The South China Block-Indochina collision: where, when, and how?

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Michel Faure[1*], Claude Lepvrier[2], Nguyen Van Vuong[3], Vu Van Tich[3], Wei Lin[4], Zechao Chen[4]

1 Institut des Sciences de la Terre d'Orléans, UMR CNRS 7327, Université d'Orléans, 45067 Orléans cedex 2, France. michel.faure@univ-orleans.fr

2 Institut des Sciences de la Terre de Paris, UMR CNRS 7193, Case 129, Université Pierre & Marie Curie, 75252 Paris cedex 05, France

3 Faculty of Geology, Hanoi University of Science, Hanoi, Vietnam

4 State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

*: Corresponding author

ABSTRACT

This study uses new field observations and existing studies to shed new light on the origin and significance of two NW-SE striking orogens in NW and NE Vietnam. We conclude that the architecture of each belt is a stack of NE-directed nappes formed either under deep ductile synmetamorphic conditions, or under shallow depth in the SW and NE parts, respectively. The Song Ma zone and Song Chay ophiolitic melange represent two ophiolitic sutures. However, the Late Permian Song Da and Babu mafic rocks are not ophiolites but intraplate basalts related to the Emeishan plume. A Late Triassic unconformity, the 225-205 Ma postorogenic plutonism, and the 250-230 Ma syntectonic metamorphism support an Early to Middle Triassic age for these tectonic events. Both NW and NE belts are due to SW-directed subduction with arc magmatism, ocean closure, and continental collision. Though two contemporary S-dipping subduction zones might explain the structural evolution of the two belts, a single convergent system, offset by the Tertiary Red River fault, is preferred as this S-directed subduction better accounts for the Late Permian intraplate magmatism. This scenario is discussed in the general geodynamic framework of SE Asia.

1. Introduction

Asia was formed during the Phanerozoic by the welding of several continental blocks including Siberia, Tarim, North China, South China, Indochina, India, and several small-sized microcontinents. All published models acknowledge subduction, and accretion of Gondwana derived fragments to the North, but in many cases the timing and nature of collision is poorly defined. Concerning the collision between the South China Block (SCB) and Indochina, several aspects remain controversial, specifically: 1) Where is the ophiolitic suture corresponding to the intervening ocean? 2) When did the collision occur? 3) How the collision developed, i.e. what was the subduction polarity, and which structures accommodated the collision? The aim of this paper is to answer these questions on the basis of structural observations conducted in N. Vietnam and SW China, and to discuss the context of the rocks in N. Vietnam belts in the general tectonic framework of Asia.

The boundary between Indochina and SCB is often located along the Song Ma zone (Fig. 1; e.g. Helmcke, 1985; Hutchison, 1989; Findlay, 1997; Findlay and Pham, 1997; Lepvrier et al., 1999, 2004, 2008; Metcalfe, 1996, 2002, 2013; Tran and Vu, 2011). However, some authors suggested that the Song Da (Sengor and Hsu, 1984) or the Babu mafic rocks in South China represent the ophiolitic suture (Zhong et al., 1998; Wu et al., 1999; Cai and Zhang, 2009). The age of the collision is generally considered as Triassic (Lepvrier et al., 1999, 2004, 2008; Liu et al., 2012), but older ages such as Early Paleozoic (Janvier et al., 1996; Thanh et al., 1996; Findlay, 1997; Findlay and Pham, 1997, Carter et al., 2001), or Middle Carboniferous (Helmcke, 1985; Hutchison, 1989; Metcalfe, 1996, 2002, 2013) have been also put forward. Carter and Clift (2008) argue that contact between Indochina and South China, occurred before the Devonian, and that in N. Vietnam, the Triassic Indosinian orogeny was a thermo-tectonic reactivation event.

The Red River Fault (RRF) is the major continental-scale structure of northern Vietnam. This Cenozoic left-lateral shear zone that accommodated the extrusion of Sundaland due to Indian collision (e.g. Tapponnier et al., 1990; Leloup et al., 1995), it is not an ophiolitic suture (i.e. a plate boundary). To resolve this debate it is essential to define where ophiolitic suture zones are located in northern Vietnam and to define their age. Currently there is little information, indeed, structural studies dealing with the SCB-Indochina collision are rare (Findlay and Pham; 1997; Lepvrier et al., 1997; 2004, 2008, 2011). Although early works (e.g. Deprat, 1914, 1915; Jacob, 1921; Bourret, 1922, Fromaget, 1941), recognized two distinct fold belts in northern Vietnam, namely the NE and NW Vietnam belts, on both sides of the RRF (Fig. 1), their significance and the role of the RRF remains unclear. The goal of this study is therefore to integrate new field data and analyses with published work to better define the timing and nature of the South China-Indochina collision. As the two belts are separated by the RRF, their architecture will be presented separately, then their geodynamic relationships will be discussed.

2. The NW Vietnam belt

Despite Cenozoic deformation represented by high-angle brittle thrusts that placed the Triassic rocks upon Cretaceous continental red beds (Lacassin et al., 1998), most of the ductile structures observed SW of the RRF are older than the Late Triassic deposits that unconformably cover the Early Mesozoic-Paleozoic formations. This unconformity was the keystone for the definition of the "Indosinian" orogeny (Fromaget, 1941; Tran and Vu, 2011).

The dominant NW-SE strike of the NW Vietnam belt is deflected to a NNW-SSE trend by the dextral Dien Bien Fault. As a result, the fold axes progressively turn to NW-SE and then to NNW-SSE strike. This 100 km-scale oroclinal bending, of probably Cenozoic age, does not significantly alter the primary structure of this orogen. The north-verging folds change to east verging ones, and the N-S striking streching lineation becomes NE-SW and E-W. In the NW

Vietnam belt, from the NE to the SW, we identified the following litho-tectonic units (Figs. 1, 2, 3).

