fig. 5. U–Pb Concordia and histogram diagram of detrital zircons. Data-point error ellipses are 1 sigma.

CL (Fig. 4) and have high Th/U values (>0.4) (Appendix A), indicating a magmatic origin (Wu and Zheng, 2004).

4.1.1. Sample KHE-1

Of the 100 analyses conducted on 100 zircons for this sample, 99 analyses are concordant within uncertainties (Fig. 5A). The measured ^{206}Pb/^{238}U (<1000 Ma) and ^{207}Pb/^{206}Pb (>1000 Ma) ages range from 3573 to 443 Ma. There are two major age peaks at ca. 444 Ma and 963 Ma, with two subordinate age peaks at ca. 1119 Ma and 2474 Ma.

4.1.2. Sample ALU-5

Of the 80 analyses conducted on 80 zircons for this sample, all of the analyses are concordant within uncertainties (Fig. 5B). The measured

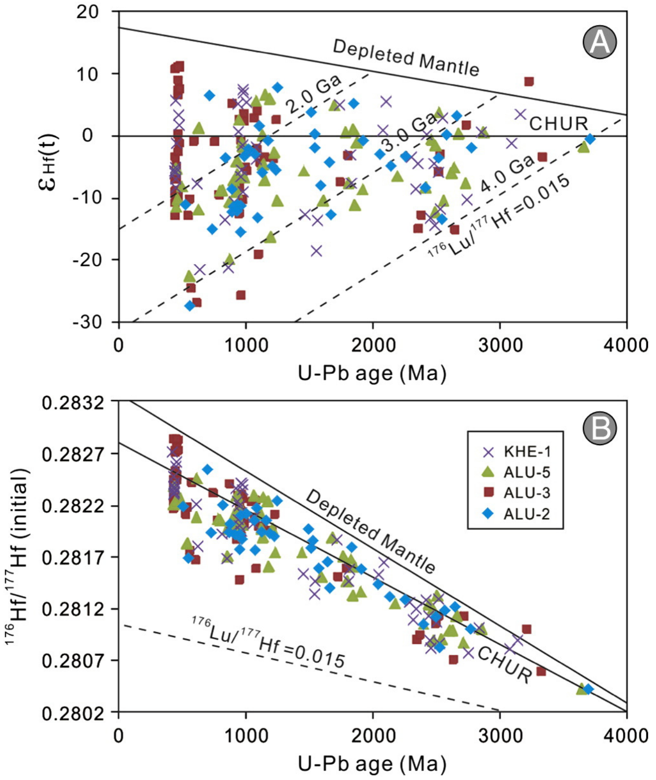

Fig. 6. Plots of crystallization ages versus (a) $\varepsilon_{Hf}(t)$, and (b) $^{176}Hf/^{177}Hf$ for all detrital zircon. CHUR: Chondritic Uniform Reservoir; dashed lines show the evolution of crustal volumes with $^{176}Hf/^{177}Hf = 0.015$, corresponding to the average continental crust.

$^{206}Pb/^{238}U$ (<1000 Ma) and $^{207}Pb/^{206}Pb$ (>1000 Ma) ages range from 3646 to 447 Ma. There are two major age peaks at ca. 921 Ma and 1127 Ma, along with five subordinate age peaks at ca. 448 Ma, 610 Ma, 1829 Ma, 2495 Ma and 2633 Ma.

4.1.3. Sample ALU-3

Of the 69 analyses conducted on 69 zircons for this sample, 67 analyses are concordant within uncertainties (Fig. 5C). The measured $^{206}Pb/^{238}U$ (<1000 Ma) and $^{207}Pb/^{206}Pb$ (>1000 Ma) ages range from 3327 to 443 Ma. There are two major age peaks at ca. 448 Ma and 965 Ma, with two subordinate age peaks at ca. 1083 Ma and 2513 Ma.

