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Does Neoproterozoic Nam Co formation in Northwest Vietnam belong to South China or Indochina?

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ABSTRACT

The Nam Co belt is located to the northeast of Song Ma fault in Northwestern Vietnam. The nature of the Precambrian basement rocks in this area and its tectonic attribute have still been controversial. In this study, zircon U-Pb-Hf isotopic compositions and whole rock geochemical compositions of meta-sedimentary rocks from the Nam Co Formation in this belt have been integrated to reveal the components and tectonic setting of the formation of the basement rocks in the Nam Co belt. Zircon U-Pb dating results show that the Nam Co Formation is of middle-late Neoproterozoic age. The lower Nam Co Formation probably formed between 821 and 726 Ma, and the upper Formation was deposited later than 726–721 Ma. The sedimentary rocks from the lower and upper Nam Co formations are characterized by numerous Neoproterozoic (900–800 Ma) detrital materials, but the upper part contains more Meso- to Paleoproterozoic sediments than the lower part. Detrital zircon age distribution and Hf-isotope compositions of the Nam Co Formation are similar to those of Neoproterozoic sedimentary rocks in the southern Yangtze Block. Both zircon U-Pb-Hf isotopic and whole rock geochemical data suggest that the source materials of the Neoproterozoic Nam Co Formation were dominated by felsic rocks with minor mafic materials, and the detrital materials were mainly derived from the Jiangnan Orogenic Belt in the southern Yangtze Block, with minor contribution from the Panxi belt in the western Yangtze Block, Ailaoshan-Song Hong and Phan Si Pan belts. The lower Nam Co Formation contains more sediments derived from the Panxi belt than the upper part. The middle-late Neoproterozoic Nam Co Formation probably was deposited in a continental extensional basin, and the sedimentation environment in later period (< 726–721 Ma) was more stable. Integration of our data with other lines of evidence suggests that the Nam Co Formation belongs to the basement of the Yangtze Block, and the Nam Co belt was originally located in the southwest corner of the Yangtze Block. This further suggests that the Song Ma fault probably is the boundary between the South China and Indochina blocks.

1. Introduction

The Indochina Block (ICB) is an important Precambrian continental block in East Asia. The Precambrian basement rocks in the ICB are mainly distributed in central and northern Vietnam, and sporadically in North Laos and central Thailand (Fig. 1a). Previous researches show that the amalgamation between the ICB and the South China Block (SCB) occurred during Phanerozoic, but the specific collision time and model have always been hotly debated (e.g. Cai and Zhang, 2009; Carter et al., 2001; Carter and Clift, 2008; Faure et al., 2014; Findlay, 1997; Lan et al., 2003b; Lepvrier et al., 2008; Liu et al., 2012b; Metcalfe, 2002, 2013). Many NW striking faults were considered as the boundary between the SCB and ICB in past decades, including the Song Chay fault (e.g. Chen et al., 2013, 2014b), the Song Hong fault (e.g. Findlay and Trinh, 1997; Leloup et al., 1995), the Song Da fault (e.g. Sengor and Hsu, 1984), the Song Ma fault (e.g. Faure et al., 2014; Hutchison, 1989; Lepvrier et al., 1997, 2008; Metcalfe, 2013; Tran and Khuc, 2011) and the Dian-Qiong (or Babu) suture (e.g. Cai and Zhang, 2009; Wu et al., 1999; Zhong et al., 1998) (Fig. 1a). All these possible boundaries, except of the last one, are located in Northern Vietnam. They divided Northern Vietnam into several units (Fig. 1).

Northern Vietnam has been divided into two major parts, Northwest and Northeast Vietnam, with distinct folding systems by the NW-striking Song Hong fault (Faure et al., 2014; Tran et al., 2016a). Recent studies show that the basement rocks in Northeastern Vietnam have the affinity with the Yangtze Block in the SCB (Zhou et al., 2017, 2018).

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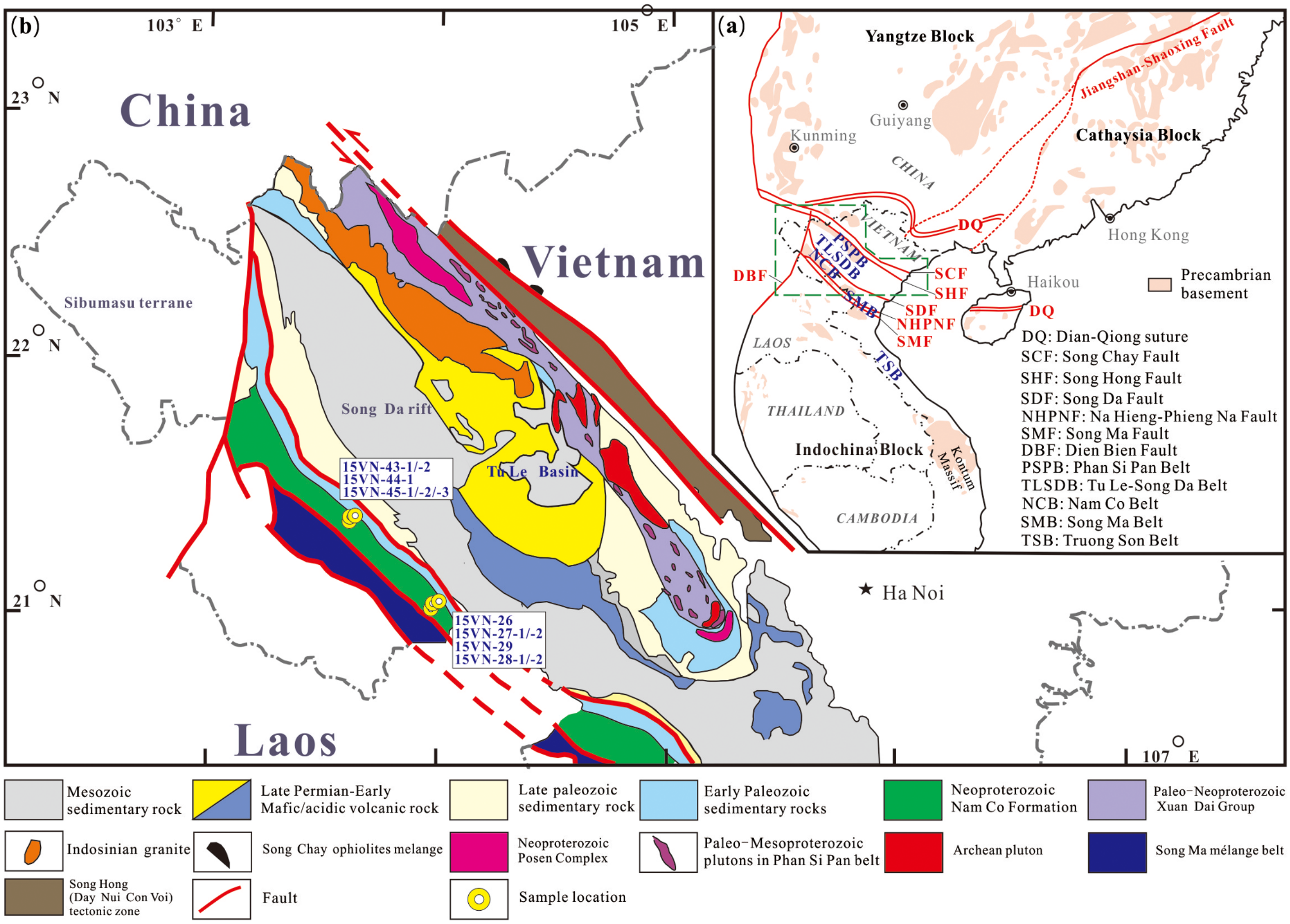

Fig. 1. (a) Simplified geological map showing the distribution of Precambrian basement rocks in South China and the Indochina blocks, and major tectonic belts in northwestern Vietnam (modified after Mineral resources map of Vietnam at 1:1,000,000 scale; Zhao and Cawood, 2012; Usuki et al., 2009). (b) Geological map of Northwestern Vietnam and sampling locations (modified after Faure et al., 2014).

Thus, Northwestern Vietnam has been the key area for understanding the basement components of the ICB and the amalgamation process between the SCB and ICB.

On the other hand, the Cenozoic collision between Indian and Eurasian continents resulted in the lateral extrusion of the ICB along the Song Hong fault (Gilley et al., 2003; Leloup et al., 1995, 2001). This Cenozoic collision and Indosinian collision caused intense metamorphism, deformation and magmatism in Northern Vietnam (Anczkiewicz et al., 2007; Faure et al., 2016a, 2016b; Leloup et al., 1995; Liu et al., 2012a; Wang et al., 1998). Precambrian basement rocks in the area are just exposed in the Phan Si Pan belt, Nam Co belt and Truong Son belt (Fig. 1a). Previous studies mostly focused on the Precambrian igneous rocks in the Phan Si Pan belt (Hoang et al., 2015; Lan et al., 2001; Li et al., 2018; Tran et al., 2003; Wang et al., 2016b). The Nam Co belt is located to northeast of Song Ma fault and Truong Son belt, which is generally considered as an important tectonic element within the ICB (Usuki et al., 2013;Wang et al., 2016a). However, the nature of the basement rocks in the Nam Co belt and their tectonic attribute are still enigmatic. Therefore, comprehensive studies on the basement rocks in the Nam Co belt carried out in this study will reveal the components and tectonic attribute of the Precambrian crust in this area and further provide evidence to constrain the boundary between the SCB and ICB.

2. Geological background and sample features

Northwest Vietnam is made up of several tectonic belts with different rock associations, including the Phan Si Pan belt, Tu Le- Song Da belt, Nam Co belt, Song Ma belt and Truong Son belt from NE to SW (Fig. 1a). They are separated from each other by a series of the NW-SE strike faults, which are deflected to NNW-SSE trend dextral Dien Bien fault (Fig. 1a and b).

The NW-striking Phan Si Pan belt is separated from the Tu Le - Song Da belt by a series of regional faults to the southwest and is bordered by the Song Hong fault to the northeast. The Precambrian basement rocks in the Phan Si Pan belt consist mainly of Mesoarchean, Paleoproterozoic and Neoproterozoic metamorphic igneous rocks and Paleoproterozoic to Neoproterozoic meta-sedimentary rocks (Fan et al., 2010; Lan et al., 2001; Pham et al., 2009, 2012; Tran et al., 2003; Wang et al., 2011, 2016b).

