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Sources of the Nanwenhe-Song Chay granitic complex (SW China - NE Vietnam) and its tectonic significance

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Abstract

The Nanwenhe - Song Chay complex (NSCC) is a large early Paleozoic pluton straddling the border between SW China and NE Vietnam. It is located at the tectonic junction of the Yangtze, Cathaysia and Indochina blocks so that the source of the complex is still enigmatic. The rocks from the complex are high-K calc-alkaline and peraluminous S-type granite. LA-ICP-MS U-Pb dating of zircons from twelve granitic samples in the complex gives crystallization ages in the range of 436-423 Ma. Zircon U-Pb-Hf isotopes and geochemical data show that the Nanwenhe granites in the northern part of the NSCC probably were mainly derived from Neoproterozoic metamorphic pelites analogous to those in the Xiajiang and Danzhou Groups. In contrast, the Song Chay granites in the southern part of the NSCC were probably derived from Neoproterozoic metamorphic psammites analogous to those in the Fanjingshan and Sibao groups in the southwestern Yangtze Block. The granites from the complex contain abundant inherited zircons with a main peak at 836-808 Ma and subordinate peaks at ~734 Ma and 528-665 Ma. The inherited zircons have age distribution patterns and Hf-isotopic compositions similar to those for the detrital zircons from Neoproterozoic to Early Paleozoic sedimentary rocks in the southwestern part of the Yangtze Block, but different from those of the Cathaysia Block and Indochina Block. Therefore, the basement of the NSCC is equivalent to the Yangtze Block, and the complex may represent the westernmost tip of the early Paleozoic orogenic belt in the SCB. We thus assume that the boundaries between the Yangtze Block and the Cathaysia Block and between the SCB and ICB should be
located to the southeast and southwest of the Nanwenhe - Song Chay area, respectively.

**Keywords:** Early Paleozoic granites; Zircon U-Pb-Hf isotopes; Nanwenhe – Song Chay complex; Southwest China Block; northeastern Vietnam; boundary between the Cathaysia and Yangtze

1. **Introduction**

The South China Block (SCB) was formed by the amalgamation of the Yangtze Block and the Cathaysia Block in the early Neoproterozoic (1000-820Ma) (Li et al., 2009; Zhao et al., 2011; Zhao and Cawood, 2012 and references therein; Zhou and Zhu, 1993). The composition and evolution of the Precambrian basement in these two blocks is different (Xu et al., 2007; Yu et al., 2010; Zhang and Zheng, 2007; Zhao and Cawood, 2012; Zheng and Zhang, 2007). The eastern boundary between the Yangtze Block and Cathaysia Block is generally considered to be the Jiangshan-Shaoxing fault, along which ophiolites and blueschists have been identified (Gao et al., 2009; Li et al., 1994; Shu et al., 1994; Shu, 2012). However, the western boundary has always been controversial. Many faults have been proposed as the western extension of the boundary, e.g. the Shizong-Mile fault (Dong et al., 2002; Guo et al., 2009), the Chaling-Pingxiang fault (Hu and Deng, 2009; Wang, 1994), the Chenzhou-Linwu-Beihai fault (Wang et al., 2008a, 2010a), and the Wuchuan-Sihui fault (Wang et al., 2003; Zhang and Wang, 2007) (Fig. 1).
The Song Chay Massif is located in northeastern Vietnam, near the southwestern margin of the South China (Fig. 1). It is commonly considered as a part of the SCB (Chen et al., 2014; Lin et al., 2011; Roger et al., 2000). The Indochina Block (ICB) separated from Gondwana and amalgamated with the SCB and other continental blocks (e.g. Sibumasu Block) to form the Southeast Asian continent in the late Paleozoic to the early Mesozoic (Faure et al., 2014; Lan et al., 2003; Matcalfe, 1996, 2002; Usuki et al., 2013). However, the boundary between the ICB and SCB is still under debate. Boundaries proposed previously include the Song Ma fault (Faure et al., 2014; Lepvrier et al., 1997, 2008; Metcalfe, 2002, 2013; Tran and Khuc, 2011), the Song Hong fault (Findlay and Trinh, 1997; Leloup et al., 1995), the Song Chay fault (Chen et al., 2013, 2014), and the Dian-Qiong (or Babu) suture (Cai and Zhang, 2009; Wu et al., 1999; Zhong et al., 1998) (Fig. 1).

The Precambrian basement rocks in northern Vietnam are mainly distributed in the area between the Song Chay and Song Ma faults (Fig. 1). Some scholars have considered that the Precambrian basement rocks are parts of the SCB (Fan et al., 2010; Hieu et al., 2009; Lan et al., 2001; Wang et al., 2016a), but others have ascribed them to the ICB (Leloup et al., 2001; Nam et al., 2003). Precambrian rocks have not previously been reported in the Song Chay massif. However, the characterization of the Precambrian basement under this area is important as a constraint on the tectonic affiliation of the Song Chay massif and definition of both the southwestern boundary between the Yangtze and Cathaysia blocks and the boundary between the SCB and ICB.
The Song Chay granitic pluton, an important rock unit in northeastern Vietnam, constitutes a large granite dome together with the Nanwenhe gneissic granite in the southeastern Yunnan Province, Southwest China (Fig. 2). Some researchers have described it as a metamorphic core complex or metamorphic dome (Liu et al., 2003; Roger et al., 2000; Yan et al., 2005, 2006; Zhang et al., 1998). The Nanwenhe - Song Chay Complex (NSCC) is located at the junction of the Yangtze, Cathaysia and Indochina Blocks (Fig. 1). Its composition and inherited zircons within it may provide information about components of the deep basement. On the other hand, many Sn-W polymetallic ore fields, such as the Dulong, the Xinzhai and the Nanwenhe deposits in SE Yunnan, are distributed along the northern part of the NSCC. Previous research has focused on these Sn-W deposits and the related late Mesozoic Laojunshan and Nanwenhe granites (Fig. 2; Feng et al., 2013; Liu et al., 2007; Peng et al., 2015; Xu et al., 2015a, 2015b). Little attention has been paid to the Song Chay granite, for few Sn-W deposits have been found in this pluton in Vietnamese territory. Whether the Nanwenhe granite and the Song Chay granite have different sources and consequently different basement components beneath SE Yunnan and NE Vietnam therefore is an important issue. This study presents a dataset of new zircon U-Pb ages, Hf-isotope analyses and bulk geochemical data on the NSCC in order to provide constraints on these issues.

