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Tectonics

RESEARCH ARTICLE

10.1029/2020TC006611

Special Section:

Tethyan dynamics: from rifting to collision

Key Points:

- The main provenance of the Song Chay mélange is the South China Block (SCB), rather than Indochina Block (IB)
- A two-stage subduction model of the convergence between SCB and IB during Late Carboniferous-Late Triassic has been proposed
- In an ophiolitic mélange, the detrital material does not always come from the overriding plate

Supporting Information:

Supporting Information may be found in the online version of this article.

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Detrital Zircon U-Pb Age Distribution and Hf Isotopic Constraints From the Terrigenous Sediments of the Song Chay Suture Zone (NE Vietnam) and Their Paleogeographic Implications on the Eastern Paleo-Tethys Evolution

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Abstract The location of the suture zone between the South China Block (SCB) and the Indochina Block (IB) is disputed. Recently, along the Song Chay (Chay river) belt, a mélange zone was proposed as a potential suture zone of the SCB and IB. However, the provenance and age of the Song Chay mélange is poorly known. In order to better constrain the age and provenance of the elements forming the Song Chay mélange, nine samples of detrital material, and one orthogneiss were subjected to zircon U-Pb and Hf isotope analysis. Detrital zircons from the silty matrix of the Song Chay mélange record three major Neoproterozoic age clusters at 580–650, 700–800, and 900–1,000 Ma, which correspond well to the substratum of the SCB. Two minor Late and Early Paleozoic age groups at 270–330, and 420–500 Ma, with mainly negative $\epsilon_{\text{Hf}}(t)$ values were also recovered. We consider that the zircons in the matrix of the mélange were mainly derived from the subducting plate, namely the SCB. This interpretation is supported by the occurrence of lensoid sandstone blocks, representing the substratum of the SCB, included into the mélange. The deposition age of the Song Chay mélange is between 310 and 250 Ma. Our results demonstrate that in an ophiolitic mélange, the detrital material does not invariably come from the overriding plate, but at the onset of the collision, the subducting continental plate may also supply the terrigenous material.

1. Introduction

The south and southeast Eurasian continent consists of a series of Gondwana-derived microcontinents (e.g., Tarim, Qaidam, North Qiangtang, South Qiangtang, Lhasa, India, Sibumasu, Indochina, and South China), which were successively rifted from northern Gondwana, and then progressively accreted onto the southern margin of Laurasia. This continental transfer was coeval with the opening and closure of the Proto-, Paleo-, and Neo-Tethys oceans (Figure 1; e.g., Faure et al., 2014, 2018; Metcalfe, 2002, 2011, 2013, 2021; Metcalfe et al., 2017; Sone & Metcalfe, 2008). Among these microblock collisions, the amalgamation of the South China Block (SCB) and Indochina Block (IB) is one of the most controversial. A series of mélange belts with mafic and ultramafic rocks, such as Jingshajiing-Ailaoshan belt (Faure et al., 2014; Jian et al., 2009a, 2009b; Liu et al., 2011, 2012; Sone & Metcalfe, 2008; Zhong, 1998), Song Ma belt (Hieu, Li, et al., 2016; Nakano et al., 2008, 2010; Ngo et al., 2015; Shi et al., 2015; Trung et al., 2006; Vương et al., 2013; Y. Wang, Qian, et al., 2018; Wen et al., 2015; R. Y. Zhang et al., 2013; Zhou et al., 2020), and Dian-Qiong belt (Cai & Zhang, 2009; Halpin et al., 2016; Zhong, 1998), were proposed as the boundary between the SCB and IB. The Jingshajiing-Ailaoshan belt has long been regarded as the remnant of the Paleo-Tethys Ocean, which was considered to open in Middle Devonian and closed in Early Middle Triassic (Jian et al., 2009a, 2009b; Lai, Meffre, Crawford, Zaw, Halpin, et al., 2014; Lai, Meffre, Crawford, Zaw, Xue, & Halpin, 2014; Liu et al., 2011; Sone & Metcalfe, 2008; Zhong, 1998). The Song Ma belt was considered as the southeastern

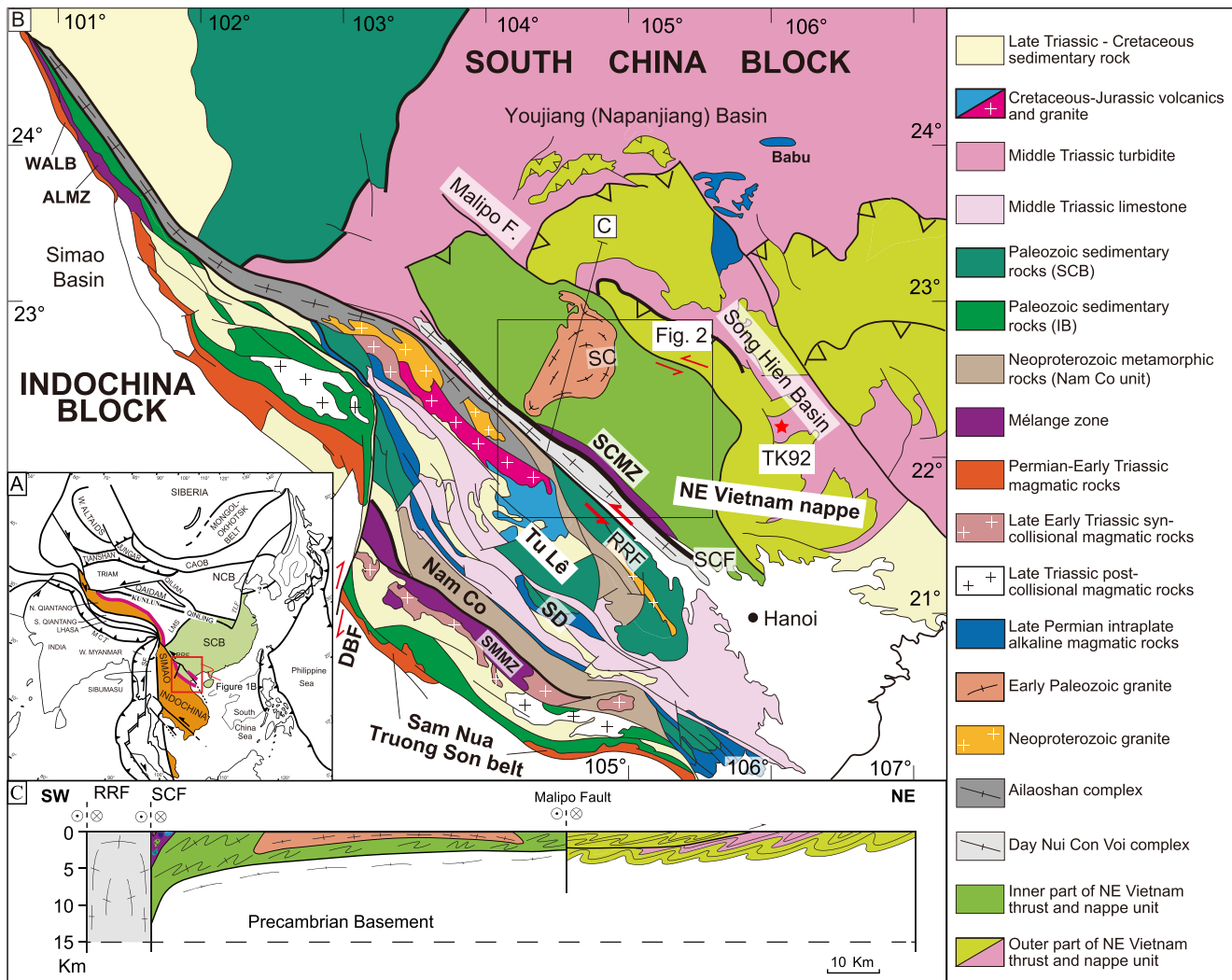


Figure 1. (a) Tectonic outline of east Asia (modified from Lin et al., 2008). (b) Tectonic map of Southwest China-North Vietnam region, modified from the 1:1500000 Geological map of the five countries of southeast Asia and adjacent areas (Chengdu Institute of Geology and Mineral Resources, 2006), showing the stack of nappes related to the Indosinian orogeny, and the sampling sites of this study. (c) Schematic cross section of the NE Vietnam belt (modified from Lin et al., 2011). Nam Co: Neoproterozoic rocks metamorphosed in Triassic during the NE-ward thrusting of the Song Ma ophiolites; SC: Song Chay massif; ALMZ: Ailaoshan mélangé zone; SMMZ: Song Ma mélangé zone; SCMZ: Song Chay mélangé zone; RRF: Red River fault; SCF: Song Chay fault; DBF: Dien Bien Phu fault; DNCV: Day Nui Con Voi metamorphic complex; SD: Song Da rift; WALB: western Ailaoshan belt.

prolongation of the Jingshajiang-Ailaoshan belt (Hieu, Li, et al., 2016; Nakano et al., 2008, 2010; Ngo et al., 2015; Shi et al., 2015; Trung et al., 2006; Vương et al., 2013; Y. Wang, Qian, et al., 2018; Wen et al., 2015; R. Y. Zhang et al., 2013; Zhou et al., 2020). However, the timing and nature of the amalgamation of the SCB and IB along the Song Ma belt is still controversial: Early Paleozoic (Carter & Clift, 2008; Carter et al., 2001; Findlay, 1997; Findlay & Pham, 1997; Janvier et al., 1996; Tong-Dzuy et al., 1996), Late Paleozoic (Helmcke, 1985; Hutchison, 1989; Metcalfe, 1999, 2002, 2013), or Early Mesozoic (Faure et al., 2014, 2016; Lepvrier et al., 1997, 2008; Lin et al., 2011; Liu et al., 2012). Recently, blocks of ultramafic rocks, mafic rocks, cherts, volcanic and volcanic-clastites enclosed in terrigenous rocks (turbidites and pebbly mudstone) were reported along the NE side of the Song Chay fault (SCF). This formation that corresponds to an olistostrome, or a “block-in-matrix” formation will be referred to as the Song Chay mélangé (Lepvrier et al., 2011). Indeed, it has been interpreted as an ophiolitic mélangé, that is, a suture zone corresponding to the boundary between the SCB and IB (Faure et al., 2014, 2016; Lepvrier et al., 2011). A Triassic age was assumed for this mélangé corresponding to the closure of Paleo-Tethys (Faure et al., 2014; Lepvrier et al., 2011), however, the

deposition age, provenance and tectonic affinity of the Song Chay mélange remain unknown because of the limited geological data.

Detrital minerals (e.g., zircon, rutile, and mica) are key tracers for quantitative and qualitative sedimentary provenance analyses for the determination of the source rock type, metamorphic grade and the crystallization or cooling ages of the provenance region (e.g., Cawood et al., 2012; Chu et al., 2016; Dickinson & Gehrels, 2009; Fedo et al., 2003; Lin et al., 2019). Detrital zircon age distribution is a useful tool that provides information on the provenance of terrigenous materials involved in the edification of an orogenic belt. This investigation can shed light on the relationships between sedimentary sources of the material in orogenic belts, plate boundary, and paleogeographic restoration. In this work, we selected 10 samples from the Song Chay mélange and its adjacent tectonic units (Figures 1 and 2, Table 1) for zircon U-Pb age and Hf isotropic analyses to better understand the mélange and its tectonic significant.