The Tu Le – Song Da belt extends over 300 km long and > 100 km wide, and is mainly composed of Devonian to Middle Triassic terrigenous volcanic-sedimentary sequences, which is unconformably overlain by late Triassic conglomerate and sandstone, or Cretaceous continental red beds. Late Permian flood basalts and mafic–ultramafic intrusions are well developed in the Song Da rift. Coeval felsic volcanic rocks also widely occur in the Tu Le Basin. The Tu Le-Song Da bimodal magmatic suite is considered to be related with continental rift (Faure et al., 2014) and/or the Emeishan plume (Tran et al., 2011, 2015; Usuki et al., 2015).

The Nam Co belt is located to the southwest of Tu Le-Song Da belt and the northeast of Song Ma belt, and separated by the Song Da fault and Na Hieng- Phieng Na fault, respectively. This belt is represented by the Neoproterozoic Nam Co Formation undergoing greenschist to

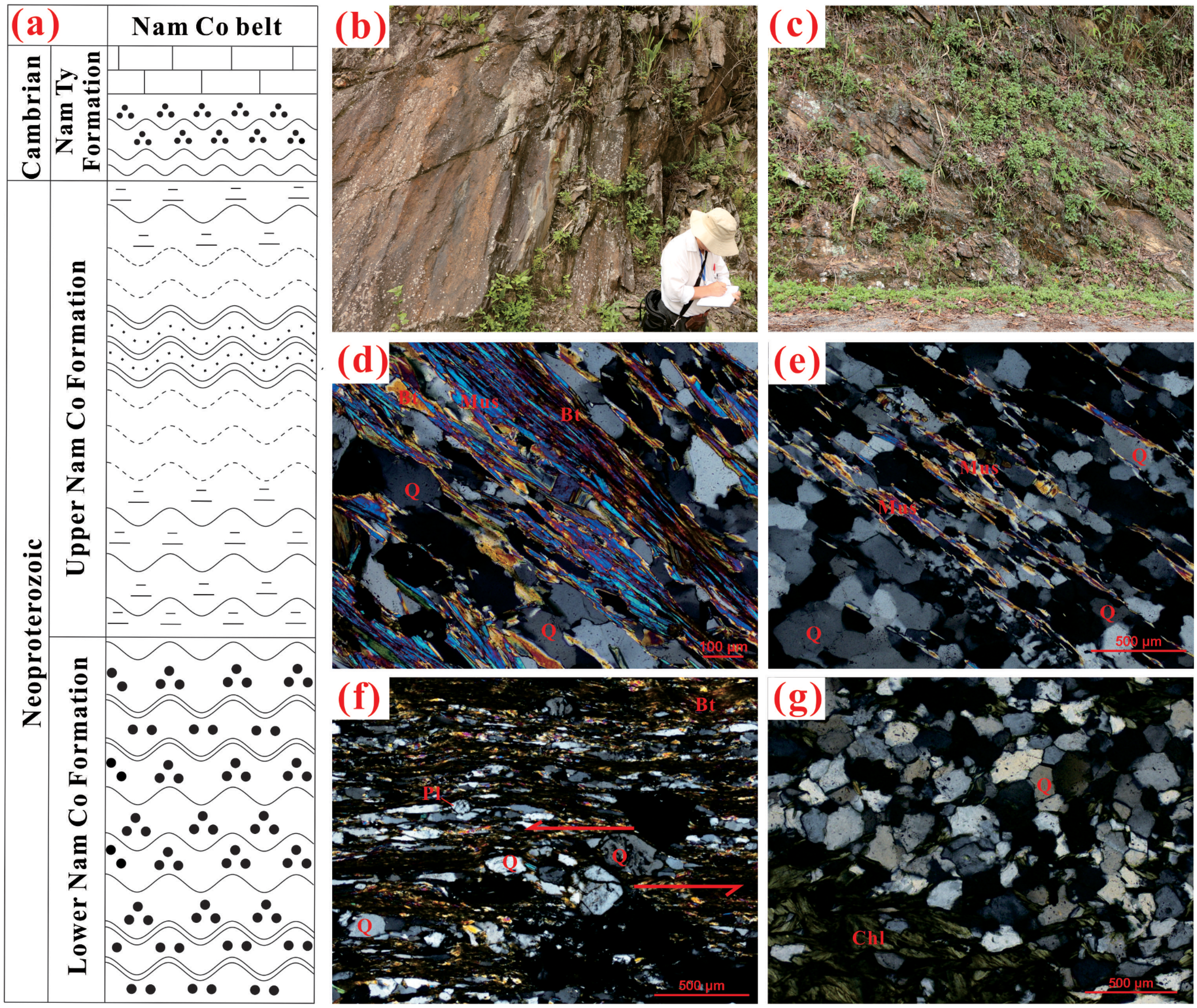

Fig. 2. (a) Simplified stratigraphic columns of Neoproterozoic strata in Nam Co belt. (b-c) Photographs showing the character of the Nam Co Formation sedimentary rocks in the field. (d-g) Photomicrographs of sedimentary rocks from Nam Co Formation. Bt-biotite, Pl-plagioclase, Mus-muscovite, Q-quartz, Chl-chlorite.

amphibolite facies metamorphism. This sequence was folded in the core of broad Song Ma anticlinorium, highly foliated and lineated (Findlay, 1997). The Nam Co Formation consists mainly of micaceous schist, sericite quartz schist, garnet-bearing micaschist, phyllite, quartzite and gneiss with insignificant amount of amphibolite (Fig. 2). The Nam Co Formation is overlain by Cambrian to Devonian terrigenous-carbonate rocks.

The Song Ma belt is an arched northwest-trending tectonic unit along the Song Ma fault to the west, and is part of an early Carboniferous to early Triassic trench-arc-basin system (Faure et al., 2014; Liu et al., 2012a). This belt is also called the Song Ma mélange belt, and composed of the late Proterozoic to early Triassic metasedimentary rocks enclosing minor granites and ultramafic–mafic lenses of ophiolitic affinity. Therefore, this belt is generally regarded as a suture between the ICB and the SCB (Findlay, 1997; Lepvrier et al., 2008; Thanh et al., 2011).

The Truong Son belt is located to the southwest of the Song Ma belt and extends southeastward to the northern Kontum massif in central Vietnam (Fig. 1a). In Northwest Vietnam, the Truong Son belt is characterized by Permian-early Triassic sedimentary-volcanic series overlying Neoproterozoic-Paleozoic sedimentary rocks (Faure et al., 2014; Tran et al., 2008). Late Paleozoic-early Mesozoic granodioritic, dioritic and gabbro-dioritic rocks occur widely in the northern Truong Son belt (i.e. Chieng Khuong, Dien Bien and Song Ma complexes), and construct the major part of the Truong Son magmatic arc (Lan et al., 2003a; Liu et al., 2012a). To the west of Chieng Khuong complex, the Permian-Triassic calc-alkaline volcanic suites constitute the Song Ca volcanic arc.

In this study, twelve samples were collected from the Nam Co Formation in the southeastern and central parts of the Nam Co belt (Fig. 1b). Phyllites, schists and minor meta-siltstones in the upper Nam Co Formation are mainly composed of quartz, muscovite and biotite with minor plagioclase and chlorite (Fig. 2a, b, d, f). The lower Nam Co Formation consists mainly of quartzites and quartz schists, which contain primarily quartz (70–80%) with minor muscovite, biotite or chlorite (Fig. 2a, c, e, g). The S-C fabrics and sigma fabrics could be found in many samples, and indicate the characteristic of the sinistral shearing (Fig. 2e). All of 12 samples were chosen for bulk geochemical analyses, and four representative samples for zircon U-Pb dating and Lu-Hf isotope analyses.

3. Analytical techniques

Clean and fresh samples for whole-rock chemical analysis were crushed and powered to 200-mesh with agate mortar. Major element concentrations of these samples were analyzed by X-ray fluorescence

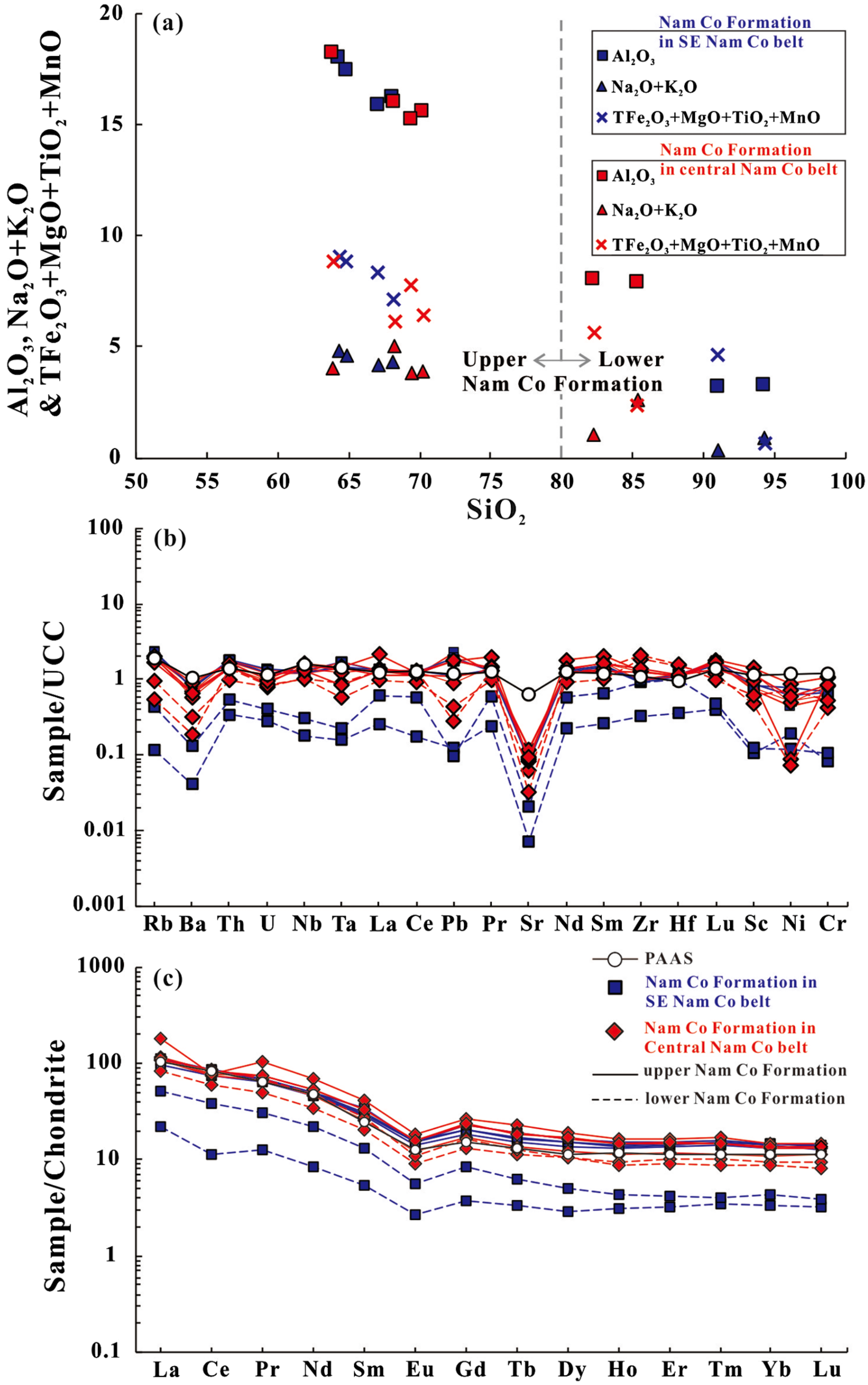

Fig. 3. (a) major elements (Al_2O_3, total alkali and total mafic components) vs. SiO_2 diagram, (b) upper continental crust (UCC)-normalized spider diagram, and (c) chondrite-normalized REE patterns for the sedimentary samples from the Nam Co Formation. Normalized values for chondrite and the UCC are from Taylor and McLennan (1985) and Rudnick and Gao (2003), respectively.