2. Geological background and sample features

The Nanwenhe – Song Chay area is bordered by the NW-SE-trending Song Chay
Fault to the southwest and the Dian-Qiong Fault to the northeast (Fig. 1). Previous studies have suggested that Mesozoic-based tectonic extension led to the development of a large domal structure in this area, which is known as the Laojunshan- Song Chay metamorphic core complex (Guo et al., 2009; Liu et al., 2003; Roger et al., 2000; Xue et al., 2010). A metamorphosed core and weakly metamorphosed cover sequence constitute this metamorphic core complex. Metamorphic grades change sharply from upper greenschist-lower amphibolite facies in the core to lower greenschist facies and even lower in the cover sequence. Both of them have been intruded by the unmetamorphosed and undeformed late Mesozoic Laojunshan granite in the northwestern corner of the NSCC (Fig. 2).

The core consists of the early Paleozoic NSCC and Neoproterozoic to Cambrian metasedimentary rocks. Early Paleozoic NSCC has an area of about 2200 km² (Fig. 2) (Chen et al., 2014; Maluski et al., 2001). Its northern part is located in SW China, and is generally termed the Nanwenhe granite, and its southern part is exposed in NE Vietnam, and called the Song Chay granite. The Nanwenhe granite is similar to the Song Chay granite in terms of mineral assemblage, texture and structure, and there is no clear boundary between them. The NSCC is composed of gneissic granites and porphyritic granites with intense NE-SW foliation and lineation, probably caused by the Indosinian orogeny (251-206 Ma) (Chen et al., 2014; Lepvrier et al., 2011; Lin et al., 2011; Roger et al., 2000; Yan et al., 2005, 2006). The NSCC intruded the Neoproterozoic to Cambrian meta-sedimentary rocks (Fig. 2). The Neoproterozoic Mengdong Group in the northern part of the NSCC underwent lower-amphibolite
facies metamorphism (Fig. 2; Lü et al., 2001). It is mainly composed of schist, leptynite and quartzite with minor amphibolite, carbonatite and gneiss. It was previously regarded as a Paleoproterozoic unit (BGMRY, 1999; Lü et al., 2001). However, SHRIMP U-Pb dating of zircons from the amphibolite of the Mengdong Group gives $^{206}\text{Pb}^{238}\text{U}$ ages of ca 760 to 830 Ma (Guo, 2006; Liu et al., 2006). Neoproterozoic to Cambrian strata are exposed in the periphery of the NSCC. In NE Vietnam, the Neoproterozoic to early Cambrian Song Chay Group is divided into the Thac Ba Formation and An Phu Formation from the base upward. The former is dominated by quartzite, schist and amphibolite with minor marble. The latter is analogous to the Xinzhai Formation in SW China and is composed mainly of schist and marble (BGMRY, 1976, 1990, 1999; DGMV, 2000; Zhang et al., 2011). The Cambrian successions consist mainly of carbonate and fine-grained siliciclastic rocks (Table 1).

The sedimentary cover sequences exposed in the study area include Devonian and minor Carboniferous to Cretaceous strata. The rock types of these strata in SW China and NE Vietnam are summarized in Table 1. There are two angular unconformities, one between the Devonian succession and the underlying Cambrian sequence, and one between early Triassic and Permian strata, in both China and Vietnam, corresponding to Early Paleozoic Orogeny and Indosinian Orogeny, respectively. Two unconformities, one between Carboniferous and Devonian strata and one between late Triassic and early-middle Triassic, were identified on a regional scale in NE Vietnam. The cover sequence is separated from the core by a series of
extensional detachment faults, and some brittle faults also are developed within the cover sequences (Yan et al., 2006).

The Late Mesozoic Laojunshan granitic pluton intruding the northwestern corner of the NSCC has an exposed area of about 150 km$^2$ (Fig. 2). This pluton consists mainly of coarse- to medium-grained two-mica adamellites, and medium- to fine-grained two-mica granites and granites, and is related to the famous Dulong Sn deposit.

Forty-seven granite samples were collected from the NSCC. Twenty-four samples were chosen for bulk geochemical analyses, and twelve of them were used for zircon U-Pb dating and Lu-Hf isotope analyses. All these granite samples show fine- to medium-grained textures and gneissic or augen structures with K-feldspar phenocrysts or augen (Fig 3a-c). The common mineral assemblages of these samples are Qz (20-50%) + Pl (5-22%) + Kf (15-50%) + Bt (2-15%) + Mus (1-12%) with accessory minerals apatite, fluorite and zircon. Garnet and tourmaline are recognized in many samples (Fig 3d-f).

3. Analytical methods

The samples for whole-rock chemical analysis were crushed and then powdered to 200-mesh in an agate mortar. Major-element concentrations were obtained using an ARL-9800 XRF at the Modern Analysis Center of Nanjing University, with analytical precision better than 2% for most elements. Trace-element analyses were carried out at the Guiyang Institute of Geochemistry, Chinese Academy of Sciences, using an
inductively coupled plasma mass spectrometer (ICP-MS). Sample preparation and
analytical procedures followed those described by Gao et al. (2003), and analytical
precision is better than 10% for most trace elements.

Zircon grains were separated using conventional magnetic and heavy-liquid
separation techniques. Then grains were handpicked under a binocular microscope,
mounted in epoxy disks and polished to expose their cores. Cathodoluminescence (CL)
imaging was carried out at the State Key Laboratory for Mineral Deposits Research,
Nanjing University, to define the morphology and origins of the zircons and to choose
potential target sites for U-Pb dating and Hf-isotope analyses. Zircon U–Pb analyses
of three samples (WS13-8, WS13-24, WS13-11-1) were carried out at the State Key
Laboratory of Continental Dynamics, Northwest University using an Agilent 7500a
equipped with GeoLas 193 nm laser-ablation system (MicroLas, Göttingen, Germany).
A spot size of 32 μm was used for all analyses. Detailed analytical procedures are
similar to those described by Liu et al. (2008) and Yuan et al. (2003). The others were
analyzed at the State Key Laboratory for Mineral Deposits Research, Nanjing
University and the GEMOC/CCFS National Key Centre, Macquarie University, using
an Agilent 7500s ICP-MS attached to a New Wave 213 nm laser ablation system.
Detailed analytical procedures are similar to those described by Griffin et al. (2004)
and Jackson et al. (2004) and Wang et al. (2007). Zircon U-Pb dating of two samples
(14VN-54-1 and 14VN-52-2) was repeated in these laboratories to ensure the data
validity and reliability. The dating results of the same sample in these laboratories are
similar within error limits. The results were reduced using the GLITTER software (ver.
4.4) (http://www.mq.edu.au/GEMOC; Griffin et al., 2008). Common-Pb corrections were made following the method of Andersen (2002). Age calculations and plotting of Concordia diagrams were done using the ISOPLOT/Ex program (ver. 3.0) of Ludwig (2003). Zircons with highly discordant ages (concordance <80%) were discarded from age calculations unless they lie on a well-defined discordia line. The \( ^{207}\text{U}/^{206}\text{Pb} \) age is cited for zircons with \( ^{207}\text{U}/^{206}\text{Pb} \) ages older than 900 Ma, and \( ^{206}\text{U}/^{238}\text{Pb} \) age for younger zircon (Yu et al., 2010).