2. Geological Setting

Northern Vietnam experienced a poly-orogenic evolution, namely the Early Mesozoic Indosinian orogeny (e.g., Deprat, 1914, 1915; Faure et al., 2014; Fromaget, 1932, 1941; Lepvrier et al., 2008; V. T. Tran & Vu, 2011), and the Cenozoic sinistral shearing that accommodated the southeastward extrusion of Sundaland due to the Indian-Eurasia collision (e.g., Leloup et al., 1995; Tapponnier et al., 1990). Furthermore, two distinct tectonic belts have been recognized in northern Vietnam, the NW Vietnam belt and NE Vietnam one, separated by the Cenozoic Red River Fault (RRF), which is the major continental-scale strike-slip structure in northern Vietnam (Leloup et al., 1995; V. T. Tran & Vu, 2011). The Late Triassic unconformity of the continental red coarse-grained sandstone beds, corresponding to a post-orogenic molasse deposit, was the key-point used by Fromaget (1932, 1941) to define the “Indosinian movement.” In the NE Vietnam orogenic belt, three domains have been recognized, from the SW to the NE, they are: (a) the Day Nui Con Voi unit, (b) the Song Chay mélange unit, (c) the NE Vietnam nappe unit (Figures 1–3; Faure et al., 2014; Lepvrier et al., 2011).

2.1. The Day Nui Con Voi Unit

It consists of quartzite, biotite-garnet-sillimanite micaschist, amphibolite, and biotite-quartz schist (V. T. Tran & Vu, 2011). Deformed gabbro, diorite and granodiorite intrude the sedimentary rocks. This large-scale antiformal complex, is bounded by the RRF and SCF to its southwest and northeast sides, respectively (Anczkiewicz et al., 2007; Leloup et al., 1995; Nam et al., 1998; P. L. Wang et al., 1998, 2000; Yeh et al., 2008). This unit is characterized by left-laterally sheared Cenozoic high temperature metamorphic rocks exhumed from middle to lower crust (Leloup et al., 1995; Nakano et al., 2018; Nam et al., 1998; P. L. Wang et al., 1998, 2000).

2.2. The Song Chay Mélange Unit

Along the NW-SE-trending SCF, gabbro, plagiogranite, and serpentinitized ultramafic bodies crop out together with blocks of chert, limestone, siliceous mudstone, and sandstone. This varied lithological occurrence led to the recognition of the Song Chay suture zone or Song Chay mélange unit (Lepvrier et al., 2011). Most of these blocks, and also, the mudstone, and siltstone that form the matrix of the blocks are highly sheared but weakly metamorphosed. In outcrops, blocks of serpentinite, chert, and limestone are embedded in a foliated or cataclastic siltstone-mudstone or black shale matrix. Thus, the Song Chay unit represents an olistostrome, or a gravity sliding deposit, that was subsequently sheared (Figure 3). The slaty cleavage observed in the Song Chay mélange is NW-SE-trending and generally dipping at a high angle to the SW along the SCF. The matrix of the Song Chay mélange experienced a pervasive deformation, characterized by horizontal to subhorizontal NW-SE trending semi-penetrative lineation or striation indicating a sinistral strike-slip deformation. A foliation gently dipping to the NE or SW with a NE-SW-trending mineral and stretching lineation can be observed when it departs from the SCF. In the geological map, the Song Chay mélange unit is ascribed to Neoproterozoic to Middle Cambrian ages (V. T. Tran & Vu, 2011). However, as documented below by the detrital zircon dating, a younger age should be taken into consideration, at least for a part of these rocks.

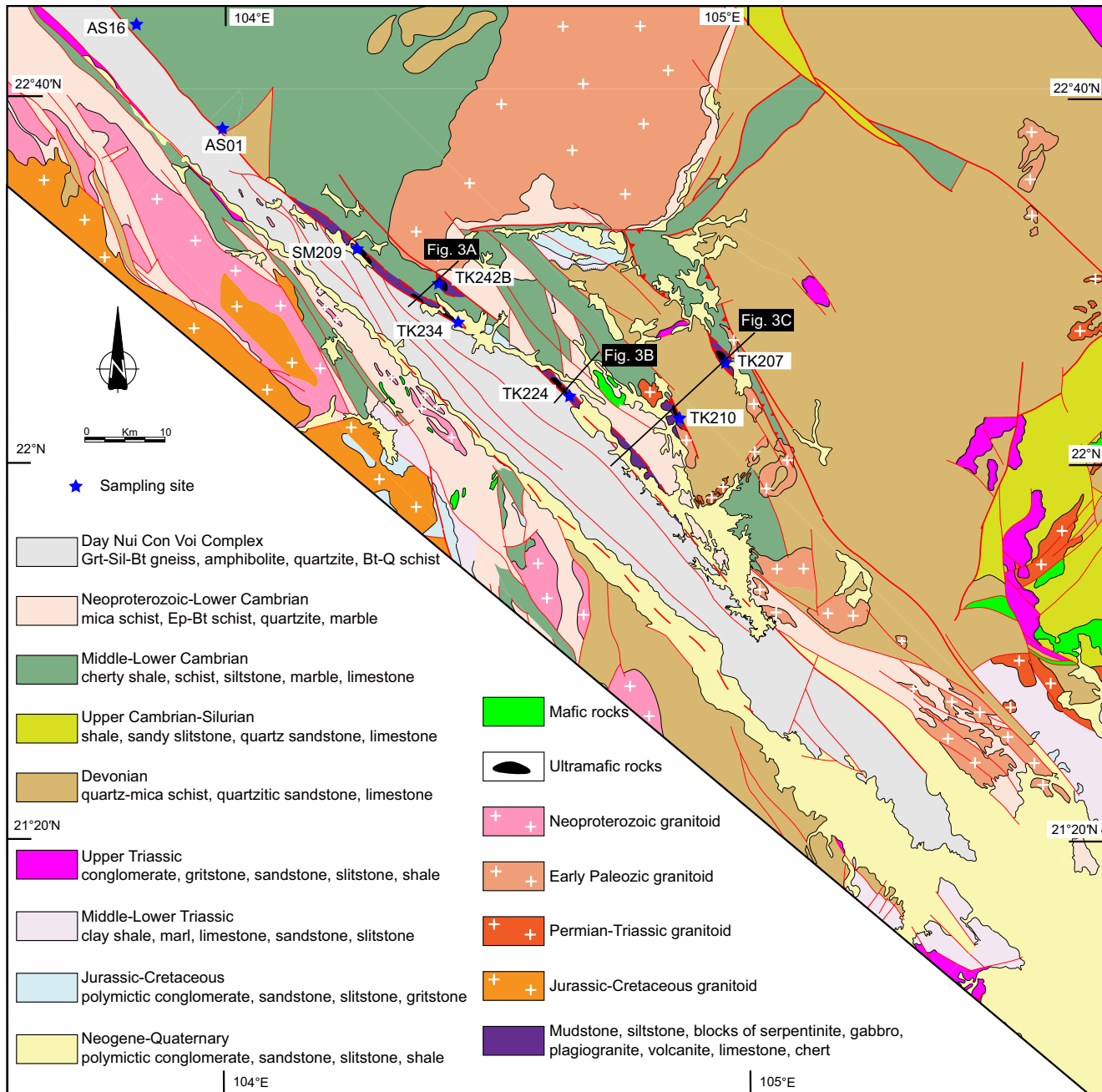


Figure 2. Geological map of the Song Chay mélangé unit and adjacent area (Drawn from the 1:200000 geological maps of Vietnam) showing the sampling sites.

2.3. The NE Vietnam Nappe Unit

This nappe unit could be subdivided into inner and outer parts by the Malipo fault (Figure 1). In the SW side of the Malipo fault, the inner part of the nappe unit is characterized by a pervasive ductile deformation with low angle foliation, N-S to NE-SW trending mineral and stretching lineation, and isoclinal folds coeval with a greenschist to amphibolite facies metamorphism (Jolivet et al., 2001; Maluski et al., 2001). By contrast, on the NE side of the Malipo fault, the outer part of the nappe unit is characterized by a weak ductile deformation with upright to slightly inclined folds without significant metamorphism (Figure 1; Lepvrier et al., 2011). Geometrically, the inner part thrusts upon the outer part (Figures 1 and 3; Lepvrier et al., 2011). Lithologically, the inner part of the NE Vietnam nappe consists of ductilely deformed

Table 1
Brief Summary of the Petrography and Tectonic Positions of the Analyzed Samples

	Sample number	GPS location	Petrography	Tectonic position
Group 1A	TK242B	22°17.552'	Intensive sheared meta-sandstone	Song Chay mélangé unit
		104°26.096'		
	TK210	22°04.424'	Intensive sheared meta-sandstone	Song Chay mélangé unit
		104°51.802'		
	TK207B	22°10.807'	Intensive sheared meta-sandstone	Song Chay mélangé unit
TK207A	22°10.807'	Foliated orthogneiss in sheared meta-sandstone	Orthogneiss in Song Chay mélangé unit	
	104°57.369'			
SM209	22°21.827'	Lithic sandstone	Song Chay mélangé unit	
	104°15.920'			
Group 1B	TK234	22°15.246'	Sandstone	Song Chay mélangé unit
		104°26.483'		
	TK224	22°06.963'	Sandstone	Song Chay mélangé unit
104°39.546'				
Group 2	AS01	22°36.108'	Intensive sheared sandstone	NW prolongation of the Song Chay mélangé unit
		103°57.840'		
	AS16	22°58.170'	Meta-sandstone	NW prolongation of the Song Chay mélangé unit
		103°37.074'		
TK92	22°38.636'	Intensive sheared sandstone	Middle Triassic	
	105°50.778'		Outer part of the NE Vietnam nappe	

and metamorphosed Neoproterozoic to Early Paleozoic sedimentary rocks, and the Song Chay augen orthogneiss massif, both of which recorded a top-to-the-NE shearing deformation event (Figures 2 and 3; Jolivet et al., 2001; Lepvrier et al., 2011). Micaschist yields biotite and muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages around 236–234 Ma (Maluski et al., 2001), and metamorphic monazite U-Th-Pb ages around 246 Ma (Faure et al., 2014; Gilley et al., 2003). These ages are interpreted as those of the regional syn-kinematic metamorphism (Faure et al., 2014). The protolith of the Song Chay orthogneiss was a porphyritic monzogranite emplaced at ~428 Ma (Roger et al., 2000), but it experienced a top-to-the-NE ductile shearing with much younger SHRIMP zircon and $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole ages at ~237 Ma (Yan et al., 2006). More to the North, the