spectrometer (XRF) on a fused glass disk at ALS Chemex (Guangzhou, China) Co., Ltd., following the method described by Zhao et al. (2015). The analytical precision was better than 5% for elements with concentrations of > 1 wt%, and approximately 10% for those with concentrations of < 1 wt%. Trace element analyses were carried out at the State key laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, by using a Quadrupole inductively coupled plasma mass spectrometer (ICP-MS). Detailed sample preparation and analytical procedure have been described by Qi et al. (2000), and analytical precision is better than 5% for most trace elements.

Zircon U-Pb dating and Hf-isotope analyses were carried out at the State Key Laboratory for Mineral Deposits Research, Nanjing University, China. Zircon grains for these analyses were separated using conventional magnetic and heavy liquid separation techniques. Zircon mounts were polish to expose the zircon cores. These zircons were examined with transmitted and reflected light. Cathodoluminescence (CL) imaging was performed to define the morphology and internal

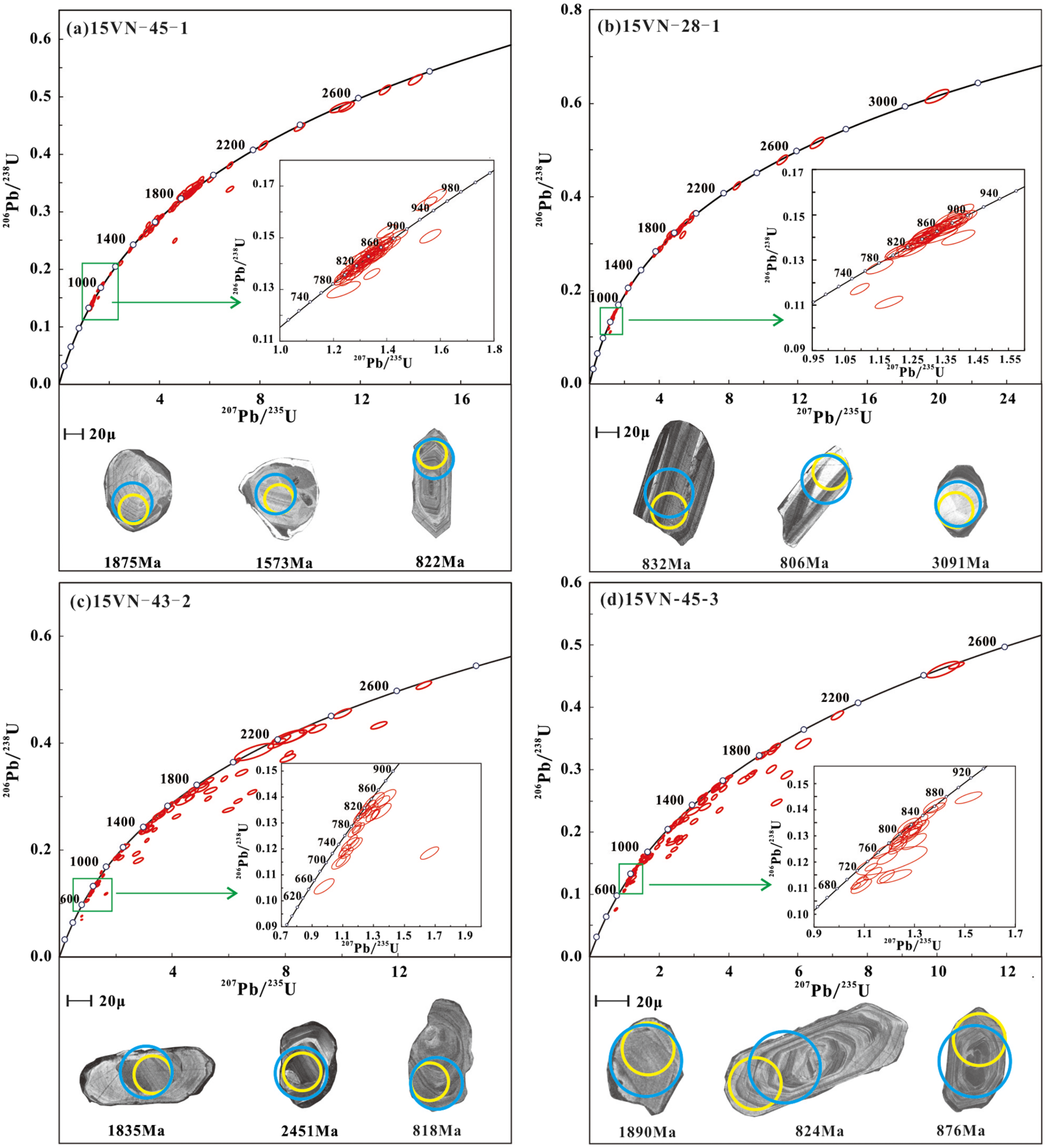

Fig. 4. (a-d) Zircon U-Pb Concordia plots and representative CL images of sedimentary rocks from the Nam Co Formation. Big yellow and small blue circles are spots for U-Pb and Hf isotope analyses, respectively.

textures and to choose potential target sites for U-Pb dating and Hf-isotope analyses.

In situ zircon U-Pb dating was conducted by using an Agilent 7500 s ICP-MS attached to a New Wave 213 nm laser ablation system. Each run consists of 4 analyses of GJ standard zircons (at the beginning and end), 10–15 analyses of unknown zircon grains and one analysis of exterior Mud Tank standard. Laser spot size of 32 μm, repetition rate of 5 Hz and energy of 10–20 J/cm^2 were set for all analyses. Detailed analytical procedures are similar to those described by Griffin et al. (2004), Jackson et al. (2004) and Wang et al. (2007b). The analytical results were calculated using the software GLITTER (ver. 4.4) (http://www.mq.edu.au/GEMOC; Griffin et al., 2008). All age calculations and plotting of Concordia diagrams were made 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 for younger zircons (Yu et al., 2010). The discordant ages with concordance of < 85% were discarded from age probability and histogram plotting.

In situ zircon Lu-Hf isotope analyses were conducted using a Neptune Plus multi-collector ICP-MS, equipped with a New Wave ArF193nm laser ablation system. These analyses were done with an

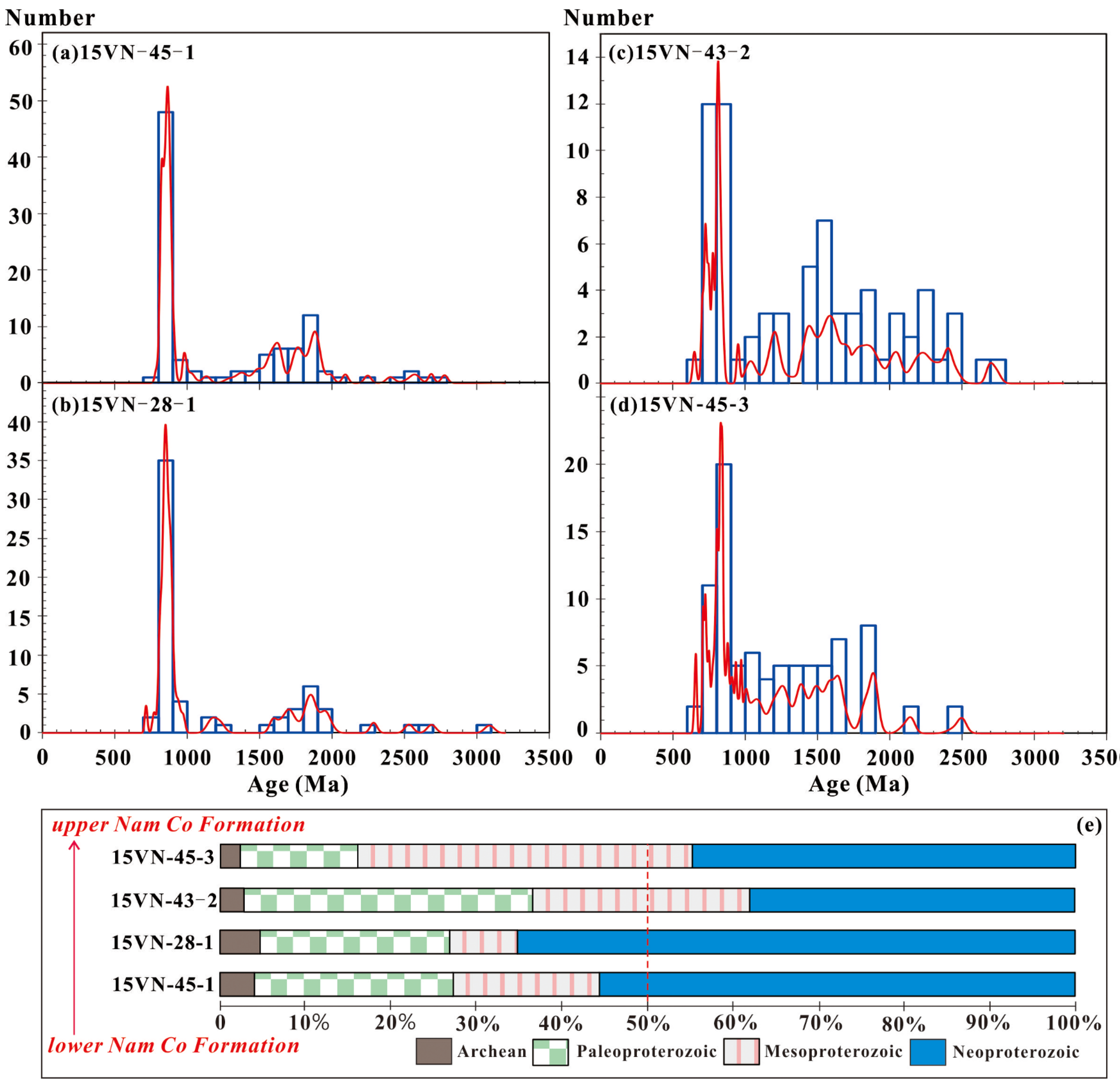

Fig. 5. (a-d) Age spectra of the detrital zircons from the sedimentary rocks in the Nam Co Formation. (e) statistic diagram of the proportion of Archean to Neoproterozoic zircons in the four samples. Age data used here are those with concordance > 85%.