*In situ* zircon Hf-isotope analyses were conducted using a Neptune Plus multi-collector ICP-MS, equipped with a 193nm laser, at the State Key Laboratory for Mineral Deposits Research in Nanjing University. Hf-isotope analyses were performed on the same or similar zircon domains used for U-Pb dating (Fig. 4). The analyses were done with ablation pits 44\( \mu \)m in diameter and a repetition rate of 10Hz. The analytical conditions and procedures are similar to those described by Hou et al. (2007) and isobaric interference corrections were done using the methods of Wu et al. (2006). The \( ^{176}\text{Lu} \) decay constant adopted in this paper is \( 1.865 \times 10^{-11} \) per year (Scherer et al., 2001). A depleted-mantle model (\( ^{176}\text{Hf}/^{177}\text{Hf} = 0.283250, ^{176}\text{Lu}/^{177}\text{Hf} = 0.0384; \) Griffin et al., 2002) and a chondritic model (\( ^{176}\text{Hf}/^{177}\text{Hf} = 0.282772, ^{176}\text{Lu}/^{177}\text{Hf} = 0.0332; \) Blichert-Toft and Albarède, 1997) are used to calculate model ages (\( T_{DM} \)) and epsilon Hf values. We have adopted a mean crustal composition (\( ^{176}\text{Lu}/^{177}\text{Hf} = 0.015; \) Griffin et al., 2002, 2004) to calculate two-stage crustal model ages (\( T_{DM}^C \)) for each zircon.
4. Zircon U-Pb ages and Hf-isotope compositions

4.1 The Nanwenhe granites in the northern NSCC

Zircons from five samples of the Nanwenhe gneissic granite in the northern part of the NSCC were collected for U-Pb age dating and Hf isotope analyses. The zircons are generally euhedral to subhedral and prismatic in shape, and have sizes mostly between 70μm to 200 μm. Most of them are transparent to subtransparent, and light yellow or colorless. These grains mostly have clear oscillatory zoning in CL images (Fig. 4) and high Th/U ratios, characteristic of typical magmatic zircon; some grains have inherited cores.

Twenty to thirty-five grains were chosen from each sample for U-Pb dating. The analyses on the rims of the grains or on the uniform grains that have Th/U >0.2 yielded concordant ages ranging from 446 Ma to 420 Ma. These magmatic zircons from each sample give similar mean $^{206}$Pb/$^{238}$U ages of 433.1 ± 2.7 Ma (n =23), 429 ± 2.1 Ma (n=17), 433.3 ± 2.5 Ma (n=15), 429.1 ± 4.5 Ma (n=14) and 429.0 ± 3.3 Ma (n=18) for samples WS13-8, 14WS-7, 14WS-16, WS13-11-1 and WS13-24, respectively (Appendix Table 1). These are interpreted as the crystallization ages of these granites.

Zircon cores from five samples yield a range of ages, dominantly Neoproterozoic with fewer Mesoproterozoic (1.6-1.4 Ga), Paleoproterozoic (~1.85 Ga and 2.3-2.1 Ga) and Neoarchean (~2.5 Ga) (Fig. 5). A few analyses produce ages of 545-513 Ma.

The magmatic zircons from each sample have εHf(t) values ranging from -9.9 to +2.0, but the most concentrate around -6.0 to -0.1 (Fig. 6a; Appendix Table 2). These
samples have average $\varepsilon$Hf(t) values of -1.7 to -4.4. Two-stage Hf model ages ($T_{DM}^C$) of all magmatic zircons vary from 2.0 Ga to 1.3 Ga with mean model ages in the Mesoproterozoic (Fig. 6b). Neoproterozoic inherited zircons have $\varepsilon$Hf(t) ranging from -17.7 to +6.7 (Fig. 6c; Appendix Table 2), corresponding to Paleo- to Mesoproterozoic Hf model ages ($T_{DM}^C = 2.1$-1.3 Ga), similar to those of early Paleozoic magmatic zircons. Mesoproterozoic zircons have variable $\varepsilon$Hf(t) values, and their $T_{DM}^C$ are similar to those of the early Paleozoic and Neoproterozoic zircons (Fig. 6c), whereas all three Paleoproterozoic ones have negative $\varepsilon$Hf(t) values and significantly older $T_{DM}^C$ model ages (3.1-2.8 Ga; Fig. 6c).

4.2 The Song Chay granites in the southern NSCC

The zircons from the Song Chay granites show fine euhedral prismatic shapes with aspect ratios of 1.5 - 4. All grains have clear oscillatory zoning except for some cores (Fig. 4), and core-mantle structure is common in some samples. Zircon rims or uniform zircon grains from seven samples yield early Paleozoic U-Pb ages ranging from 458 Ma to 404 Ma. If a few younger outliers are excluded, the remaining analyses give average $^{206}$Pb/$^{238}$U ages for seven samples varying from 436 Ma to 423 Ma (Fig. 5). These ages, similar to those of the Nanwenhe granites, are taken as the crystallization ages of the Song Chay gneissic granites. The rim of one grain in sample 15VN-58-1 has an early Mesozoic age (224 Ma). This rim has low Th/U (0.09) and blurry compositional zoning, suggesting a metamorphic overprint in the early Mesozoic. The inherited zircons from the Song Chay granites are dominated by
Neoproterozoic ages, like those from the Nanwenhe granites. Other ages concentrate at ca 1.40 Ga, 1.87 Ga, 2.10 Ga and 2.5 Ga (Fig. 5).

The early Paleozoic zircons from each sample have similar $\epsilon_{\text{Hf}}(t)$ variation ranging from -6.0 to +2.3 (Fig. 6a; Appendix Table 2), corresponding to Hf model ages of 1.79-1.27 Ga with a peak at 1.49 Ga. The mean $\epsilon_{\text{Hf}}(t)$ values of early Paleozoic magmatic zircons of seven samples are -3.0 to -0.52, similar to those from the Nanwenhe granites. The Hf-isotope compositions of inherited zircons also show significant variation. Like those in the Nanwenhe granites, Neoproterozoic inherited zircons mostly have $\epsilon_{\text{Hf}}(t)$ of -5.7 to +10.1 and $T_{\text{DM}}^C$ of 1.1 Ga to 2.1 Ga. All Mesoproterozoic zircons have positive $\epsilon_{\text{Hf}}(t)$ (+1.75 - +12.9), and corresponding Hf model ages fall close to the range seen in the Neoproterozoic to early Paleozoic zircons (Fig. 6c). Three Paleoproterozoic zircons show low initial $^{176}_{\text{Hf}}/^{177}_{\text{Hf}}$ and high Hf model ages ($T_{\text{DM}}^C$ =2.6-3.4 Ga; Appendix Table 2).