2. 1. The Po Sen-Hoa Binh zone consists of a Precambrian metamorphic basement (Lan et al., 2001) conformably covered by Paleozoic-Early Triassic sedimentary and magmatic rocks. This series is unmetamorphozed but folded by NW-SE trending upright folds (Fig. 4A) with locally an axial planar cleavage. In contrast to the view of Deprat (1914), these rocks do not form the allochthonous unit called "nappe de la rivière Noire" but represent the deepest part of the NW Vietnam belt. To the NW, per-alkaline and meta-aluminous plutons that form part of the Phan Si Pan massif yield zircon U-Pb LA-ICP-MS ages at 253-251 Ma (Pham et al., 2012; Fig. 1, Table 1).

2. 2. The Son La-Lai Chau zone, in vertical fault contact with the Po Sen-Hoa Binh zone, is represented by Devonian to Permian formations conformably overlain by Early to Middle Triassic series, and unconformably covered by Late Triassic conglomerates and sandstones, or by Cretaceous continental red beds. Gabbro, pillow basalt, mafic volcanic breccia are well developed particularly along the Da River (i. e. Song Da in Vietnamese) in the Son La-Lai Chau zone. Due to their alkaline geochemistry, these rocks were interpreted as formed in the Song Da rift (Poliakov et al., 1999; Tran et al., 2008b; Tran and Vu, 2011). The mafic suite is overlain by a Late Permian formation with shallow water marine limestone, then by coal, bauxite, and iron horizons indicative of a continental environment. (Tran and Vu, 2011; Metcalfe, 2012). An acidic to intermediate magmatic suite, known as the "Tu Lê volcanic rocks", is recognized north of the Song Da rift (Fig. 1; Tran and Vu, 2011). On the basis of their Late Permian zircon, U-Pb SHRIMP radiometric ages, the "Tu Lê volcanic rocks" are coeval with the mafic rocks, and thus are also placed in the Song Da rift (Table 1; Tran and Vu, 2011).

A Late Permian-Early Triassic turbiditic series (Co Noi formation) that includes cm to km-sized limestone and mafic (i.e. pillow basalts, gabbro) olistoliths, enclosed in a pebbly mudstone matrix with slumped beds overlies the mafic rocks (Fig. 4B). This sedimentary suite argues for a gravity-driven chaotic sedimentation that would fit with the proposed rift setting (Poliakov et al., 1999; Tran et al., 2008b; Tran and Vu, 2011). It is worth noting that deep-sea sediments, such as chert or siliceous mudstone, and mantle peridotites or serpentinites are not present there. In agreement with most of authors, we argue that the Song Da-Tu Lê bimodal magmatic suite does not represent an ophiolitic series but rather an intracontinental rift. The chaotic sedimentation, and the overlying Middle Triassic limestone represent the syn-rift, and the post-rift sequences, respectively.

The rocks of the Son La-Lai Chau zone experienced a Middle Triassic polyphase deformation. The entire Paleozoic-Middle Triassic series is deformed by upright, or overturned to the NE, NW-SE striking folds (Fig. 5A). To the West, the fold axes progressively turn to a NNW-SSE and N-S strike due to the dextral motion of the Dien Bien fault. Thus folds are E-verging there. Moreover, the Paleozoic-Triassic series experienced a ductile deformation. The foliation contains a N-S to NE-SW striking mineral and stretching lineation represented by elongated or boudinaged pebbles, clasts or vesicules in lava (Fig. 5B). Kinematic indicators such as sigmoidal lenses, quartz or chlorite pressure shadows, tilted dolomite fragments show a top-to-the-N shearing (Fig. 4D). This ductile shearing is coeval with a syn-tectonic metamorphism represented by quartz-sericite-chlorite assemblages in the pre-Late Triassic pelitic and mafic rocks, whereas in the carbonated rocks, calcite clasts are recrystallized and locally white mica may develop.

Furthermore, the vertical beds deformed by upright folds exhibit a moderately dipping cleavage, which is incompatible with upright folding. However, if the beds are restored to horizontal, the bedding-cleavage relationships comply with N-verging structures. This kinematic pattern is in agreement with the top-to-the NE ductile shearing observed in the mafic rocks to the NE (Fig. 6).

The Ta Khoa antiform (TK in Fig. 1), exposes the deepest rocks of the Son La-Lai Chau zone, where Devonian terrigenous rocks have been metamorphosed to a biotite-garnet-sillimanite gneiss. N- or NE-directed stretching lineation and intrafolial folds are coeval with the metamorphism (Fig. 4C). NW-SE striking upright folds deform this flat-lying ductile shearing.

2.3. The Inner zone developed SW of the previous one. The present boundary with the Son La-Lai Chau zone is a late high-angle brittle fault (Findlay, 1997; Findlay and Pham, 1997; Lepvrier et al. 2004). As presented above, on the northeastern side of the fault, the pre-late Triassic rocks are ductiley deformed but not metamorphozed. In contrast, on the southwestern side, pervasively foliated and lineated metamorphic rocks predominate (cf below). In order to account for the contrasted deformation and metamorphism between the two zones, this fault must have had a major vertical component. Since Triassic sedimentary rocks are absent in the Inner zone, it is difficult to settle the age of the thrusting. It certainly took place before the Cretacous, as the continental red beds are never ductilely deformed nor metamorphozed. Nevertheless, a Triassic thrusting seems likely, but not documented yet. The interpretative cross section (Fig. 2), assumes that the metamorphic Inner zone rocks overthrust the weakly metamorphosed Triassic rocks of the Son La-Lai Chau zone. The Inner zone is divided into two tectonic units formed by sedimentary-magmatic series differing by their metamorphic grade.