4.1.4. Sample ALU-2

Of the 64 analyses conducted on 64 zircons for this sample, 59 analyses are concordant within uncertainties (Fig. 5D). The measured $^{206}Pb/^{238}U$ (<1000 Ma) and $^{207}Pb/^{206}Pb$ (>1000 Ma) ages range from 3699 to 516 Ma. There is one major age peak at ca. 957 Ma, along with a number of subordinate age peaks at ca. 706 Ma, 1076 Ma, 1216 Ma and 2516 Ma and one “broad” age group between 1669 Ma and 1506 Ma.

4.2. Zircon Lu–Hf isotopic composition

LA-MC-ICP-MS zircon Lu–Hf isotope measurements were performed after LA-ICP-MS U–Pb dating. One hundred ninety-nine dated zircon grains from the four samples were selected for in situ Lu–Hf isotopes analyses. The result shows a broad range of the in initial $^{176}Hf/^{177}Hf$ ratios from 0.280450 to 0.282809, with the $\varepsilon_{Hf}(t)$ values of -27.2 to $+11.2$ (Appendix A and Fig. 6). The Archean zircons display $\varepsilon_{Hf}(t)$ values mostly between -5.7 and $+3.7$ and the Proterozoic zircons have $\varepsilon_{Hf}(t)$ values ranging from -27.2 to $+7.7$. The Paleozoic zircons show $\varepsilon_{Hf}(t)$ values between -12.8 and $+11.2$. The Hf isotopic model ages (T_{DM2}) for these zircons range from 3.93 to 0.67 Ga, with a concentration in 2.2–1.4 Ga (Appendix A and Fig. 7).

4.3. Zircon trace elements

In this study, most of the zircons are enriched in heavy REE compared to light REE, and show a distinctive positive Ce anomaly as well as negative Eu anomaly (Appendix A and Fig. 8), consistent with crystallization from granitoid, pegmatite, or dolerite (Hoskin and Ireland, 2000; Belousova et al., 2002). All zircons are enriched in HREE except for three grains with flatter REE patterns, which probably represent