5. Whole-rock geochemistry

5.1 Major elements

Twenty-four samples define relatively large compositional variations (Appendix Table. 3) with SiO$_2$ of 66.6-76.0 wt%, Al$_2$O$_3$ of 12.2-15.9 wt%, Fe$_2$O$_3^T$ of 1.03-4.47 wt%, and MgO of 0.20-1.73 wt%. Most samples have SiO$_2$ >70 wt%, K$_2$O/Na$_2$O >1.0 and ALK of 6.47-8.47 wt%; they belong to the high-K calc-alkaline series (Fig. 7a). In the TAS classification diagram, most samples plot in the granite field (Fig. 7b). They have high A/CNK values (mostly >1.1) and A/NK (1.20-1.73), consistent with
the geochemical characteristics of peraluminous S-type granites (Fig. 7c-d). In Harker diagrams (Fig. 8), the NSCC exhibit negative correlations of Al₂O₃, Fe₂O₃^T, TiO₂, and CaO with SiO₂, but little correlation between K₂O and SiO₂ (Fig. 8, 7a). Although the Nanwenhe granites and the Song Chay granites have similar ranges in SiO₂, and similar Al-rich (high A/CNK) and high-K features (Fig. 7), they also show some differences. At a given SiO₂ content, the Nanwenhe granites have higher Al₂O₃ (A/CNK) and P₂O₅ contents, and lower CaO, MgO contents than the Song Chay granites (Fig. 8), implying that these S-type granitic magmas were derived from different sources or generated under different P-T conditions (Fig. 7c, d).

5.2 Trace elements

The NSCC granites all have high Rb, low Ba and Sr with high Rb/Sr and Rb/Ba ratios, similar to highly-fractionated S-type granites (Whalen et al., 1987). The Nanwenhe granites in the northern NSCC also have higher Rb, Cs, Nb, Ta, W, Sn and lower Sr, Ba, Cr, Ni, Co, Cu and REE than the Song Chay granites (Fig. 9; Appendix Table 3). Consequently, the Nanwenhe granites exhibit higher Rb/Sr, Rb/Ba, Nb/La and lower Nb/Ta, Zr/Hf than the Song Chay ones (Fig. 9h, i, n, o). With the evolution of the magmas, some trace element contents or ratios of the NSCC exhibit large variations and correlations with SiO₂ (Fig. 9). For example, as SiO₂ increases, Ba, Sr, Eu, Nb, Zr, Th and Nb/Ta in the NSCC decrease, and Rb/Sr generally increases.

All NSCC samples have similar chondrite-normalized patterns of rare-earth elements (REE) with moderate LREE enrichment (most (La/Yb)_N = 2.55-14.9) and
negative Eu anomalies (most Eu/Eu* = 0.21-0.49) (Fig. 10a). They have low total REE contents varying from 33.3 ppm to 217 ppm with averages of 85 ppm and 105 ppm for the Nanwenhe and Song Chay granites, respectively. With increasing SiO₂, the REE contents and La/Yb of the NSCC granites decrease (Fig. 9g, j). In the upper-crust-normalized spidergram (Fig. 10b), all the samples exhibit similar patterns with obvious negative anomalies in Ba, Nb, La, Ce, Sr, Ti and positive anomalies in Cs, Rb, U, Ta, Pb.

6. Discussion

6.1 Timing of the Nanwenhe - Song Chay complex

Although the NSCC is the largest granitic batholith in SW China and NE Vietnam, previous geochronological studies mostly have focused on its northern part, i.e. the Nanwenhe granites in SE Yunnan, China. Only a few researchers have paid attention to the Song Chay granites in NE Vietnam (Carter et al., 2001; Gilley et al., 2003; Roger, et al., 2000). No systematic and comprehensive geochronological work has been done on the whole NSCC pluton until now. Our new LA-ICP-MS zircon U-Pb dating for twelve gneissic granites from the Nanwenhe and Song Chay area gives formation ages of 433-429 Ma and 436-423 Ma, respectively. These ages are roughly consistent with previous data (Carter et al., 2001; Guo et al., 2009; Peng et al., 2015; Roger et al., 2000; Xu et al., 2015b), suggesting that granites of the huge NSCC were formed almost simultaneously in middle Silurian (Telychian to Homerian) time. However, these granites show some age variation, ranging from 436 Ma to 423 Ma.
Detailed analyses show that the younger samples, such as 15VN-65 and 15VN-63, are generally distributed in the center of the NSCC (Fig. 2), implying that the granites in the center of the NSCC probably crystallized a little later than those in the outer zone.

Previous studies suggest that there are some Neoproterozoic orthogneisses in the NSCC (Yan et al., 2006). However, no Neoproterozoic granite was recognized in the NSCC in this study. The Neoproterozoic zircons, which show variable ages in each sample, are regarded as inherited from the magma sources. Previous multi-system geochronological data indicate that the NSCC underwent multiple phases of metamorphism and deformation after its emplacement (Chen et al., 2014; Gilley et al., 2003; Maluski et al., 2001; Roger et al., 2000; Yan et al., 2006). However, the zircon U-Pb dating results on these deformed granites in the NSCC show little overprinting, except for one zircon rim with an age of 224 Ma in sample 15VN-58-1. These results are similar to those of Xu et al. (2015b), indicating that late tectono-thermal events were relatively weak and did not have a strong influence on the NSCC, except for deformation, even though Triassic and Cretaceous magmatic and tectonic activity is extensive in the southeastern part of the Song Chay massif (Lepvrier et al., 2011; Chen et al., 2014 and references therein).

6.2 Sources of the Nanwenhe – Song Chay complex

The source composition is the major factor controlling the geochemical features of granitic magmas (e.g. Chappell, 2004; Clemens and Stevens, 2012; Collins, 1998). There are significant differences between the Nanwenhe and Song Chay granites in
some element contents and ratios, such as Ca, Sr, W, Sn, Cu, Cs, Cr, Ni and Co, and Zr/Hf, Nb/Ta, Rb/Sr and Nb/La (Fig. 8, 9). These differences cannot be explained by the differentiation of similar magmas through fractional crystallization, and thus are probably related to their sources (Appendix Table 3; Fig. 8, 9b, i, k-o). The S-type geochemical characteristics of the NSCC granites indicate that their sources consisted mainly of metasedimentary rocks, consistent with the presence of abundant inherited zircons displaying a range of ages (Chappell and White, 1992, 2001; Kalsbeek et al., 2001; Yu et al., 2009).