2. 3.1. The Nam Co unit is represented by Neoproterozoic sandstone, pelite, and acidic tuffs metamorphosed under greenschist to lower amphibolite facies conditions. with a SW-ward increasing grade. Cambrian to Devonian terrigenous-carbonate rocks overlie the Precambrian terrigenous series. The metamorphic foliation, folded as a NW-SE anticline, called the “Song Ma anticlinorium” (Findlay, 1997; Findlay and Pham, 1997). Chlorite, biotite and garnet progressively appear from the NE to the SW in the Nam Co unit. Although we did not carry out thermo-barometric studies, the evolution of the metamorphic mineral assemblages qualitatively complies with pressure and temperature increase to the SW. Since in the micaschists, metasandstone, amphibolites, and metatuffs, the same planar and linear synmetamorphic microstructures are observed whatever the metamorphic grade, the simplest interpretation is to consider that these rocks experienced the same deformation event with changing P-T conditions. A N-S to NE-SW striking stretching lineation is well developed on the metamorphic foliation. Asymmetric quartz veins, pressure shadows, and shear bands show a top-to-the-NE shearing (Figs. 4E, F). The rocks of the Nam Co unit yields biotite, muscovite, and amphibole $^{40}Ar/^{39}Ar$ ages between 266-240 Ma

(Lepvrier et al., 2004, Table 1). These Middle Permian to Early Triassic ages indicate that, at this time, the Nam Co unit underwent a metamorphic temperature around 450°C-350°C, corresponding to the closure temperature of the analyzed minerals for the $^{40}Ar/^{39}Ar$ method. Since magmatic intrusions are not recognized in the Nam Co unit, the Middle Permian to Early Triassic time can be considered as the age of the syn-tectonic metamorphic event experienced by this unit.

2. 3.2. The high-pressure (HP) unit contains low temperature eclogites (Nakano et al., 2010; Zhang et al., 2013). East of Dien Bien, recrystallized marble, pelite, and amphibolite representing retrogressed HP rocks, are characterized by a N-S to NE-SW striking mineral and stretching lineation (Fig. 5C, D), intrafolial folds with axes parallel to the lineation, and top-to-the-NE shear criteria. Monazite from phengite-garnet-chloritoid micaschist, and zircon from eclogite yield chemical U-Th-Pb, and SHRIMP U-Pb ages at 243±4 Ma, and 230.5±8 Ma, respectively (Table 1). Both ages are interpreted as that of the HP event coeval with the SCB-Indochina collision (Nakano et al., 2010; Zhang et al., 2013).

2. 4. The Song Ma zone consists of chlorite-albite-epidote micaschists, mafic volcani-clastic rocks, and lenses of serpentinized peridotite, gabbro, plagiogranite, diabase, basalt, and limestone. Serpentinized lherzolitic harzburgite yields chromian spinel comparable to Tethyan ophiolites (Thanh et al., 2011). REE patterns of associated gabbro suggest a MORB affinity for this rock (Trung et al., 2006; Tran and Vu, 2011). These geochemical studies conclude that the mafic-ultramafic rocks that crop out in the Song Ma zone represent fore-arc ophiolites. A metabasalt has been dated at 254±12 Ma on zircon by LA-ICP-MS method (Pham et al., 2008).

SE of Song Ma city, the Chieng Kuong complex that consists of granite-granodiorite and plagiogranite massif received a lot of attention. The Chieng Kuong plagiogranite is dated by zircon LA-ICP-MS and U-Pb TIMS methods at 262±8 Ma, and 222±4 Ma (Pham et al., 2008; Nguyen et al., 2012). Moreover, a quartz-diorite (also placed in the “Chieng Kuong complex”), which exhibits subduction-related geochemical features, yields zircon LA-ICP-MS ages at 271±3 Ma (Liu et al., 2011). However, according to the GPS coodinates provided in Liu et al. (2011), and

Nguyen et al. (2012) papers, the dated samples were not picked up in the same place, and thus probably belong to petrologically distinct magmatic bodies. On the basis of geochemistry, the Chieng Kuong quartz-diorite studied by Liu et al. (2011) seems to belongs to the Sam Nua zone (cf below).

Several metagabbro and amphibolite analyzed by Sm-Nd method on whole rock-amphibole-pyroxene-titanite define isochrons ranging between 387±56 Ma and 313±32 Ma (Nguyen et al., 2012). Although these ages are considered as crystallization ages, the large error bars of these measures make their interpretation delicate.

In addition to the geochemical and geochronological insights, simple field observations of the lithological diversity: serpentinized peridotite, gabbro, mafic lava, mafic volcanic-sedimentary rocks, and siliceous mudstone, it is quite difficult to rule out the view that these rocks deposited in a deep marine basin underlain by an oceanic lithosphere. In agreement with most of authors, we interpret the rocks of the Song Ma zone as a highly sheared and metamorphozed ophiolitic suite (Hutchison, 1989; Findlay, 1997; Findlay and Pham, 1997; Lepvrier et al., 2004, 2008; Trung et al., 2006; Tran and Vu, 2011; Nguyen et al., 2012). Nevertheless, the magmatic age of these ophiolites remains loosely fixed yet (Table 2).

2. 5. The Sam Nua zone, to the South of the Song Ma zone, is characterized by a weakly deformed and unmetamorphozed Permian-Early Triassic sedimentary-volcanic series with andesite and dacite yielding a magmatic arc geochemical signature (Tran et al., 2008). This series overlies Paleozoic sedimentary rocks. Granodioritic, dioritic, and gabbro-dioritic plutons, including the Chieng Kuong quartz-diorite massif, are dated between 280±3 Ma and 247±3 Ma by U/Pb LA-ICP-MS method on zircon (Liu et al., 2012). These calc-alkaline plutons represent the deep part of a magmatic arc related to oceanic subduction.