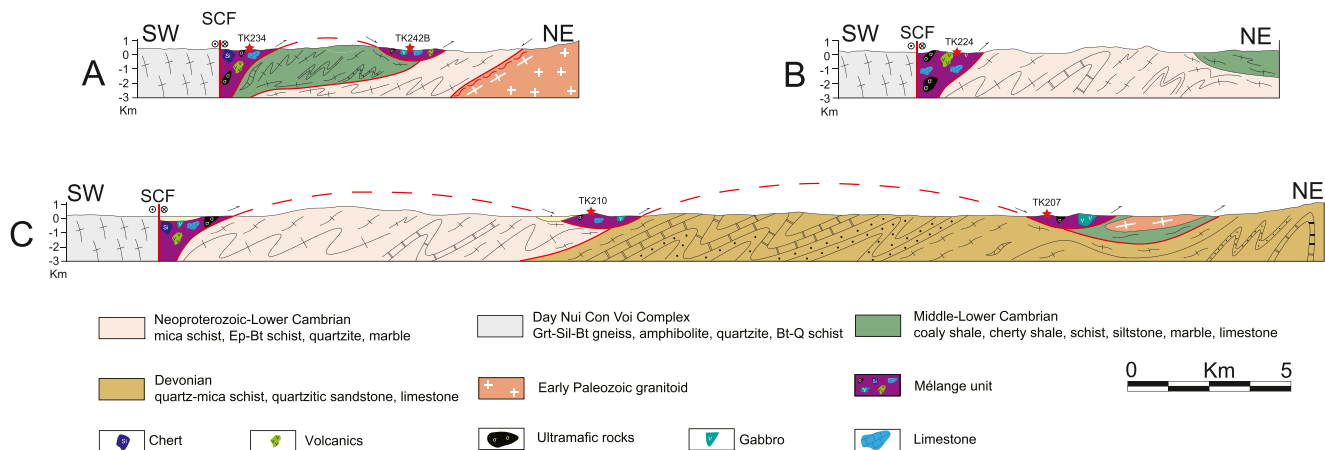


Figure 3. Schematic cross sections of the NE Vietnam Belt showing the tectonic succession, from the SW to the NE: Day Nui Con Voi unit, Song Chay mélangé unit, and the inner part of the NE Vietnam nappe unit (located in Figure 2); Ep: epidote, Bt: biotite, Grt: garnet, Sil: sillimanite, Q: quartz.

outer part of the NE Vietnam nappe consists of Late Paleozoic to Middle Triassic sedimentary rocks (mostly limestone) characterized by a series of NE verging folds, and thrust faults with a top-to-the-NE sense of shear (Figure 1; Deprat, 1915; Faure et al., 2014; Lepvrier et al., 2011; Lin et al., 2011). The non-metamorphosed Late Paleozoic series is stratigraphically overlain by a Lower to Middle Triassic turbiditic sandstone that corresponds to a syn-tectonic deposit coeval with folding and thrusting (Lepvrier et al., 2011). However, the Paleozoic series frequently overthrusts the Lower to Middle Triassic turbidite (Figure 1). Due to the Indosinian tectonics, a décollement may develop at the base of the turbidite, and brittle thrusts place Paleozoic limestone on top of the turbidite. In NE Vietnam, this turbiditic deposit is ascribed to the Song Hien basin (Figure 1), which is correlated to the Youjiang basin in Guangxi province of China. Therefore, the NE Vietnam nappe represents a fold-and-thrust belt developed at the expense of litho-stratigraphic elements belonging to the SCB (Faure et al., 2014). It is worth noting that the unconformably overlying Upper Triassic formation, represented by the continental red/gray conglomerate and sandstone, was considered as molassic formation deposited in a continental environment (Lepvrier et al., 2011).

3. Analytical Procedures

3.1. U-Pb Dating

Zircons from the samples were separated by conventional heavy liquid and magnetic techniques, and then picked by hand under a binocular microscope. For all samples, about 250 zircon grains were randomly selected from over 500 grains when available (if the total zircon grain number was less than 200, all grains were selected), and mounted in epoxy resin, and polished to expose the inner part of the zircon grains. Transmitted and reflected light were used to avoid cracks and inclusions, and cathodoluminescence (CL) images, obtained by a CAMECA electron microscope, were used to identify the morphology and internal texture of the zircon grains.

Zircon U-Pb age analyses were conducted by using an Agilent 7500a ICP-MS equipped with a 193 nm laser ablation system at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS) in Beijing. Laser ablation was operated at a constant energy 80 mJ and at 10 Hz, with a spot diameter of 44 μm . Gas flow rate of highly purified He as the carrier gas was 0.7 L/mn; auxiliary gas Ar was 1.13 L/mn. Total acquisition time of one spot was 45 s. The details of analytical procedures were the same as those described by Xie et al. (2008). The standard zircons (91500 and GJ-1) were used to determine the U-Th-Pb ratios and absolute abundances of the analyzed zircon. Data were processed with the GLITTER program (van Achterbergh et al., 2001). The $^{206}\text{Pb}/^{238}\text{U}$ ages are used for zircons with concordant ages less than 1,000 Ma, and $^{207}\text{Pb}/^{206}\text{Pb}$ ages are used for zircons when $^{206}\text{Pb}/^{238}\text{U}$ ages are older than 1,000 Ma. A data plot was conducted by using the Density Plotter program (Vermeesch, 2012). In this work, ages with more than $\pm 10\%$ discordance were excluded.

3.2. Zircon Lu-Hf Isotopes

In situ Hf isotopic analysis was carried out on a Neptune multicollector ICP-MS equipped with a Geolas-193 laser ablation system housed at the IGGCAS. The analyzed spots of Lu-Hf isotopic analysis were performed on the same places as previously analyzed zircon grains for U-Pb isotopes, and detailed analytical procedures were described by Wu et al. (2006). Measuring settings mainly include beam diameter of 44 μm , repetition rate of 6 Hz, and laser beam energy density of 100 mJ/cm^2 , and ablation time of 30s. During the analytical period, the weighted mean $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the zircon standards MUD ($0.282503 \pm 7, 2\sigma$, $n = 102$) are in perfect agreement with reported values (Woodhead & Hergt, 2005).

4. Zircon U-Pb and Lu-Hf Analytical Results

The representative field photos of outcrops are shown in Figure 4, and the corresponding descriptions of the samples are provided in the Supporting Information S1. Representative CL images of the analyzed zircons are demonstrated in Figure 5. Most of the zircon grains exhibit a sub-rounded to rounded shape indicating a relatively long transportation, and only a small part of grains are prismatic crystals. Most of the grains manifest a zonal structure, and some of the grains possess an inner core surrounded by recrystallization rims.

Table 2
Brief Summary of the Results of U-Pb Ages and $\epsilon_{\text{Hf}}(t)$ Values of 10 Analyzed Samples

Samples		U-Pb age	$\epsilon_{\text{Hf}}(t)$ values
Group 1A	TK242B	A dominant age group between 300 and 850 Ma, with one major age peak around 760 Ma and several minor age peaks at around 310, 440, and 550 Ma (Figure 6a)	-17.3 to +5.8 with one major peak at -2.6 and one subordinate peak at -7.4 (Figure 9, Figure S2)
	TK210	Three major age groups occur at 550-650, 650-700, and 700-850 Ma, and two subordinate groups are at 400-500 Ma and 900-1,000 Ma (Figure 6b)	-20.5 to +10.8 with one major peak at +3.7 and one subordinate peak at -13.5 (Figure 9, Figure S2)
	TK207B	One major age group at 700-800 Ma, and four subordinate groups at 450-550, 600-650, 850-950, and 2,400-2,500 Ma (Figure 6c)	-28.2 to +7.4 with three major peaks at -14.9, -0.5 and + 2.1 (Figure 9, Figure S2).
	TK207A SM209	A weighted mean age of 253.9 ± 0.7 Ma with a MSWD value of 0.87 (Figure 6j) A major age group at 950-1,100 Ma, and two subordinate groups at 450-500 Ma and 600-700 Ma (Figure 6d)	-8.97 to -3.60 (Figure 9)
Group 1B	TK234	A dominate Neoproterozoic age cluster, with two major peaks at around 740 Ma and 960 Ma (Figure 6e)	-36.8 to +6.5 with two major peaks at -7.6 and + 5.4 (Figure 9, Figure S2)
	TK224	Two major peaks at around 540 Ma, 760 Ma, 940 Ma, and two minor peaks at around 1,760 Ma and 2,440 Ma (Figure 6f)	-15.3 to +8.6 with one major peak at -3.3 and two minor peaks at -12.7 and + 3.2 (Figure 9, Figure S2)
Group 2	AS01	A dominant cluster at 750-900 Ma, with an age peak around 840 Ma (Figure 6g)	-8.9 to -0.2 with one major peak at -2.8 (Figure 9, Figure S2)
	AS16	A single major cluster at 750-900 Ma, with an age peak around 840 Ma (Figure 6h)	-30.9 to +9.2 with one major peak at -7.4 and one subordinate peak at +7 (Figure 9, Figure S2)
	TK92	A major age group between 230-250 Ma, with age peak at around 242 Ma (Figure 6i)	-25 to -1.6 with one major peak at -11.2 (Figure 9, Figure S2)

Lu-Hf isotopic analyses were carried out on dated zircon grains, with analytical spots adjacent to those corresponding to the U-Pb dating. The U-Pb ages and $\epsilon_{\text{Hf}}(t)$ values are briefly summarized in Table 2 and plotted in Figures 6 and 9, detailed descriptions of the results are provided in the Supporting Information S1. All the LA-ICP-MS U-Pb and Lu-Hf results of 10 samples are provided in Table S1 and S2 in the supporting information.

5. Discussion

5.1. Consistency of the Song Chay Mélange From the View of the Detrital Zircon

Based on our new detrital zircon data, three groups of samples were revealed, namely, Group 1A: TK242B, TK210, TK207B, and SM209, in which Late Paleozoic detrital zircons form a significant cluster; Group 1B: TK234 and TK224, characterized by three major Neoproterozoic age groups and lack of Paleozoic detrital zircons; and Group 2: AS01 and AS16, characterized by only one Neoproterozoic age peak located at 840 Ma (Figure 8a).

As fine-grained sandstone, siltstone, and mudstone, the rocks represented by Group 1A is reclassified as the Song Chay mélange unit (Figure 2). In the 1:200,000 geological map, this unit is marked as a Neoproterozoic or Middle Cambrian sedimentary sequence previously (V. T. Tran & Vu, 2011). Our analytical results exhibit age peaks ranging from Paleoproterozoic to Late Paleozoic at 2,440, 1,775, 1,560, 970, 770, 730, 620, 460, and 310 Ma (Figure 7b). A large amount of zircon ages less than 485 Ma (Ordovician/Cambrian) indicate that the previous considered stratigraphy deserves re-evaluation. The existence of the Late Paleozoic cluster suggests that the deposition of these rocks was much younger than the previous indication (V. T. Tran & Vu, 2011). Combined with the occurrence of mafic, ultramafic, chert, and siliceous mudstone blocks in the mélange unit, it is reasonable to interpret these sedimentary rocks as related to a potential suture zone, and we argue that the Group 1A could be interpreted as the matrix of the ophiolitic mélange.

As the matrix of the olistostrome, it was arduous to pick up detrital zircon grains in the fine grain siliceous mudstone and siltstone. Samples TK234 and TK224 (Group 1B), which are lenticular coarse sandstone, were chosen to carry out the analytical work. Zircons from these two samples yield the youngest age peaks at around 625 and 540 Ma respectively (Figures 6e and 6f) along with three main age groups at 500–650, 700–800, and 900–1,000 Ma. This is significantly different from samples in Group 1A (Figure 7b). Together with a cataclastic texture (Figure S1), we interpret these lenticular sandstones as olistoliths enclosed in the Song Chay mélange unit.