The Song Chay granites have higher Ni, Cr, Co and Cu and lower W, Sn, Nb, Ta, and Cs contents than the Nanwenhe granites and the average upper crust (Rudnick and Gao, 2003; Appendix Table 3; Fig. 9), suggesting that the source of the Song Chay granites might have more mafic components (Taylor and Melennan, 1985), or that the sedimentary rocks in the source were less mature. The low Ca and Sr contents of the Nanwenhe granites suggest that the sedimentary rocks in their source underwent stronger weathering, leading to the decomposition of plagioclase and leaching of Ca and Sr.

Melting experiments show that CaO/Na$_2$O ratios of peraluminous granites are mainly controlled by the contents of plagioclase and clay in their sources (Clemens and Stevens, 2012; Sylvester, 1998). Moreover, the mineral assemblages in the source rocks can also affect the Rb/Ba and Rb/Sr ratios of granitic melts (Sylvester, 1998). Most Nanwenhe granites have lower CaO/Na$_2$O (<0.3) and high Al$_2$O$_3$/TiO$_2$, Rb/Ba, Rb/Sr ratios than the Song Chay granites (Fig. 11a, b), suggesting that the Nanwenhe
granites were derived mainly from pelite-dominated sources while the Song Chay granites probably originated from psammite-dominated sources. This inference is also supported by the discrimination diagram based on molar CaO/(MgO+TFeO) vs molar Al₂O₃/(MgO+TFeO) (Fig. 11c). The higher Rb/Sr and Rb/Ba values of the Nanwenhe granites relative to the Song Chay granites (Fig. 11b) also suggest that the source of the former contained more pelitic component, whereas source of the later was composed of more psammitic material (Fig. 11b).

Hf-isotopic compositions generally are not modified during fractional crystallization or partial melting, and thus can serve as a tool to trace the petrogenesis of granites and constrain their sources (Andersen et al., 2007; Bolhar et al., 2008). In this study, the early Paleozoic magmatic zircons from the Nanwenhe and Song Chay granites exhibit similar Hf isotope compositions (Fig. 6a, b). Two-stage Hf model ages (T⁰DM) of early Paleozoic magmatic zircons in the Nanwenhe granites vary from 2.0 Ga to 1.3 Ga with a peak at 1.68 Ga, similar to their whole-rock Nd-isotope model ages (average of 1.69 Ga; Peng et al., 2015; Xu et al., 2015b). Early magmatic zircons from the Song Chay granites have T⁰DM values of 1.8-1.3 Ga with the peak at 1.49 Ga (Fig. 6b), as do the zircons of the Nanwenhe granites. However, magmatic zircons from each sample show large variations in Hf-isotope composition. For example, the εHf(t) values of magmatic zircons in sample WS13-8 vary from -8.9 to +2.0, and those of sample 15VN-65 from -6.3 to +2.3. Significant Hf isotope variation within one sample is often explained by 1) mixing of low-εHf(t) magmas (e.g. crust-derived) and high-εHf(t) melts (e.g. mantle-derived) (Castro et al., 1995; Griffin et al., 2002;
Kemp et al., 2007; Yu et al., 2005; Zhu et al., 2009), 2) inheritance from a heterogeneous source (Villaros, et al., 2012), or 3) disequilibrium melting of zircon at the source (i.e. zircon effect; Tang et al., 2014). However, typical evidence of strong magma mixing, such as coeval mafic microgranular enclaves (MME) or mantle-derived mafic rocks, are not found in the study area. Disequilibrium reaction textures are also not observed in these samples. On the other hand, the NSCC granites all have low contents of Mg, Cr, Ni and Co. The samples with relatively high Mg, Cr, Ni and Co do not show more radiogenic Hf-isotope compositions. Therefore, significant Hf-isotope variations in the NSCC may not be caused by mixing with mantle-derived magmas. In fact, it is almost impossible that frequent mixing during short magma crystallization time (similar crystallization ages) occurred equally in each specimen of magmas with high viscosity.

Villaros et al. (2012) found that Hf-isotope variations of magmatic zircons in many S-type granites are consistent with those of the inherited zircons, and deemed that heterogeneous Hf-isotope compositions of granitic magmas are inherited from their source and cannot efficiently be homogenized via mechanical mixing and/or diffusion. Therefore, the large ranges in zircon Hf-isotope observed in each sample probably result from the different extents of mixing of the inherited cores, rather than of mantle-derived magmas. Inherited zircons are common in the NSCC S-type granites, implying low formation temperatures for the magmas (<850°C), which is consistent with the low Zr saturation temperatures of the NSCC granites (Appendix Table 3). Therefore, the Hf-isotope variations in our samples probably result from the
mechanism proposed by Villaros et al. (2012). The mixing of cores and rims by laser ablation during Hf-isotope analysis is a possible alternative mechanism to explain the Hf-isotope variations, but it is unlikely that such mixing could affect the large proportion of grains seen in this study.

Fig. 6c shows that the Hf-isotope compositions of early Paleozoic magmatic zircons all fall on the evolution trend of the majority of inherited (Mesoproterozoic to Neoproterozoic) zircons, which demonstrates that these inherited cores probably were derived from the source, and that the source consists mainly of Neoproterozoic to Mesoproterozoic detritus. These Neoproterozoic - Mesoproterozoic inherited zircons also have Hf-isotope compositions similar to coeval detrital zircons from the Neoproterozoic Xiajiang, Danzhou, Fanjingshan and Sibao groups in the southern Yangtze Block (Fanjingshan-Sibao area) (Fig. 6c; Fig. 13b). The Fanjingshan and Sibao groups are dominated by meta-sandstone and meta-siltstone, and the overlying Xiajiang and Danzhou groups consist mainly of pelitic slate and phyllite with less meta-sandstone. These characteristics are consistent with those of the inferred source components of the Song Chay and Nanwenhe granites, respectively. Consequently, we conclude that the NSCC granites probably were mainly derived from Neoproterozoic metamorphic basement rocks analogous to the Xiajiang, Danzhou, Fanjingshan and Sibao groups in the southern Yangtze Block.