2. 6. The Nam Su Lu unit, SE of Dien Bien, consists of biotite-sillimanite ±cordierite migmatite that encloses amphibolite and granulite restites (Nakano et al., 2008; Fig. 5E). The radial dip of the foliation suggests a dome structure. Monazite from metapelite yields a U-Th-Pb age of 233±5Ma interpreted as that of a high-temperature metamorphism (Nakano et al., 2008). Due to poor outcrop conditions, the structural relationships of the Nam Su Lu unit with the Sam Nua and Song Ma zones are unclear. In the interpretative cross section (Fig. 2), the Nam Su Lu migmatite is represented as a migmatitic dome superimposed on the Sam Nua arc.

2. 7. Tectonic interpretation of the NW Vietnam belt.

The Sam Nua, Song Ma, and Inner zones are intruded by undeformed granitic plutons (e.g. Song Ma, Dien Bien massifs) dated at ca. 230-200 Ma on zircon U-Pb by LA-ICP-MS method (Liu et al., 2011). Field observations show that the Dien Bien pluton is unconformably covered by subhorizontal, shallow water, marine sandstone and mudstone beds dated as Norian by ammonoids and molluscs (Tran and Vu, 2011).

The litho-tectonic units defined above can be interpreted in terms of geodynamic elements, hence the Sam Nua zone, and Nam Su Lu unit represent a Permian-Early Triassic magmatic arc. The location of the Nam Su Lu high temperature unit within the Sam Nua zone, and south of the Song Ma zone might suggest that the Nam Su Lu unit represents the deep part of the Sam Nua zone. The Song Ma zone is an ophiolitic nappe, or ophiolitic melange, overthrust to the North upon the Inner zone that represents sedimentary series deposited on a continental basement. The rocks of the HP unit experienced a deeper subduction, under ca 20-28kbar and 600-700°C (Nakano et al., 2010; Zhang et al., 2013), than those of the Nam Co unit. The Son La-Lai Chau zone can be interpreted as an outer orogenic domain with weakly to unmetamorphozed, but highly sheared, sedimentary series. Lastly the Po Sen-Hoa Binh zone is an outermost domain, also devoid of metamorphism, and moderately deformed.

In conclusion, the NW Vietnam belt appears as a typical collision orogen with a SW to NE tectonic polarity from: i) a volcanic and plutonic magmatic arc in the Sam Nua zone, ii) an ophiolitic suite in the Song Ma zone, iii) a highly deformed and metamorphosed inner domain formed during the subduction of sedimentary rocks deposited upon a continental crust, iv) a weakly to unmetamorphozed, but ductilely deformed, domain in the Son La-Lai Chau and Po Sen-Hoa Binh zones, representing the orogen outer domain. The Late Triassic granitoids are post-orogenic stitching plutons. The structural data unambiguously indicate NE-directed nappe stacking. The available stratigraphic data support a Middle Triassic deformation age. Biotite, muscovite and amphibole $^{40}Ar/^{39}Ar$, and monazite U-Pb ages support the existence of a tectonic-thermal event between 250 Ma and 230 Ma (Table 2). The Sam Nua magmatic arc, and the SW to NE increase in metamorphism and deformation suggest that subduction was dipping to the SW. The boundary between the Sam Nua and the Song Ma zones represents the Song Ma suture (Figs. 1, 2). However, it is worth noting that in contrast to many orogens, a large foreland molassic basin is lacking in the NE Vietnam belt. One possible explanation of this absence would be to consider that the missing molassic basin has been smeared by the RRF shearing during the Cenozoic.

3. The NE Vietnam belt

NE of the RRF, is another orogenic belt that extends to the Chinese provinces of Yunnan and Guangxi (Figs. 1, 2, 3). As its bulk architecture has been recently reassessed (Lepvrier et al., 2011), only the main features are summarized here. From NE to SW, several tectonic zones stacked to the North or NE are recognized.

3. 1. The outer zone is dominated by a Middle Triassic turbiditic series (Fig. 7A), with locally interbedded acidic lava flows and tuffs. Our observations near Cao Bang, in NE Vietnam, show that the alkaline mafic rocks are olistoliths reworked in the turbidite (Fig. 8B, C, D). Immediately to the North, in Guangxi and Yunnan provinces, these turbidites form a large sedimentary basin know as the Nanpanjiang or Yujiang basin (e.g. Guangxi BGMR, 1985; Galfetti et al., 2008) deposited upon the Devonian-Carboniferous-Permian-Early Triassic carbonate platform that extended widely in South China. In NE Vietnam, the existence of Late Permian bauxite deposits indicate an emergent episode before the deposition of Middle Triassic turbidite (Tran and Vu, 2011). The Devonian formations unconformably cover Early Paleozoic rocks deformed by south-verging folds belonging to the Early Paleozoic orogen of the South China block (Lin et al., 2008; Faure et al., 2009; Charvet et al., 2010; Li et al., 2010). In NE Vietnam, a North-directed decollement with drag folds, and NE-SW striking lineation, develops at the base of the Triassic turbidite (Fig. 7E). Due to the decollement, the Carboniferous-Early Triassic series may be absent, thus the Triassic turbidite tectonically directly overlies the Devonian limestone series. This Outer zone is overthrust by the NE Vietnam nappe.

3. 2. The NE Vietnam nappe consists of several units of ductilely deformed and metamorphosed Paleozoic rocks transported to the North (for details see Lepvrier et al., 2011). This nappe includes the Silurian Song Chay porphyritic monzogranite (Roger et al., 2000; Yan et al., 2006) now changed into orthogneiss by a Triassic top-to-the-N ductile shearing, which represents a post-orogenic pluton emplaced at the end of the Early Paleozoic orogeny of S. China. The Song Chay orthogneiss does not represent a Cenozoic metamorphic core complex as previously proposed (Maluski et al., 2001; Yan et al., 2006) as the detachment fault is missing.

