Precambrian Research 308 (2018) 92–110

Contents lists available at ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

Component variation in the late Neoproterozoic to Cambrian sedimentary rocks of SW China – NE Vietnam, and its tectonic significance

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ARTICLE INFO

Keywords:
Late Neoproterozoic – Cambrian
Detrital zircon U-Pb-Hf isotopes
Geochemistry
Provenance change
SW South China – NE Vietnam
Yangtze/Cathaysia boundary

ABSTRACT

The Nanwenhe-Song Chay (NSC) area straddles the border of SW China and NE Vietnam, at the tectonic junction of the Yangtze, Cathaysia, and Indochina blocks. However, the lack of a systematic understanding of the basement rocks in this area has led to a debate about its tectonic affinity. This study presents integrated bulk geochemical and zircon U-Pb-Hf isotopic data for the basement rocks in the NSC area. Zircon U-Pb dating results suggest that the Mengdong Group in SW China and the Thac Ba Formation in NE Vietnam were deposited in the late Neoproterozoic (< 619–592 Ma), while the Tianpeng Formation in SW China and the Ha Giang Formation in NE Vietnam were deposited in the Cambrian (< 527–507 Ma). Bulk geochemical data and zircon Hf-isotope compositions indicate that the sources of these sedimentary rocks were dominated by felsic rocks. The sources of the late Neoproterozoic sedimentary rocks probably underwent weaker weathering under drier and colder conditions than those of the Cambrian ones. The late Neoproterozoic Mengdong Group and the Thac Ba Formation contain abundant 802–747 Ma zircons. Their age distributions and the Hf-isotope compositions are similar to those of Neoproterozoic sedimentary rocks in the southern Yangtze Block (Fanjingshan-Sibao area). In contrast, the Cambrian Tianpeng and Ha Giang formations are characterized by Grenvillian detrital zircons with an age peak at ~980 Ma. The age spectra and Hf-isotope compositions of the detrital zircons from these rocks are similar to those in the Cathaysia Block (Nanling-Yunkai area) and/or Indochina Block.

Integration of our data with published geological data suggests that the Precambrian basement under the NSC area is the part of the Yangtze Block. Thus, the western boundary between Yangtze and Cathaysia blocks must be located to the south or southeast and the boundary between the South China and Indochina blocks should be to the southwest of the NSC area.

Numerous Pan-African (600–500 Ma) detrital zircons and the diagnostic age spectra of detrital zircons in the early Paleozoic sedimentary rocks indicate that the SCB was located at the northern margin of East Gondwana during the early Paleozoic. The dramatic change in the clastic components from the late Neoproterozoic to Cambrian sedimentary rocks suggests that the NSC area was probably affected by the Pan-African orogeny.

1. Introduction

Southeast Asia has been built up by the amalgamation of many Gondwana-derived Precambrian microcontinents, including South China, Indochina, Sibumasu and west Burma (Metcalfe, 1996, 2002). The South China Block (SCB) consists of the Yangtze Block to the northwest and Cathaysia Block to the southeast, which were joined along the Jiangshan-Shaoxing fault during the early to middle Neoproterozoic (Gao et al., 2009; Li et al., 1994, 2009; Shu et al., 1994, 2006; Shu, 2012; Wang et al., 2007a, 2008b). The compositions and evolution of the Precambrian basements of the Yangtze and Cathaysia blocks are different (Yu et al., 2010; Zhao and Cawood, 2012; Zhang and Zheng, 2007; Zheng and Zhang, 2007). However, the southwest extension of the boundary between the Yangtze and Cathaysia blocks has not been well constrained. Different faults have been considered as the boundary in past decades (Fig. 1a), including the Wuchuan-Sihui

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https://doi.org/10.1016/j.precamres.2018.02.003
Received 30 October 2017; Received in revised form 7 February 2018; Accepted 10 February 2018
Available online 10 February 2018

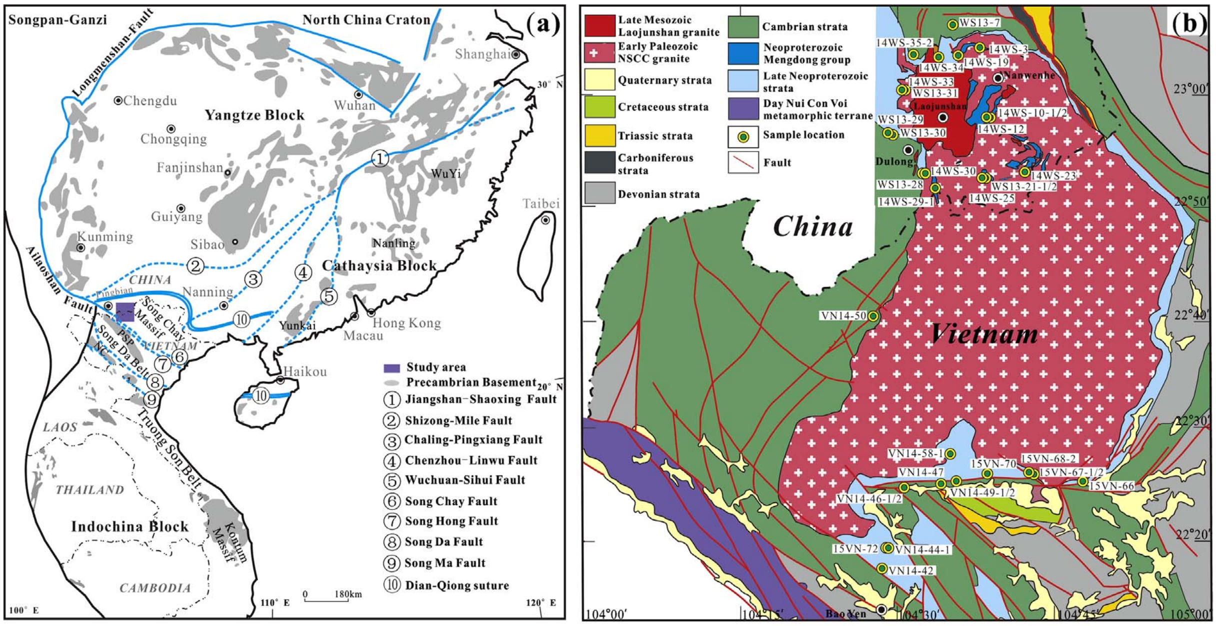

Fig. 1. (a) Simplified geological map showing the tectonic outline and distribution of Precambrian basement rocks in South China (modified after Zhao and Cawood, 2012) and Indochina (modified after Mineral resource map of Vietnam at 1: 1,000,000 scale; Usuki et al., 2009). PSP-Phan Si Pan Belt, NC-Nam Co Belt. (b) Simplified geological map and sample locations in the Nanwenhe-Song Chay area (modified after Maguan, Bac Quang and Ma Quan Geologic maps at 1:200,000 scale; Roger et al., 2000).

fault (e.g. Wang et al., 2003; Zhang and Wang, 2007), the Chenzhou-Linwu-Beihai fault (e.g. Wang et al., 2008a, 2012c), the Chaling-Pingxiang fault (e.g. Hu and Deng, 2009; Wang, 1994), and the Shizong-Mile fault (e.g. Dong et al., 2002; Guo et al., 2009).

The Indochina Block (ICB) is one of the largest continental blocks in Southeast Asia. However, the boundary between the ICB and the SCB also has been controversial. Several possibilities have been proposed, such as the Dian-Qiong (or Babu) suture (Cai and Zhang, 2009; Wu et al., 1999; Zhong et al., 1998) in southwestern China, the Song Chay (Chen et al., 2013, 2014a), the Song Hong (Findlay and Trinh, 1997; Leloup et al., 1995), Song Da (Sengor and Hsu, 1984) and the Song Ma faults (Faure et al., 2014; Lepvrier et al., 1997, 2008; Metcalfe, 2013; Tran and Khuc, 2011) in North Vietnam (Fig. 1a). These NW-striking faults divide Northern Vietnam into several terranes. Each of them has experienced a complex tectonic evolution history. These terranes recorded not only the collision between the SCB and ICB, but also Tertiary tectonic events in Northern Vietnam, which are related to the India-Asia collision and the subsequent lateral extrusion of the Indochina Block along the Red River shear zone (Gilley et al., 2003; Leloup et al., 1995, 2001; Tapponnier et al., 1990). Therefore, previous studies on Northern Vietnam have mostly focused on the tectonic, metamorphic and igneous activity associated with both collision events (Anczkiewicz et al., 2007, 2012; Chen et al., 2014a; Faure et al., 2016a, 2016b; Halpin et al., 2016; Leloup et al., 1995; Liu et al., 2012b; Wang et al., 1998; Liu et al., 2012a), whereas only a small number of studies have examined the Precambrian basement rocks, such as those in the Phan Si Pan Belt that lies between the Song Da and Song Chay faults (Fig. 1a; Hoang et al., 2015; Lan et al., 2001;Nam et al., 2003; Pham et al., 2012; Wang et al., 2016a).

The Nanwenhe (SW China) - Song Chay (NE Vietnam) area (NSC) has been attributed to the Yangtze Block (e.g. Wang et al., 2016a; Zhou et al., 2014), the Cathaysia Block (e.g. Cheng and Mao, 2010; Guo et al., 2009; Xu et al., 2015), or the ICB (Cai and Zhang, 2009). These uncertainties are mainly ascribed to the lack of a systematic understanding of the Precambrian basement rocks in this area. No Precambrian basement has been studied in detail in NE Vietnam until now. In this study, we present a suite of bulk geochemical data of the Neoproterozoic-Cambrian meta-sedimentary rocks and U-Pb geochronology and Hf-isotope compositions of detrital zircons from these rocks in the NSC area, aiming to decipher the detrital components, provenance features and depositional environments of these sedimentary rocks, and to sort out the affinity of the NSC basement with the Yangtze, Cathaysia or Indochina blocks and the crustal evolution of their provenances. This will help us to clarify the tectonic attributes of the NSC area and consequently to constrain the boundary between the Yangtze and Cathaysia blocks as well as between the South China and Indochina blocks.

2. Regional geology and sample petrography

The Precambrian basement rocks in Northern Vietnam are dominantly distributed in the Song Da Belt between the Song Ma fault and Song Hong fault, including the Phan Si Pan and Nam Co belts (Fig. 1a). The Phan Si Pan Belt, which outcrops to the southwest of the Song Hong fault, mainly consists of middle Archean, Paleoproterozoic and Neoproterozoic metamorphic igneous rocks and Paleoproterozoic - Neoproterozoic meta-sedimentary rocks (Fan et al., 2010; Lan et al., 2001; Nam et al., 2003; Pham et al., 2009, 2012; Wang et al., 2011, 2016a). The Nam Co Belt, exposed to the northeast of the Song Ma fault, is comprised of Neoproterozoic sedimentary rocks that have undergone greenschist to lower amphibolite facies metamorphism (Faure et al., 2014).

Our study area is located on the northeastern side of the Song Chay fault, southwest of the Dian-Qiong suture and southeast of the Shizong-Mile fault (Fig. 1a). In the Nanwenhe area of SE Yunnan province, China, the oldest Precambrian sequences generally have been assigned to the Paleoproterozoic Mengdong Group, which occurs as large irregular bodies or relicts exposed within the centre of the Nanwenhe granite (BGMRYN, 1999). However, recent research suggests that it was probably formed in Neoproterozoic time (Guo, 2006; Liu et al., 2006). The lower part of the Mengdong Group is mainly composed of two-mica schist and quartz schist interbedded with amphibolite and gneiss, and the upper part is dominated by leptynite and quartzite. The Xinzhai Formation, exposed in the periphery of the Nanwenhe granite, is considered to be Neoproterozoic, younger than the Mengdong Group (BGMRYN, 1999), and consists mainly of mica schist, and quartz schist interbedded with fine-grained impure marble. The Cambrian strata are