The difference in source compositions between the Nanwenhe and the Song Chay granites also may be an important reason for the differences in Sn-W mineralization between the northern and southern NSCC. Many Sn-W polymetallic
ore districts have been found in the Nanwenhe granites of the northern NSCC and nearby areas (Feng et al., 2013; Liu et al., 2007; Xu et al., 2015a), which is evidently related to high Sn and W abundances in the source. The much lower Sn (W) contents of the Song Chay granites (Fig. 9k) thus imply low Sn (W) concentrations in the source. Consequently, Sn (W) mineralization in the Song Chay granites is minor. On the other hand, the higher Zr/Hf and Nb/Ta ratios (Fig. 9n) in the Song Chay granites suggest a lower degree of magmatic differentiation. These factors may explain why no industrially important Sn (W) deposits have yet been found in the Song Chay granite in NE Vietnam.

6.3 Constraints on the boundary between the Yangtze and Cathaysia blocks

The tectonic attribution of the Nanwenhe - Song Chay area is still debated. It is generally accepted that the study area is a part of the SCB (Chen et al., 2014; Lin et al., 2011; Roger et al., 2000), but it is unclear whether it should be assigned to the Yangtze Block (Hieu et al., 2009; Wang et al., 2016a) or the Cathaysia Block (Chen et al., 2015b; Cheng et al., 2013; Guo et al., 2009; Dong et al., 2002). In addition, some scholars consider the Dian-Qiong (Babu) suture as the boundary between the SCB and ICB, in which case the study area would be placed in the ICB (Cai and Zhang, 2009; Zhong et al., 1998). Therefore, clarifying the tectonic affinity of the study area is crucial to constraining the boundaries between the Yangtze, Cathaysia and Indochina blocks.
Fig. 11 shows that the NSCC has source compositions similar to those of the early Paleozoic granites in the southern Yangtze Block, but different from those in the Cathaysia and Indochina blocks. Early Paleozoic magmatic zircons in the NSCC have Hf-isotope compositions similar to those of the coeval magmatic zircons from the Yangtze Block, while those from the Cathaysia Block have a larger range of Hf-isotope compositions and lower εHf(t) values (Fig. 6c). Early Paleozoic granites in the Cathaysia Block also have lower εNd(t) values (-12.2 to -6.14; Wang et al., 2011; Zhang et al., 2012) than those in the Yangtze Block (εNd(t) = -8.9 to -4.9; Xu et al., 2006; Zhang et al., 2012; Zhao et al., 2013) and the NSCC (-8.0 to -4.1; Peng et al., 2015; Xu et al., 2015b).

Granitoids are generally derived from the lower continental crust, and consequently their chemical and isotopic compositions may be used to constrain the composition of the deep crust. The inherited zircons in the rocks can directly provide important information on deep source components. The Nanwenhe - Song Chay S-type granites contain abundant Precambrian inherited zircons, implying that the Precambrian basement probably exists at depth. Although the Nanwenhe and Song Chay granites show some difference in geochemistry (Fig. 11), their inherited zircons exhibit similar age spectra (Fig. 12a, b). Coupled with the similar Hf-isotope compositions of their magmatic and inherited zircons (Fig. 6), it can be inferred that the metasedimentary rocks in the sources of the Nanwenhe and Song Chay granites were derived from the same provenance.

The inherited zircons from the NSCC are characterized by a main peak at
836-808 Ma and subordinate peaks at ~734Ma and 528-665Ma with minor Mesoproterozoic to Neoarchean (~2520Ma) ages (Fig. 12c). This age spectrum is comparable with that of Neoproterozoic sedimentary rocks in the southern Yangtze Block (Fanjingshan-Sibao area) except for the ages of <730 Ma, and different from those in the western Yangtze Block (central Yunnan area), Cathaysia Block (Nanling-Yunkai area) and ICB (Fig. 12a-g). In addition, the Hf-isotope compositions of inherited zircons in the NSCC are similar to those of detrital zircons from the western and southwestern Yangtze Block (central Yunnan and Fanjingshan-Sibao area), but significantly different from those from the Cathaysia and Indochina blocks (Fig. 6; Fig. 13). All these features demonstrate that the Nanwenhe - Song Chay area probably has its closest affinity with the Yangtze Block.

Although there is strong similarity between the source of the NSCC granites and Neoproterozoic sedimentary rocks in the southern Yangtze Block in terms of the age distribution and Hf-isotope composition of zircons, the NSCC granites have many 730-500 Ma inherited zircons (Fig. 12c), which are absent in Neoproterozoic sedimentary rocks, but present in Early Paleozoic sedimentary rocks (Wang et al., 2012c; Xia et al., 2016). These ages are mostly concordant and were obtained from the inherited cores. Some of them may reflect Pb loss from the older (750-800 Ma) zircons during the early Paleozoic magmatism, or the mixing of the inherited zircons and early Paleozoic magmatic zircons during the LA-ICPMS dating process. However, they mostly should represent the real ages of inherited zircons, suggesting that the source contains a minor component of younger metasedimentary rocks, e.g. Cambrian
sediments. The presence of inherited zircons with Pan-African ages in the source of the NSCC granites indicates that study area may have been close to the northern margin of East Gondwana during Neoproterozoic to Early Paleozoic time.

The above discussions suggest that the basement under the Nanwenhe - Song Chay area most likely belongs to the Yangtze Block. Thus, the boundary between the Yangtze and Cathaysia blocks should be located southeast of the Nanwenhe - Song Chay area, rather than along the Shizong-Mile fault to the northwest (Guo et al., 2009; Dong et al., 2002; Fig. 1), and the boundary between the SCB and ICB should be southwest of the study area rather than along the Dian-Qiong suture (Cai and Zhang, 2009; Wu et al., 1999; Fig. 1).

6.4 Western tip of the early Paleozoic orogen in the SCB

Early Paleozoic granites and metamorphic rocks are widely distributed across the SCB, especially in the Cathaysia Block. The NSCC, as a unique early Paleozoic granitic pluton exposed in the southwestern SCB and northeastern Vietnam, lies far from the main distribution of early Paleozoic granites in the SCB (Fig.1). No early Paleozoic granites or metamorphic rocks have been identified between the study area and eastern Guangxi Province, where there are early Paleozoic granites and metamorphic rocks. Is the NSCC a part of the Early Paleozoic orogenic belt of the SCB or related to other orogens?

Published geochronological data show that the early Paleozoic granites in the Yangtze, Cathaysia and Indochina blocks mainly intruded at 438-381 Ma (with peaks
at 432 Ma and 417-402 Ma), 468-405 Ma (at 447 Ma and 435 Ma) and 469-392 Ma (at 447 Ma and 435 Ma) and 469-392 Ma (at 465 Ma and 451 Ma), respectively (Fig. 14). Moreover, U-Pb age spectra of detrital zircons from river sediment samples in Hunan Province, in the southern Yangtze Block, give an age peak at 424 Ma (He et al., 2014) and those from the Truong Son belt of the ICB show a peak at 450 Ma (Usuki et al., 2013), similar to the age peaks of early Paleozoic granites in these two areas. Detrital zircons from Devonian sandstones in the central Cathaysia Block contain many early Paleozoic zircons with a striking peak at 440 Ma (Xiang and Shu., 2010), consistent with the peak of early Paleozoic magmatism in the Cathaysia Block. Available data show that the NSCC rocks have ages in the range of 226-236 Ma with weighted average age at 429.6±1.5 Ma, similar to granites in the southern margin of the Yangtze Block, but significantly later than those in the ICB (Fig. 14).