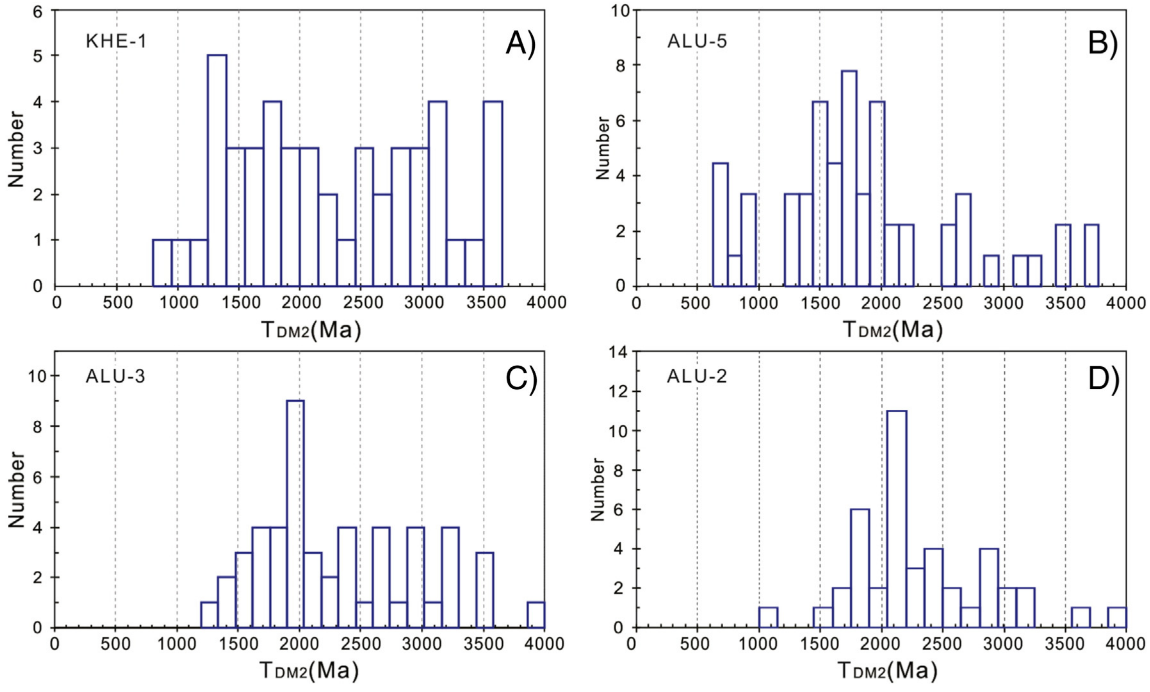

Fig. 7. Histograms of the two-stage Hf model ages for detrital zircons.

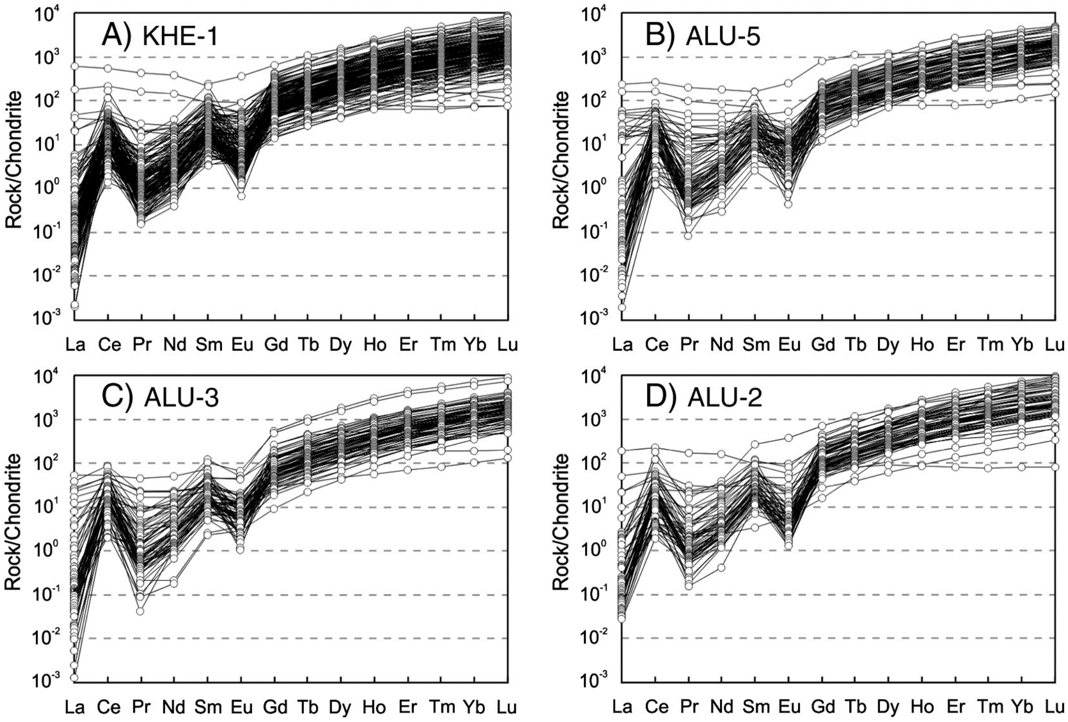

Fig. 8. Chondrite-normalized REE diagrams of detrital zircon from Cambrian to Devonian sedimentary rocks in the Truong Son Belt. The chondrite values are from Sun. and McDonough (1989).

the differences in source material or subsequent metamorphism (Whitehouse and Platt, 2003). The contents of REE range from 69 to 3722 ppm, suggests that these grains are most likely typical crust-derived magmatic zircons (Heaman et al., 1990; Hoskin and Ireland, 2000; Hoskin and Schaltegger, 2003).