Group 2 was regarded as the northwestern-most prolongation of the Song Chay mélange unit. The unimodal detrital zircon age pattern of the two samples and the tuffaceous interlayers are indicative of a pyroclastic source (Figure 4g). The peaks at around 840 Ma (Figures 6g and 6h) represent the maximum deposition age of this meta-sandstone. Therefore, we consider that the Group 2 is likely part of the Neoproterozoic strata that represent the basement of SCB, rather than the Song Chay mélange unit, even flysch rhythms was observed in the field. The present location of this Group 2 as the prolongation of the Song Chay mélange unit is not supported by the detrital zircon age distribution in samples AS01 and AS16. The Cenozoic strike-slip significantly changed the early Mesozoic structure.

The TK92 is a deformed Middle Triassic sandstone from the Early Mesozoic Song Hien basin, in the north of the NE Vietnam nappe. The dominant age group of detrital zircons at 230–260 Ma with a peak around 242 Ma, suggests that the deposition age of this sandstone is younger than 242 Ma. We can also conclude that the thrusting that placed the Devonian limestone upon the Middle Triassic turbidite was younger than Anisian, but older than the Late Triassic molasse (Figure 1).

5.2. Deposition Age of the Song Chay Mélange

The Song Chay mélange unit was previously interpreted as a suture zone between the SCB and IB (Lepvrier et al., 2011). However, the deposition age of the Song Chay mélange was poorly constrained, although a Triassic age (Indosinian) has been assumed in agreement with the Triassic regional metamorphism and deformation age, and the closure of the Paleo-Tethys Ocean (Faure et al., 2014).

As the matrix of the Song Chay mélange, the compilation of the age data of Group 1A provides the possibility of understanding the age of this unit. Since the youngest age cluster is around 310 Ma (~5.4%), the deposition age should be younger than Late Carboniferous, instead of the Neoproterozoic or Middle Cambrian ages indicated by the geological map (Figure 7b).

According to the results of the orthogneiss sample TK207A, enclosed in the sheared meta-sandstone TK207B, the concordant age at ca. 254 Ma (253.9 ± 0.7 Ma) is interpreted as the crystallization age for the granitoid protolith. However, it is difficult to determine the deposition age of this sandstone related to the TK207B because of the ambiguous relationship between these two samples: TK207A is a block or an intrusive body in the TK207B sandstone. If TK207A is an exotic block fallen into the TK207B sandstone, the deposition age of TK207B sandstone should be younger than 254 Ma. Only one zircon gives an age of 236.4 ± 1.7 Ma (Figure 6c), which suggests TK207A was an intrusive body in the sandstone of sample TK207B. This would mean that the deposition age of TK207B is older than 254 Ma.

The evidence suggests that the deposition age of the Song Chay mélange is between 254 Ma and 310 Ma which is the youngest age peak of Group 1A (Figure 7b), that is, the deposition of the Song Chay mélange started as early as Late Carboniferous and continued in to the Late Permian.

5.3. Tectonic Affinity of Song Chay Mélange Unit

According to our discussion above, Groups 1A and 1B represent the matrix and olistoliths of the Song Chay mélange unit. The age spectrum of Group 1A demonstrates four major age groups at 400–500, 550–650, 700–800, and 900–1,000 Ma with three minor age groups at 270–340, 1,500–1,800, and 2,400–2,500 Ma, whereas Group 1B has three major age clusters at 500–650 Ma, 700–800 Ma, 900–1,000 Ma and two minor age clusters at 1,500–1,800 Ma, 2,400–2,500 Ma. However, the sources of the detrital zircon in the micaschists, were considered to be the metamorphosed Cambrian and Neoproterozoic sequences of the inner part of the NE Vietnam nappe, since they exhibit a major age group at 900–1,000 Ma and 700–800 Ma (Fig-

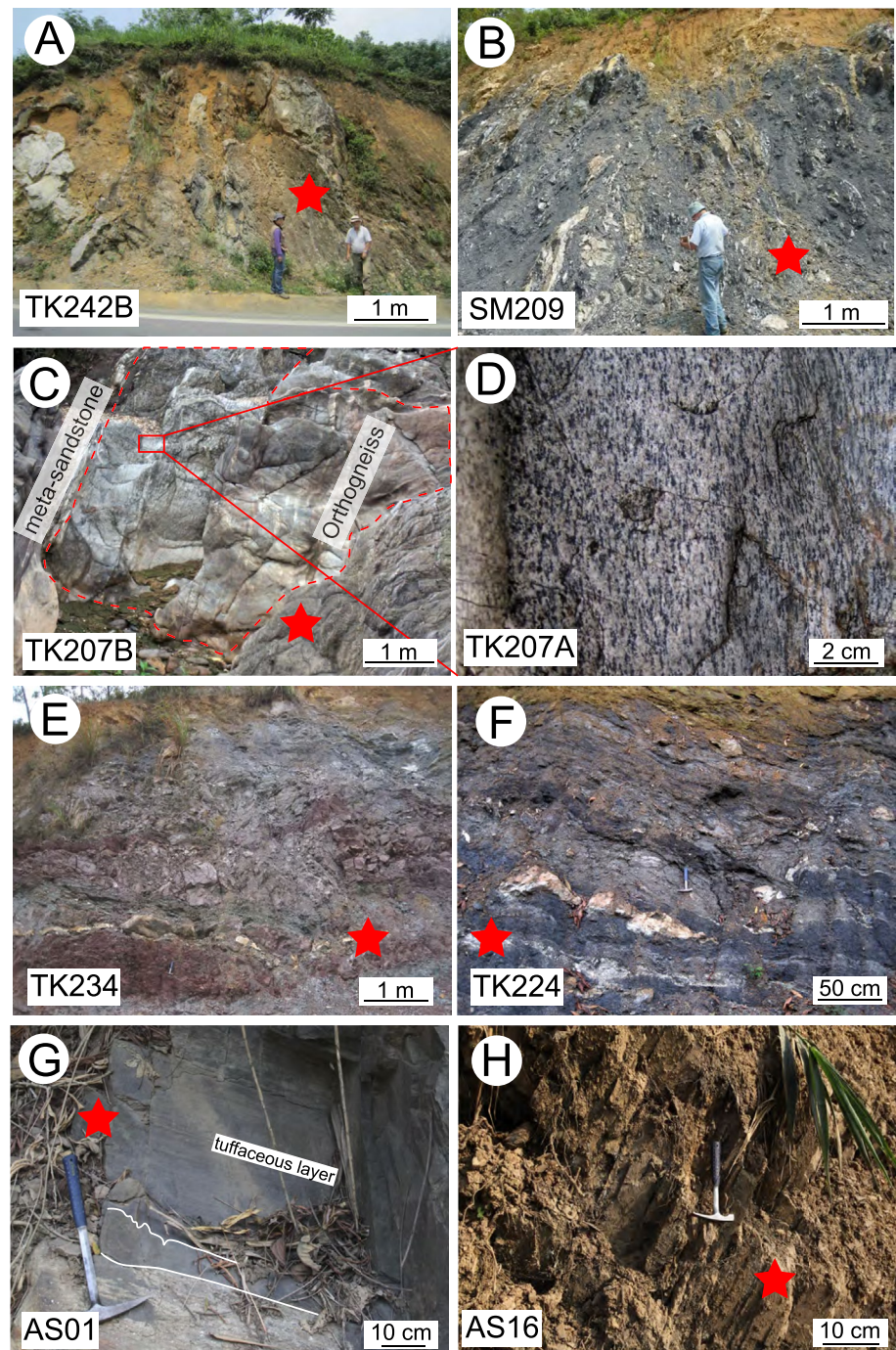


Figure 4. Representative field photos of outcrop. (a) Sheared meta-sandstone with serpentinite, gabbro, and marble blocks enclosed (TK242B); (b) Sheared black mudstone matrix enclosing variously blocks of serpentinite, gabbro, and marble blocks (SM209); (c) intensively sheared meta-sandstone (paragneiss, TK207B) and enclosed orthogneiss with concordant foliations. In the field, it is difficult to establish if the orthogneiss is a block in the mélangé or an intrusion (see text for details); (d) foliated orthogneiss (TK207A) in meta-sandstone of TK 207B; (e) and (f) blocks of serpentinite, gabbro, marbles, and sandstone in mudstone matrix (TK224 and TK234); (g) tuffaceous layer interbedded in the schistose sandstone (AS01); (h) pervasive cleavage in the meta-sandstone (AS16).

ure 7; Zhou et al., 2018). If correct, a significant difference between the Song Chay mélangé and the inner part of the NE Vietnam nappe unit should be confirmed (Figure 7). From the lithological point of view, the mélangé unit possesses the characteristics of a “block-in-matrix” formation in which the matrix is formed

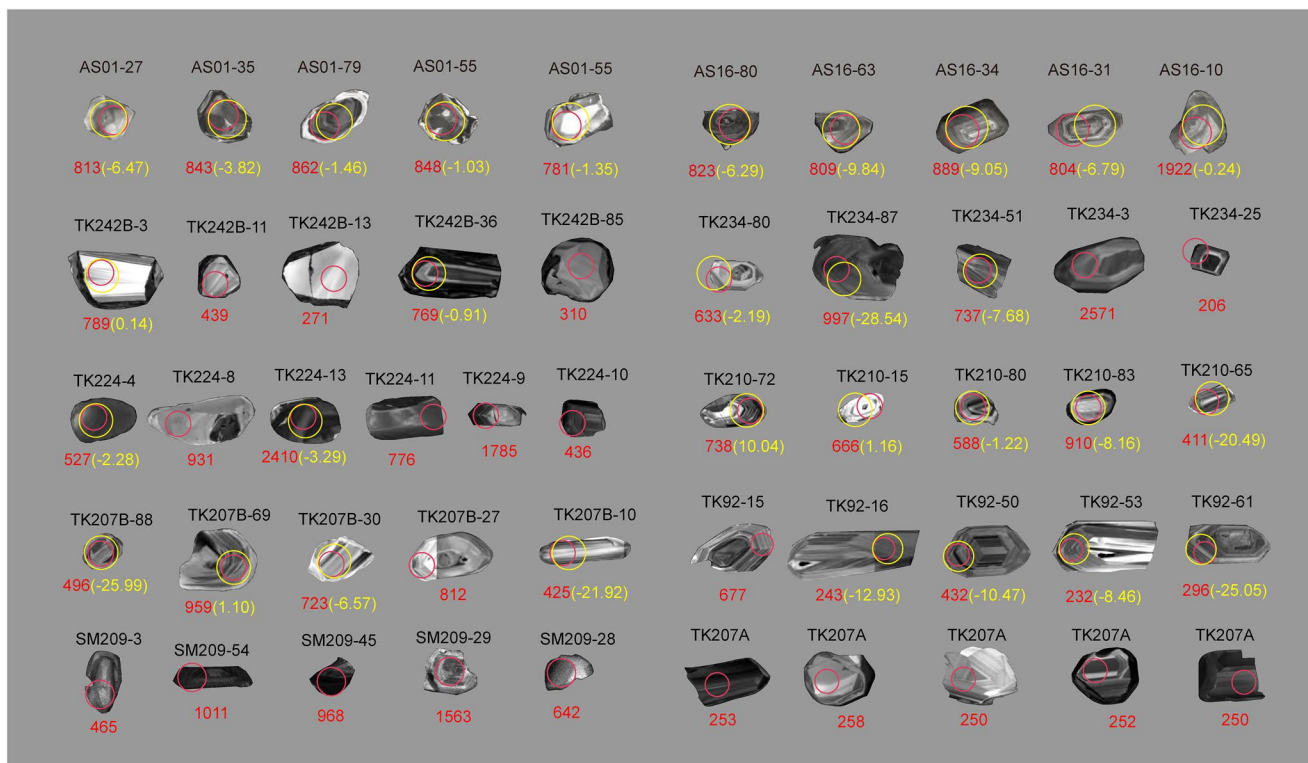


Figure 5. Representative cathodoluminescence (CL) images of selected detrital zircons from the Song Chay mélangé and the NE Vietnam nappe. The red and yellow circles represent U-Pb and Lu-Hf isotopic analytical sites, respectively. The red and yellow numbers represent U-Pb age and $\epsilon_{\text{Hf}}(t)$ values, respectively.

by sandstone, siltstone, mudstone, and volcano-sedimentary layers deformed during the Early Mesozoic thrusting and Cenozoic strike-slip shearing (Figures 3, 4a, 4b, 4e and 4f). This “block-in-matrix” formation is clearly different from the well-organized sandstone, pelite or limestone sequences of the inner part of the NE Vietnam nappe. All these observations led us to interpret the Song Chay mélangé as a potential ophiolitic mélangé (Lepvrier et al., 2011).