Combined with the similarity of source components between the NSCC and the interior of South China, it is suggested that the NSCC probably is a part of the Early Paleozoic orogenic belt in the SCB. The early Paleozoic igneous or metamorphic rocks between the Nanwenhe - Song Chay area and eastern Guangxi probably are covered by the huge Youjiang basin (also called the Dian-Qian-Gui basin or Nanpanjiang basin). This basin is bounded by the Shizong-Mile, Ziyuan Danchi and Chaling-Pingxiang Faults and the Dian-Qiong suture (Babu suture) (Fig. 1), and was filled by thick Devonian to Triassic marine sediments (Huang et al., 2013b; Liao et al., 2015; Yang et al., 2012). In this basin, pre-Devonian strata, only Cambrian-Ordovician ones, occur sporadically and are unconformably overlain by the
Devonian–Triassic strata (Cai et al., 2014; Yang et al., 2012). Evidently, the Youjiang basin developed after the early Paleozoic orogeny, and the thick sediments in the basin extensively covered the pre-Devonian basement rocks, including any early Paleozoic plutons. This inference is also supported by the presence of numerous subhedral-euhedral early Paleozoic zircons in Triassic sedimentary rocks and captured in volcanic rocks in the Youjiang basin (Hu et al., 2012; Huang et al., 2012; Yang et al., 2012). Therefore, the Early Paleozoic organic belt of South China probably extends continuously westward to the study area, and the NSCC represents the westernmost tip of this orogenic belt.

5. Conclusions

(1) Systematic and comprehensive geochronological studies show that the Nanwenhe granites in SE Yunnan province, SW China and Song Chay granites in NE Vietnam have similar crystallization ages, and those in the center crystallized a few m.y. later than those in the outer zone.

(2) The Nanwenhe – Song Chay Complex (NSCC) consists of high-K, calc-alkaline, strongly peraluminous S-type granites. Major- and trace-element variations mainly reflect different source compositions in the northern and southern NSCC, as well as fractional crystallization. The Nanwenhe granites have lower CaO/Na₂O, and higher Al₂O₃/TiO₂, Rb/Ba, and Rb/Sr than the Song Chay granites, suggesting that the primitive magmas of the Nanwenhe granites originated from pelitic rocks, whereas the Song Chay granites were derived from psammitic rocks. Geochemical
data and zircon Hf-isotope compositions indicate that the sources of Nanwenhe and Song Chay granites were mainly Neoproterozoic basement rocks analogous to the Xiajiang and Danzhou groups, and the Fanjingshan and Sibao groups in southern Yangtze Block, respectively. The existence of scarce 730-500 Ma inherited zircons in the NSCC indicates that the magma sources probably contain a minor component of younger metasedimentary rocks, e.g. Cambrian sediments.

(3) In terms of age distribution and Hf-isotope compositions, the inherited zircons of the NSCC are similar to the detrital zircons of Neoproterozoic sedimentary rocks in the southern Yangtze Block. This indicates that the SE Yunnan and NE Vietnam area has a tectonic affinity with the Yangtze Block. Therefore, the boundary between the Yangtze and Cathaysia blocks should be located to the southeast of the Nanwenhe - Song Chay area.

(4) The early Paleozoic orogenic belt of South China probably extends continuously westward to the study area, and the NSCC represents the westernmost tip of this belt.

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Captions:

Fig. 1. Simplified geological map showing the distribution of Precambrian basement rocks and early Paleozoic rocks in South China (modified after Sun, 2006; Zhao and Cawood, 2012) and Indochina (modified after Mineral resources map of Vietnam at 1:1000000 scale; Usuki et al., 2009).

Fig. 2. Geological map of the NSCC (modified after Maguan, Bac Quang and Ma Quan Geologic map at 1:200000 scale; Roger et al., 2000).

Fig. 3. (a-c) Photographs showing the character of granitic samples in the field, (d-f) Photomicrographs of the NSCC granites. Bt- biotite, pl- plagioclase, kf- potassium feldspar, grt- garnet, mus- muscovite, q- quartz, tour- tourmaline.

Fig. 4. CL images of representative zircons from the NSCC. Solid yellow circles are spots for U-Pb isotope analyses, and dashed red circles are spots for Hf isotope analyses.

Fig. 5. Zircon U-Pb Concordia diagrams of representative samples from the NSCC.

Fig. 6. (a) εHf (t) values vs U-Pb ages of magmatic zircons from the NSCC; (b) Histogram of two-stage model age ($T_{DM}^C$) of magmatic zircons in the NSCC; (c)
$\varepsilon$Hf(t) values vs U-Pb ages of all zircons from the NSCC. The data of the Neoproterozoic sedimentary rocks in the Xiajiang, Danzhou, Fanjingshan and Sibao groups are from Wang et al. (2010b; 2012b; 2012d). Field of the early Paleozoic granites in the Yangtze and Cathaysia blocks are based on the data from Chu et al. (2012), Wang et al. (2011), Yang et al. (2014), Zhang et al. (2012) and Zhao et al. (2013).

Fig. 7. (a) K$_2$O vs. SiO$_2$ variation diagram (solid lines from Peccerillo and Taylor, 1976; dashed lines from Middlemost, 1985), (b) Total alkali vs. silica (TAS) diagram (Wilson, 1989), (c) A/CNK vs. A/NK diagram (after Maniar and Piccoli, 1989) and (d) AFC diagram (after White and Chappell, 1977).

Fig. 8. Harker diagram of the NSCC granites.

Fig. 9. Variation plots of some trace elements and ratios of the NSCC granites.

Fig. 10. (a) Chondrite-normalized REE patterns and (b) Upper continental crust (UCC) -normalized trace element spidergrams for the NSCC. Normalized values for chondrite are from Taylor and McLennan (1985) and for UCC are from Rudnick and Gao (2003).