5. Discussion

5.1. The depositional ages of the studied strata

The youngest U–Pb age of the detrital zircons from sedimentary rocks provide a maximum age of deposition and may approximate the depositional age in cases where there is continuous magmatism and sedimentation (Dickinson and Gehrels, 2009; Cawood et al., 2012). The depositional ages of the strata in Truong Son Belt were not well defined in the past (Khuc, 2011). U–Pb ages of detrital zircon in the Paleozoic sedimentary rocks give new maximum estimates for the timing of deposition of the Cambrian–Middle Ordovician, Upper Ordovician–Silurian and Lower Devonian. The youngest zircon from Cambrian–Middle Ordovician sample (ALU-2) gives an age of ca. 516 Ma. Samples ALU-3, ALU-5 and KHE-1 yield minimum zircon ages of about 443 Ma, 446 Ma and 443 Ma, respectively, indicates that the maximum depositional age of Upper Ordovician–Silurian and Lower Devonian was ca. 443 Ma. The zircon data suggests that late Ordovician to early Silurian igneous rocks were the source of the younger zircon grains in the Upper Ordovician–Silurian and Lower Devonian sedimentary rocks but not the inferred Cambrian–Middle Ordovician strata. Therefore, we infer that the deposition age of Cambrian–Middle Ordovician in the Truong Son Belt was between 516 Ma and 443 Ma.

5.2. Source of detrital zircons

Detrital zircon of Paleozoic sedimentary rocks in the Truong Son Belt record a geological history from Paleoarchean to Paleozoic, as illustrated in Fig. 5. CL images (Fig. 4), REE patterns (Fig. 8) and Th/U values (Appendix A) reveal that the majority of the zircon grains are of magmatic origin, with only a small amount of obviously metamorphic zircon grains.

The zircon populations at ca. 446 Ma and 448 Ma in ALU-3, ALU-5 and KHE-1 are mostly having euhedral-subhedral shapes (Fig. 4), suggestive of a short transportation from the local source region. Coeval granitic rocks in the Truong Son Belt and adjacent areas yield zircon ages ranging from 460 to 400 Ma (Carter et al., 2001; Usuki et al., 2009; Tran et al., 2014; Shi et al., 2015), and were likely the source of the detritus. In addition, the range of ages in our samples yielded εHf(t) values of −11.83 to +11.15 with model ages between 674 Ma and 1847 Ma (Appendix A), suggesting that they were derived from reworking of Mesoproterozoic crust (1200–1850 Ma) and some juvenile crustal materials older than 670 Ma.

The late Neoproterozoic to middle Cambrian (700–500 Ma) and middle Mesoproterozoic to early Neoproterozoic (1300–900 Ma) tectonic events were not dominate events in the eastern Indochina Block. Zircons of these ages were likely sourced from areas outside of Indochina. The late Neoproterozoic to middle Cambrian zircons are dominated by grains about 600 Ma and could have been derived from magmatic or orogenic provinces that predate Gondwana assembly in East Africa or Western Australia (Meert and Van Der Voo, 1997; Cawood and Buchan, 2007; Cawood and Korsch, 2008; Wang et al., 2014). The Grenville orogeny and synchronous events (1300–900 Ma) are widely recorded in Laurentia and Gondwana and are related to the orogenic events that formed the Rodinia supercontinent (Hoffman, 1991; Wingate et al., 2002; Meert and Torsvik, 2003; Li et al., 2008). The large population of ca. 950 Ma zircons in the Indochina strata is similar to detrital zircons of similar ages (ca. 940 Ma) in Ordovician sedimentary rocks of the Qiangtang Block (Fig. 9). Zircons of this age could have ultimately been derived from rocks in the Tethyan Himalaya or parts of East Gondwana, particularly India or Antarctica (Zhu et al., 2011). Grenvillian zircon ages between 1300 Ma and 1100 Ma in the Indochina strata are similar in age to zircons also within Lhasa terrane strata (Leier et al., 2007; Dong et al., 2010) (Fig. 9). These zircons of this age may have ultimately originated from the Albany-Fraser belt in southwest Australia (Zhu et al., 2011), or other parts of Gondwana.