ablation pit of 44 μm in diameter, ablation time of 35 s, a repetition rate of 10 Hz, and laser beam energy of 8 J/cm^2. The analytical conditions and procedure are similar to those described by Hou et al. (2007). Isobaric interference correction was made by the methods of Wu et al. (2006). In order to calculate 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) and a chondritic model (^{176}Hf/^{177}Hf = 0.282772, ^{176}Lu/^{177}Hf = 0.0332; Blichert-Toft and Albarede, 1997) were used to calculate depleted mantle model age (T_{DM}) and epsilon Hf values, respectively. We have adopted a mean crustal composition (^{176}Lu/^{177}Hf = 0.015; Griffin et al., 2002, 2004) to calculate two-stage crustal model age ($T_{DM}{}^{C}$) for each zircon.

4. Analytical results

4.1. Whole rock geochemistry

The metamorphic rock samples from the Nam Co Formation in the southeastern and central Nam Co belt have similar major element compositions with negative DF values (Supplementary Table 1), indicating sedimentary protoliths of these metamorphic rocks. The samples from the upper Nam Co Formation contain SiO_2 of 63.8–70.2 wt%, Al_2O_3 of 15.2–18.2 wt%, total alkali (ALK = K_2O + Na_2O) of 3.81–5.05 wt%, with similar SiO_2/Al_2O_3 ratios (3.50–4.56). However, four quartzite or quartz schist samples from the lower Nam Co sequence have higher SiO_2 contents (82.2–94.2 wt%) and SiO_2/Al_2O_3 ratios (10.2–29.0), and lower Al_2O_3 (3.20–8.04 wt%) and ALK (0.24–2.59 wt %), indicating high compositional maturity. All the samples have low CaO concentrations varying from 0.01 wt% to 0.12 wt%. The abundances of mafic components (TFe_2O_3 + MgO + TiO_2 + MnO) of all analyzed samples are 0.63–9.07 wt% (Fig. 3a; Supplementary Table 1). The rocks from the lower Nam Co Formation have relatively higher K_2O/Na_2O ratios (11.0–20.7; average of 16.8) and chemical index of alteration (CIA = 74.0–92.3; average of 82.9) than those from the upper Nam Co Formation with K_2O/Na_2O of 5.13–20.0 (average of 11.4) and CIA of 75.1–80.2 (average of 77.4), suggesting that the source of early sedimentary rocks suffered relatively intense weathering and leaching, or contained a higher proportion of mature sediments.

The Nam Co Formation metasedimentary rocks have scattered trace-element concentrations, implying complex provenances or varying degree of weathering. In the upper continent crust (UCC)-normalized spider diagram (Fig. 3b), most of samples show similar patterns with relatively depletion of Ba and Sr, and varying Pb and Ni. These metasedimentary rocks have roughly similar REE patterns (Fig. 3c), with moderate negative Eu anomalies (Eu/Eu* = 0.49–0.61) and moderate

REE fractionation ($(La/Yb)_N$ = 6.50–12.6), implying similar provenance. Their REE patterns are in accordance with the post-Archean Australian shale (PAAS, Taylor and McLennan, 1985). The samples from the lower Nam Co Formation have REE ranging from 33 ppm to 188 ppm, lower than those from the upper sequences (REE = 177–242 ppm) (Supplementary Table 1). Low trace element concentrations of these samples in the lower part probably result from the high mode of quartz.

4.2. Zircon U-Pb ages and Hf-isotope compositions

Most zircon grains separated from four samples are transparent to light brown, and have rounded morphology, but some are euhedral with long prismatic (Fig. 4a–d). Zircon grains from these samples are 40–100 μm long with the aspect ratios of 1.5:1–4:1. CL images show that the majority of zircons have obvious oscillatory zoning or broad compositional zoning, but a few grains have weak zoning, heterogeneous internal structure or overgrowth rims. All zircons have large range of Th (42–5714 ppm) and U (171–1592 ppm), and 97% of them have Th/U > 0.3 (Supplementary Table 2). These features indicate that the most of zircons are of magmatic origin. The oldest magmatic zircons from four samples (15VN-45-1, 15VN-28-1, 15VN-43-2, 15VN-45-3) are subhedral to euhedral with clear oscillatory zoning. The oldest ages were obtained from the rounded zircons with broad compositional zoning or the inherited core within rounded zircons.

4.2.1. Biotite quartz schist (15VN-45-1)

A total of 102 zircon grains were collected from this sample for U-Pb isotope analysis. Most of these analyses plot on or close to the Concordia line (Fig. 4a). The youngest and oldest concordant ages (concordance > 90%) are 788 ± 12 Ma and 2781 ± 22 Ma, respectively. Eighteen zircons in the youngest age population yield a weighted average $^{206}Pb/^{238}U$ age of 826 ± 4 Ma (MSWD = 1.5; concordance > 90%). The most notable feature for this sample is a striking age population at 862–825 Ma. Another significant age population is Paleoproterozoic (1883–1620 Ma), and concordant Mesoproterozoic zircons only take up minor proportion. Four Archean zircon grains have the concordant ages of 2.78–2.55 Ga (Fig. 5a; supplementary Table 2).

Hf isotope compositions of 52 grains in this sample have been analyzed (Fig. 6a; Supplementary Table 3). $^{176}Hf/^{177}Hf$ ratios of the Neoproterozoic zircons scatter from 0.281813 to 0.282562, corresponding to T_{DM}^{C} between 2.69 Ga and 1.0 Ga. Most of these zircons have εHf(t) ranging from −15.5 to +11.9. One 879 Ma grain has extremely low εHf(t) (–32.6) and Eoarchean T_{DM}^{C} (3.76 Ga). All but one of the late Paleoproterozoic to early Mesoproterozoic (1.64–1.49 Ga) zircon grains have positive εHf(t) (+3.13 to +8.66), whereas all 1.90–1.85 Ga ones exhibit negative εHf(t) (−9.56 to −2.75). The Archean zircons have εHf(t) of −6.62 to +6.33, and T_{DM}^{C} of 3.62–2.61 Ga.

4.2.2. Biotite quartzite (15VN-28–1)

Sixty-four analyses from this sample yield concordant U-Pb ages ranging from 714 Ma to 3091 Ma with a major peak at 848 Ma. Mesoproterozoic and Archean ages are scattered (Fig. 5b). Paleoproterozoic ages mainly concentrate at 2000–1600 Ma, with a minor age peak at 1862 Ma (Fig. 4b, 5b; Supplementary Table 2), similar to sample 15VN-45-1. Ten youngest concordant zircons yield similar $^{206}Pb/^{238}U$ age ranging from 837 Ma to 806 Ma and a weighted mean $^{206}Pb/^{238}U$ age of 821 ± 7 Ma (MSWD = 1.13; concordance > 90%).

Thirty-one grains are selected for Hf-isotope analysis. Most Neoproterozoic (819–714 Ma) zircons have negative εHf(t), ranging from −8.51 to −0.57; only two grains with the ages of 832 Ma and 836 Ma have positive εHf(t) of +2.39 and +7.62, respectively. Three Mesoproterozoic zircons have εHf(t) varying from +2.69 to −0.82, corresponding to Paleoproterozoic Hf model age (T_{DM}^{C} of

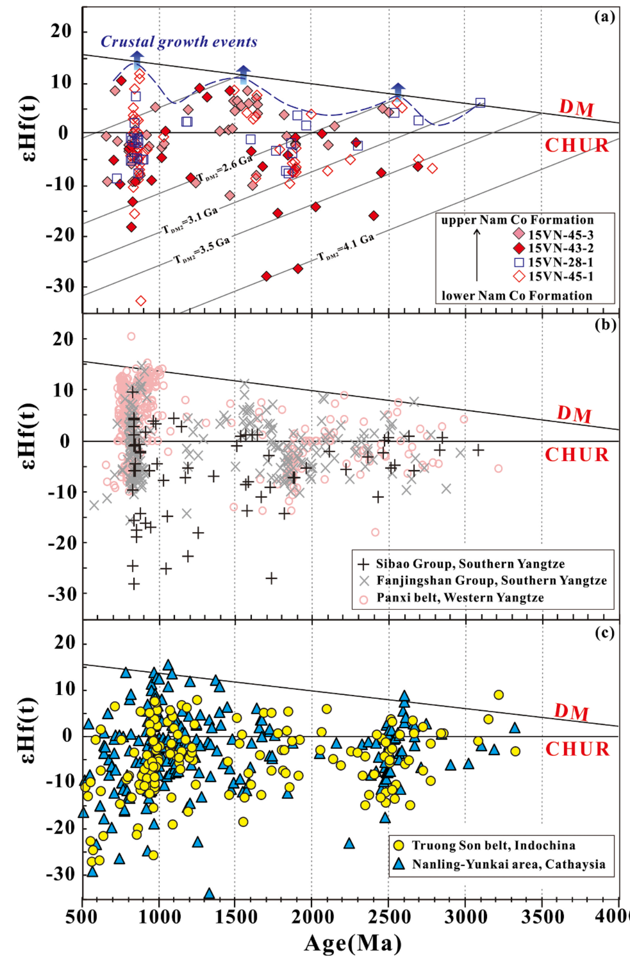

Fig. 6. Hf isotope composition of detrital zircons in the sedimentary rocks from the study area, the southern (Wang et al., 2010, 2012b) and western Yangtze Block (Sun et al., 2009; Wang et al., 2012a), Cathaysia Block (Wang et al., 2008a; Xu et al., 2013; Yu et al., 2008, 2010) and the ICB (Wang et al., 2016a).