Based on field observations and kinematic analysis, the mélangé unit is located on top of the inner part of the NE Vietnam nappe. In some locations, the mélangé unit appears as klippe upon the NE Vietnam nappe (Figures 3a and 3c). The NE Vietnam nappe has long been recognized as a fold and thrust belt even before plate tectonics (Deprat, 1914, 1915; Fromaget, 1932, 1941). This nappe is the result of large-scale crustal shortening in NE Vietnam before the deposition of the Late Triassic molasse during the “Indosinian movement” (Deprat, 1914, 1915; Lepvrier et al., 2011). The NE-SW trending mineral and stretching lineation and various kinematic criteria (shear bands, sigmoidal quartz vein, and asymmetrical pressure shadow around K-feldspar porphyroclasts) indicate a top-to-the-N/NE sense of shear (Jolivet et al., 2001; Lepvrier et al., 2011; Maluski et al., 2001) that together with the NE verging folds, document a N/NE transportation direction of the NE Vietnam nappe (Lepvrier et al., 2011). At the southwest section of the Day Nui Con Voi, the NW Vietnam belt (or Song Da belt), this top-to-the NE deformation is not obvious (Faure et al., 2014). Considering the bulk architecture of the NE Vietnam belt, the root zone of the NE Vietnam nappe should be located below the Song Chay mélangé (Figure 1). Therefore, due to its lithological composition difference from NE Vietnam, the Song Chay mélangé was interpreted as an ophiolitic mélangé derived from the Paleo-Tethys (Faure et al., 2014; Lepvrier et al., 2011).

An ophiolitic mélangé is a peculiar litho-tectonic formation that includes: (a) magmatic and sedimentary ophiolitic rocks (e.g., basalts, diabases, gabbros, cherts, siliceous mudstones), (b) materials derived from the magmatic arc developed in the overlying plate (e.g., lava, volcanic-sedimentary rocks, greywackes, limestones), (c) various parts of dismembered sea mounts (e.g., basalt, volcanic-sedimentary rocks, limestones), and (d) sedimentary clastic rocks (e.g., turbidites, pebbly mudstone, and olistostromes) deposited in

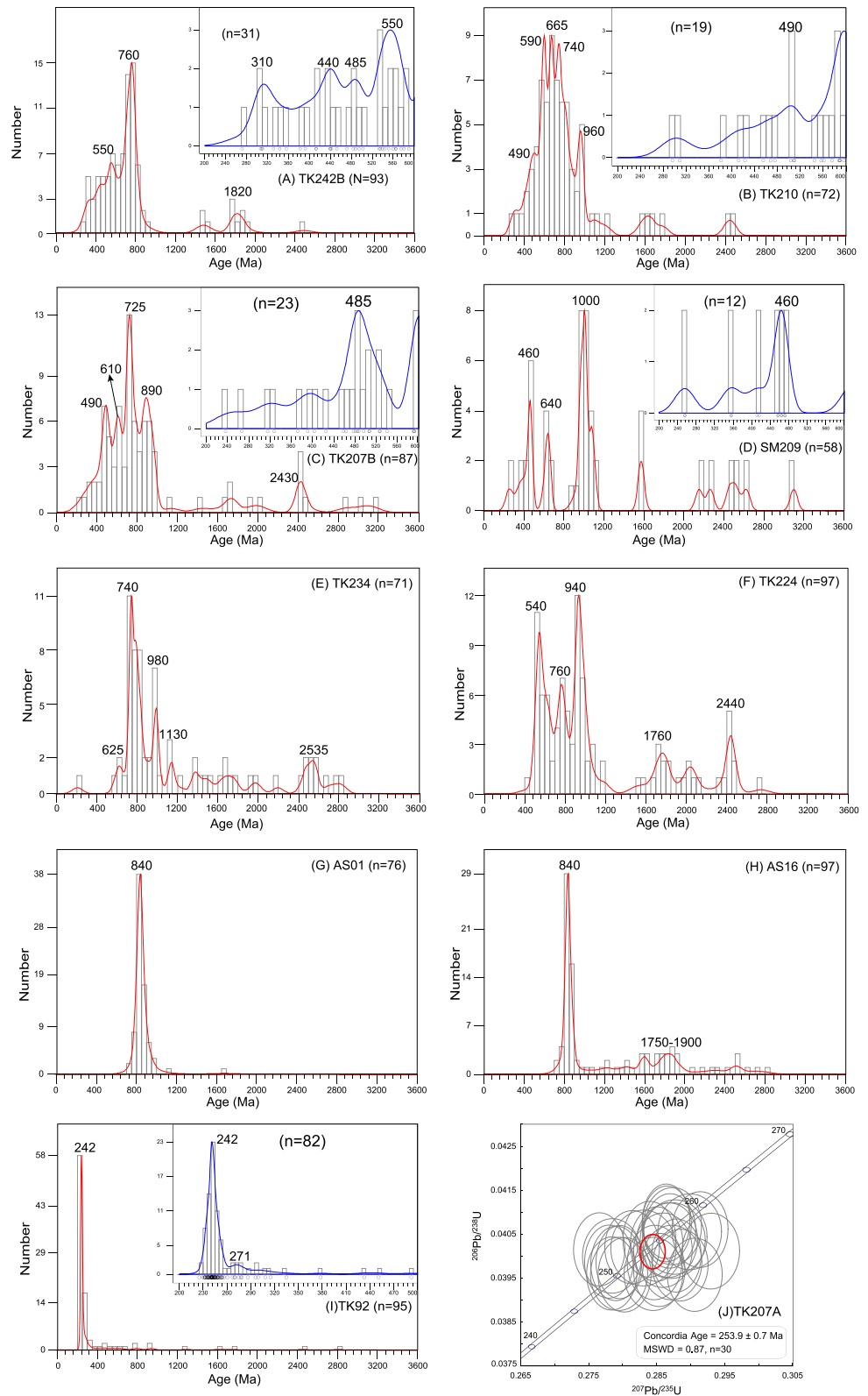


Figure 6. (a–i): Kernel Density Estimate diagrams of U/Pb ages of the detrital zircons from the Song Chay mélangé and its NW prolongation, and the NE Vietnam nappe; (h): Zircon U-Pb Concordia diagrams for the orthogneiss (TK207A).

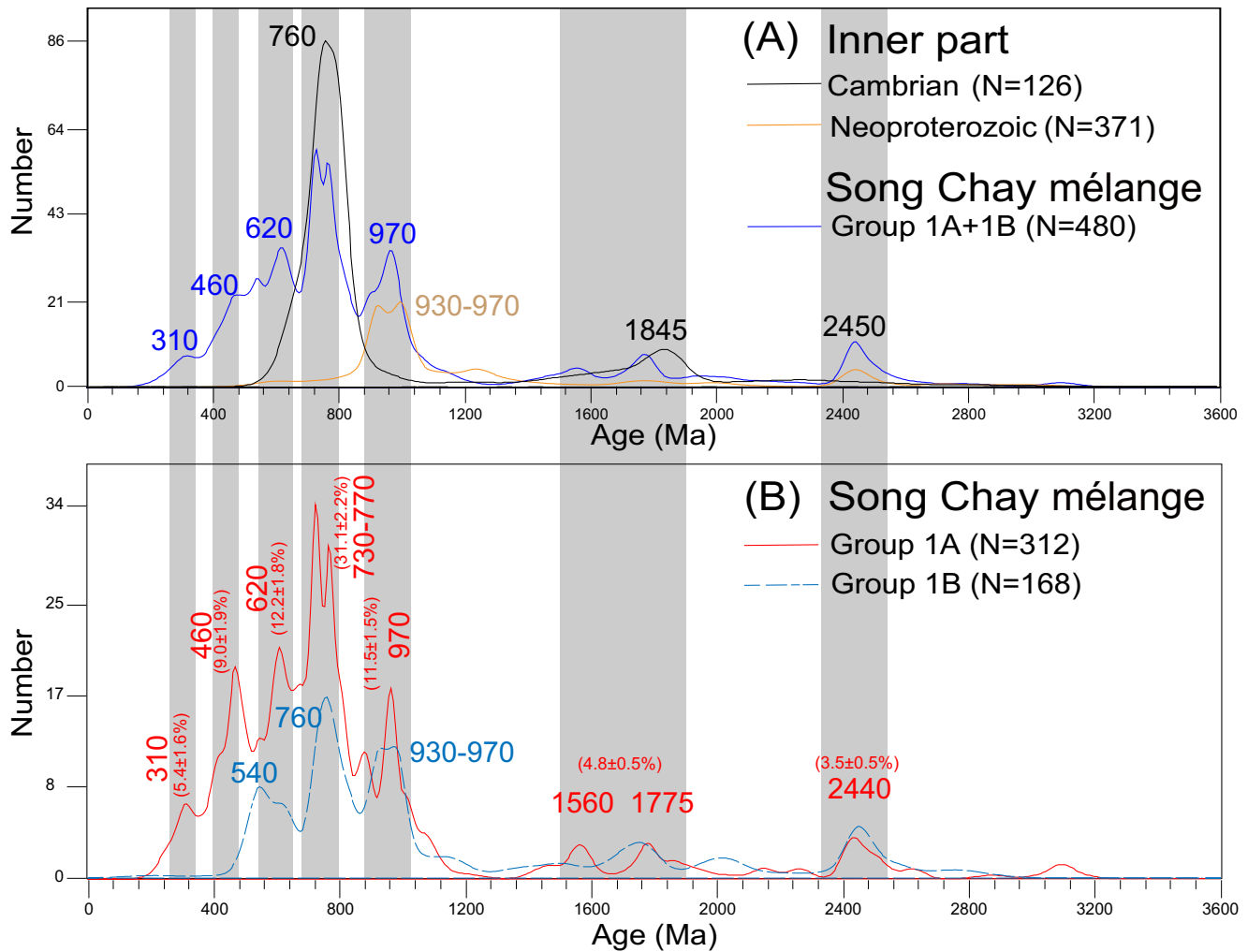


Figure 7. Synthesis and comparison of Kernel Density Estimate diagrams of detrital zircon U-Pb ages in the Song Chay mélangé and the inner part of the NE Vietnam nappe (Zhou et al., 2018).

a subduction trench. This assemblage is regarded as one of the key markers of a suture zone (Dewey, 1977; Şengör, 1992; Smith & Colchen, 1988). The Song Chay mélangé zone contains many of these elements and therefore should be considered as an ophiolitic mélangé zone. Combined with the 310–254 Ma deposition age, our new detrital zircon U-Pb ages also support the view that the Song Chay ophiolitic mélangé represents the remnants of the Paleo-Tethys Ocean.