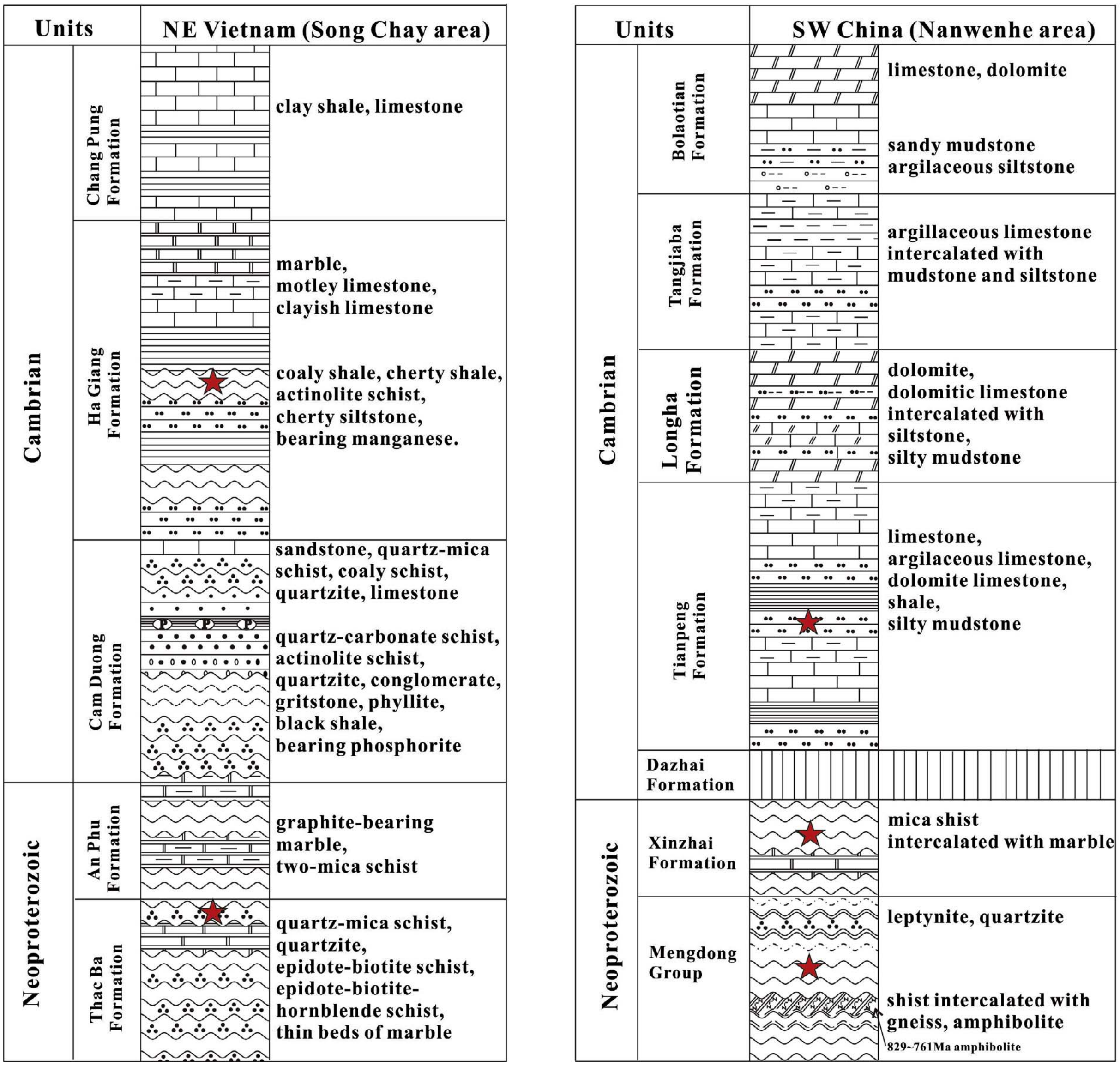

Fig. 2. Simplified stratigraphic columns of Late Neoproterozoic to Cambrian strata in the Nanwenhe area, SW South China and Song Chay area, NE Vietnam (after BGMRYN, 1990, 1999; DGMV, 2000; Zhang, 1996). The columns are not strictly to scale.

divided, from the base upward, into the Dazhai, Tianpeng, Longha, Tangjiaba and Bolaitian formations (Fig. 2). The Dazhai Formation is not exposed in the study area. The Tianpeng Formation is made up of a succession of limestone, shale, and silty mudstone. The lithology of the Longha Formation is dolomite, dolomitic limestone with less siltstone, and silty mudstone. The Tangjiaba Formation consists mainly of argillaceous limestone, intercalated with thin layers of mudstone and siltstone. The Bolaitian Formation contains massive limestone and dolomite in its upper part and sandy mudstone and siltstone in its lower part (Fig. 2; BGMRYN, 1999; Zhang, 1996).

In the Song Chay area, NE Vietnam, the Song Chay Group was defined as Neoproterozoic to early Cambrian strata, which are divided into the Thac Ba and An Phu formations. The former is dominated by quartzite, mica schist, epidote-plagioclase-hornblende schist with less interbedded marble, while the latter is composed mainly of graphite-bearing marble and two-mica schist. The overlying Cambrian successions consist of the Cam Duong, Ha Giang and Chang Pung formations. They are composed mainly of meta-sandstone, black schist and phyllite, with lesser marble (Fig. 2). The Cambrian strata and the Song Chay Group are intruded by the early Paleozoic Song Chay granite, which together with the Nanwenhe granite, constitutes the huge Nanwenhe-Song Chay complex (NSCC) (Zhou et al., 2017). A series of ductile detachment fault zones developed between these Neoproterozoic to Cambrian sedimentary rocks and the NSCC. The late Mesozoic Laojunshan granitic pluton intruded the northwestern corner of the NSCC (Fig. 1b). The NSCC and the circumjacent Neoproterozoic-Cretaceous sedimentary sequence have been defined as the Laojunshan-Song Chay metamorphic core complex (Liu et al., 2003; Roger et al., 2000). The metamorphic grade changes sharply from lower amphibolite facies near the NSCC to the unmetamorphosed cover sequence further from the NSCC.

In order to reveal the relationship of the basement rocks in the study area with those in the Yangtze, Cathaysia or Indochina blocks, fifty-one samples were collected. Based on their petrologic features and distribution, eighteen of them in the Nanwenhe area (SW China) and eleven in the Song Chay area (NE Vietnam) were chosen for further bulk geochemical analyses, and fourteen samples were chosen for zircon U-Pb dating. Based on the zircon age spectra and CL images, eight samples were selected for Lu-Hf isotopic analyses. These samples mostly show gneissose, schistose or phyllitic structures (Fig. 3a-d). The samples from the Cambrian Tianpeng and Ha Giang formations are mainly schists, which contain primarily quartz, biotite and muscovite

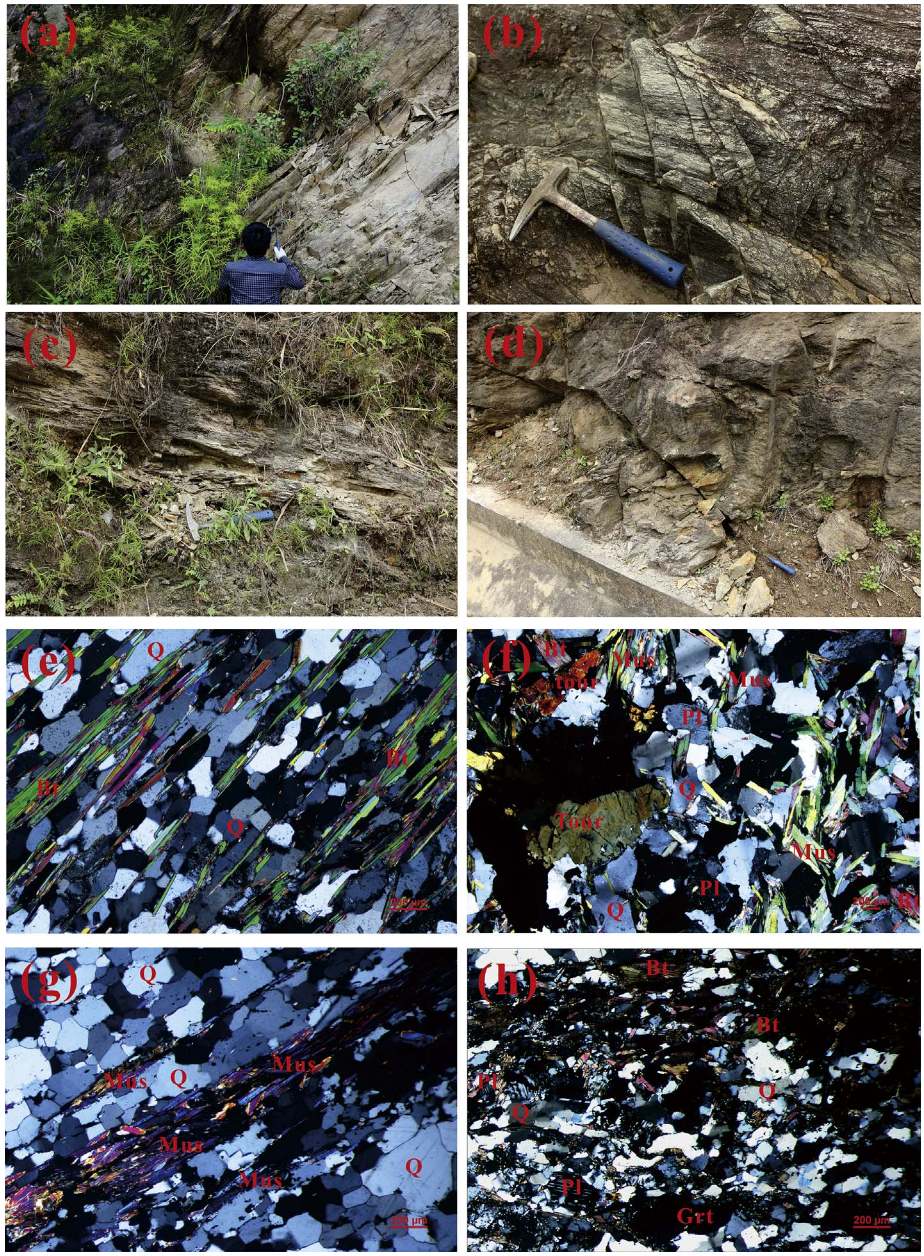

Fig. 3. (a–d) Outcrop features of the Tianpeng Formation (a), Mengdong Group (b), Ha Giang Formation (c), and Thac Ba Formation (d). Hammer is 28 cm long. (e–h) Photomicrographs of represented samples in the NSC area: (e) biotite schist of Tianpeng Formation; (f) tourmaline-bearing two-mica gneiss of Mengdong Group; (g) fine-grained muscovite quartzite of Ha Giang Formation; (h) garnet-bearing biotite quartz schist of Thac Ba Formation. Bt-biotite, Pl-Plagioclase, Grt-Garnet, Mus-Muscovite, Q-Quartz, Tour-Tourmaline.

with minor plagioclase (Fig. 3e, g). Gneiss, schist and minor quartzite from Neoproterozoic Mengdong Group, Xinzhai and Thac Ba formations are dominated by quartz, plagioclase, biotite, and muscovite. Chlorite, garnet and tourmaline can be found in many samples (Fig. 3f, h).

3. Analytical techniques

Whole-rock major-element concentrations for the samples collected from the Nanwenhe area, SW China were determined using an ARL-9900 X-ray fluorescence spectrometer (XRF) at the State Key Laboratory for Mineral Deposits Research, Nanjing University, with analytical precisions better than 1% for Si, Al, Fe, Mg, Ca, Na and Ti, and better than 3% for Mn and K. The samples collected from NE Vietnam were analyzed by XRF at ALS Laboratory Group's Mineral Division, ALS Chemex (Guangzhou, China) Co., Ltd., following the methods described by Zhao et al. (2015). For elements with concentrations > 1 wt%, the precision was 1–3%, and for those with concentrations < 1 wt%, the precision was approximately 10%. Trace-element concentrations were obtained at the State Key Laboratory of Ore Deposit Geochemistry in Guiyang Institute of Geochemistry, Chinese Academy of Science, using a Quadrupole ICP-MS. The analytical precisions are generally better than 5% for most elements (e.g. Sc, V, Cr, Co, Ni, Rb, Sr, Y, Zr, Nb, Ba, U, Th, Hf, Pb and REEs), and better than 10% for Cs and Ge. Detailed sample preparation and analytical procedure have been described by Qi et al. (2000).

Cathodoluminescence (CL) imaging, U-Pb dating and Hf-isotope analyses of the zircon grains were carried out at the State Key Laboratory for Mineral Deposits Research, Nanjing University, China. The zircons were separated using conventional magnetic and heavy-liquid separation techniques. Then zircon grains were handpicked under a binocular microscope, mounted in epoxy disks and polished to expose their cores. *In situ* zircon U-Pb dating was carried out using an

Agilent 7500s ICP-MS attached to a New Wave 213 nm laser ablation system. Each run consists of 4 analyses of GJ standard zircon (at the beginning and end) and 10–15 analyses of unknown zircon grains and one analysis of an external standard (Mud Tank zircon). A laser spot size of 32 μm, repetition rate of 5 Hz and energy of 10–20 J/cm^2 were used for all analyses. Detailed analytical procedures are similar to those described by Griffin et al. (2004) and Jackson et al. (2004). The results were reduced using the software GLITTER (ver. 4.4) (Griffin et al., 2008). All age calculations and plotting of Concordia diagrams were done using the ISOPLOT/Ex program (ver. 3.0) of Ludwig (2003). The $^{207}U/^{206}Pb$ ages without common-Pb correction are used for zircons with $^{207}U/^{206}Pb$ ages older than 900 Ma, and $^{206}U/^{238}Pb$ ages with common-Pb correction are accepted for younger zircons in this study (Yu et al., 2010). Discordant ages with concordance of < 85% were discarded from average age calculations and the following discussions.