2.35–1.81 Ga). Paleoproterozoic (2.29–1.76 Ga) grains have dominantly negative εHf(t) (−1.49 to −7.52), and T_{DM}^{C} of 2.95–2.59 Ga, similar to those in sample 15VN-45-1. Three Archean (3.09–2.53 Ga) grains have positive εHf(t) ranging from +2.94 to +6.41. That Mesoarchean zircon has the model age of 3.07 Ga, similar to its crystallization age (3.09 Ga) (Fig. 6a; Supplementary Table 3), suggesting juvenile crust generation during that time.

4.2.3. Meta-siltstone (15VN-43-2)

Eighty-seven zircon grains were analyzed for U-Pb ages, and show a large age variation from 799 Ma to 2733 Ma (Fig. 4c; Supplementary Table 2). Many grains with ages of older than 1000 Ma are discordant, whereas the most of Neoproterozoic zircons are concordant. Neoproterozoic zircons are dominant in this sample, with a major peak at 811 Ma and a subordinate peak at 723 Ma. Meso- to Paleoproterozoic zircons are also abundant, but do not show significant age peaks. Two oldest grains have the Neoarchean ages of 2688 Ma and 2733 Ma (Fig. 5c). Except for one 647 Ma zircon, eight youngest concordant analyses give a weighted average $^{206}Pb/^{238}U$ age of 726 ± 6 Ma (MSWD = 2.9; concordance > 90%).

Twenty-eight zircons from this sample yield $^{176}Hf/^{177}Hf$ ranging from 0.280801 to 0.282603 with εHf(t) of −27.7 to +10.6, showing complex origins (Fig. 6a; Supplementary Table 3). All Neoproterozoic zircons have negative εHf(t) (−18.3 to −2.33) and Archean to Paleoproterozoic model ages (2.84–1.85 Ga), except for one grain with

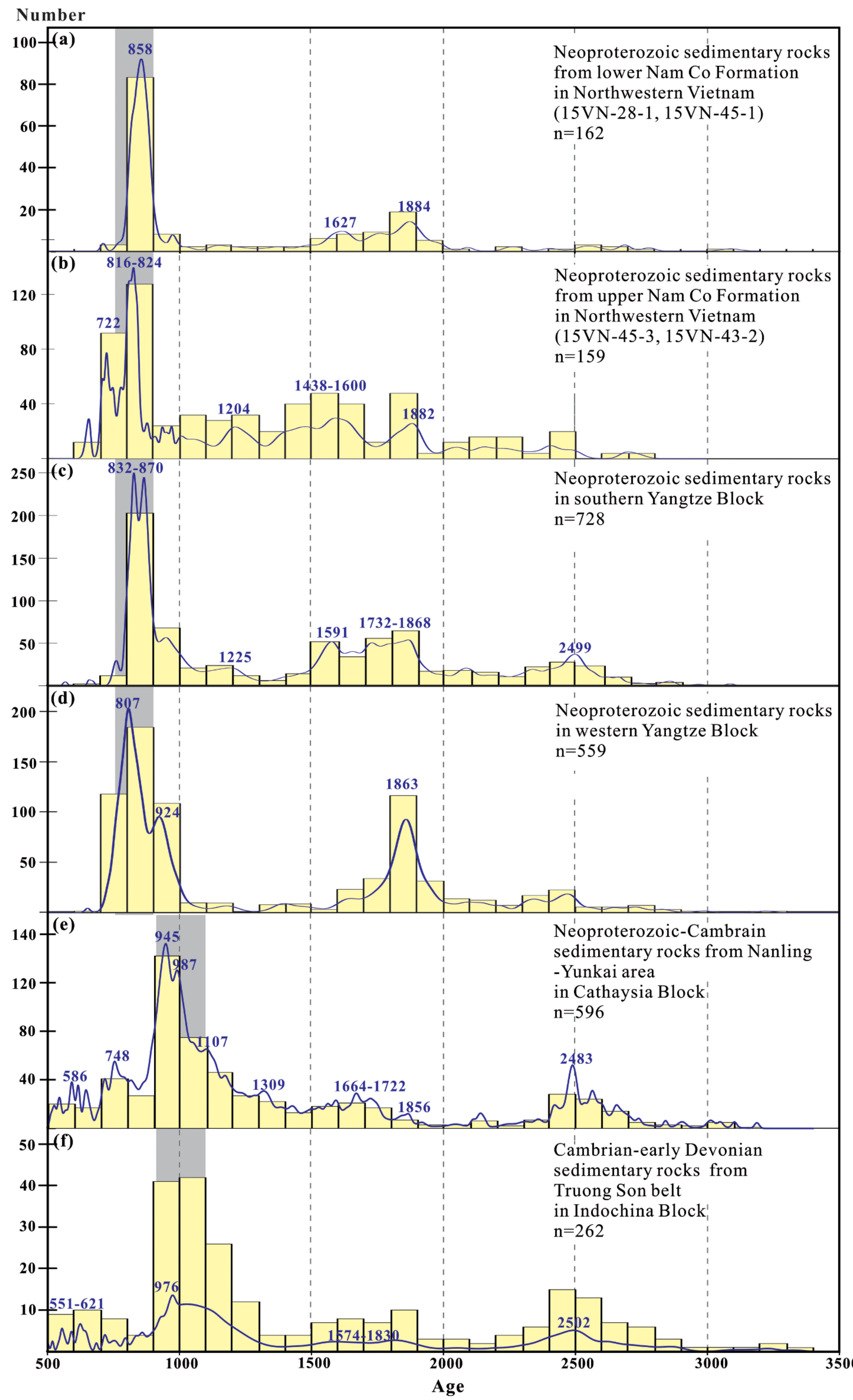

Fig. 7. Relative probability plots for detrital zircon ages in this study. Only the data with concordance > 85% are used here. Data sources for age comparison are: Wang et al. (2012b, 2010), and Zhou et al. (2009) for southern Yangtze block; Sun et al. (2009) and Wang et al. (2012a) for western Yangtze block; Yu et al. (2008, 2010), Wang et al. (2008a), and Xu et al. (2013) for Cathaysia block; and Wang et al. (2016a) for the ICB.

relatively high εHf(t) (+10.6). Mesoproterozoic zircons commonly have positive εHf(t) up to +9.10; only two grains have negative εHf(t) of −8.62 and −4.54. Except for one 2.05 Ga zircon having positive εHf (t) of +0.28, all the other Paleoproterozoic to Archean zircons have negative and variable εHf(t) ranging from −27.7 to −0.60, corresponding to the model ages of 4.13–2.50 Ga.

4.2.4. Meta-siltstone (15VN-45-3)

U-Pb ages of 106 detrital zircons are analyzed, and only 82% analyses passed the concordance test (> 85% concordance). These zircons mainly formed in Neoproterozoic with a major age peak at 811 Ma and a subordinate age peak at 724 Ma, similar to those in sample 15VN-43–2 (Fig. 5c and d; Supplementary Table 2). As sample 15VN-43–2, this sample also contains abundant Paleo- to Mesoproterozoic zircons,