5.4. Provenance of the Detrital Zircons in Song Chay Mélangé

5.4.1. Provenance of the Detrital Zircons in Group 1A

In Group 1A, corresponding to the matrix of the Song Chay mélangé, our new detrital zircon U-Pb ages exhibit several peaks from Paleoproterozoic to Late Paleozoic at 2,440, 1,775, 1,560, 970, 770, 730, 620, 460, and 310 Ma (Figure 7b). Statistically, more than 50% of all analyzed zircons yield Neoproterozoic ages that can be subdivided into four groups with age peaks at 970, 730–770, and 620 Ma, among which the 730–770 Ma one is predominant (with 31.1% of all results; Figure 7b). In addition, two secondary Paleoproterozoic to Neoproterozoic age peaks are found at around 1,775 and 2,450 Ma. Next to 20% of the analytical results with Phanerozoic ages yielded two peaks at 310 and 460 Ma (Figure 7b).

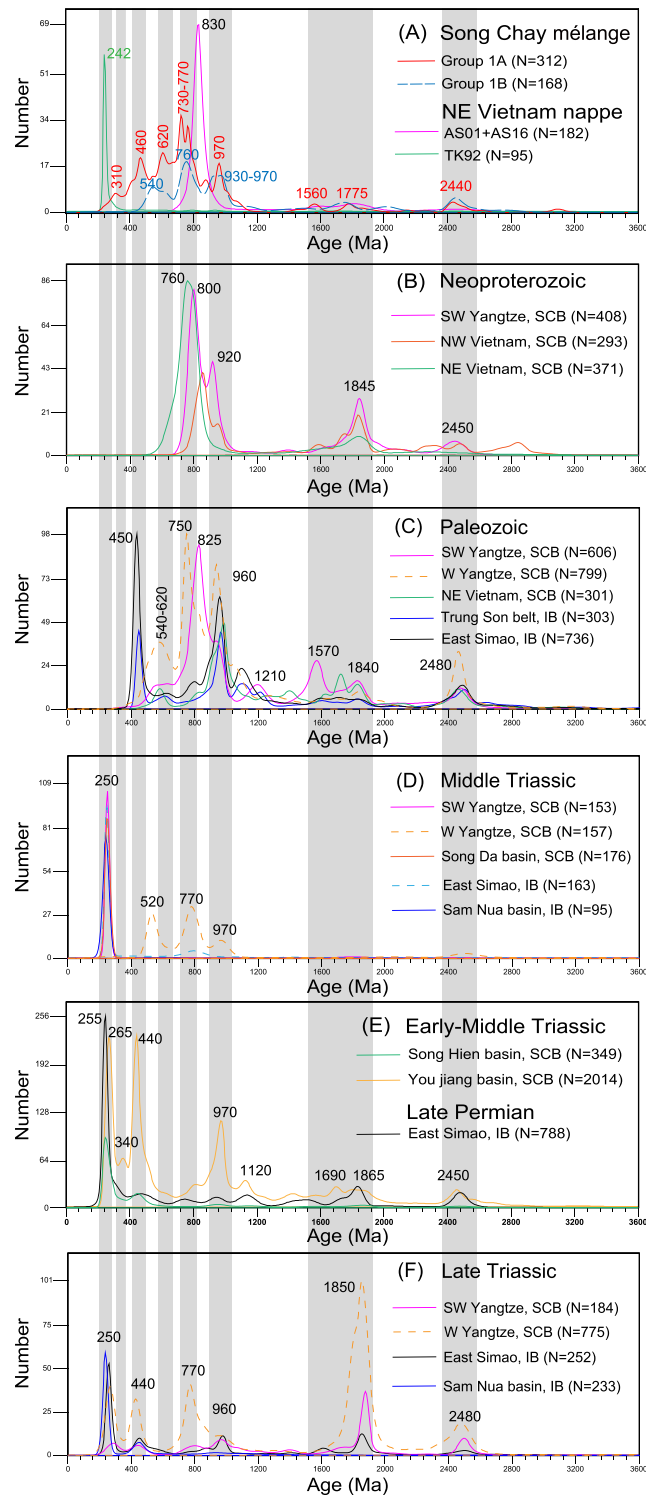


Figure 8. Synthesis and comparison of Kernel Density Estimate diagrams of detrital zircon U-Pb ages. (a) the Song Chay mélange and NE Vietnam nappe (this study); (b) Neoproterozoic sequence in SW Yangtze (Sun et al., 2009), NW Vietnam (Hau et al., 2018), NE Vietnam (Zhou et al., 2018); (c) Paleozoic sequence in SW Yangtze (Q. Wang et al., 2014; Xia et al., 2016), Paleozoic sequence in West Yangtze (Chen et al., 2016, 2018), NE Vietnam (Zhou et al., 2018), Truong Son belt (C. Wang et al., 2016), East Simao (Q. Wang et al., 2014; Xia et al., 2016); (d) Middle Triassic sequence in SW Yangtze (Xu et al., 2019), West Yangtze (Zhu, 2016), Song Da basin (Rossignol et al., 2018), East Simao (Xu et al., 2019), Sam Nua basin (Rossignol et al., 2018); (e) Early Middle Triassic sequence in Song Hien basin (Yang et al., 2012), Youjiang Basin (Duan et al., 2017; Hu et al., 2015, 2017; Qiu et al., 2017; Yang et al., 2012), Late Permian sequence in East Simao (Huang, 2018); (f) Late Triassic sequence in SW Yangtze (Xu et al., 2019), West Yangtze (Shao et al., 2016; Zhong et al., 2017), East Simao (Xu et al., 2019), Sam Nua basin (Rossignol et al., 2018).

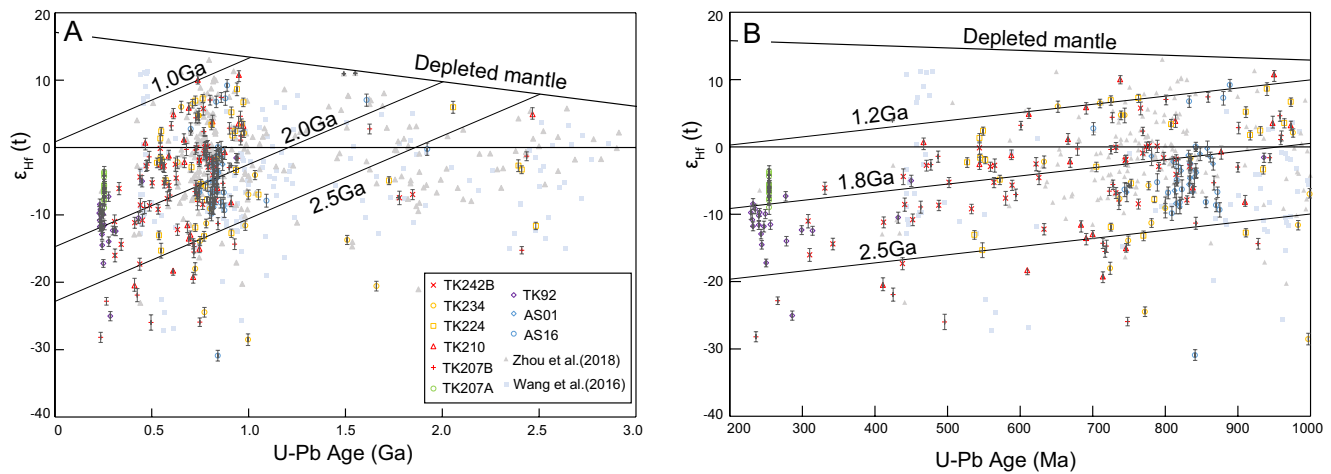


Figure 9. (a) Temporal variations of $\epsilon_{\text{Hf}}(t)$ values at 0–3.0 Ga of this study and the results from C. Wang et al. (2016) and Zhou et al. (2018). The crustal evolution range comes from Griffin et al. (2002). (b) Diagram of $\epsilon_{\text{Hf}}(t)$ value versus age for younger zircons at 1,000–200 Ma.

5.4.1.1. Provenance of the Paleozoic Zircons

The Paleozoic zircons are well represented in Group 1A (TK242B, TK210, TK207B, and SM209; Figure 6). However, a Permian-Triassic age peak was not present in every single sample even though Indosinian zircons have been detected (Figure 6), but two Paleozoic age peaks at 310 Ma and 460 Ma were obtained in the compiled results (Figure 8a). Interestingly, there is no 310 Ma peak in detrital zircons from both the SCB and IB (Figure 8), and ca. 300 Ma magmatism is rare as a few granite and diorite with this age have been reported in the southern Sam Nua-Truong Son belt (Kamvong et al., 2014; Y. Li, 2012; X. Wang, Cao, et al., 2018). These rocks were considered as related to the subduction of Paleo-Tethys Ocean (Kamvong et al., 2014). The round shape of these zircons may be indicative of a long-distance transport or a polycyclic history (Figure 5). Thus, it is feasible that these late Carboniferous detrital zircons originated from magmatic rocks located in a remote southern part of the Sam Nua-Truong Son belt.

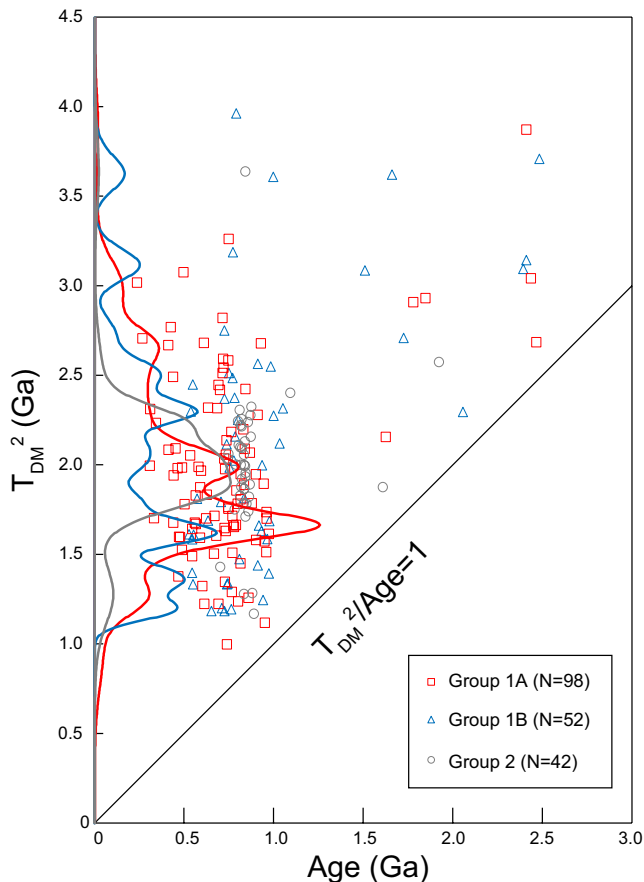


Figure 10. Diagram of the two-stage model Hf age (T_{DM}^2) versus age plots for detrital zircons, indicating the source of zircons.