In situ zircon Hf-isotope analyses were carried out using a Neptune Plus multi-collector ICP-MS, equipped with a 193 nm laser ablation system. Ablation pits of 44 μm diameter, ablation time of 35 s, a repetition rate of 10 Hz, and laser beam energy of 8 J/cm^2 were used. Before analyzing unknown samples, the Mud Tank zircon was analyzed to check instrument reliability and stability, and mean $^{176}Hf/^{177}Hf$ ratio of 0.282489 ± 0.000012 (n = 36) was obtained in our analyses, comparable with a recommended value for Mud Tank (0.282497 ± 0.000018, Hawkesworth and Kemp, 2006). The analytical conditions and procedure were similar to those described by Hou et al. (2007) and isobaric interference correction was made by the methods of Wu et al. (2006). For calculation of the initial $^{176}Hf/^{177}Hf$ ratios, the ^{176}Lu decay constant adopted in this paper is 1.865×10^{-11} per year (Scherer et al., 2001). A depleted-mantle model ($^{176}Hf/^{177}Hf$ = 0.283250, $^{176}Lu/^{177}Hf$ = 0.0384; Griffin et al., 2002) and a chondritic model ($^{176}Hf/^{177}Hf$ = 0.282772, $^{176}Lu/^{177}Hf$ = 0.0332; Blichert-Toft and Albarède, 1997) were used to calculate depleted-mantle model ages (T_{DM}) and epsilon Hf values, respectively. We have adopted a mean crustal composition ($^{176}Lu/^{177}Hf$ = 0.015; Griffin et al., 2002) to calculate a two-stage crustal model age (T_{DM}^{C}) for each zircon.

4. Analytical results

4.1. Whole-rock geochemical results

Major- and trace-element compositions of the samples from the Nanwenhe – Song Chay (NSC) area are presented in Appendix Table 1. Most samples have negative DF values (Shaw, 1972; Appendix Table 1), and plot in the sedimentary rock field in the Niggli index discrimination diagram (Winkler, 1976; the plot is omitted), suggesting that the protoliths of these metamorphic rocks from the Neoproterozoic to Cambrian strata are sedimentary rocks, consistent with their petrographic features, the presence of abundant phyllosilicate minerals and quartz (Fig. 3) and the morphology and age spectra of the zircon grains within them. The Cambrian meta-sedimentary rocks from the NSC area have similar major-element compositions (Appendix Table 1). They have relatively low SiO_2 (mostly 55.6–66.0 wt%), Na_2O (0.14–2.65 wt%), CaO (0.02–1.98 wt%) and high Al_2O_3 (11.8–21.3 wt%, mostly > 15.0 wt%), K_2O (2.91–5.64 wt%). In contrast, those from Neoproterozoic strata have slightly higher SiO_2 (mostly 57.8–73.5 wt%), Na_2O (0.15–5.35 wt%), CaO (mostly 0.71–3.88 wt%) and a little lower Al_2O_3 (9.6–19.3 wt%), K_2O (0.62–4.19 wt%). These sedimentary rocks have similar SiO_2/Al_2O_3 values (2.72–8.04) with an average of 4.31 (Appendix Table 1; Fig. 4a), similar to the Neoproterozoic sedimentary rocks from the Fanjingshan-Sibao area (average of 4.84; Wang et al., 2010a, 2012a; Wang and Zhou, 2012) and the Kunming area (average of 4.80; Sun et al., 2008; Wang et al., 2010b), southern and western Yangtze Block (Fig. 1a), but lower than those from the Nanling -Yunkai area, Cathaysia Block (average of 5.42; Wei et al., 2009; Zhou et al., 2015). K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$ ratios of sedimentary rocks may indicate the degree of the weathering and decomposition of feldspars in the source. The samples from the Cambrian Tianpeng and Ha Giang formations show generally higher K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$ than the Neoproterozoic meta-sedimentary rocks (Fig. 4b), suggesting stronger weathering and decomposition of feldspars in their source.

Most of the samples have Rb, Sr, Nb, Th, U, Ni, Cr contents lower than the Post- Archean Australian Shale (PAAS) (Fig. 5a). In the upper continental crust (UCC)-normalized spider diagram (Fig. 5a), they display roughly similar patterns, except for Ba, U and Ni. Most samples show strong depletion of Sr, and moderate depletion of Zr, Hf, Ba, U and Ni. The chondrite-normalized REE patterns of the Cambrian and Neoproterozoic samples from the NSC area are characterized by moderate to strong REE fractionation ($(La/Yb)_N$ = 5.41–20.9) and moderate negative Eu anomalies (Eu/Eu* = 0.46–0.78), which are similar to those of PAAS (Fig. 5b). Detailed comparisons indicate that the samples collected from the Song Chay area have slightly higher REE contents than those from the Nanwenhe area (Fig. 5b; Appendix Table 1), and Neoproterozoic sedimentary rocks from both areas have lower total REE (averages of 131–184 ppm) and differentiation degrees (average $(La/Yb)_N$ of 8.25–10.3) than the Cambrian sedimentary rocks, which have average REE contents of 171–218 ppm and $(La/Yb)_N$ of 11.2–12.3.

4.2. Zircon U-Pb-Hf isotopic results

4.2.1. Cambrian Tianpeng Formation in Nanwenhe area, SW China

Two schist samples (14WS-34, 14WS-35-2) from the Tianpeng Formation were chosen for zircon U-Pb-Hf isotope analyses. Zircons in both samples are small, and translucent to light brown. Rounded morphology is common, but some grains are euhedral and long-prismatic. CL images of most grains show broad compositional zoning or oscillatory zoning, and some grains have overgrowth rims and inherited cores (Fig. 6a,b).

208 analyzed detrital zircons from these two samples have Th contents of 3–850 ppm, U contents of 28–2455 ppm, and 88% of zircons have Th/U > 0.1 (Appendix Table 2). Most of the zircons give concordant U-Pb ages ranging from 3224 ± 19 Ma to 507 ± 7 Ma, and can be divided into four major age populations: ~585 Ma, ~980 Ma, 1700–1900 Ma, and ~2500 Ma. Sample 14WS-35-2 contains more Mesoproterozoic zircons with an age peak at ~1414 Ma (Fig. 7a, b). Because of Pb loss, some grains in both samples are discordant, but they roughly form two similar Discordia lines with upper and lower intercept ages at 2528–2477 Ma and 958–898 Ma (Fig. 6a, b).

$^{176}Hf/^{177}Hf$ ratios of 34 zircons from these two samples range from 0.28100 to 0.28263 with εHf(t) of −21.1 to +7.6, suggesting complex sources and origins for the magmas from which these zircons crystallized (Fig. 8a; Appendix Table 3). Eight zircons with U-Pb ages of ~1.0 Ga have large variation of εHf(t) (−20.3 to +2.8) and T_{DM}^{C} (3.07–1.73 Ga). Most Mesoproterozoic zircons have positive εHf(t) values (+2.3 to + 6.4), while the Paleoproterozoic zircons are dominated by negative εHf(t) (Fig. 8a). One 1877 ± 24 Ma grain has the lowest εHf(t) (−21.1) and an Eoarchean model age (T_{DM}^{C} = 3.8 Ga). Three Archean (~2.5 Ga) grains have positive εHf(t) varying between + 2.4 and + 5.8.

4.2.2. Neoproterozoic Mengdong Group in the Nanwenhe area, SW China

The detrital zircons separated from three Mengdong Group samples 14WS-23, 14WS-10-1 and 14WS-10-2 are transparent, subhedral to euhedral, and stubby prismatic or sub-rounded. The zircons from samples 14WS-23 and 14WS-10-1 are relatively small: 20 μm to 70 μm long and 20 μm to 45 μm wide. Most zircons have clear oscillatory zoning, and some have overgrowth rims or underwent metamictization, resulting in heterogeneous internal structures (Fig. 6c ~ e).

Zircons from samples 14WS-23 and 14WS-10-1 show similar age distributions with a concentration of Phanerozoic ages, different from sample 14WS-10-2 (Fig. 7c ~ e; Appendix Table 2). Thirty-seven

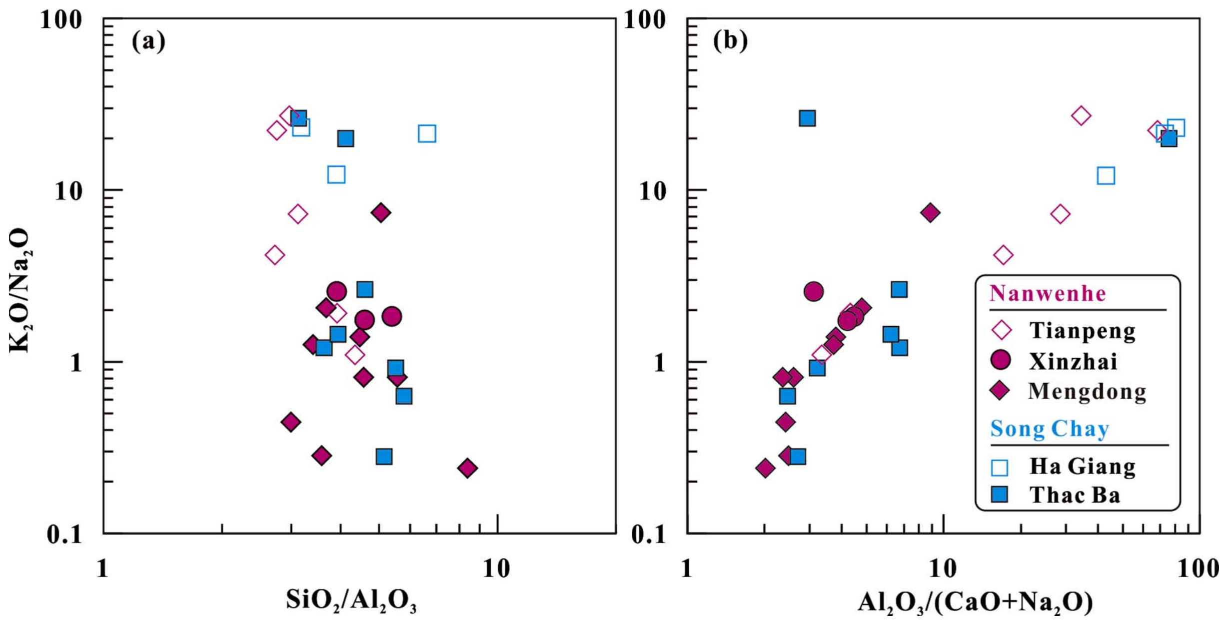

Fig. 4. Plots of SiO_2/Al_2O_3 *vs* K_2O/Na_2O (a) and $Al_2O_3/(CaO + Na_2O)$ *vs* K_2O/Na_2O (b). Pink symbol – Nanwenhe samples, blue symbol – Song Chay samples, open symbols – Cambrian samples, solid symbols – Neoproterozoic samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

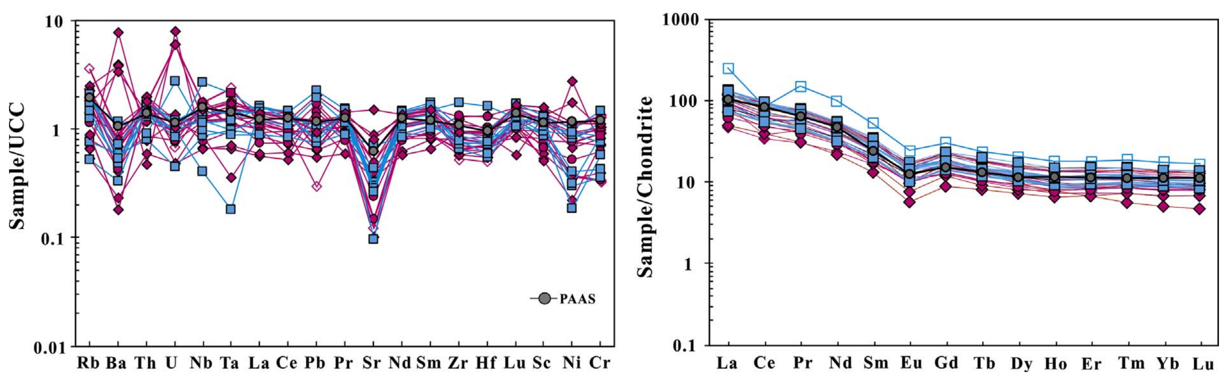

Fig. 5. (a) Upper continental crust (UCC) – normalized trace-element spider diagrams and (b) Chondrite – normalized rare earth element (REE) patterns for metasedimentary rocks from the NSC area. The UCC composition is from Rudnick and Gao (2003) and data of chondrite and PAAS are from Taylor and McLennan (1985).

concordant Phanerozoic zircons from both samples give two age peaks at ~426 Ma and ~245 Ma (Appendix Table 2). These analyses were carried out on the dark rims or on grains with planar zoning or fan-shape zoning, which together with their relatively low Th/U values (most of them < 0.2), suggests a metamorphic origin. The other 146 Precambrian zircons from these three samples have relatively high Th/U, and give concordant U-Pb ages from 2538 Ma to 619 Ma. The major age groups for samples 14WS-23 and 14Ws-10-1 range from 621 Ma to 829 Ma, with three age peaks at ~630 Ma, 743–709 Ma, 820–800 Ma (Fig. 7c, d). However, sample 14WS-10-2 shows a single age peak at 782 Ma (Fig. 7e). These Mengdong Group sedimentary rocks all contain minor Mesoproterozoic to Neoarchean materials, and sample 14WS-10-1 yields a small age group with a peak at 1838 Ma.