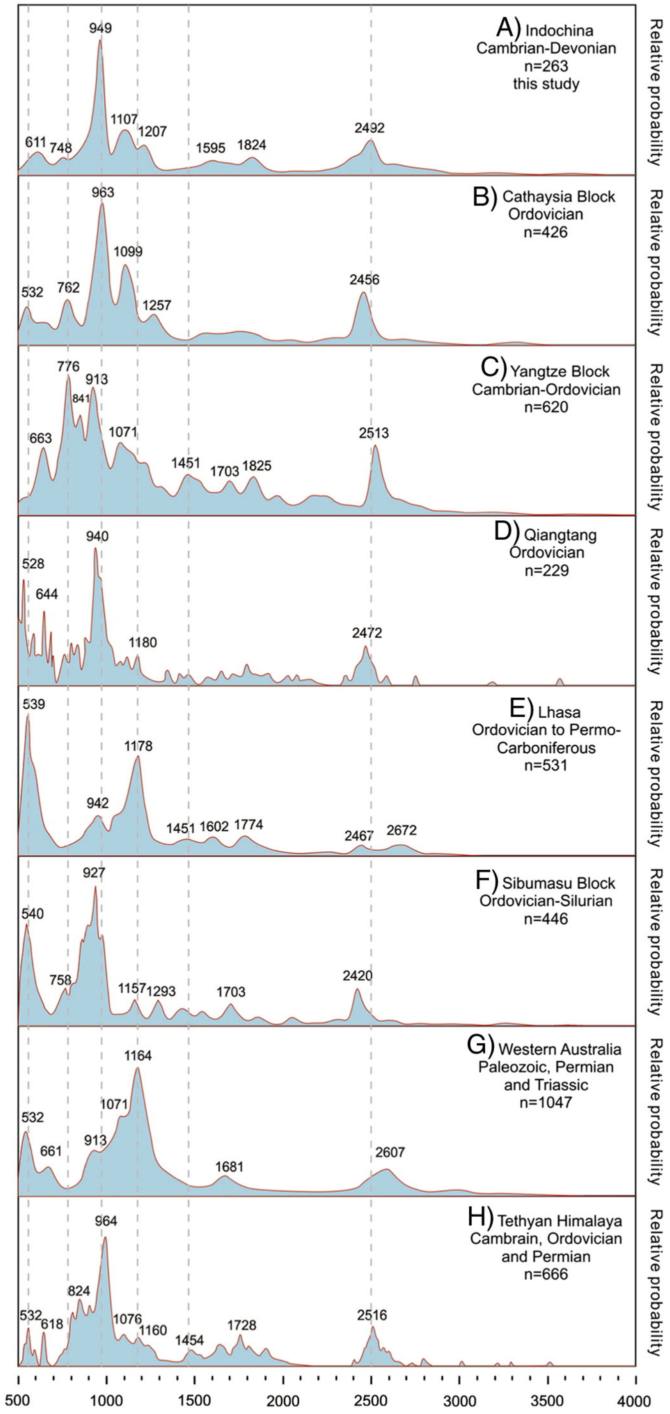

Fig. 9. Summary of detrital zircon age of distribution of sedimentary rocks of this study and previous work. Date for Cathaysia Block are from Yao et al. (2011). Date for Yangtze Block are from Wang et al. (2010). Date for Qiangtang are from Dong et al. (2011) and Zhu et al. (2011). Date for Lhasa are from Leier et al. (2007) and Zhu et al. (2011). Date for Sibumasu are from Cai et al. (in press). Date for Western Australia are from Cawood and Nemchin (2000), Veevers et al. (2005) and Condie et al. (2009).