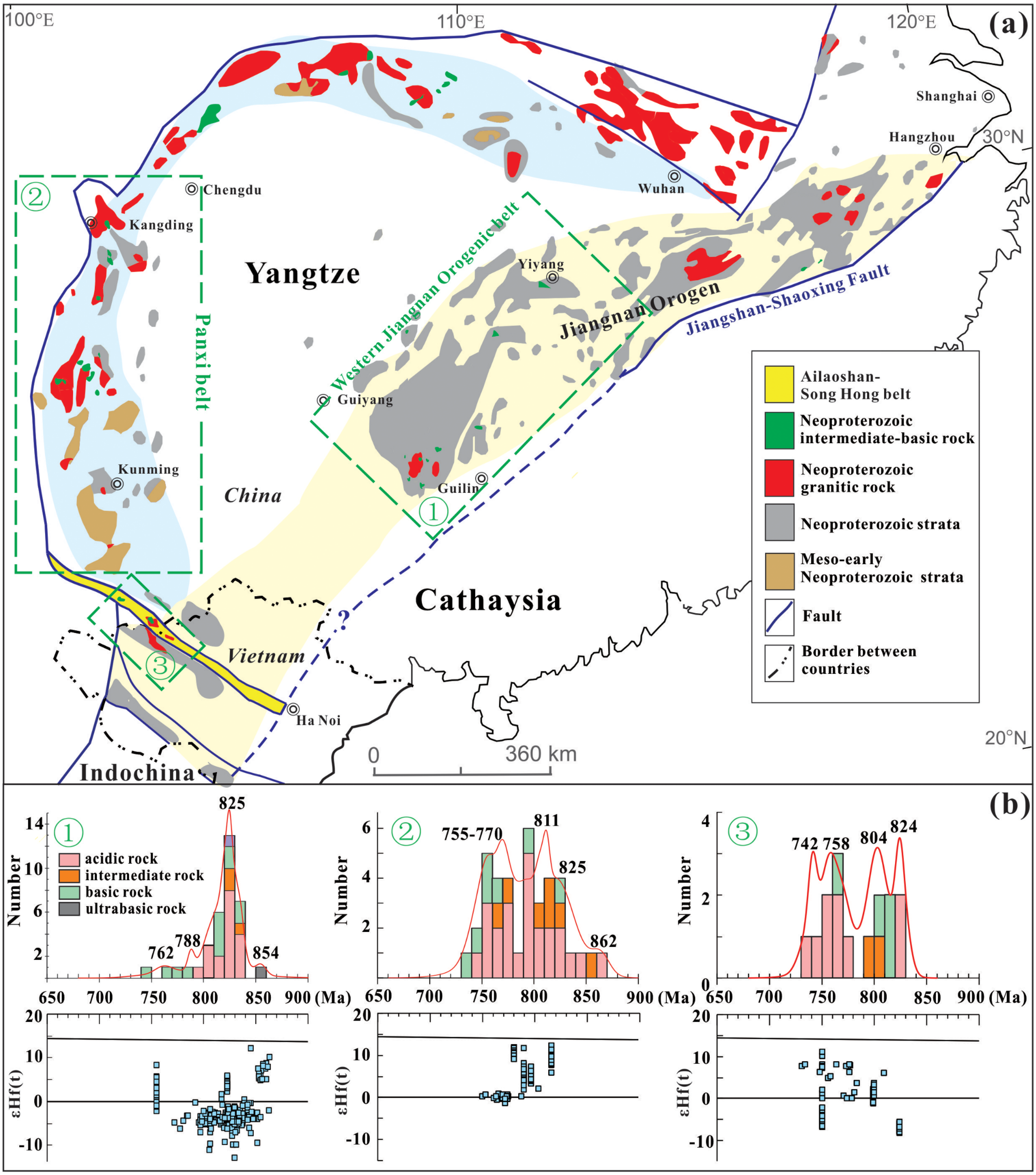

Fig. 8. (a) Simplified geotectonic map showing the Neoproterozoic tectonic framework of Yangtze Block; (b) Age frequency for Neoproterozoic magmatic rocks and their corresponding zircon Hf-isotope compositions. Data for western Jiangnan Orogenic Belt (plot b-1) are from Chen et al. (2014a, 2018b), Ge et al. (2001), Huang et al. (2019), Li (1999), Wang et al. (2006, 2007a, 2007c, 2008c, 2013b), Yao et al. (2014), Zang et al. (2005), Zhao et al. (2013), Zhang et al. (2012, 2013) and Zhou et al. (2009); Data for the Panxi belt (plot b-2) are from Du et al. (2007), Huang et al. (2008), Lai et al. (2015), Li et al. (2002a , 2003a, 2003b, 2003c), Lin et al. (2012), Ling et al. (2001), Liu et al. (2008), Ma et al. (1989), Roger and Calassou (1997), Zhao et al. (2008), Zhao and Zhou (2007), Zhou et al. (2002, 2006), Sinclair (2001)) and Zhu et al. (2006, 2008) and data for the Ailaoshan-Song Hong and Phan Si Pan belts (plot b-3) are from Cai et al. (2014, 2015), Li et al. (2012, 2018), Wang et al. (2011), Qi et al. (2012), and Tran et al. (2016b).

which cluster in two prominent groups of 1646–1264 Ma and ~1881 Ma. The concordant age of youngest detrital zircon is 649 ± 8 Ma and the oldest one is 2498 ± 29 Ma. Seven youngest zircons yield a coherent age cluster with a weighted mean $^{206}Pb/^{238}U$ age of 721 ± 5 Ma (MSWD = 5.7; concordance > 90%).

Forty-four dated grains were further analyzed for Hf-isotopes (Fig. 6a; Supplementary Table 3). Neoproterozoic zircons have relatively high initial $^{176}Hf/^{177}Hf$ (0.281998 to 0.282572), with T_{DM}^{C} ranging from 2.29 Ga to 1.09 Ga. With the exception of three grains with positive εHf(t) (+0.93 to +8.50), most of zircons have negative εHf(t) of −9.35 to −0.08. Late Paleoproterozoic to early Mesoproterozoic (1.89–1.45 Ga) zircons vary in εHf(t) from −12.04 to +8.54, with T_{DM}^{C} of 2.94–1.76 Ga. Two late Neoarchean (~2.5 Ga) grains show high εHf(t) (+4.37 and +5.18) with model ages similar to their crystallization ages.

5. Discussion

5.1. The depositional age of the Nam Co Formation

As the core of the Song Ma anticlinorium, the Nam Co Formation suffered multi-phase deformation and metamorphism. It is unfossiliferous, and the volcanic interlayers are absent in the sedimentary sequence. Thus, the precise depositional age of the Nam Co Formation cannot be well defined. On the Vietnamese 1:200,000 geological map, the Nam Co Formation has been mapped as Neoproterozoic stratum without any reliable geochronological evidence (Findlay, 1997).

For this dumb formation, the U-Pb age of the youngest detrital zircon is commonly used to constrain the maximum depositional age. Detrital zircons in two samples from the lower Nam Co Formation (15VN-45-1, 15VN-28-1) and another two from the upper Nam Co Formation (15VN-43-2, 15VN-45-3) yield the youngest concordant (Concordance > 90%) $^{206}Pb/^{238}U$ ages of 788 Ma, 714 Ma, 647 Ma, and 649 Ma, respectively. Mean ages of the youngest population of the detrital zircons in these four samples are 826 Ma, 821 Ma, 726 Ma, and 721 Ma, respectively. Considering the uncertainty and occasionality of the LA-ICPMS dating process, these mean ages are more reliable and consequently used to constrain the maximum depositional age.

Therefore, the lower Nam Co Formation probably formed during 821 Ma and 726 Ma, and the upper Nam Co Formation deposited later than 726–721 Ma. The Nam Co Formation was unconformably overlain by the Song Ma Formation, which contains numerous Cambrian-Ordovician fossils (e.g. *Lingulella*, *Westonia* and *Obolus*) and was considered as a middle Cambrian stratum (DGMV, 2005). Moreover, our samples did not contain any early Paleozoic detrital zircons. Thus, the Nam Co Formation was most likely a middle-late Neoproterozoic stratum.

5.2. Provenance of the Nam Co formation sediments

All sedimentary rocks from the lower and upper Nam Co formations in central and southeastern Nam Co belt are characterized by numerous Neoproterozoic (900–800 Ma) detrital materials. The sedimentary rocks from the lower Nam Co Formation have a striking age peak at ~858 Ma, and contain minor Mesoproterozoic to Archean detrital materials with two small age peaks at 1627 Ma and 1884 Ma (Fig. 7a). By contrast, Neoproterozoic zircons in the sedimentary rocks from the upper Nam Co Formation have a wider Neoproterozoic age span with a major age peak at 824–816 Ma and a subordinate age peak at ~722 Ma. On the other hand, the upper Nam Co Formation contains more zircon grains with Meso- to Paleoproterozoic ages than does the lower formation, and these zircons form three subordinate age peaks at 1204 Ma, 1600–1438 Ma and 1882 Ma (Fig. 7b). This kind of age distribution and their Hf-isotopic signatures of the Nam Co Formation detrital zircons are similar to those of the Neoproterozoic sedimentary rocks in the western Jiangnan Orogenic Belt (southern Yangtze Block), indicating the similar source components (Figs. 6a and b, 7a–c). In contrast, these age spectra are significantly different from those in the Nanling-Yunkai terrane (Cathaysia Block) and Truong Son belt (Indochina Block), which are dominated by Grenvillian (1100–900 Ma) detrital zircons (Figs. 6 and 7). Neoproterozoic sequences in the Panxi belt, western Yangtze Block, have great Neoproterozoic and Paleoproterozoic detritus populations, similar to the Nam Co Formation. But, they contain more Grenvillian and Paleoproterozoic (~1.86 Ga) detrital zircons with two obvious subordinate age peaks at ~924 Ma and ~1863 Ma (Fig. 7d). Moreover, Neoproterozoic (900–700 Ma) zircons from the Panxi belt also have overwhelming positive εHf(t) values (Fig. 6b).

Middle Neoproterozoic (865–710 Ma) magmatic rocks are widespread in the periphery of the Yangtze Block (Fig. 8a), while coeval magmatism was absent in the western Cathaysia and Indochina blocks. Most of middle Neoproterozoic zircons in the Nam Co Formation are euhedral to subhedral (Fig. 4), indicating a proximal provenance. In the western Jiangnan Orogenic Belt, the early stage (860–790 Ma) magmatic rocks mainly occurred at ca 825 Ma and are dominated by felsic rocks with minor intermediate-mafic–ultramafic rocks (Fig. 8b-1). The zircons from these rocks have large εHf(t) variation, most of them being negative (Fig. 8b-1). However, mafic magmatism tends to be more active at the late stage (790–740 Ma) in the western Jiangnan Orogenic Belt, and the zircons in the late stage of magmatic rocks are dominantly characterized by positive εHf(t). Neoproterozoic magmatism is also widely developed in the Panxi belt of the western Yangtze Block. The majority of Neoproterozoic magmatic rocks in this belt formed at 770–755 Ma and 825–811 Ma, and most of them are granitoids (Fig. 8b-2). Almost all zircons from these Neoproterozoic magmatic rocks have positive εHf(t) (Fig. 8b-2). Recently, increasing Neoproterozoic (828–736 Ma) magmatic rocks have been identified in the Ailaoshan-Song Hong belt and the Phan Si Pan belt (Cai et al., 2014, 2015; Li et al., 2012, 2018; Qi et al., 2012; Tran et al., 2016b; Wang et al., 2011). These Neoproterozoic magmatic rocks mainly formed at 758–742 Ma and 824–804 Ma, and the zircons within these rocks show both positive (55%) and negative (45%) εHf(t) (Fig. 8b-3). The Neoproterozoic (900–700 Ma) zircons from the lower Nam Co Formation have large variation of εHf(t) (–32.6 ~ +11.9). About 30% of them have positive εHf(t), and the most of these zircons plot close to the evolution line of the Depleted Mantle (DM). However, about 85% of the Neoproterozoic (900–800 Ma) zircons from the upper Nam Co Formation have negative εHf(t), and nearly all of them lie below or close to the evolution line of the Chondritic Uniform Reservoir (CHUR). Therefore, the Neoproterozoic (900–700 Ma) sediments in the Nam Co Formation were mainly derived from the western Jiangnan Orogenic Belt, while the minority of them from the Ailaoshan-Song Hong belt, Phan Si Pan belt and/or Panxi belt. Moreover, the Panxi belt probably provided more sediments to the lower Nam Co Formation than the upper part.

A handful of Grenvillian zircons in the lower and upper Nam Co Formation may have been derived from the Panxi belt where the 1142–958 Ma magmatic rocks are widely exposed (Chen et al., 2018a; Li et al., 2002b; Mou et al., 2003; Zhu et al., 2016). Moreover, younger sedimentary rocks in the western Yangtze Block, such as the Kunyang Group, contain abundant Grenvillian detrital zircons (Greentree et al., 2006). Many Mesoproterozoic (1.45–1.2 Ga) detrital materials exist in the sedimentary rocks from the upper Nam Co Formation. This period of magmatic and metamorphic rocks is absent in the Yangtze Block and the hinterland of the Cathaysia Block, but is only identified in Hainan Island, the southern Cathaysia Block (Li et al., 2002b, 2008, 2014; Yao et al., 2017). It is suggested that Hainan Island may even have been located between the Yunkai area of the Cathaysia Block and Northeast Vietnam before the Cenozoic era (Chen et al., 2013; Replumaz and Tapponnier, 2003). Thus, the Mesoproterozoic basement rocks in Hainan Island may be a potential source for the Nam Co Formation. Moreover, Mesoproterozoic 1.45–1.4 Ga igneous rocks and Grenvillian (1.3–1.0 Ga) mobile belts are identified in East Antarctica (Goodge et al., 2004, 2008, 2017), which lay adjacent to Cathaysia Block during the Rodinia breakup in Neoproterozoic (Yu et al., 2008; Wang et al., 2013a). Thus, some rounded Mesoproterozoic zircons probably derive from East Antarctic.