54 zircon grains were chosen from samples 14WS-10-1 and 14WS-10-2 for Hf-isotope analysis (Appendix Table 3; Fig. 8b). Zircons in the major age population of 829–621 Ma show a large range of εHf(t) (−6.9 to +13.0) with T_{DM}^{C} ages of 2.1–0.87 Ga, suggesting a diversity of parental-magma compositions. However, they mostly have positive εHf(t), similar to those from Neoproterozoic sedimentary rocks in the southern Yangtze Block (Fig. 8b). Three Paleoproterozoic (2.2–1.8 Ga) zircons have negative εHf(t) and similar Mesoarchean model ages (T_{DM}^{C} = 3.1–2.8 Ga).

4.2.3. Cambrian Ha Giang Formation in the Song Chay area, NE Vietnam

Detrital zircons in samples VN14-46-2 and VN14-49-2 from the Cambrian Ha Giang Formation are transparent to light brown, anhedral to euhedral and 40 μm to 140 μm long, with aspect ratios of 1.5:1–2.5:1 (Fig. 6f, g). These zircons generally have oscillatory zoning, typical of a magmatic origin, but some grains show no or irregular internal structure.

155 zircon grains in these two samples yield a large range of Th (15–2518 ppm), U (22–3272 ppm) and Th/U (0.12–5.37) (Appendix Table 2). The largest population of zircons gives concordant Grenvillian ages with a peak at *ca* 983 Ma (Fig. 7f, g). Mesoproterozoic to Archean grains define three small age populations of 1248–1221 Ma, 1814–1545 Ma, and 2517–2430 Ma. Many Archean ages are quite discordant, but some of them fall along discordia lines with upper intercepts at 2443 Ma, 2495 Ma and 3055 Ma (Fig. 6f, g). The youngest concordant age of detrital zircons in these two samples is 527 ± 7 Ma and the oldest one is 3054 ± 27 Ma.

Hf-isotope compositions were analyzed in 42 grains from sample VN14-46-2 (Fig. 8a; Appendix Table 3). Grenvillian zircon grains have εHf(t) values of −17.1 to +3.0 and T_{DM}^{C} of 2.9–1.6 Ga, showing a higher proportion of zircons with negative εHf(t) than those from the Cambrian Tianpeng Formation in the Nanwenhe area. Mesoproterozoic (1.6–1.1 Ga) detrital zircons all have negative εHf(t) varying from −14.0 to −0.87. The grain with the lowest εHf(t) (−14.0) has a

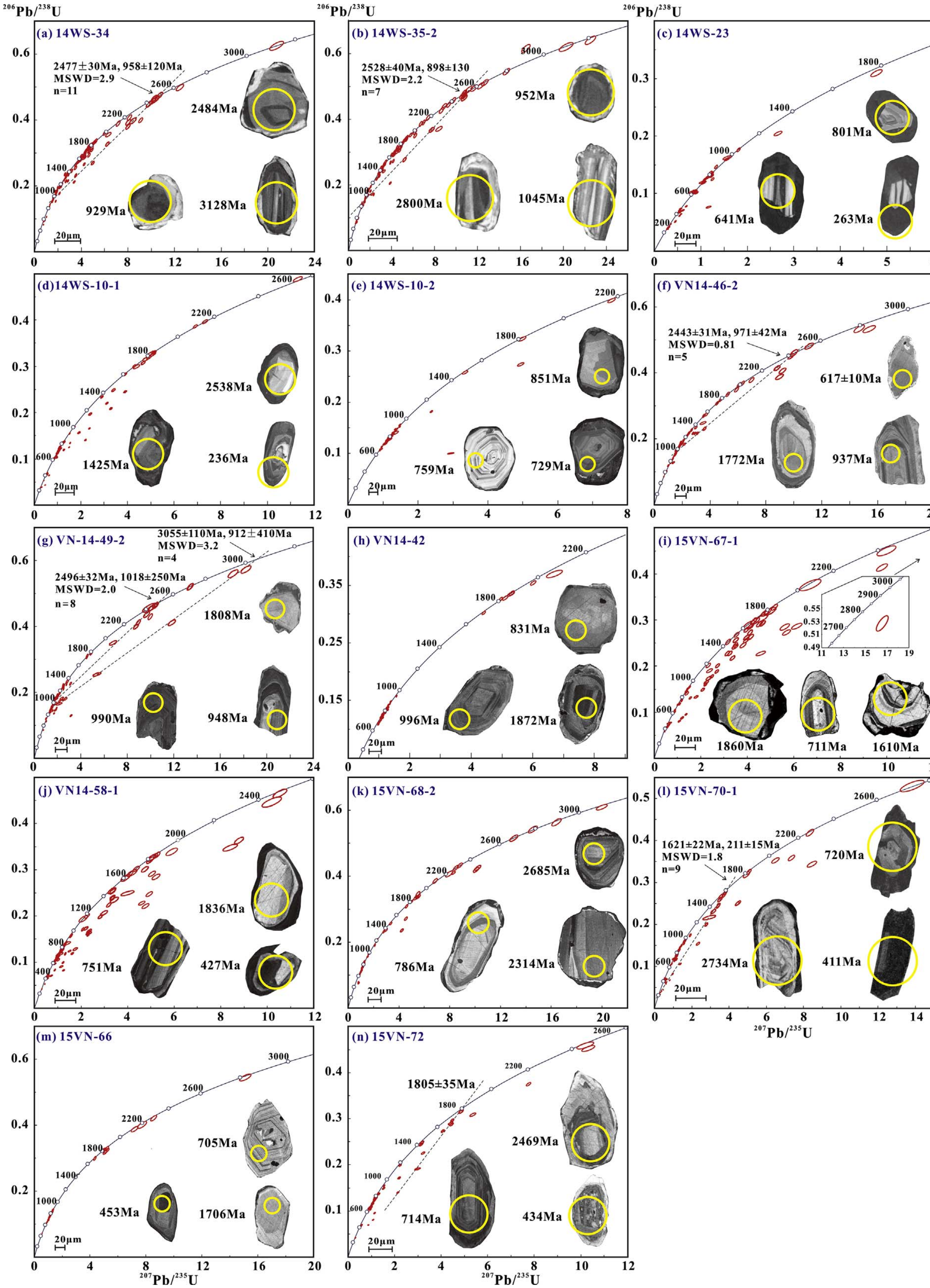

Fig. 6. Zircon U-Pb Concordia plots and CL images of representative zircons from the metasedimentary rocks in the NSC area. Solid yellow circles are spots for U-Pb isotope analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

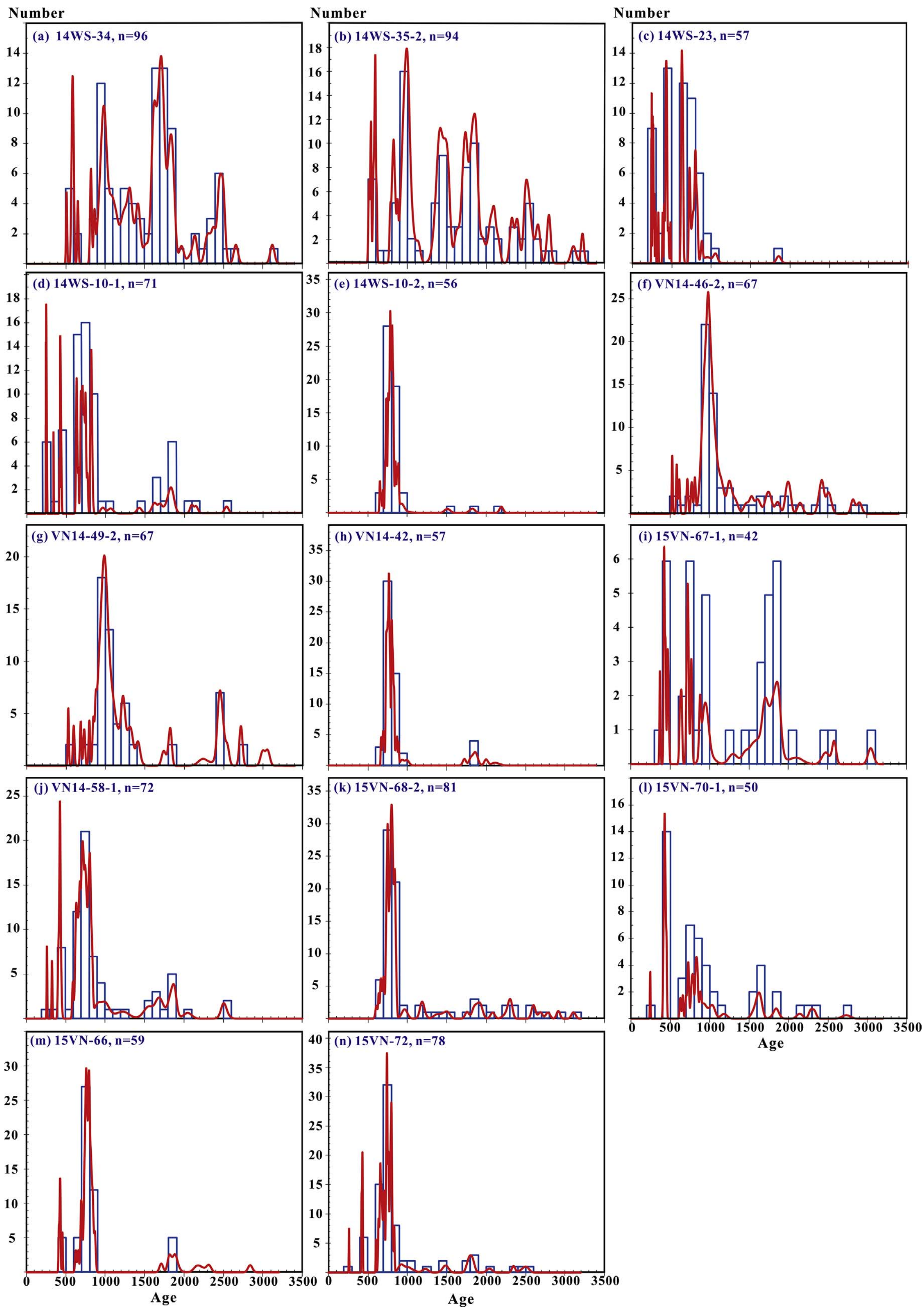

Fig. 7. Age spectra of the detrital zircons from the metasedimentary rocks in the NSC area.

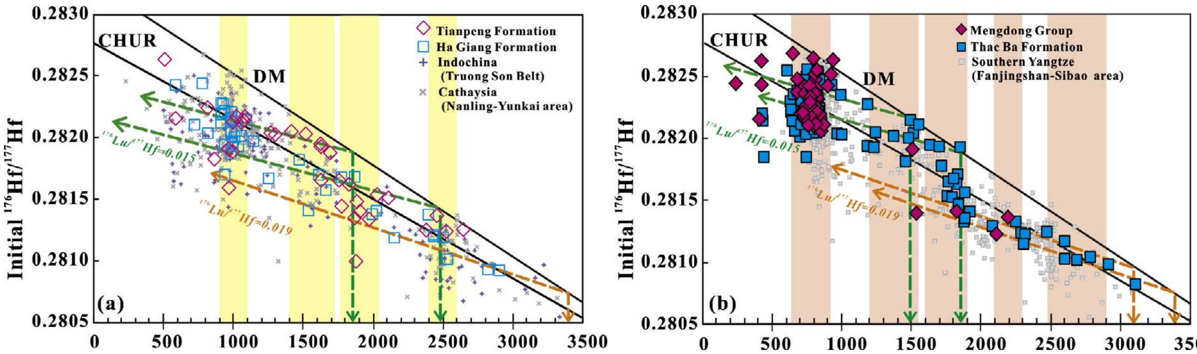

Fig. 8. Hf isotope compositions of detrital zircons in the sedimentary rocks from the study area, southern Yangtze Block (Wang and Zhou, 2012; Wang et al., 2010a, 2012a), Cathaysia Block (Wang et al., 2008d; Xu et al., 2013; Yu et al., 2008, 2010) and Indochina Block (Wang et al., 2016b).

Mesoarchean T_{DM}^{C} age (ca 3.1 Ga). Paleoproterozoic zircons show a large variation in εHf(t), from −7.97 to +4.30. Three zircons with 2.9–2.5 Ga ages all have negative εHf(t) of −5.5 to −0.1 and similar Mesoarchean T_{DM}^{C} ages (3.4–3.3 Ga).