Early Paleozoic detrital zircons of 440–460 Ma are widely identified in the Paleozoic sedimentary sequences in IB (C. Wang et al., 2016; Q. Wang et al., 2014; Xia et al., 2016; Yang et al., 2018). A contemporaneous magmatism also widely distributed in the northern Kontum Massif (e.g., Carter et al., 2001; Gardner et al., 2017; Hieu, Dung, et al., 2016; Jiang et al., 2020; Nagy et al., 2001; Roger et al., 2007). Moreover, 440–460 Ma detrital zircons have been found also in the SCB, as an example in the Paleozoic sequences of the Cathaysia block and the North margin of the Yangtze block, such as Qinling-Dabie orogenic belt (Xu et al., 2013, 2014; X. Zhang et al., 2018; Zhu et al., 2017). Furthermore, Early Paleozoic granitic plutons are widely exposed in the SCB, including NE Vietnam (Roger et al., 2000; Song, 2017; Y. Wang et al., 2007, 2013). In our results, almost all Early Paleozoic detrital zircons yield $\epsilon_{\text{Hf}}(t)$ negative values (Figure 9), indicating a reworked old continental crust origin (Figure 10). However, the $\epsilon_{\text{Hf}}(t)$ values of the Early Paleozoic detrital zircons from IB exhibit next to 50% positive $\epsilon_{\text{Hf}}(t)$ values (Figure 9; C. Wang et al., 2016), which is indicative of a significant input of the juvenile crustal materials during the Early Paleozoic. In contrast with the IB, the SCB, including NE Vietnam, is characterized by an Early Paleozoic magmatism quin-

essential of crustal melting, with negative $\epsilon_{\text{Hf}}(t)$ values (e.g., Lin et al., 2008; Maluski et al., 2001; Roger et al., 2000; Song, 2017; Y. Wang et al., 2007, 2013). Therefore, we prefer to ascribe the provenance of the Early Paleozoic zircons to the SCB instead of the IB.

In summary, in the Song Chay mélange, the most feasible provenance of the Late Paleozoic detrital zircons is the magmatic rocks of the southern Sam Nua-Truong Son belt, but the SCB is the most feasible source for the Early Paleozoic detrital zircons.

5.4.1.2. Provenance of the Neoproterozoic Zircons

In our samples, the Neoproterozoic detrital zircon ages split into three groups (550–650, 700–800, and 900–1,000 Ma; Figures 6, 7b and 8a). As the major one, the 700–800 Ma cluster contributes for more than 30% of all the zircons (Figure 7b). A large number of plutons yielding Neoproterozoic ages at ca. 700–800 Ma are exposed in the western and southwestern margins of the Yangtze block and Phan Si Pan region of NW Vietnam (Cai et al., 2015; Chen et al., 2017; Huang et al., 2008; X. Li, Li, Ge, et al., 2003; Z. Li, Li, Kinny, et al., 2003; X. C. Li et al., 2018; X. H. Li et al., 2002; Minh et al., 2020; P. L. Wang et al., 2011; Zhao et al., 2008; Zhou et al., 2006). Moreover, the 700–850 Ma age group is also the predominant population in the Neoproterozoic sedimentary rocks of the inner part of the NE Vietnam nappe and of the southwestern Yangtze block (Figure 8b), and so as to the Paleozoic and Late Triassic rocks in western Yangtze block (Figures 8c and 8f). By contrast, 700–800 Ma detrital zircons are absent from Paleozoic and Triassic rocks in the Sam Nua-Truong Son belt, in eastern Simao block (IB) (Figure 8; Rossignol et al., 2018; C. Wang et al., 2016; Q. Wang et al., 2014; Xia et al., 2016; Xu et al., 2019). Moreover, 700–800 Ma plutons have not been found in the IB (C. Wang et al., 2016). Therefore, we consider that the sedimentary rocks and the Neoproterozoic plutons of the western and southwestern margins of the Yangtze block are the most likely provenance of the 700–800 Ma detrital zircons recovered in the Song Chay mélange. Combined with the CL images and morphometric features of this group (Figure 5), we consider that these detrital zircons were probably recycled from the sedimentary rocks exposed in western and southwestern margins of the Yangtze block, but we cannot exclude the Neoproterozoic plutons, especially those in southwestern margins of the Yangtze block and Phan Si Pan region of NW Vietnam, as a feasible provenance.

The Late Neoproterozoic age group (550–650 Ma, $12.1 \pm 1.8\%$) with age peak at 620 Ma is documented in the Song Chay mélange. No igneous rocks with 500–650 Ma ages have yet been identified in the adjacent regions. However, abundant detrital zircons of this age cluster have been reported in the Neoproterozoic to Paleozoic sequence in western and southwestern margins of Yangtze block (Figure 8c; Chen et al., 2016, 2018; Q. Wang et al., 2014; Xia et al., 2016; Xu et al., 2013, 2014; Zhou et al., 2018). However, this cluster is not significant in the IB (Figure 8; C. Wang et al., 2016). Combined with the CL images and morphometric features of this group, the 550–650 Ma detrital zircons in the Song Chay mélange were most possibly recycled from the Neoproterozoic to Paleozoic rocks located in the western and southwestern margins of the Yangtze block.

The 900–1,000 Ma age group ($11.5 \pm 1.5\%$) appears as a subordinate cluster in the Song Chay mélange (Figure 8a). However, similar to the 550–600 Ma age group, no contemporary igneous rocks have been recognized in the adjacent regions, but this detrital zircon age group occurs widely in the Early Paleozoic sedimentary rocks of the inner part of the NE Vietnam nappe, IB, and Cathaysia block (C. Wang et al., 2016; Xia et al., 2016; X. Zhang et al., 2018; Zhou et al., 2018). However, the provenance of 900–1,000 Ma detrital zircons in our samples cannot be clarified because of the widespread occurrence of this age group and the high similarity of $\epsilon_{\text{Hf}}(t)$ values, and model ages between them (Figures 8 and 9). Nevertheless, we consider that the Paleozoic sedimentary rocks of western and southwestern margins of the Yangtze block was the most likely source, for the 700–800 Ma and 500–600 Ma detrital zircons.

In summary, the most feasible provenance for the Neoproterozoic detrital zircons is the Neoproterozoic to Early Paleozoic sedimentary rocks that occur along the western and southwestern margins of the SCB (Figure S3). Although the source of the 900–1,000 Ma zircons is unidentified, we speculate that these detrital zircons were derived from the SCB (Figure S3), as it seems to be the case with the other two main groups of detrital zircons.

5.4.1.3. Inherited Neoproterozoic and Paleoproterozoic Zircons

The Neoproterozoic and Paleoproterozoic zircon grains with peak ages at ca. 1,750 Ma and 2,450 Ma are widely recorded in the Neoproterozoic and Paleozoic sequences in the Gondwana affinity blocks, such as South China, Indochina, Sibumasu, and Qiangtang blocks (Cai et al., 2017; Gehrels et al., 2011; D. Li et al., 2015; Sun et al., 2009; C. Wang et al., 2016; Xia et al., 2016; Zhu et al., 2011), although the contemporary igneous rocks have not been reported neither in the SCB nor in the IB. Therefore, the Neoproterozoic and Paleoproterozoic detrital zircon grains in the Song Chay mélangé are probably derived from multicycle sources in the SCB and the IB (Usuki et al., 2013).

5.4.2. Provenance of the Detrital Zircon in Group 1B

According to the above discussion, the Group 1B (TK234 and TK224) is considered as the blocks (olistoliths) in the Song Chay mélangé unit. Our new detrital zircon U-Pb ages demonstrate three main age groups of 500–650, 700–800, and 900–1,000 Ma (Figure 8a), which are highly similar to those obtained from the Paleozoic sedimentary rocks in the western and southwestern margins of the Yangtze block (Figures 8a and 8c). This suggests that the Group 1B zircons were supplied from the SCB. This conclusion is supported by the high similarity of $\varepsilon_{\text{Hf}}(t)$ values and model ages between Group 1A, 1B and NE Vietnam (Figures 9 and 10).

5.4.3. Provenance of the Detrital Zircon in the NE Vietnam Nappe

As a significant single cluster around 840 Ma, these ages match those found in the Nam Co Formation (Zhou et al., 2020) and support the Yangtze Block basement as a source of the detrital material (Figure S3). Therefore, the Group 2 zircons (AS01 and AS16) should be supplied by the Neoproterozoic sediments of the SCB. The single age cluster contains about 90% of all the analytical results (Figures 6g and 6h). Together with the tuffaceous layers, a univocal igneous rock source is documented. According to previous works, the 750–900 Ma age group in the Neoproterozoic sequences of southwest SCB was interpreted as derived from the Neoproterozoic felsic to mafic plutons along the western and southwestern margins of the SCB and Phan Si Pan region of NW Vietnam (Minh et al., 2020; Sun et al., 2009; Q. Wang et al., 2014; Xia et al., 2016).

As for the sample TK92 from the Middle Triassic turbidite in the Song Hien basin in the outer part of the NE Vietnam nappe, most of the analyzes fall into 220–260 Ma age interval, with an age peak at 242 Ma (Figure 6i). Combined with the previous works of detrital zircon, the age pattern for this basin exhibits two main groups at 230–280 and 420–460 Ma (Figure 8e), which are similar with the results available for the Youjiang (or Nanpanjiang) basin (Figure 8e, Duan et al., 2017; Hu et al., 2015, 2017; Qiu et al., 2017; Yang et al., 2012). Therefore, the results of the detrital zircon age distributions comply with the stratigraphic and sedimentological records to support the analogy between the Youjiang and Song Hien basins, which is inconsistent with the existence of the Dian-Qiong Ocean, that has been inferred to separate two major blocks (Cai & Zhang, 2009).

5.5. Tectonic Implications

Generally, in a subduction-related mélangé, the trench is filled with sedimentary clastic material mainly supplied from the overlying plate, especially from arc related plutonic, volcanic, and sedimentary rocks. These volcano-clastic sediments constitute the matrix of the trench-filled sediments in which the components of the active continental margin and pelagic sediments are included as blocks of various sizes. Such a process is well documented in present-day subduction zones such as the Nankai trough or Japan Trench (e.g., Kimura et al., 1992; Le Pichon et al., 1987a, 1987b).