After 726–721 Ma, these old basement rocks were increasingly uplifted, and provided more Mesoproterozoic detrital materials for the upper Nam Co Formation. The sedimentary rocks in the Nam Co Formation also contain numerous late Paleoproterozoic to early Mesoproterozoic (1.7–1.5 Ga) zircons with positive εHf(t) (Fig. 6a). The most likely source for these zircons is the Panaxi belt, because 1.7–1.5 Ga mafic igneous rocks and minor felsic volcanic rocks are exposed in the Panaxi belt (Fan et al., 2013; Greentree and Li, 2008; Guan et al., 2011; Zhao et al., 2010; Zhao and Zhou, 2011), but absent in the southern Yangtze Block and northern ICB. Middle Paleoproterozoic (1.9–1.8 Ga) igneous rocks in the northern Yangtze and eastern Cathaysia blocks, and Phan Si Pan belt are the possible candidates as the sources for numerous middle Paleoproterozoic zircons in the Nam Co Formation (Hoang et al., 2015; Liu et al., 2009, 2014; Wang et al., 2016b; Xiong et al., 2009; Yu et al., 2009). However, those rocks in the northern Yangtze and Phan Si Pan belt have much lower εHf(t) (−26.3 to −8.7; Chen and Xing, 2016; Hoang et al., 2015; Peng et al., 2012; Xiong et al., 2009) than the Paleoproterozoic (1.9–1.8 Ga) detrital zircons in the Nam Co Formation (mostly −7.56 to −0.37). Moreover, the existence of many euhedral Paleoproterozoic zircons in the Nam Co Formation can also preclude the distant northern Yangtze and eastern Cathaysia blocks as the main provenance. Expect for these magmatic rocks, the old sedimentary rocks in Panxi belt, e.g. early Neoproterozoic to late Paleoproterozoic Kuangyang, Huili, Hekou and Dahongshan groups, contain numerous 1.9–1.6 Ga zircons with similar Hf-isotope compositions to those in the Nam Co Formation (Sun et al., 2009; Wang et al., 2012a; Zhao et al., 2010), and probably are the major sources of the Nam Co Formation. In addition, there are many late Paleoproterozoic-Archean zircons in those older sedimentary rocks in Panxi belt. Early Paleoproterozoic to Mesoarchean igneous rocks are sporadically exposed in the Phan Si Pan belt, such as ~2.8 Cavinh complex, ~2.3 Ga Xom Giau complex and 2.3–2.2 Phan Si Pan complex (Lan et al., 2001; Tran et al., 2001; Wang et al., 2016b), and in the northern Yangtze Block, e.g. 3.3–2.9 Ga Kongling complex (Gao et al., 2011; Jiao et al., 2009; Qiu and Gao, 2000; Zhang et al., 2006). They may provide old clastic materials for the Nam Co Formation. Given that the later Cenozoic collision between Indian and Eurasian blocks triggered the southeastward extrusion of the ICB, a series of left-lateral strike-slip faults probably leaded to the southeastward shift of the Nam Co belt. The original position of this belt should have gone back northward or northwestward near the southern Panxi belt. Thus, the Nam Co belt can received easily sediments derived from the Panxi belt in the western Yangtze Block, the Jiangnan belt in the southern Yangtze Block, Ailaoshan-Song Hong and Phan Si Pan belts (Fig. 8a).

The chemical compositions of the sedimentary rocks can also provide useful information to trace their source components (e.g. Dostal and Keppie, 2009; McLennan et al., 1993; Roser and Korsch, 1988). In the major element discrimination diagram of sediment provenance (Fig. 9a), the samples from the lower Nam Co Formation plot in the quartzose sedimentary and mafic igneous provenances, but most of samples from the upper Nam Co Formation plot in the field of intermediate igneous provenance or transition zone between intermediate, felsic and quartzose sedimentary provenances (Fig. 9a), implying a mixed source, consistent with their complicated components of detrital zircons (Fig. 7b). By contrast with major element, some trace elements, such as Th, Zr, Co, Sc and Cr, probably are less mobile in the process of weathering, erosion and transport. In general, Th, Zr and La are enriched in felsic rocks relative to mafic rocks, whereas Co, Sc and Cr are more abundant in mafic rocks (McLennan et al., 1993), and consequently their ratios can be used to better constrain the primary information of the source. The sedimentary rocks from the upper and lower Nam Co Formation have relatively higher Th/Sc ratios (average of 1.31 and 2.24, respectively) than UCC (0.75; Rudnick and Gao, 2003) and PAAS (0.91; Taylor and Mclennan, 1985). In Zr/Sc vs. Th/Sc and La/Sc vs. Sc/Th diagrams (Fig. 9b and c), all but one samples from the lower Nam Co Formation plot near the Neoproterozoic Ailaoshan diorite, whereas those from the upper formation are more close to the Neoproterozoic granite compositions from the western and southern Yangtze Block and the Phan Si Phan belt (Fig. 9b, c), which is consistent with numerous Neoproterozoic igneous rocks exposed in periphery of the Yangtze Block (Wang et al., 2006, 2014; Zhao et al., 2011, 2002). Moreover, these diagrams also show that the sedimentary rocks from the central Nam Co belt probably contain more mafic materials than those from the southeastern Nam Co belt, implying that the central Nam Co belt is closer to the Panxi and Ailaoshan-Song Hong belts, where more mafic basement rocks were exposed. In the La/Th vs. Hf diagram (Fig. 9d), many samples plot in the acidic arc source field, and some samples deviate from this field and show the increasing old sediment components. Neoproterozoic arc-related granitoids have been identified in the Yangtze Block and Pan Si Pan Belt (Li et al., 2018; Wang et al., 2006; Zhou et al., 2002). These conclusions deduced from the geochemical characteristics are all consistent with those from the detrital zircon ages and Hf-isotope compositions as above discussions and indicate that the detrital materials of the Nam Co Formation derived from the mixing of the multisource materials.

5.3. Crustal evolution of the provenance

Ages and Hf-isotope compositions of detrital zircons from the Nam Co Formation suggest that there were several periods of magmatism occurring in the nearby provenance. Of them, numerous zircons in the ~2.6 to ~2.5 Ga, ~1.65 to ~1.45 Ga and 0.9–0.8 Ga age populations have positive εHf(t) (Fig. 6a), with some even plotting above the evolution line of depleted mantle (DM), suggesting episodic juvenile crustal growth in these three periods (Fig. 6a). Three main crust growth events are similar to those in the southern and western Yangtze Block (Wang et al., 2010, 2014), but different from those in the ICB and Cathaysia Block (Fig. 6c).

These three main periods of magmatism had not only involved significant juvenile crust growth, but also strong reworking of old crust (Fig. 6a). The earliest crustal reworking probably occurred in Archean (~2.8 Ga to ~2.7 Ga). These Neoarchean zircons together with three Paleoproterozoic zircons construct an evolution line intersecting with the DM at ~3.5 Ga, indicating that their host magmas probably originated from a Paleoarchean crust. Two Paleoproterozoic zircons (~1.69 Ga, ~1.90 Ga) from the upper Nam Co Formation have lowest Hf-isotopic ratios with ~4.1 Ga T_{DM}^{C} age, possibly suggesting a little Hadean crust in the source. Most of Paleoproterozoic (2.4–1.7 Ga) zircons have negative εHf(t) values. These and some younger zircons of 1.7–1.6 Ga, 1.2 Ga and 0.9–0.8 Ga ages fall between two evolution zones of 3.1 Ga and 2.6 Ga crusts (Fig. 6a), suggesting that the host magmas of these zircons derived from the reworking of the Neoarchean and Paleoarchean crusts or their mixed source. About 75% of the Neoproterozoic (1.0–0.7 Ga) zircons have negative Hf(t) and most of them have T_{DM}^{C} ranging from 2.6 Ga to 1.6 Ga, manifesting that this period of strong magmatism mainly involved with the reworking of these two episodes of juvenile crust and their mixed materials. It is also suggested that Neoproterozoic magmatism probably occurred in a continental arc setting.

5.4. Tectonic setting and attribute of the Nam Co formation

In the K_2O/Na_2O vs. SiO_2 diagram, all the samples from the Nam Co Formation plot in the passive margin setting (Fig. 10a). The relatively low index of compositional variability (ICV) of these sedimentary rocks (average of 0.82) show their high maturity, and probably indicate a relatively stable tectonic setting (Cox et al., 1995; Kamp and Leake, 1985). In order to exclude the analytical errors and other influences (e.g. weathering, recycling and post-depositional processes), we use major element discriminant-function multi-dimensional diagram (D_1-D_2 diagram of Verma and Armstrong-Altrin, 2013) to further distinguish their tectonic setting. In this diagram (Fig. 10b), most of the samples plot in the continental rift field, also indicating that the middle-late Neoproterozoic (< 821 ~721 Ma) Nam Co Formation probably deposited in a relatively stable and continental extensional basin. The presence of numerous ancient detrital materials in the sedimentary rocks of the Nam Co Formation (Fig. 5e, 7a) is also in accordance with the depositional environment of the continental extensional basin (Goodge et al., 2002, 2004). Moreover, the proportion of the older