4.2.4. Neoproterozoic Thac Ba Formation in Song Chay area, NE Vietnam

Seven metasedimentary rocks from the Thac Ba Formation (VN14-42, 15VN-67-1, VN14-58-1, 15VN-68-2, 15VN-70-1, 15VN-66, 15VN-72) were collected from the south part of the NSCC (Fig. 1b) for zircon U-Pb dating. Zircons in these samples have subrounded-rounded, stubby or irregular shapes, with a few euhedral prismatic grains. The CL images of most zircons show oscillatory zoning, and a few have planar zoning, weak zoning or overgrowth rims (Fig. 6 h ~ n). Like those in sample 14WS-23 from the Nanwenhe area, many zircons from sample 15VN-70-1 have broad dark rims (Fig. 6c, l).

A total of 547 zircon grains from these 7 samples were dated (Appendix Table 2). They mostly have concordance > 85% and Th/U > 0.3. The most notable feature of these samples is a large population of Neoproterozoic zircons with concordant ages between 900 Ma and 620 Ma, and striking age peaks at 836–714 Ma (Fig. 7 h ~ n). The other two zircon groups are Paleoproterozoic, with age peaks at 1710–1617 Ma and 1884–1807 Ma. Concordant Mesoproterozoic zircons make up a small proportion of these samples. Thirteen Archean detrital zircons in these samples have concordant ages ranging from 3105 Ma to 2501 Ma without any significant age peak.

Furthermore, the samples from the Thac Ba Formation commonly contain many early Paleozoic (Caledonian) zircons and five late Paleozoic (366–240 Ma) zircons. These Phanerozoic ages are mostly obtained from the dark rims, overgrowth rims or zircon grains with little zoning, planar zoning or heterogeneous internal structures, suggesting a metamorphic origin. However, they have a range of Th/U (0.12–2.53), and a few grains have euhedral and prismatic morphology with oscillatory zoning. These features indicate that some of them probably represent anatectic zircons. Pb loss from older zircons and the growth of metamorphic zircons probably are the response to widespread Indosinian and Caledonian tectonothermal events in this area. With the exception of these metamorphic zircons, the youngest concordant age of detrital zircons is 592 ± 8 Ma.

129 zircons in three samples 15VN-68-2, 15VN-72 and VN14-58-1 were chosen for Hf-isotope analysis (Fig. 8b; Appendix Table 3). The results show that most Neoproterozoic zircons with U-Pb ages of < 730 Ma have negative εHf(t); only 4 of 24 grains have positive εHf(t). The main (730–856 Ma) zircon group exhibits a broad range of εHf(t), mostly between −9.8 and +10.0. One ~745 Ma grain has the lowest εHf(t) of −16.4, corresponding to an Archean T_{DM}^{C} age (2.67 Ga). All but three of the Mesoproterozoic zircons have positive εHf(t), and all early Paleoproterozoic (2.0–2.3 Ga) zircons have negative εHf(t), but late Paleoproterozoic (1.6–1.9 Ga) grains exhibit variable εHf(t) (−9.5 – +8.1) (Fig. 8b). Archean (3.1–2.5 Ga) grains have εHf(t) near zero and T_{DM}^{C} ages of 3.4–2.9 Ga.

5. Discussion

5.1. The depositional and metamorphic ages of meta-sedimentary rocks in the NSC area

The basement metamorphic rocks around the Nanwenhe-Song Chay Complex in SE Yunnan and NE Vietnam were poorly studied before, and their depositional ages constrained loosely, due the degree of metamorphism. The results of this study can provide significantly better constraints on the depositional age of these sequences. The youngest detrital zircons in two Tianpeng Formation samples are 507 Ma and 508 Ma, suggesting that the deposition of Tianpeng Formation did not occur before 507 Ma. The Tianpeng Formation is intruded by the 423–436 Ma Nanwenhe-Song Chay granitic Complex (Zhou et al., 2017), and therefore must be deposited between 507 and 436 Ma. This age is consistent with the typical middle Cambrian Trilobita identified in this formation and the overlying Longha Formation (Zhu et al., 2011a; Zhang, 1996). The samples from the Ha Giang Formation in the Song Chay area have an age distribution similar to the Tianpeng Formation and yield a maximum depositional age of 527–529 Ma, suggesting that they are also Cambrian sedimentary rocks.

The Mengdong Group samples have many young detrital zircons with ages varying from 652 Ma to 619 Ma, but lack early Paleozoic detrital zircons. Seven samples from the Thac Ba Formation also contain abundant young detrital zircons of 600–700 Ma, and the three youngest concordant ages are 592–607 Ma. These ages indicate that the Mengdong Group in the SW China and the Thac Ba Formation in NE Vietnam have similar depositional ages, and probably were deposited in late Neoproterozoic time. Liu et al. (2006) defined a gneiss in the Mengdong Group as metamorphosed Neoproterozoic igneous rock formed at *ca* 761 Ma. However, the sample contains numerous Neoproterozoic zircons with ages varying from 852 Ma to 726 Ma, and the ~761 Ma zircons show fragmental shapes and are indistinguishable from other Neoproterozoic ones. Moreover, this sample has extremely high Al_2O_3 (22.9% at SiO_2 of 53.3%), showing geochemical features of sedimentary rocks. Therefore, this sample probably is a meta-sedimentary rock, and the dated zircons are detrital ones, suggesting that it deposited later than 726 Ma, consistent with our data in this study.

As mentioned above, the zircon U-Pb dating results and CL images indicate that most of the late Neoproterozoic sedimentary rocks experienced two phases of metamorphism in the early Paleozoic (Caledonian) and the early Mesozoic (Indosinian) respectively. Metamorphic zircons are mainly found in the medium-grade metamorphic rocks from the Mengdong Group and the Thac Ba Formation, and are rare in the samples from the Cambrian Tianpeng and Ha Giang formations (Figs. 6, 7). The peak ages of Caledonian metamorphic zircons in the Mengdong Group and Thac Ba formations are 426 Ma and 423 Ma, coinciding well with the ages of the magmatism in the Nanwenhe-Song Chay complex (Peng et al., 2015; Xu et al., 2015; Zhou et al., 2017). The peak age of Indosinian metamorphic zircons is ca

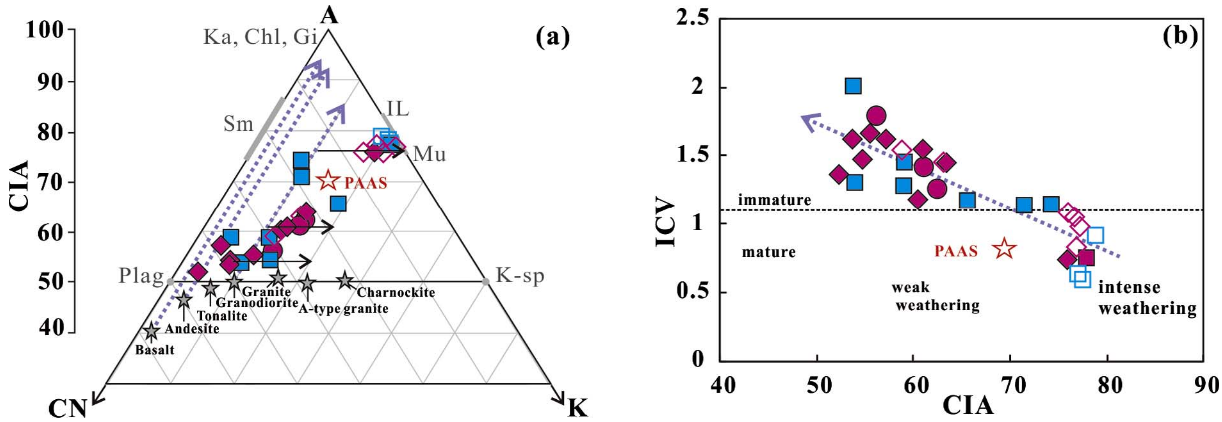

Fig. 9. (a) A-CN-K diagram (after Nesbitt and Young, 1984; Fedo et al., 1995). (b) CIA *vs* ICV diagram (after Cox et al., 1995; Nesbitt and Young, 1982, 1984). Data for PAAS (post-Archean Australian average shale) is from Taylor and McLennan (1985).

246 Ma, similar to the ages of Indosinian granites in the southern Song Chay Massif (Chen et al., 2014a; Roger et al., 2012; Tran et al., 2008). Two angular unconformities between Cambrian and overlying Devonian successions and between early Permian and Triassic sequences in the study area correspond to these two metamorphism events, suggesting that both tectonothermal events in the area were closely related to strong orogeny.

5.2. The sources of the sedimentary rocks

5.2.1. Paleoweathering conditions

Whole-rock compositions of the sedimentary rocks can provide important information on the paleo-weathering conditions and characteristics of sedimentary source. The chemical index of alteration (CIA) and the index of compositional variability (ICV) are commonly used to deduce the paleo-weathering processes in the source area of sediments (Bahlburg and Dobrzinski, 2011; Cox et al., 1995; Fedo et al., 1995; Nesbitt and Young, 1982). Post-depositional K metasomatism is common in many sedimentary rocks, and can lead to incorrect CIA and ICV calculations and influence the evaluation on paleoweathering and paleoclimate. If the effect of K metasomatism is ignored, the weathering trend line of sedimentary rocks should be subparallel to the A-CN edge of the A-CN-K diagram (Fig. 9a; Fedo et al., 1995; Nesbitt and Young, 1984). However, many samples in the study area deviate from the weathering trend line toward the K apex (Fig. 9a), suggesting various degrees of K metasomatism. Most of them are parallel to the CN-K join, indicating that K metasomatism in our samples mainly result in the replacement of plagioclase by K-feldspar. Because this kind of K metasomatism mainly involves mole for mole substitution of K_2 for Ca or Na_2, it does not significantly change the CIA and ICV values of our samples (Wang and Zhou, 2013; Fedo et al., 1995). Most of the Neoproterozoic sedimentary rocks have relatively low CIA values ranging between 50 and 65, similar to tillite and glacial clay (Nesbitt and Young, 1982). However, their ICV values are relatively high (most of them > 1.1; Fig. 9b). These geochemical features indicate that the Neoproterozoic sedimentary rocks are immature, poor in clay minerals, and were derived from first-cycle source materials in an active tectonic setting (Kamp and Leake, 1985; Cox et al., 1995). Their source probably underwent relatively weak weathering in relatively dry or cold conditions. The relatively simple age distributions of the detrital zircons from these rocks also support this inference (Goodge et al., 2004; Cawood et al., 2012).

In contrast, most of the sedimentary rocks from the Cambrian Tianpeng and Ha Giang formations have higher CIA and lower ICV values than the Neoproterozoic samples and PAAS (Fig. 9b; Appendix Table 1), suggesting that they contain a high proportion of mature materials (clay minerals) and were deposited in a tectonically quiescent

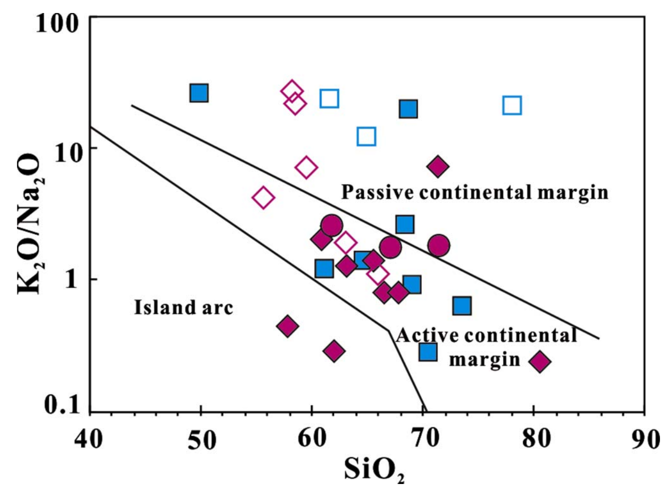

Fig. 10. K_2O/Na_2O *vs* SiO_2 discrimination diagram of tectonic setting (after Roser and Korsch, 1986).

environment during the Cambrian; their sources experienced stronger chemical weathering, probably in a warm-humid environment, (Cox et al., 1995; Fig. 9b; Appendix Table 1). In the discrimination diagram of tectonic setting (Fig. 10), most Cambrian samples fall into the field of passive continental margins, whereas late Neoproterozoic samples dominantly fall into the field of active continental margins, which is consistent with their ICV values (e.g. Cox et al., 1995; Kamp and Leake, 1985; Perri, 2014). On the other hand, the detrital zircons in the Cambrian samples have relatively complicated age distributions, and many zircons are small and highly rounded (Fig. 6). These characteristics indicate a higher proportion of recycled materials in their provenance. The variation of the CIA values indicates that the paleoclimate changed from dry-cold to warm-humid conditions from the late Neoproterozoic to Cambrian in the study area (Bahlburg and Dobrzinski, 2011; Nesbitt and Young, 1982). The relatively cold paleoclimatic conditions in the late Neoproterozoic was probably related to the Gaskier glaciation, like that found in the Doushantuo Formation in the southern Yangtze Block based on the stratigraphical and carbon-isotope studies (Condon et al., 2005; Nie et al., 2006; Zhao and Zheng, 2010; Zhu et al., 2007).