The country rock of the Song Chay orthogneiss includes marble, quartzite, and metapelite with biotite and muscovite yielding $^{40}Ar/^{39}Ar$ ages around 236 and 234 Ma (Maluski et al., 2001). A monazite U-Th-Pb age of 246±8 Ma has been obtained from a micaschist to the East of the orthogneiss (Gilley et al., 2003). SE of the Song Chay orthogneiss, a biotite-garnet-staurolite micaschist (GPS: 22° 21.405N, 104° 29.245E) yielded monazite that has been dated by the U-Th-Pb chemical method (Suzuki and Adachi, 1991; Cocherie et al., 1991; Suzuki and Kato, 2008; Bé Mézème et al., 2006). As monazite grains occur in textural equilibrium with the main metamorphic minerals in the micaschist matrix, it is likely that they crystallized during the same metamorphic event. In back-scattered electron mode, the dated grains, of ca 200µm size, have a sub-euhedral shape with patchy zoning (Fig. 8A). The lack of inherited core in the monazite grains argue for a crystallization time coeval with the regional metamorphism. Therefore, the average age, calculated from 67 measurements, at 246±10 Ma can be considered as that of the regional synkinematic metamorphism (Fig. 8B). The Tertiary ages measured in the orthogneiss and its country rocks represent the final uplift of the massif.

3. 3. The Song Chay ophiolitic mélange is a discontinuous unit formed by m- to km-scale blocks of serpentinite, mafic rocks (gabbro, plagiogranite, volcanite), limestone, and chert enclosed in a highly sheared sandstone-mudstone matrix (Fig. 9A-F). These rocks differ significantly from the surrounding Paleozoic formations dominated by carbonates, and their "broken" aspect results both in a chaotic sedimentation and a tectonic overprint. Due to the intense shearing, the age of this unit is unknown yet, but it cannot be younger than Early Neogene as conglomerate of this age unconformably covers the Song Chay ophiolitic mélange (Lepvrier et al., 2011).

3. 4. The Day Nui Con Voi unit consists of high temperature metamorphic rocks. In spite of the Cenozoic deformation and metamorphism (Leloup et al., 1995; Viola and Anczkiewicz, 2008; Yeh et al., 2008), the protoliths of the Day Nui Con Voi preserve numerous masses of gabbro, diorite, and granodiorite generally foliated and boudinaged during the Cenozoic deformation along the RRF (Fig. 7F). Some of these alkaline and calc-alkaline plutons yield zircon U-Pb SHRIMP ages between 263 and 240 Ma, which are considered as the protolith ages (Zelaznievicz et al., 2012). The country rock of these plutons consists of biotite-garnet-sillimanite micaschist of Cenozoic age. In these rocks, garnet contains monazite inclusions dated at 225-230 Ma (Gilley et al., 2003). Hence, these inclusions argue for a Triassic tectono-metamorphic event in the Dai Nui Con Voi unit.

3.5. Plutonic events. In addition to the Song Chay orthogneiss, two groups of granitoid bodies crop out in the NE Vietnam belt. The 235-210 Ma undeformed meta-aluminous biotite granite (Table 1, Roger et al., 2000, 2012; Maluski et al., 2001; Yan et al., 2006; Chen et al. in press) form post-orogenic plutons. The second group consists of quartz syenite, norite, and alkaline gabbro, foliated and lineated in accordance with their country rocks. These rocks, dated around 250-246 Ma by

SIMS and LA-ICP-MS U-Pb methods on zircon (Tran et al., 2008a; Chen et al., in press), and their alkaline geochemistry, are compatible with pre-orogenic plutons emplaced rather in an intraplate setting than in a magmatic arc (Tran et al., 2008b; cf. Discussion section below).

3.6. Tectonic interpretation of the NE Vietnam belt. The tectonic zones of the NE Vietnam belt are interpreted in terms of geodynamic domains. In spite of lack of geochemical constraints, the Day Nui Con Voi unit is tentatively considered as a magmatic arc. In agreement with Lepvrier et al., (2011), a Triassic age is assumed for the Song Chay ophiolitic melange. The Song Chay fault that forms the boundary between the Song Chay ophiolitic melange, and the Day Nui Con Voi unit is an ophiolitic suture. The NE Vietnam nappe represents elements of the SCB folded and thrust to the N-NE before the Late Triassic regional unconformity (Deprat, 1915; Bourret, 1922; Tran and Vu, 2011).

Therefore, the NE Vietnam belt can also be viewed as a collision orogen with a SW-to-NE polarity. The Middle Triassic syntectonic turbiditic sedimentation, the synkinematic metamorphism, and the post-orogenic plutonism support an Early Mesozoic age for the NE Vietnam belt. The top-to-the-North nappe displacement and the possible arc magmatism in the Day Nui Con Voi unit comply with a South-directed subduction.

4. Discussion

4. 1. Ophiolites or intraplate basalts for the Song Da and Babu mafic rocks?

In the NW Vietnam belt, the Late Permian Song Da rocks are acknowledged as intraplate magmas correlated with the Emeishan basalts of SW China (Hanski et al., 2004, Ali et al., 2005), these rocks are not ophiolites, thus the Song Da zone is not a suture. In NE Vietnam, Yunnan, and Guangxi Provinces, Permian gabbro, pillow basalts, and mafic dykes have been interpreted as the "Babu ophiolites" (Zhong et al., 1999, Wu et al., 1999; Cai and Zhang, 2009). The reality of the Babu ophiolites is a crucial point for the understanding of the SCB-Indochina connection. The geochemical analyses of the Babu mafic rocks plot in a large range of composition from calc-alkaline basalts to oceanic island alkaline basalts, through island arc tholeiite, MORB, and oceanic island tholeiite (Cai and Zhang, 2009). From such a wide data scattering, an unequivocal conclusion cannot be reached. Other geochemical analyses argue for intraplate basalts (Fan et al., 2008). Zircon SHRIMP age at 250±5 Ma, and the alkaline geochemical signature of these basalts support a correlation with the Emeishan flood basalts (Fan et al., 2008).