The ca. 1595 Ma, 1824 Ma and 2492 Ma detrital zircon age populations are also likely to have been derived from sources external to the Indochina block. Similar zircon age populations are found in the strata in the Cathaysia, Yangtze and Lhasa blocks (Fig. 9). The Lu–Hf isotopic data from the Paleoproterozoic zircons with mainly negative εHf(t) values but some positive ones is consistent with greater Gondwana provenance for these grains (Fig. 6).

5.3. Gondwana affinity of Indochina

As an important tectonic element of the Indochina block, the Truong Son Belt is key to determining the paleogeography of Indochina in Gondwana. Detrital zircon age data from the Paleozoic Indochina samples is compared with the published data from potentially adjacent Gondwana fragments in Fig. 9. The detrital zircon age compositions of Cambrian–Devonian sedimentary rocks in eastern Indochina show strong similarities with blocks from East Gondwana, including: South China (Yangtze and Cathaysia), Qiangtang, Sibumasu and Tethyan Himalaya (Fig. 9). South China has close relationship with those of East Gondwana supercontinent, especially Australian Gondwana (Burrett, 1973; Metcalfe, 1988; Li et al., 1995), however, many studies also show that South China located on the north Indian margin (Yu et al., 2008; Duan et al., 2011; Cawood et al., 2013). Qiangtang has affinity with India and was likely located close to Indian margin in East Gondwana (Yin and Harrison, 2000; Dong et al., 2011; Metcalfe, 2011). Usuki et al. (2013) suggests that the Indochina was likely derived from the India–Antartica region of East Gondwana. The results from the Indochina samples are, therefore, helpful in distinguishing between these extant models for it's location in Gondwana. The Indochina detrital zircon U–Pb ages are most similar to those from strata in the Yangtze, Cathaysia and Tethyan Himalaya blocks (Fig. 9). This is consistent with these blocks having been in relatively close proximity in Gondwana with similar sedimentary provenance. This could be either from first or polycyclic detritus. The abundant late Mesoproterozoic–early Neoproterozoic and late Neoproterozoic–middle Cambrian detrial zircons are consistent with a Gondwanan provenance (Duan et al., 2011), and suggest that Indochina was in fact part of Gondwana as opposed to a discrete continental block as was suggested by Torsvik and Cocks (2009). The early Neoproterozoic zircon age population (ca. 950 Ma) from the Truong Son Belt samples is typical of the Indian margin of East Gondwana (Zhu et al., 2011). The 1200–1050 Ma zircons from samples ALU-2 and ALU-5 (Fig. 5) would be more likely to be derived from the Albany-Fraser Belt of Australia (Fitzsimons, 2000; Meert, 2003; Zhu et al., 2011). The close age spectra affinities among these blocks disintegrated from the East Gondwana are consistent with a location for Indochina and the Tethyan Himalaya, northeast of India and Western Australia in East Gondwana (Fig. 9). The εHf(t) values of detrital zircon also give us information about the paleogeography of the Indochina. The broad εHf(t) values of 700–500 Ma are similar among the Indochina, western Australia and Tethyan Himalaya, suggests that they were mainly reworked from the old continental crust (Fig. 10). The εHf(t) values of early Neoproterozoic ages from Indochina zircons have an affinities with those in the Tethyan Himalaya, whereas the late Mesoproterozoic ages are similar with the Western Australia, implying the grains were derived from both juvenile crustal materials