5.2.2. Source components of the sedimentary rocks

The A-CN-K diagram is also an effective tool to constrain the primitive compositions of source rocks (Fig. 9a; Fedo et al., 1995). As shown in this diagram, most of the sedimentary rocks from the late Neoproterozoic – Cambrian strata plot near the predicted weathering trend starting from granodiorite, with only a few of the Neoproterozoic

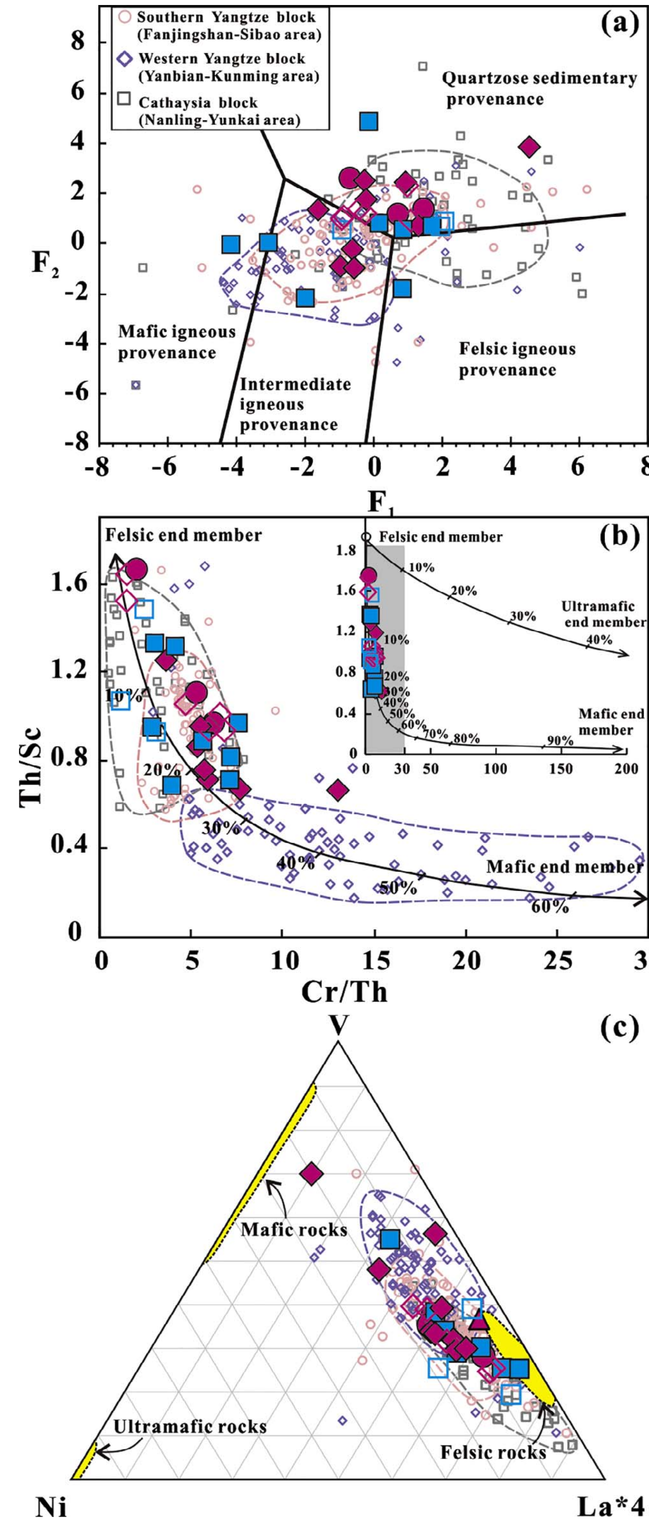

Fig. 11. (a) F_1-F_2 discrimination diagram of sedimentary provenance (after Roser and Korsch, 1988). (b) Th/Sc *vs* Cr/Th diagram (Condie and Wronkiewicz, 1990; Totten et al., 2000). (b) Is a part (shaded area) of inset. Two-component mixing curves are from Bracciali et al. (2007). (c) V-Ni-La*4 ternary diagram. Data for late Neoproterozoic- early Paleozoic sedimentary rocks in Cathaysia and Yangtze Block are from Sun et al. (2008), Wang and Zhou (2012), Wang et al. (2012a, 2010b), Wei et al. (2009), Zhou et al. (2015).

samples near the weathering trend of basalt-andesite, suggesting that their sources were dominated by felsic rocks with a few mafic or intermediate rocks. In the provenance discrimination diagram based on major elements (Fig. 11a), the Cambrian samples mainly plot in the field of quartzose sedimentary provenance, similar to the late Neoproterozoic sedimentary rocks in the Cathaysia Block (Wei et al., 2009; Wang et al., 2012b, 2013), whereas the provenance for late Neoproterozoic sedimentary rocks in the study area is more similar to those in the southern Yangtze Block (Fig. 11a).

These source compositions deduced based on the major elements can be further supported by some data on immobile trace elements, such as REE, HFSE (e.g. Zr, Hf, Th, U) and transition metals (e.g. Co, Cr, Sc, Ni, V). In general, felsic rocks have lower contents of Co, Sc, Cr and higher Th, Zr, Hf, La than mafic rocks (Condie, 1993; Jahn and Condie, 1995). In the plots of Cr/Th *vs* Th/Sc and V-Ni-La∗4 (Fig. 11b, 11c), all Neoproterozoic - Cambrian sedimentary rocks in the NSC area plot near the mixing field between felsic and mafic end members with higher proportions of the felsic end member. Moreover, the Neoproterozoic sedimentary rocks generally have higher proportions of mafic components in their source than the Cambrian ones. Fig. 11b and 11c also show that the sources for the late Neoproterozoic and Cambrian sedimentary rocks in the NSC area may be comparable with Neoproterozoic sedimentary rocks in the southern Yangtze and Cathaysia blocks, respectively, but different from those in the western Yangtze Block.

5.2.3. Provenance of the sedimentary rocks

Detrital zircons from the Neoproterozoic Mengdong Group in SW South China and the Thac Ba Formation in NE Vietnam have roughly similar age distributions (Fig. 7c–e, h–n). They contain abundant middle-late Neoproterozoic detritus with a major age population at 802–747 Ma and a subordinate age population at 700–630 Ma. Minor Mesoproterozoic-Mesoarchean grains with an age peak at 1843 Ma are present in these samples. These age spectra are similar to those of detrital zircons from Neoproterozoic sedimentary rocks in the southern Yangtze Block (Fanjingshan-Sibao area) (Fig. 12a, b). On the other hand, the Neoproterozoic and early Mesoproterozoic - late Paleoproterozoic (1.7–1.5 Ga) zircons in the Mengdong Group and Thac Ba Formation mostly have positive εHf(t) values, resembling the detrital zircons from the Neoproterozoic-early Paleozoic sedimentary rocks in the southern Yangtze Block (Fanjingshan-Sibao area) (Fig. 8b), suggesting that they probably have similar provenance.

The NSC area is located at the intersection of the southern extension of the N-S Panxi-Hannan rifting belt in the western margin of the Yangtze Block, and the western extension of the NEE-striking Jiangnan orogenic belt on the southern margin of the Yangtze Block (Zhao and Cawood, 2012). Neoproterozoic magmatism is extensive in these two belts, including 864–738 Ma basic, intermediate and felsic intrusions in the Panxi belt (e.g. Huang et al., 2008; Li et al., 2003; Liu et al., 2008; Zhao and Zhou, 2007a, 2007b; Zhou et al., 2002, 2006), and *ca* 800–836 Ma granites with minor 747–855 Ma mafic–ultramafic rocks in the Jiangnan orogenic belt (e.g. Chen et al., 2017a; Ge et al., 2001; Wang et al., 2006a, 2007b, 2008c; Yao et al., 2014a; Zhou et al., 2009). In addition, Neoproterozoic granitic rocks (~828 Ma), diorites (~800 Ma) and amphibolites (815–800 Ma) have been identified in the southeastern part of the Ailaoshan fault zone (Fig. 1a; Cai et al., 2014, 2015; Li et al., 2012), and 736–824 Ma granites have been found in the northwestern part of the Phan Si Pan Belt, NW Vietnam (Li et al., 2017a; Tran et al., 2016; Wang et al., 2011). These Neoproterozoic igneous rocks are dominated by felsic rocks with lesser mafic rocks, consistent with the provenance components identified above. However, such rocks are absent in the Indochina and Cathaysia blocks. In the plot of La/Sc *vs* Co/Th and Sc/Th (Fig. 13), most samples cluster near the average compositions of the Neoproterozoic granites and diorite in the western Jiangnan orogenic belt (southern Yangtze) and granites in the Phan Si Pan Belt, and are similar to the Neoproterozoic sedimentary rocks in the southern Yangtze block (Fanjingshan-Sibao area). Moreover, these Neoproterozoic rocks have a large range of zircon Hf-isotope compositions (Li et al., 2017a; Wang et al., 2006b, 2008c; Zhao et al., 2008; Zheng et al., 2007; Zhou et al., 2009), as do the Neoproterozoic detrital zircons in our samples. Thus, these Neoproterozoic

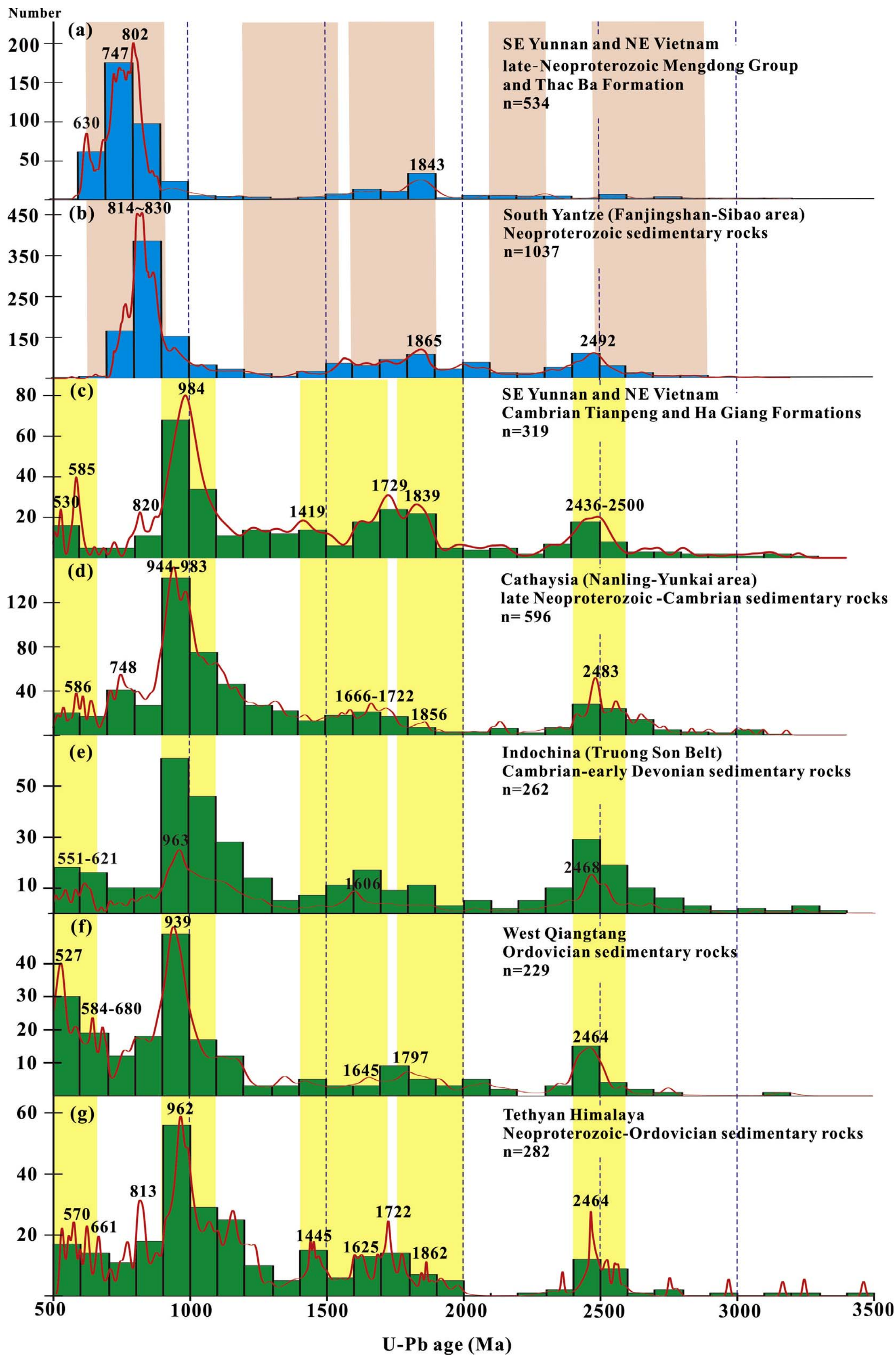

Fig. 12. Relative probability plots of detrital zircon ages. Only data with concordance > 85% are shown. Data sources for age comparison are the southern Yangtze Block (Wang et al., 2012a, 2010a; Wang and Zhou, 2012), Cathaysia Block (Wang et al., 2008d; Xu et al., 2013; Yu et al., 2008, 2010), Indochina Block (Wang et al., 2016b), Qiangtang (Zhu et al., 2011b; Dong et al., 2011), and Tethyan Himalaya (Mcquarrie et al., 2008; Myrow et al., 2010).