Fig. 11. (a) Al$_2$O$_3$/TiO$_2$ vs CaO/Na$_2$O and (b) Rb/Sr vs Rb/Ba (after Sylvester, 1998); (c) molar Al$_2$O$_3$/(MgO + TFeO) vs molar CaO/(MgO + TFeO) (from Altherr et al., 2000). Fields of early Paleozoic granites from the Yangtze, Cathaysia and Indochina blocks are from Bai et al. (2014); Shi et al. (2015); Wang et al. (2011); Zhang et al. (2012); Zhao et al. (2013); Zhong et al. (2013).

Fig. 12. Relative probability plots for zircon ages from this study and other related
areas. Data sources: inherited zircons from the Nanwenhe complex (this study; Peng et al., 2015; Xu et al., 2015b; Yan et al., 2006) and the Song Chay complex (this study), detrital zircons from the Fanjingshan-Sibao area (Wang et al., 2007, 2010b, 2012b; Zhou et al., 2009), central Yunnan area (Sun et al., 2009; Wang et al., 2012c), Nanling-Yunkai area (Wang et al., 2008b; Xu et al., 2005, 2007; Yu et al., 2007, 2010; Zhou et al., 2015) and central Vietnam area (Wang et al., 2016b). The discordant U-Pb ages (concordance < 85%) or mixed U-Pb ages of inherited core with overgrowth rim were excluded.

Fig. 13. (a-b) Comparison of Hf isotope compositions of zircons from the NSCC with those from Neoproterozoic sedimentary rocks in Nanling-Yunkai area (Wang et al., 2008b; Yu et al., 2006, 2007, 2010), Fanjingshan-Sibao area (Wang et al., 2010b, 2012b), central Yunnan area (Sun et al., 2009; Wang et al., 2012c), and Cambrian-Devonian sedimentary rocks in central Vietnam area (Wang et al., 2016b).

Fig. 14. Age frequency for NSCC and the early Paleozoic granites in Yangtze, Cathaysia and Indochina blocks. Data sources: the NSCC (Carter et al., 2001; Guo et al., 2009; Peng et al., 2015; Roger et al., 2000; Xu et al., 2015b; Yan et al., 2006; this study), the Yangtze Block (Bai et al., 2014, 2015; Chu et al., 2012; Fan, 2014; Guan et al., 2014; Yang et al., 2015; Zhang et al., 2010, 2012; Zhao et al., 2013; Zhong et al., 2013), Cathaysia Block (Huang et al., 2013a; Li et al., 2010, 2011; Wan et al., 2010; Wang et al., 2011, 2012a; Xu et al., 2009; Zhang et al., 2012), and Indochina Block (Carter et al., 2001; Lan et al., 2003; Nagy et al.,
2001; Nakano et al., 2013; Roger et al., 2007; Shi et al., 2015; Tran et al., 2014; Usuki et al., 2009).
Figure 1
Figure 2
Figure 3
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Figure 5
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Figure 12
Figure 13
Figure 14

**weighted average age:**

429.6 ± 1.5 Ma

\( n=30, \text{MSWD}=1.4 \)
**Table 1** Sedimentary sequence in the Nanwenhe – Song Chay area, SW China and NE Vietnam (after BGMRY, 1999; DGMV, 2000; Lepvrier et al., 2011).

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Nanwenhe area (Southeast Yunnan, China)</th>
<th>Song Chay area (Northeast Vietnam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jurassic-Cretaceous</td>
<td>sandstone, siltstone, conglomerate, shale, tuffaceous sandstone,</td>
<td>sandstone, siltstone, shale,</td>
</tr>
<tr>
<td>late Triassic</td>
<td>-----</td>
<td>felsic and intermediate volcanic rocks,</td>
</tr>
<tr>
<td>early-middle Triassic</td>
<td>silstone, slate, phyllite, interbeds of marble,</td>
<td>silstone, tuffaceous sandstone, mafic effusive rocks, clay shale, sandstone</td>
</tr>
<tr>
<td>Triassic</td>
<td>mafic effusive rocks with minor hornblende</td>
<td></td>
</tr>
<tr>
<td>Carboniferous-Permian</td>
<td>limestone, silicalite, siliceous shale, marble</td>
<td>limestone, silicalite, shale, sandstone</td>
</tr>
<tr>
<td>Devonian</td>
<td>Gedang Fm</td>
<td>Khao Loc Fm</td>
</tr>
<tr>
<td></td>
<td>limestone, dolostone, marble</td>
<td>limestone</td>
</tr>
<tr>
<td></td>
<td>Donggangling Fm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>limestone, marble</td>
<td>Mia Le Fm</td>
</tr>
<tr>
<td></td>
<td>Gumu Fm</td>
<td>sandstone, shale, limestone</td>
</tr>
<tr>
<td></td>
<td>Pojiao Fm</td>
<td>Tong Ba Fm</td>
</tr>
<tr>
<td></td>
<td>slate, silty slate</td>
<td>schist, siltstone, shale</td>
</tr>
<tr>
<td></td>
<td>Tangjiaba Fm</td>
<td>Chang Pung Fm</td>
</tr>
<tr>
<td></td>
<td>limestone with minor sandstone</td>
<td>limestone, marble with minor shale and claystone</td>
</tr>
<tr>
<td>Cambrian</td>
<td>Longha Fm</td>
<td>Ha Giang Fm</td>
</tr>
<tr>
<td></td>
<td>limestone, silty phyllite</td>
<td>schist, phyllite, marble, limestone</td>
</tr>
<tr>
<td></td>
<td>Tianpeng Fm</td>
<td>Cam Duong Fm</td>
</tr>
<tr>
<td></td>
<td>phyllite, interbeds of marble</td>
<td>schist, shale, phyllite, quartzite, sandstone, limestone</td>
</tr>
<tr>
<td>Neoproterozoic-early Cambrian</td>
<td>Xinzhai Fm</td>
<td>An Phu Fm</td>
</tr>
<tr>
<td>Mengdong Group</td>
<td>schist with minor marble</td>
<td>schist, marble</td>
</tr>
<tr>
<td></td>
<td>Saxiyan Fm</td>
<td>Thac Ba Fm</td>
</tr>
<tr>
<td></td>
<td>leptynite, quartzite with minor amphibolite and carbonatite</td>
<td>schist, quartzite, amphibolite, interbeds of marble</td>
</tr>
<tr>
<td></td>
<td>Nanyantian Fm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>schist with minor amphibolite and gneiss</td>
<td></td>
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</tbody>
</table>

Fm: Formation; Unconformity (-----)
Highlights

The Nanwenhe-Song Chay complex (NSCC) is located at SW China - NE Vietnam area;

The NSCC is a large early Paleozoic granitic pluton;

The magma was mainly derived from the Neoproterozoic metasedimentary rocks;

The source has the closest affinity with the Yangtze Block;

The boundary between the Yangtze and Cathaysia blocks must be located southeast of the study area.