Moreover, the typical ophiolitic rock assemblage cannot be recognized in the Babu rocks, since serpentinites are very rare or even absent in Guangxi province (Guangxi BGMG, 1985). Early Permian radiolarian have been described in siliceous mudstone underlying the mafic rocks (Feng and Liu, 2002). This observation shows that a deep marine basin preceded the emplacement of the lava flows, but it does not demonstrate the existence of an oceanic lithosphere during the Late Permian. In the field, the mafic rocks are exposed in the core of anticlines, and not as large allochthonous thrust sheets as it would be expected for an ophiolitic nappe. Late Permian bauxite deposits that crop out in NE Vietnam and SW Guangxi provinces argue for land exposure coeval with magma emplacement. The bauxite yielded detrital zircons, dated at 261-256 Ma by SHRIMP method. Since these zircons exhibit geochemical features similar to those of zircons from the Emeishan-type intraplate basalts (Deng et al., 2010), in Late Permian, the alkaline mafic rocks were exposed and altered in a continental environment. Sedimentological studies demonstrated that the emplacement of the Emeishan plume induced a ca 500 km wide crustal dome responsible for progressive emergence, and changes in the sedimentary environnement from deep marine, shallow marine, to continental (He et al., 2003). In SW Guangxi province, near Baise and Bama, we observed a thermal contact metamorphism developed in the Late Paleozoic platform limestone host rocks around the Permian gabbro intrusions. These petrological features do not comply with mafic intrusions emplaced in the floor of a deep ocean basin.

The petrological, structural, and sedimentological lines of evidence presented above suggest that the Babu Late Permian mafic rocks, alike the Song Da ones,b do not represent an ophiolitic suite. Conversely, the bimodal character and the alkaline geochemical signature of the mafic rocks, and the surrounding sedimentary rocks do not support a deep oceanic setting, but rather argue for an an intraplate setting, coeval with the Emeishan plume (Poliakov et al., 1999; Ali et al., 2005; Tran et al., 2008a, Fan et al., 2008).

4. 2. Paleogeographic evidence for Indochina-South China connection up to Middle Carboniferous?

Early and Middle Devonian deposits in North and Central Vietnam are characterized by shallow water deltaic to continental facies whereas Late Devonian rocks are dominated by carbonate platform facies. These formations were deposited in a passive continental margin (Tran and Vu, 2011; Thanh et al., 2012). Since the faunal assemblages show close affinities with Devonian fossils of Yunnan and Guangxi provinces of S. China, it has been argued that SCB and Indochina were welded together in the Devonian (Janvier et al., 1989, 1996, 1997; Than et al., 1996; Racheboeuf et al., 2005, 2006). More precisely, Middle Devonian (Emsian) to Late Devonian (Frasnian) terrigenous formations, yielding endemic placoderm fish fossils have been reported in each of the three tectonic domains discussed here, namely: i) in the Outer zone NE Vietnam belt, (Do Son formation, near Hai Phong); ii) South of the Black River (i. e. Song Da), in the Po Sen-Hoa Binh zone, and iii) South of the Song Ma suture, near cape Ly Hoa, in the southeastern extension of the Sam Nua zone (Janvier et al., 1989, 1996, 1997; Than et al., 1996; Racheboeuf et al., 2005, 2006). The paleogeography is consistent with the common view that NE Vietnam is part of SCB. The Black River and Ly Hoa sites supports the view that, from Emsian to Frasnian, Indochina, or at least the continental mass immediately South of the Song Ma suture, was connected to South China.

Some authors (e. g. Helmcke 1985; Hutchison 1989; Metcalfe 1996, 2002, 2013) proposed that Indochina and South China amalgamation took place in Early Carboniferous (Visean, ca 340 Ma). This view is supported by the occurrence in Central Thailand, near Loei, of Visean terrigenous series of conglomerate, sandstone, shale, and coal measures, containing Peripteris ferns fossils with Eurasian affinities (Laveine et al., 2003). The occurrence of the Peripteris flora in

Indochina implies that this block was close to South China, as documented by similar flora in nearby Guangdong province, as well as other places in Eurasia (Laveine et al., 1993).

Nevertheless, paleontological evidence that Indochina and SCB were in contact in the Devonian-Early Carboniferous does not exclude the possibility that an oceanic domain might have separated Indochina and SCB during the Late Carboniferous and Permian. Indeed, two groups of ages are presently available for the Song Ma ophiolites (Table 2): 1) Middle to Late Carboniferous, ca 350 Ma to 300 Ma, Sm-Nd ages considered as crystallization ages of the gabbro (Nguyen et al., 2012), and 2) Middle to Late Permian, ca 270 Ma to 250 Ma, zircon U-Pb ages that could be interpreted either as magmatic crystallization or as metamorphic recrystallization ages (Pham et al., 2008; Nguyen et al., 2012). In the present state of knowledge, it is difficult to decide which interpretation is correct since detail petrological discussion, and cathodoluminescence images of the dated grains are not provided. Whatever the right interpretation about the time of opening of the oceanic domain that separated Indochina and SCB, this basin was probably a narrow one, since it lasted around 100Ma, closed in Early to Middle Triassic by a South-directed subduction.

4. 3. Middle Triassic collision and N-directed thrusting.