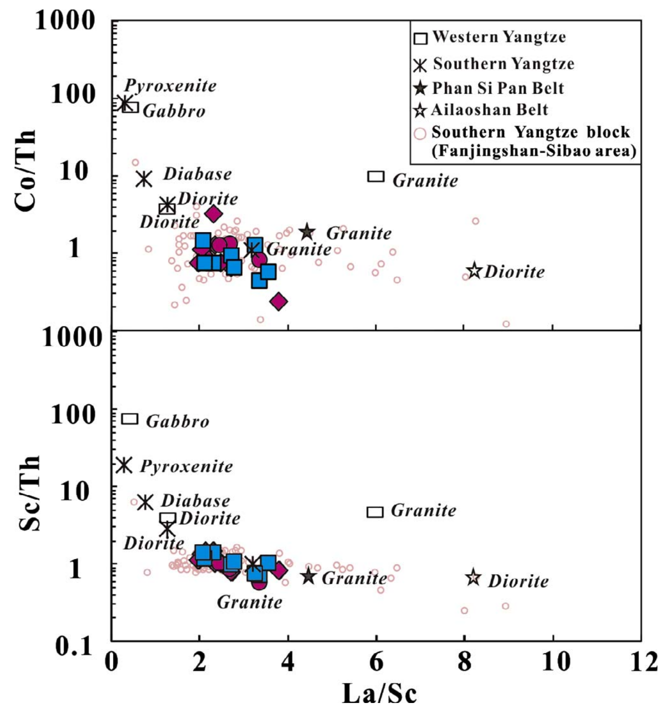

Fig. 13. La/Sc *vs* Co/Th and La/Sc *vs* Sc/Th variation diagram. Average compositions of Neoproterozoic igneous rocks from the western Yangtze (Lai et al., 2015; Ling et al., 2001; Zhao and Zhou, 2007a, 2007b), southwestern Yangtze (Chen et al., 2014b, 2017a; Wang et al., 2006a), Phan Si Pan belt (Li et al., 2017a) and Ailaoshan belt (Cai et al., 2015) are used here for comparison. Data for late Neoproterozoic sedimentary rocks in southern Yangtze Block (Fanjingshan-Sibao area) are from Wang and Zhou (2012), Wang et al. (2012a, 2010b).

(830–730 Ma) magmatic rocks in the southern Yangtze Block and NW Vietnam probably provided primary detrital materials for the late Neoproterozoic Mengdong Group and Thac Ba Formation. Late Paleoproterozoic to early Mesoproterozoic (1.7–1.5 Ga) mafic magmatism occurred in the western part of the Yangtze Block (Fan et al., 2013; Guan et al., 2011; Zhao et al., 2010), and may have provided minor volumes of detritus for the Mengdong Group and the Thac Ba formation. ~1.85 Ga basement rocks crop out sporadically in the northern Yangtze Block (Xiong et al., 2009), eastern Cathaysia (Liu et al., 2009, 2014; Yu et al., 2009, 2012; Zhao et al., 2014) and northwestern Vietnam (Hoang et al., 2015; Wang et al., 2016a). However, the late Paleoproterozoic (~1.85 Ga) granites in the northern Yangtze Block and NW Vietnam have much lower zircon εHf(t) (−16.7 to −26.3; Hoang et al., 2015; Xiong et al., 2009) than contemporaneous zircons in our samples, suggesting that these igneous rocks are unlikely to be the source for the late Neoproterozoic sedimentary rocks analyzed here. Similarly, it is unlikely that these detrital zircons are derived from distant eastern Cathaysia, since many are euhedral and unrounded. *Ca* 1.8 Ga detrital zircons are abundant in the late Paleoproterozoic to early Neoproterozoic sedimentary rocks in the western Yangtze Block, e.g. the Yinming Formation, Huili Group and Dongchuan Group (Greentree and Li, 2008; Sun et al., 2009; Zhao et al., 2010), and show similar Hf-isotope compositions to those in the late Neoproterozoic sediments in the NSC area. This suggests that they probably have a similar provenance, or that the late Neoproterozoic sediments in the NSC area partially came from the recycling of these older sedimentary rocks. These older sedimentary rocks also contain numerous early Paleoproterozoic to Mesoarchean detrital zircons (3.2–2.1 Ga). Therefore, these rocks in the western and southwestern Yangtze and northwestern Vietnam are the most probable source for the late Neoproterozoic sediments in the NSC area.

The Cambrian Tianpeng Formation in SE Yunnan and South China, and the Ha Giang Formation in NE Vietnam, are characterized by dominantly Grenvillian detrital zircons with an age peak at ~980 Ma. Subordinate age peaks are Mesoproterozoic (1.4–1.2 Ga), late Paleoproterozoic (1.85–1.65 Ga), and early Paleoproterozoic to late Neoarchean (2.5–2.4 Ga) (Fig. 12c). Minor younger grains constitute two age peaks at 530 Ma and 585 Ma. Compared with the sedimentary rocks of the Ha Giang Formation (Fig. 7f, g), the Tianpeng Formation contains more 1.85–1.65 Ga and ~1.4 Ga zircons and fewer ~1.2 Ga zircons (Fig. 7a, b). Overall, the age spectra of the detrital zircons from these Cambrian sedimentary rocks are similar to those of the Neoproterozoic to early Paleozoic sedimentary rocks in the Nanling-Yunkai area, western Cathaysia Block, and the Cambrian-early Devonian sedimentary rocks in the Truong Son Belt of the Indochina Block (Fig. 12c~e). Furthermore, they have similar Hf-isotope compositions (Fig. 8a), indicating that they probably have the same provenance. In particular, the early Neoproterozoic zircons in these sedimentary rocks are characterized by negative εHf(t), much different from the middle-Neoproterozoic zircons in the late Neoproterozoic sedimentary rocks in the study area.

Grenvillian magmatic rocks are sparsely exposed in the northern to western parts of the Yangtze Block (Chen et al., 2017b; Deng et al., 2017; Jiang et al., 2016; Li et al., 2002, 2017b; Ling et al., 2003), but the Neoproterozoic (830–740 Ma) magmatism is much more extensive in these areas. Consequently, it is unlikely that the detritus in the Cambrian sedimentary rocks is derived from these areas. Although few Grenvillian rocks are known in the Cathaysia and Indochina blocks, the Neoproterozoic and later sedimentary rocks in the Cathaysia (Nanling-Yunkai area) and Indochina blocks (Truong Son Belt) characteristically carry numerous Grenvillian detrital zircons (Fig. 12d, e).

From the southeast to the northwest of the NSC area (i.e. from NE Vietnam to SE Yunnan), the grain size of Grenvillian zircons in the Cambrian sedimentary rocks decreases, the psephicity increases and the age complexity of the detrital zircon populations increases (Figs. 6, 7), implying that their provenance probably lay to the south or southeast of the NSC area. This scenario is consistent with the inference raised above, that a Grenvillian orogenic belt probably existed along the southern margin of the Cathaysia Block, or nearby to the south (Wang et al., 2008d; Yu et al., 2008, 2010). Mesoproterozoic 1.3–1.0 Ga metamorphism and ~1.43 Ga magmatism only occurred on Hainan Island, in the southwestern part of the Cathaysia Block (Li et al., 2008a, 2008b, 2014). Some studies have proposed that Hainan Island probably was located between NE Vietnam and the Yunkai area until the opening of the Cenozoic Beibu Gulf (Chen et al., 2013; Replumaz and Tapponnier, 2003). The old basement in the western part of Hainan Island should be a potential source. Late Paleoproterozoic (1.9–1.6 Ga) and ~2.5 Ga detrital materials are abundant in the sedimentary rocks of Cathaysia and Indochina blocks (Fig. 12d, e). 1.91–1.83 Ga granitoid rocks exposed in eastern Cathaysia have a range of Hf-isotope compositions similar to contemporaneous detrital zircons in our Cambrian samples (Liu et al., 2009, 2014; Yu et al., 2009; Zhao et al., 2014), and consequently are a possible source. In addition, ~1.65 Ga detrital zircons are abundant in Neoproterozoic sedimentary rocks in the Yunkai terrane of southwestern Cathaysia Block. They have similar Hf-isotope compositions to zircons in Cambrian sedimentary rocks in the study area, suggesting a similar provenance. Therefore, the detritus of Cambrian sedimentary rocks in the NSC area most probably is derived from the Cathaysia and/or Indochina blocks, or other nearby continents with components similar to the Cathaysia and Indochina blocks.

5.3. Crustal evolution of the source area

The U-Pb-Hf isotope characteristics of detrital zircons from the late Neoproterozoic-Cambrian sediments in the NSC area provide a clearer picture of the Precambrian crustal evolution in their source area.

Based on zircon U-Pb-Hf isotopic features (Fig. 8b; Fig. 12a), the tectonothermal events in the provenance of the late Neoproterozoic sedimentary rocks can be roughly divided into five episodes:

2.9–2.47 Ga, 2.3–2.1 Ga, 1.9–1.6 Ga, 1.55–1.2 Ga, and 0.93–0.63 Ga. Most of the Archean (2.9- ~2.5 Ga) zircons lie slightly above or close to the evolution line of the Chondritic Uniform Reservoir (CHUR) with a T_{DM}^{C} range of 3.4–3.1 Ga (Fig. 8b; calculated by using $^{176}Lu/^{177}Hf = 0.019$), suggesting that all the Neoarchean magmas probably originated from the reworking of the Paleo- to Mesoarchean (3.4–3.1 Ga) juvenile crust. All the early Paleoproterozoic (2.3–2.1 Ga) zircons have negative εHf(t) with T_{DM}^{C} of 2.9–3.4 Ga, and some of the late Paleoproterozoic (1.9–1.6 Ga) zircons with relatively low εHf(t) (−5.6 to −9.5) also have T_{DM}^{C} of 3.4–3.1 Ga (calculated using $^{176}Lu/^{177}Hf = 0.019$), suggesting that their host magmas were derived from similar Paleo-Mesoarchean crust. A smaller number of the late Paleoproterozoic zircons have Hf-isotope compositions similar to the Depleted Mantle (DM) at that time (Fig. 8b), suggesting that this period of magmatism was also associated with the generation of juvenile crust. The Mesoproterozoic (1.55–1.2 Ga) zircons mostly have positive εHf(t), except for one grain with much lower εHf(t) (−14.71, $T_{DM}^{C} = 3.2$ Ga), suggesting that the Mesoproterozoic magmas also mainly originated from juvenile crust. The Neoproterozoic magmatism is extremely strong in the provenance of the late-Neoproterozoic sedimentary rocks. This episode of magmatism may be subdivided into two stages. Early-stage (0.93–0.75 Ga) magmatism yielded large volumes of igneous rocks and was associated with the intrusion of mantle-derived magmas (Fig. 8b). Late-stage (0.75–0.63 Ga) magmatism mainly involved the reworking of older (~2.3–1.6 Ga) crust with little input of mantle-derived material. The two periods of crustal growth (3.4–3.1 Ga and 1.9–1.6 Ga) in the provenance of the late Neoproterozoic sedimentary rocks are similar to the growth history of the eastern Australian segment of the Gondwana supercontinent (Kemp et al., 2006), implying some affinity.

Four episodes of significant magmatism took place in the provenance of the Cambrian sedimentary rocks (Fig. 8a, 12c): 2.6–2.4 Ga, 2.03–1.76 Ga, 1.72–1.4 Ga and 1.1–0.9 Ga. With the exception of one late Paleoproterozoic (1.88 Ga) zircon with the lowest εHf(t) (−21.1), other grains with the lowest εHf(t) in each group scatter about an evolution line that intercepts the DM growth curve at ~3.4 Ga (Fig. 8a), implying that the oldest crust in the source regions might have been formed at *ca* 3.4 Ga. The ~2.5 Ga zircons have variable Hf-isotope compositions, and some grains lie close to the DM, suggesting an important juvenile contribution. The Paleoproterozoic (2.03–1.75 Ga) zircons mostly have negative εHf(t), and fall between two evolution lines with T_{DM}^{C} of 3.4 Ga and 2.5 Ga, suggesting that their host magmas originated from the reworking of the 3.4 Ga and 2.5 Ga crust or mixtures of them. However, the late Paleoproterozoic to the early Mesoproterozoic (1.7–1.4 Ga) magmatism involves much more juvenile components, as indicated by their high εHf(t) (Fig. 8a). Although Grenville-age zircons also show large variations in Hf-isotope composition, most of them have negative εHf(t) with T_{DM}^{C} of 3.4–1.8 Ga (Fig. 8a), indicating that Grenvillian magmatism also mainly involved the reworking of ancient crust. This scenario is similar that defined by coeval zircons in the Nanling-Yunkai area of the Cathaysia Block (Fig. 8a) and the India segment of Gondwana (Zhu et al., 2011b), demonstrating that they have similar provenance and were once linked with each other (Yu et al., 2008).