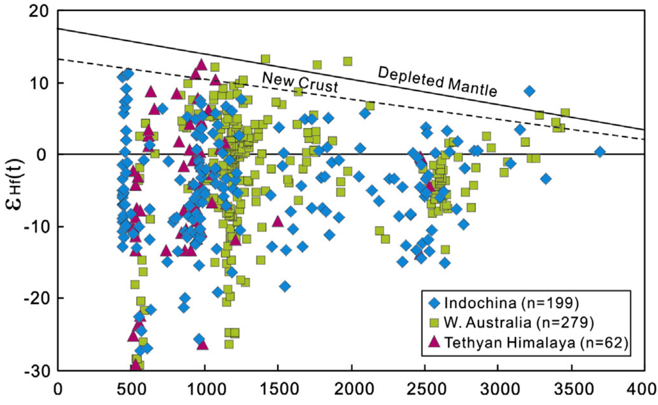

Fig. 10. Plot of $\varepsilon_{Hf}(t)$ vs. U–Pb ages of the detrital zircon from Indochina (this study), Western Australia (Veevers et al., 2005) and Tethyan Himalaya (Zhu et al., 2011). The New Crust line is from Dhuime et al. (2011).

and reworked continental crust. On the basis of these data we infer that the Indochina Block was most likely located close to the Tethyan Himalaya block along the northern margin of the India and northwestern margin of Australia in Gondwana (Fig. 11).

6. Conclusions

We draw the following conclusions based on the integrated in situ U–Pb, Lu–Hf isotopes and REE geochemistry analyses of detrital zircons from the Cambrian to Devonian sedimentary rocks in the Truong Son Belt of Indochina Block.

(1) Detrital zircon U–Pb age reveal two major age peaks at ca. 445 Ma and 964 Ma, along with three subordinate age peaks at ca. 1454 Ma, 1728 Ma and 2516 Ma and two "broad" age groups of 618–532 Ma and 1160–1076 Ma.
(2) The deposition age of Cambrian–Middle Ordovician in the Truong Son Belt occurred between ca. 516 Ma and 443 Ma. Detrial zircon ages from Upper Ordovician–Silurian and Lower Devonian strata give maximum depositional ages of 443 Ma.
(3) The younger zircon grains with age peak at ca. 445 Ma were apparently derived from late Ordovician to early Silurian igneous and metamorphic rocks in Indochina Block, whereas the older than 600 Ma are exotic or recycled from the Precambrian basement of the Indochina Block.
(4) The detrital zircon data suggests that Indochina Block having been located near the northern margin of India and northwestern Australia in Gondwana.

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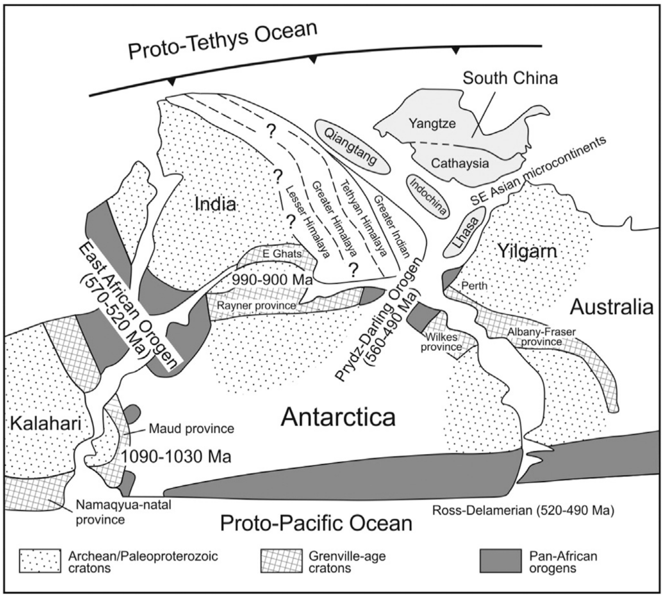

Fig. 11. Location of the Indochina Block along the northern margin of the assembled East Gondwana during 530–470 Ma, modified after Cawood et al. (2007), Cawood et al. (2013), Wang et al. (2010), Xu et al. (2013) and Xu et al. (2014).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.tecto.2016.04.008.

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