All authors acknowledge a Triassic tectonic-metamorphic event in North Vietnam, but its geodynamic significance is disputed. Instead of collision tectonics, the Middle Triassic event is sometimes considered as the result of strike slip tectonics due to a far-field collision between the already welded Indochina-SCB mass and the Qiangtang-Sibumasu block (e.g. Carter et al., 2001; Carter and Clift, 2008). However, it is now demonstrated by detail radiolarian biostratigraphic studies of the deep sea sediments that the final collision between Sibumasu and Indochina occurred in Late Triassic-Early Jurassic (Sone and Metcalfe, 2008, Metcalfe, 2013). This collision is thus younger than the Early Triassic-early Middle Triassic North Vietnamese event. It was preceded by the closure of a back-arc basin separating the Sukhotai arc and the Indochina block (Sone and Metcalfe, 2008), but such a collision is unlikely to induce a far-field continental-scale deformation as that recognized in North Vietnam. Indeed, Middle Triassic dextral strike slip deformation do exist South of the Song Ma suture in the Sam Nua magmatic arc, and Truong Son belt (Lepvrier et al., 1997, 2008). Nevertheless, both in NE and NW Vietnam belts, the dominant fabric is a low angle foliation, and a nearly down dip, NE-SW striking stretching lineation. These structural elements support thrust rather than strike-slip tectonics.

In a microstructural study of the Song Ma anticlinorium, (i. e. our Song Ma zone and Inner zone Nam Co unit), Findlay (1997), and Findlay and Pham (1997) argued that the Song Ma anticlinorium was not a Triassic subduction zone, but an allochthonous terrane accreted to the South China block in Silurian-Devonian times. This statement can be commented on two ways. Firstly, the Paleozoic age of the deformation was based on the observation near Hoa Binh that unmetamorphozed Cambrian series (Dien Lu formation) crop out immediately North of metamorphic rocks attributed to the SCB. However, as already acknowledged by the authors, a brittle fault bounds the metamorphic and sedimentary rocks, thus an unconformity cannot be documented there. Furthermore, our observations near Hoa Binh show that pre-Late Triassic upright folds deform the entire sedimentary series up to the Middle Triassic rocks. Secondly, the age of the synmetamorphic deformation was assumed as Middle Silurian on the basis of a K-Ar age at 425 Ma although details on the dated minerals, rock-type, mineral assemblages, and analytical conditions were not provided. It is worth noting that $^{40}Ar/^{39}Ar$ dating on biotite, muscovite, and amphibole from the Song Ma zone, and the Nam Co unit in the same area as that of Findlay (1997), yielded Permian-Triassic (266-240 Ma) ages (Lepvrier et al., 1997, 2004). Thus, a Silurian-Devonian age for the ductile deformation, and the age of the collision cannot be substantiated.

Another argument put forward against a Triassic orogeny is the lack of large molassic basins (Carter and Clift, 2008). It is right that thick terrigenous deposits of Late Triassic age are absent in the NW Vietnam belt. There, only limited patches of coarse grain sandstone and conglomerate unconformably overlying folded rocks argue for a Middle Triassic deformation. This remark does not apply anymore for the NE Vietnam belt, where a large Middle Triassic terrigenous (Nanpanjiang) basin developed in the Outer zone. Our observations west and south of

Cao Bang (see also Lepvrier et al., 2011) show that sandstone-coarsening direction is to the South. Moreover, gravity-driven chaotic sedimentation with slumps deposits, pebbly mudstones, and Paleozoic olistoliths are more abundant to the SW than to the NE of the basin suggesting a southern provenance of the detritus. Therefore, the statement that there is no evidence in NE Vietnam to support significant erosion of an uplifted mountainous terrain during the Late Triassic is not in agreement with field observations.

In summary, the two North Vietnam orogens are both characterized by N-directed nappes. As in most of collision orogens, crustal staking developed mainly at the expense of sedimentary rocks deposited above the continental crust of the lower plate. The Song Ma zone and Song Chay ophiolitic melange, are ophiolitic sutures representing plate boundaries. In each belt, stratigraphic constraints argue for a pre-Late Triassic deformation. Both in the inner zone (Nam Co and HP units) of the NW Vietnam belt, and in the NE Vietnam nappe, biotite, muscovite, and amphibole, $^{40}Ar/^{39}Ar$, monazite U-Th-Pb, and zircon U-Pb ages argue for synmetamorphic tectonics around 250 and 220 Ma (Table 2). In both belts, the deformation style evolves from deep-seated syn-metamorphic structures in the SW, to shallow synsedimentary ones in the NE. Hence, Triassic stratigraphic record, and metamorphic dates, Permian magmatic arc, intense ductile shearing of the Devonian series do not support a pre-Devonian age for the collision neither in NW nor NE belts, though paleontology supports a pre-Visean connection between Indochina and SCB. A southward subduction accounts well for arc magmatism and polarity of nappe stacking. The tentative geodynamic evolution model (Fig. 10) aims to emphasize the similar features observed in the NE and NW Vietnam belts. Both belts can be interpreted as the result of a continental collision preceded by an oceanic subduction. It is worth noting that in the NW Vietnam belt, the Early Paleozoic (pre-Devonian) orogen of S. China is absent. An explanation for this peculiar feature is proposed below.

4. 4. One or two Triassic sutures?

The striking lithological, structural, and chronological similarities of NW and NE Vietnam belts raise the question of their relationships. Presently, the two belts form two distinct structures. A simple geodynamic model with two S-dipping subduction zones and an intermediate microcontinent represented by the Po Sen-Hoa Binh and Son La-Lai Chau zones might be suggested if a limited displacement along the RRF is assumed. However, such a model does not account well for the two contemporaneous Late Permian intraplate magmatism observed in the Song Da-Tu Lê, and in the Emeishan-Babu areas. Furthermore, if two south-directed subduction zones are considered, the intermediate microcontinental domain, appears as a very narrow (ca 100 km) continental slither. Therefore, another interpretation of the two North Vietnam belts as parts of a single orogen dismembered by Cenozoic wrenching along the RRF is explored below.