5.4. Variations in sedimentary sources and their tectonic implication

The different whole-rock geochemical characteristics, age distributions and Hf-isotope compositions of detrital zircons suggest that the late Neoproterozoic and Cambrian sedimentary rocks in the study area have significantly different provenances. The Neoproterozoic sedimentary rocks have an affinity with the Neoproterozoic sedimentary rocks in the southern Yangtze Block, and the Cambrian ones have an affinity with those in the Cathaysia and/or Indochina blocks. These differences demonstrate that the provenances of sedimentation in the NSC area changed dramatically from the late Neoproterozoic (< 592 Ma) to Cambrian time (< 527 Ma). A similar provenance change from the late Neoproterozoic to Cambrian time also occurred along the southern margin of the Yangtze Block (Wang et al., 2010c, 2012b, 2013).

There are two possibilities to account for this change. In one scenario, the NSC area was on the margin of the Yangtze Block and was close to the Cathaysia Block. It received sediments from the Yangtze Block in late Neoproterozoic time. A tectonic movement led to the relative subsidence of the sedimentary basin in the NSC area and southwestern Yangtze Block, or the northwestward shift of the basin center between ~592 Ma and < 527 Ma. At that time, in the early Paleozoic, the basin in the NSC area began to receive detritus from the Cathaysia Block or from further south.

In another scenario, these Cambrian sedimentary sequences, as an allochthonous nappe, originally belonged to the Cathaysia Block, and were thrust northwestward onto the Neoproterozoic basement in the NSC area during the Caledonian or Indosinian orogeny. However, no large fault has been recognized between the late Neoproterozoic and Cambrian sequences. Deformation features are uniform in the late Neoproterozoic and the Cambrian sedimentary rocks, and both were intruded by the early Paleozoic Nanwenhe – Song Chay granitic complex (Zhou et al., 2017). Moreover, from the central to the southern parts of the Yangtze Block, the early Paleozoic sedimentary successions change from carbonate-dominated to interstratified carbonate-siliciclastic, whereas a neritic siliciclastic succession is widespread in the Cathaysia Block (Shu et al., 2014; Wang et al., 2010c; Yao et al., 2014b). The characteristics of early Paleozoic lithofacies paleogeography in the NSC area are similar to those in the southern Yangtze Block (BGMRYN, 1990, 1999; DGMV, 2000; Lepvrier et al., 2011). The phosphorite of the early Cambrian Cam Duong Formation in NE Vietnam corresponds to the important marine phosphorite sedimentation event in the Meishucun stage of the early Cambrian on the southern and western margins of the Yangtze Block (DGMV, 2000; Mao et al., 2015; Yue et al., 2013). In addition, numerous trilobite fossils have been found in the Cambrian strata from both the study area and the Yangtze Block, but coeval strata in the Nanling-Yunkai area of the Cathaysia Block are dominated by fossils of micropalaeophytes and brachipoda (BGMRGX, 1985; BGMRGD, 1988; Chen et al., 2006; Dzik and Nguyen, 2016; Lepvrier et al., 2011; Zhang, 1996). All these observations suggest that the Cambrian strata in the NSC area are autochthonous, rather than allochthonous, on the Yangtze Block, arguing against the second hypothesis.

Wang et al. (2010c) demonstrated that early Paleozoic sediments in the southern Yangtze Bock have zircon age spectra similar to those in the Cathaysia Block, although Neoproterozoic sediments in the southern Yangtze Bock exhibit different detrital components from those in the Cathaysia Block (Wang and Zhou, 2012; Wang et al., 2007a, 2010a, 2012a; Yu et al., 2008, 2010). Paleocurrent data also indicate that early Paleozoic sediments were transported toward the W-NNW (Shu et al., 2014; Wang et al., 2010c), suggesting that early Paleozoic sediments on the southern margin of Yangtze Block probably were derived from the Cathaysia Block or its adjacent plates, in agreement with our new data in this study.

Therefore, the NSC basement probably is part of the Yangtze Block, suggesting that the western boundary between the Yangtze and Cathaysia blocks is located to the south or southeast of the NSC area, and the boundary between the SCB and ICB should be to the southwest. These suggestions argue against the designation of the Shizong-Mile fault (Dong et al., 2002; Guo et al., 2009) and Dian-Qiong suture (Cai and Zhang, 2009; Wu et al., 1999; Zhong et al., 1998) as plate boundaries.

This discussion suggests that the dramatic change in the provenances of the study area was more probably caused by a tectonic event between 592 and 527 Ma. However, this period of magmatism and metamorphism, and any obvious angular unconformity, are lacking in the whole SCB and the study area, implying that this tectonic event probably only triggered uplift or depression of the sedimentary basin in

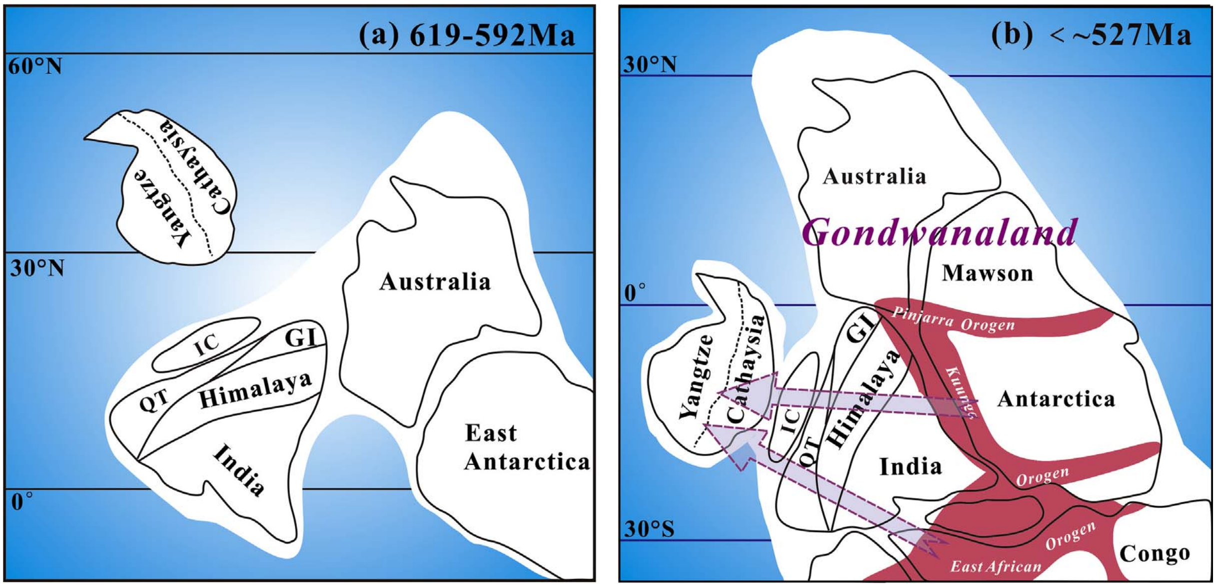

Fig. 14. Schematic illustration of the paleoposition of the SCB in East Gondwana (modified from Burrett et al., 2014; Cawood et al., 2007; Usuki et al., 2013; Wang et al., 2016b; Yao et al., 2014b). (a) After it broke away from Rodinia, the SCB gradually drifted toward the northern margin of India in Gondwana, (b) the SCB connected with Gondwana after *ca* 527 Ma and suffered the influence of the Pan-African orogeny. QT-Qiangtang, GI-Greater India, IC-Indochina.

the SCB.

In the middle Neoproterozoic, the SCB broke away from Rodinia supercontinent, and then gradually drifted toward Gondwana (Fig. 14a; Li et al., 2008b, 2013; Li and Powell, 2001). The significant change of paleoclimate from late Neoproterozoic to Cambrian in the study area, as discussed above, indicates that the SCB probably drifted into lower palaeolatitudes during this time, which is consistent with the paleomagnetic data (Yang et al., 2004; Zhang et al., 2015). The late-Neoproterozoic to early-Cambrian (600–500 Ma) Pan-African orogeny that led to the amalgamation of Gondwana is ubiquitous (Fig. 14b; Cawood, 2005; Cawood et al., 2007; Cawood and Buchan, 2007; Collins and Pisarevsky, 2005; Fitzsimons, 2003). Although the coeval magmatic rocks are absent in the SCB, detrital zircons of magmatic origin with Pan-African ages (with peaks of 530 Ma and 585 Ma) are common in the early Paleozoic sedimentary rocks of the NSC area and South China (Fig. 12c, d; Wu et al., 2010; Wang et al., 2010c, 2013; Xiang and Shu, 2010; Yao et al., 2014b), suggesting that the SCB was connected with Gondwana after *ca* 527 Ma. The age distributions of detrital zircons from the Cambrian samples in the NSC area are similar to those of the Cathaysia (Nanling-Yunkai area), Indochina, Qiangtang and Tethyan Himalaya blocks (Fig. 12c-g), suggesting that they were probably adjacent to each other along the northern margin of India (East Gondwana) during the early Paleozoic (Fig. 14b); this is also consistent with previous research (Burrett et al., 2014; Li et al., 2014; Usuki et al., 2013; Wang et al., 2010c, 2016b;Yu et al., 2008; Zhu et al., 2011b, 2013). Therefore, South China, including the study area, was a part of East Gondwana supercontinent and suffered the influence of the Pan-African orogeny. However, because South China was far from the orogenic belt, the orogeny only induced vertical movement of the basin in South China, and did not lead to extensive magmatism and metamorphism in that area.

6. Conclusions

(1) The Mengdong Group (SW China) and the Thac Ba Formation (NE Vietnam) were deposited on an active continental margin in the late Neoproterozoic (< 619–592 Ma). The Tianpeng Formation (SW China) and the Ha Giang Formation (NE Vietnam) were deposited on a passive continental margin in the Cambrian (< 527–507 Ma).
(2) The late Neoproterozoic sedimentary rocks in the NSC area have an affinity with the Neoproterozoic sedimentary rocks in the southern Yangtze Block (Fanjingshan-Sibao area). Their provenance contains relatively more mafic materials and had undergone weak weathering in cold and dry conditions. Tectonothermal events in the provenance mainly occurred at 2.9–2.47 Ga, 2.3–2.1 Ga, 1.9–1.6 Ga, 1.55–1.2 Ga and 0.93–0.63 Ga, and juvenile crust was mainly generated at 3.4–3.1 Ga, 1.9–1.6 Ga, 1.55–1.45 Ga and 0.93–0.75 Ga.
(3) The Cambrian sedimentary rocks in the NSC area have an affinity with the Neoproterozoic to early Paleozoic sedimentary rocks in the Cathaysia Block (Nanling-Yunkai area) and Indochina Block (Truong Son Belt). Their sources were dominated by felsic rocks, and had experienced strong chemical weathering in a warm and humid environment. The source area experienced significant magmatic events at 2.6–2.4 Ga, 2.03–1.76 Ga, 1.72–1.4 Ga and 1.1–0.9 Ga, with the main generation of juvenile crust at ~3.4 Ga, ~2.5 Ga and ~1.7–1.4 Ga.
(4) The basement of the NSC area belongs to the Yangtze Block. The western boundary between the Yangtze and Cathaysia blocks should be located to the south or southeast of NSC area, and the boundary between the SCB and ICB should be to the southwest.
(5) The SCB was connected to the northern margin of East Gondwana supercontinent after *ca* 527 Ma. The Pan-African orogeny caused the vertical movement of the basin in South China, and resulted in a dramatic change of the provenance of its sediments.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (2016YFC0600204), the National Science Foundation of China (grant no. 41330208), Ministry of Natural Resources and Environment of Vietnam projects for Science and Technology Development (grant no. TNMT.2017.03.03) and the program B for outstanding PhD candidate of Nanjing University (grant no. 201702B072). Dr. Tao Yang and Mr. Bing Wu are thanked for their assisting in zircon Hf-isotope analysis and U-Pb dating at Nanjing University. We are thankful for the assistance in field survey and sample collection to PhD students Xiaochun Li, Linwei Shen, and Xin Chen. This is contribution 1124 from the ARC Centre of Excellence for Core to Crust Fluid Systems (http://www.ccfs.mq.edu.au) and 1216 in the

GEMOC Key Centre (http://www.gemoc.mq.edu.au).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2018.02.003.

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