However, according to our work, the detrital zircon grains of the Song Chay mélangé mainly derive from the SCB, which is regarded as the subducting plate (Faure et al., 2014; Lepvrier et al., 2011; Lin et al., 2011). Only a limited fraction of the detrital grains is considered to derive from the overriding IB plate. Especially, the Song Chay mélangé lacks Permian zircon grains supplied by the magmatic arc. It is also worth noting that greywacke and tuffs are absent from outcrops. Our results constrain the deposition age of the Song Chay mélangé between 310 and 254 Ma, which suggests that the deposition of the Song Chay mélangé may start as early as Late Carboniferous and continue Late Permian. Three scenarios can explain the absence of arc-related detrital zircon ages in the Song Chay mélangé: (a) the zircon grains from the magmatic arc were blocked in a forearc basin and did not reach the trench; (b) similar to the Western Alps, the magmatic arc might not have been well developed; (c) the matrix of the mélangé can be subdivided in two parts, similar

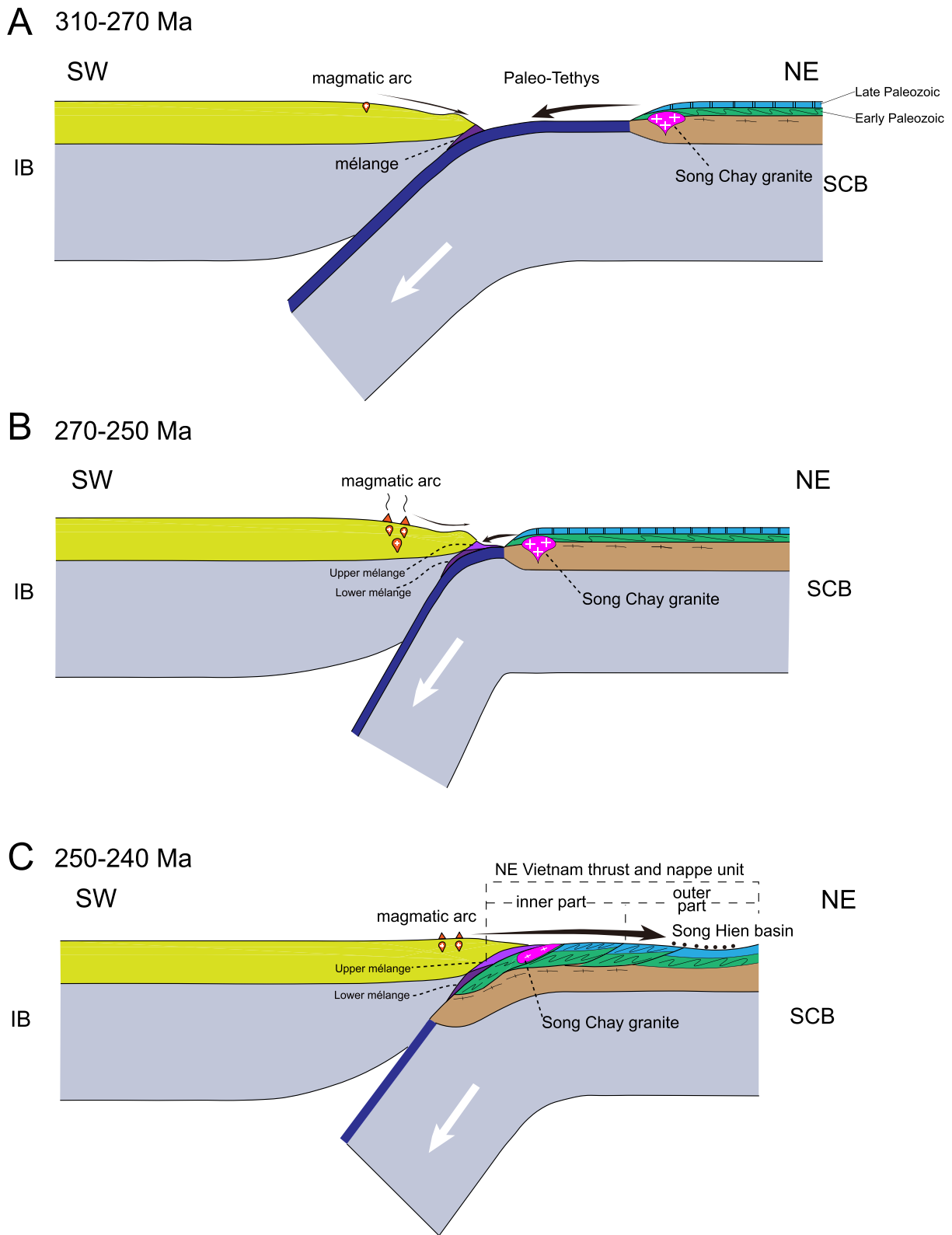


Figure 11

to the Cyclades of Greece (Grasemann et al., 2018), whereby the first part mainly originated from the passive margin of the SCB, and the upper part, which has since been eroded, derived from both the active and passive continental margins of IB and SCB, respectively.

The Early–Middle Triassic sedimentary rocks, cluster around 250–240 Ma, could be interpreted to be related to a magmatic arc (Figure 8d; Rossignol et al., 2018; Xu et al., 2019). Although small blocks of Middle Triassic granite (Chen et al., 2014; Roger et al., 2012; H. T. Tran et al., 2008) are exposed in NE Vietnam, however, it is not likely that these small scaled magmatisms in NE Vietnam supplied the 250–240 Ma detrital zircons of the Early Middle Triassic sedimentary rocks in such a large region. Furthermore, the Early Middle Triassic sedimentary rocks in the Eastern Ailaoshan belt and Song Da basin are considered as deposited in a foreland setting (Rossignol et al., 2018; Xu et al., 2019), which indicates that the detrital zircon grains supplied from the magmatic arc can reach the foreland basin located in the southwestern margin of SCB. In other words, the forearc basin, if it existed, did not prevent the zircon grains derived from the magmatic arc.

In the Song Hien and Youjiang basins, the detrital zircons included in the Early Middle Triassic sedimentary rocks yielded a major age group with peak at around 265 Ma (Figure 8e). Combined with the northward paleocurrent and the well-preserved volcanic lithic fragments, this group of Permian–Triassic detrital zircons was interpreted to record the first-cycle detrital input from a subduction–collisional system (Yang et al., 2012). This result infers that there was a magmatic arc related to the closure of the Paleo-Tethys Ocean in the Song Chay area.

Furthermore, the magmatic rocks with ages ranging from 310 to 245 Ma, interpreted as arc-related rocks have been reported in the Western Ailaoshan and Sam Nua-Truong Son belts (Figure 1; e.g., Fan et al., 2010; Hieu, Dung, et al., 2016; Hoa et al., 2008; Hou et al., 2019; Jiang et al., 2020; Kamvong et al., 2014; Lai, Mefre, Crawford, Zaw, Halpin, et al., 2014; Y. Li, 2012; Qian et al., 2019; X. Wang, Cao, et al., 2018). In contrast to the widespread Late Permian–Middle Triassic magmatism, the distribution of Late Carboniferous–Middle Permian magmatism is relatively limited in this magmatic belt (Hou et al., 2019). It seems that the magmatic arc was not well developed during the Late Carboniferous–Middle Permian. Considering the deposition age of the Song Chay mélange constrained by our detrital zircon results, we may infer that the limited amount of the Late Carboniferous–Middle Permian detrital zircons in the Song Chay mélange is due to the underdeveloped magmatic arc in this period.

One possibility is that the deposition of the Song Chay mélange started as early as Late Carboniferous and continued to the Late Permian. The Permian–Triassic detrital zircons were deposited in the upper part of the mélange which has since been eroded away, whereas the preserved lower part recorded detrital grains dominantly sourced from the SCB and limited detrital grains from IB because of the underdeveloped magmatic arc in this period. The detrital zircons from the Ailaoshan ophiolitic mélange support this view (Q. Wang et al., 2014; Xia et al., 2016). Based on this hypothesis, a feasible reconstruction of the Late Carboniferous–Middle Triassic geodynamic setting is proposed in Figure 11. During the Late Carboniferous–Middle Permian (ca. 310–270 Ma), as a part of the Paleo-Tethys, the Song Chay ocean, began to subduct under the IB. In this period, the magmatic arc was underdeveloped, and the SCB acted as the main provenance of sediments in the mélange (Figure 11a). During the Middle Permian–Middle Triassic (270–250 Ma), the magmatic arc was well developed in IB. However, during this period, the Paleo-Tethys was almost closed and the SCB was overwhelmingly close to the trench. In this situation, it was probable that the main source of the Song Chay mélange was the SCB, even though the magmatic arc was well developed (Figure 11b). A similar scenario has been reported for Timor Island where a (young) Miocene mélange supplied a large amount of material from the underlying continental plate (e.g., Barber, 2013; Tate et al., 2015; Villeneuve et al., 2010). Harris et al. (1998) demonstrated that the main source for the matrix and blocks in the Bobonaro ophiolitic mélange in Timor Island was the Australian continent, which is regarded as the lower plate of the Eurasian–Indo–Australian plate convergence.

Figure 11. Schematic reconstruction of the Late Carboniferous–Middle Triassic geodynamic evolution between the SCB and IB. A two-stage subduction model: (a) in the first stage (ca. 310–270 Ma), the magmatic arc was underdeveloped, and the matrix material of the Song Chay mélange was mainly supplied by the passive margin of SCB; (b) in the second stage (ca. 270–250 Ma), the magmatic arc began to develop extensively, and even under erosion. The upper part of the Song Chay mélange was mainly supplied by the passive margin of the SCB and the magmatic arc. (c) in the collision stage (ca. 250–240 Ma), the Song Hien basin in the SCB were supplied by magmatic arc.

During the collision period (250–240 Ma, Figure 11c), the ophiolitic mélangé was thrust upon the inner part of the NE Vietnam nappe. Due to the subsequent erosion, and possibly the intensive Cenozoic tectonics, the upper part of the ophiolitic mélangé has been eroded away, such that only a small proportion of the lower part of the Song Chay ophiolitic mélangé is preserved in the inner part of the NE Vietnam belt. A similar scenario can also be found in the present Bobonaro ophiolitic mélangé in Timor Island. There, the Bobonaro ophiolitic mélangé was emplaced on a duplicated Late Triassic–Jurassic Gondwana Sequence on the NW Australian continental shelf. Because of the obduction of the Banda Arc during the collisional period (~7.1 Ma to present), Timor was uplifted and began to suffer erosion from ca. 4.5 Ma (Harris & Long, 2000; Harris et al., 1998; Nguyen et al., 2013; Tate et al., 2014, 2015), leading to the removal of the upper part of the Bobonaro ophiolitic mélangé.

6. Conclusion

From the view of tectonic and sedimentology, the composition of a mélangé, especially an ophiolitic mélangé, is complex as demonstrated by our geochronological and in-situ Hf isotope detrital zircon analyses of samples from the Song Chay mélangé and NE Vietnam nappe. Based on the result we draw the following conclusions: (a) Detrital zircons recovered from the matrix of the Song Chay mélangé display predominant Neoproterozoic populations with peak ages at ca. 750, 960, and 620 Ma. A limited number of Paleozoic zircons exhibit two minor peaks at ca. 310 and 460 Ma; (b) The deposition age of the Song Chay mélangé was between 310 and 254 Ma; (c) The Neoproterozoic age populations correspond well to the substratum of the NE Vietnam nappe, and the western and southwestern margins of the Yangtze block, and suggests that the SCB was the main provenance of the material included in the Song Chay mélangé; (d) The Song Chay mélangé developed in a two-stage subduction process: (a) in the early stage (ca. 310–270 Ma), the magmatic arc was underdeveloped, and the matrix material of the mélangé was mainly supplied by the subducting plate, that is, the SCB; (b) in the late stage (ca. 270–250 Ma), the magmatic arc was well exposed, and under erosion. Therefore, the detrital material found in the Song Chay ophiolitic mélangé did not exclusively come from the overriding plate, but the subducting plate may have also been a source of material.

Data Availability Statement

All data can be archived online at [10.6084/m9.figshare.13187372](https://doi.org/10.6084/m9.figshare.13187372).

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