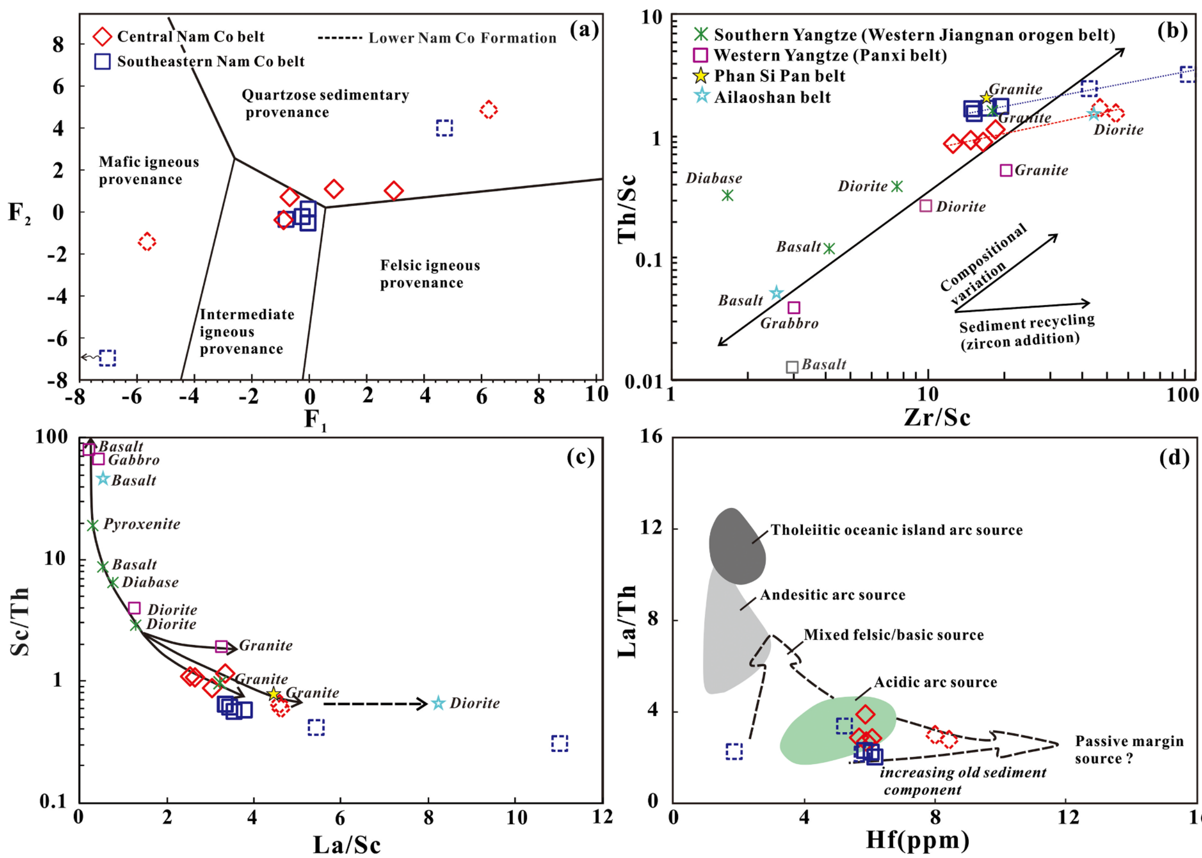

Fig. 9. (a) Discrimination diagram of sediment provenance using major elements ratios (after Roser and Korsch, 1988). (b) Th/Sc vs. Zr/Sc diagram (after McLennan et al., 1993). (c) Sc/Th vs. La/Sc diagram. (d) La/Th vs. Hf diagram (after Floyd and Leveridge, 1987). Date of Neoproterozoic magmatic rocks in western Yangtze block (Panxi belt) are from Sun et al. (2007), Zhao and Zhou (2007a, 2007b), Zhou et al. (2002), those in the southern Yangtze Block (western Jiangnan Orogenic Belt) are from Chen et al., 2014, 2018b), Wang et al., 2006Zhou et al., 2000, 2004, 2007), those in the Phan Si Pan and Ailaoshan-Song Hong belts are from Li et al. (2018) and Cai et al., (2014, 2015), respectively.

detrital materials in the upper Nam Co Formation is over 50% and obviously higher than those in the lower part (Fig. 5e), showing that sedimentation environment in later period (< 726–721 Ma) was more stable, leading to the adding of more recycled ancient sediments. Therefore, the type of the Neoproterozoic basin in the Nam Co belt is similar to that of the central SCB in the late Neoproterozoic (Wang and Li, 2003).

Zhou et al. (2017, 2018) demonstrated that the Precambrian basement of the Song Chay area in Northeast Vietnam has the tectonic affinity with the southern Yangtze Block. In this study, we conclude that the Neoproterozoic Nam Co Formation in Northwest Vietnam has the provenances similar to the Neoproterozoic sedimentary rocks in the western and southern margins of the Yangtze Block, but significantly different from those in the Cathaysia and Indochina blocks. This implies that the basement in the Nam Co belt also has the tectonic affinity with the Yangtze Block. In addition, Devonian faunal assemblage in the Phan

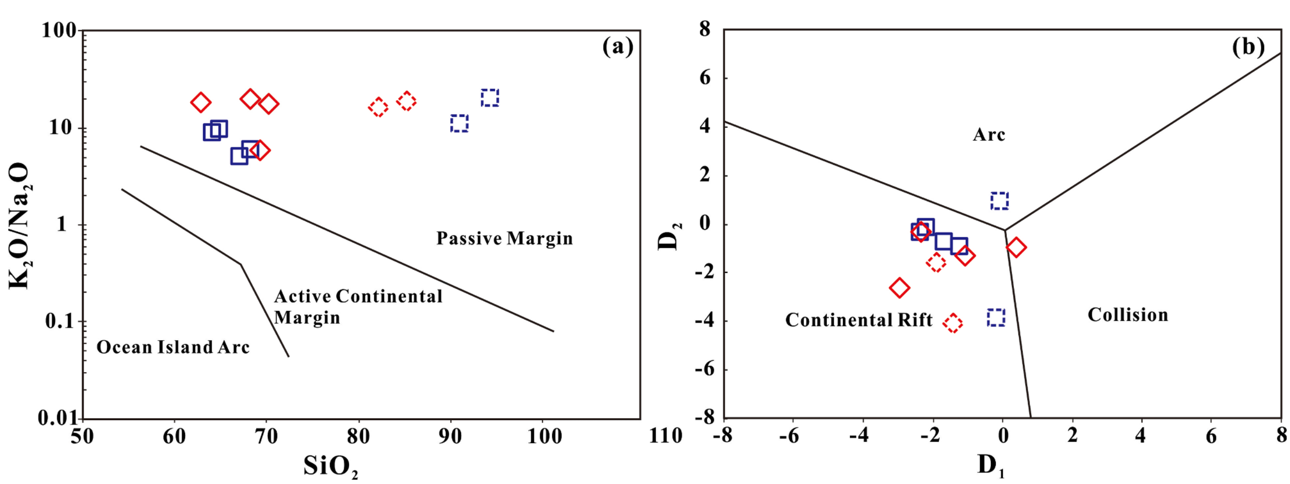

Fig. 10. (a) K_2O/Na_2O vs. SiO_2 discrimination diagram of tectonic setting (after Roser and Korsch, 1986). (b) Multi-dimensional (D_1-D_2) diagram for tectonic discrimination of high-silica clastic sediments (after Verma and Armstrong-Altrin, 2013).

Si Pan belt, which is located to the northeast of the Nam Co belt, is more similar to those in the Yangtze Block than the Indochina Block (central Vietnam) (Janvier et al., 1997). Cambrian phosphorite and other Paleozoic paleogeographic characteristics in the Song Da belt, which is located between the Phan Si Pan and Nam Co belts, also have similarity with those in the Yangtze Block (Yue et al., 2013). Consequently, we strongly argue that the Nam Co belt belongs to the Yangtze Block, and originally was situated at the southwestern corner of the Yangtze Block. Thus, the Song Ma fault, now located to the southwest of the Nam Co belt, is most likely to be the boundary between the SCB and ICB, rather than the other NW-trending faults, such as the Song Da fault (Sengor and Hsu, 1984), Song Chay fault (Chen et al., 2013, 2014b), and Dian-Qiong suture (Cai and Zhang, 2009; Wu et al., 1999; Zhong et al., 1998).

During the Neoproterozoic (1000–820 Ma), the Yangtze and Cathaysia blocks were welded together and resulted in the Jiangnan orogeny between them (Chen et al., 1991; Li et al., 2009; Wang et al., 2007a; Zhao et al., 2011; Zhao and Cawood, 2012 and reference therein; Zhou and Zhu, 1993). Along the Jiangnan Orogenic Belt, a series of Neoproterozoic (879–800 Ma) peraluminous granitic rocks, arc-related mafic–ultramafic rocks and later extensional mafic dykes were formed, indicating the transformation of tectonic settings from the subduction, collision to the post-collisional extension (e.g. Ge et al., 2001; Huang et al., 2019; Wang et al., 2006, 2007, 2008b, 2008c; Zhou et al., 2009). The 770–750 Ma extensional regime is consistent with the sedimentation basin setting of the Nam Co Formation (Chen et al., 2018b; Wang et al., 2008c; Zhou et al., 2007). The tectonic setting in the Panxi belt, western Yangtze Block, are slightly different from the study area. There are many MORB-type and OIB-type basalts in the Yanbian (920–858 Ma) and Kangding (830–721 Ma) Groups (Du et al., 2005, 2007; Sun et al., 2007; Sun and Zhou, 2008) in the Panxi belt. Moreover, the 764–748 Ma adakitic granites, 860–740 Ma arc-related granites and intermediate-mafic plutons also were reported in this area (Du et al., 2009; Huang et al., 2009; Shen et al., 2003; Sun et al., 2008; Zhao and Zhou, 2007a, 2007b; Zhou et al., 2002, 2006a, 2006b). These rocks suggest that the subduction in the western Yangtze Block probably continued until the middle Neoproterozoic (~740 Ma). Therefore, the Nam Co belt at the junction of the Panxi and Jiangnan belts has closer affinity with the southern Yangtze Block, although it also received many Neoproterozoic detrital materials derived from the Panxi belt.

6. Conclusions

(1) The Nam Co Formation is a middle-late Neoproterozoic sedimentary sequence in Northwest Vietnam. The lower Nam Co Formation formed between 821 Ma and 726 Ma, and the maximum depositional age of the upper Nam Co Formation is 726–721 Ma.
(2) The sedimentary rocks from the lower and upper Nam Co Formation are characterized by numerous Neoproterozoic (900–800 Ma) detrital materials, and the upper Formation contains more Mesoproterozoic to Paleoproterozoic sediments than the lower Formation. The clastic materials of the Nam Co Formation were mainly derived from the Panxi belt in the western Yangtze Block and the Jiangnan belt in the southern Yangtze Block with minor contribution from the Ailaoshan-Song Hong and Phan Si Pan belts.
(3) Three main crustal growth events occurred in the provenance of the Nam Co Formation: ~2.6 Ga to ~2.5 Ga, ~1.65 Ga to ~1.45 Ga and 0.9 Ga to 0.8 Ga. These periods of magmatism also involve the reworking of old crustal materials. The Neoproterozoic (1.0–0.7 Ga) igneous rocks were mainly generated from the reworking of the first two episodes of juvenile crust and their mixed materials.
(4) The Nam Co Formation probably deposited in a continental extensional basin after the collisional orogeny between the Yangtze and Cathaysia blocks, and sedimentation environment was more stable in late stage (< 726–721 Ma).
(5) The Nam Co belt belongs to the Yangtze Block and was originally located at the southwest corner of the Yangtze Block. Thus, the Song Ma fault located to southwest of the Nam Co belt is most likely the boundary between the SCB and ICB.

Conflict of interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.precamres.2019.105556.

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