In NW Yunnan, the Middle Triassic Jinshajiang suture is the first plate boundary encountered at the western margin of the SCB (e.g. Wang et al., 2003, Fig 11). To the south, this suture is interrupted by the RRF near Weixi (1 in Fig. 11). The Song Chay suture is also the first plate boundary cropping out in the SW margin of the SCB, as the Babu rocks cannot be considered as an ophiolitic suture. Both sutures are located on the northern side of the RRF. A correlation between these two sutures is attractive but the intermediate segment is missing. West of the Dien Bien fault, the Song Ma suture ends in Mojiang (1' in Fig. 11). Considering the left-lateral offset along the RRF, a pre-Tertiary reconstruction placing the Song Ma suture between the Jinshajiang and Song Chay sutures would fill the gap between the two segments. This reconstruction requires about 600-700 km of displacement along the RRF, which corresponds to some geological estimates (Leloup et al., 1995; 2007; Royden et al., 2008), also in agreement with paleomagnetism (e.g. Otofuji et al., 2012 and references therein) that document 570±270 km of displacement, but exceeds the recently proposed 250 km (Van Hinsberger et al., 2011; Mazur et al., 2012). However, as the exact finite offset along the RRF remains disputed (cf. Searle et al., 2006; Leloup et al., 2007, and enclosed references), this tentative reconstruction might help to set the question.

Assuming a single and continuous suture, the SCB-Indochina collision can be simply depicted as the result of the Middle Triassic closure of a branch of the Paleo-Tethys ocean, followed by southward continental subduction of the SCB below the Indochina-Qiangtang block (Fig. 12). The single suture model accounts better for the distribution of the intraplate Late Permian Emeishan-Song Da magmatism that have been confined to the SCB plate only. As pointed out by Janvier et al., (1996), the Devonian faunal assemblage of the Po Sen-Hoa Binh zone is more similar to that of Yunnan province than that of Central Vietnam representative of the Indochina block. Thus, the paleontological comparison complies well with the tectonic conclusion that before the Cenozoic, the Po Sen-Hoa Binh and Son La-Lai Chau zones were probably located more to the NW than at present. Lastly, at variance with the NE Vietnam belt, in the NW Vietnam one, the Early Paleozoic orogen is missing. This difference between two two belts can be explained when considering that this intracontinental belt develops only in the southeastern part of the SCB, and never existed elsewhere.

In conclusion, field based observations in North Vietnam allows us to answer the questions asked in the introduction. We conclude that:. 1) The Song Ma zone and Song Chay ophiolitic melange represent two sutures zones, and that based on the available data there is no support of the Song Da and Babu mafic rocks being part of an ophiolite assemblage. 2) Stratigraphy, and radiometric dates of the plutonic and metamorphic rocks argue for a Middle Triassic age for the SCB-Indochina collision, rather than for a Paleozoic one. 3) North to NE-directed thrusts that characterize both the NW and NE Vietnam belts comply with a south-dipping subduction, in agreement with the southern position of the magmatic arcs. Lastly, lithological, structural, and chronological resemblances between the NW and NE Vietnam belts allow us to suggest that they might in fact belong to the same orogen duplicated by the left-lateral Cenozoic Red River Fault.

Acknowledgements

This cooperative study has been funded by the French CNRS and the universities of Orléans, and Paris VI for MF and CL, respectively, Hanoi University of Sciences for NVV and VVT, and Chinese Academy of Sciences for WL and ZC. Y. Chen, M. Vidal, F. Choulet, Andrew Carter, and an anonymous reviewer are deeply acknowledged for their constructive comments and suggestions to improve the manuscript.

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Figure captions

Fig. 1. Tectonic map of North Vietnam showing, on both sides of the Red River Fault (RRF), the two N-directed Triassic belts in NW and NE Vietnam, respectively. Pz arc refers to the Paleozoic arc rocks in the Sam Nua zone. DNCV: Dai Nui Con Voi; HB: Hoa Binh, SL: Son La, TG: Tong Giao, DB: Dien Bien, LC: Lao Cai, F: Fan Si Pan, CB: Cao Bang; DBF: Dien Bien Fault. Insert shows the location of the NE and NW Vietnam belts, on both sides of the Red River Fault (RRF).

Fig. 2. Crustal-scale cross section of northern Vietnam (located in Fig. 1). In the present geometry, the NW and NE belts are both Middle Triassic orogens formed by collision of Indochina and a “North Vietnam” continental block, and Dai Nuy Con Voy (DNCV) and South China Block, respectively. Depending on the amount of sinistral offset along the RRF, these two belts can be correlated or not (see text for discussion).

Fig. 3. Synthetic lithostratigraphic log of each litho-tectonic zone described in the text showing the dominant rock types, the main olistoliths or tectonic block in the Son La-Lai Chau and outer zone, and Song Ma zone and Song Chay ophiolitic melange, respectively. The main plutonic types are also represented: Silurian Song Chay granite (now changed into Triassic orthogneiss), syenite/gabbro intraplate plutons, gabbro/tonalite and ganite/granodiorite plutons corresponding to magmatic arcs, and Late Triassic post-orogenic plutons. Pt: Proterozoic basement, Pz1: Early Paleozoic, D: Devonian, C: Carboniferous, P: Permian, T1: Early Triassic, T2: Middle Triassic, T3: Late Triassic, K: Cretaceous continental red beds in Po Sen-Hoa Binh and Son La-Lai Chau zones, E: Neogene. Note that in the Outer zone and the NE Vietnam nappe of the NE Vietnam orogen, the Early Paleozoic series experienced a pre-Devonian orogeny.

Fig. 4. Field pictures of NW Vietnam belt. A: undeformed and unmetamorphozed Devonian limestone forming the sedimentary cover of the Po Sen-Hoa Binh zone. B: Chaotic formation with limestone lenses in a redish brown pelitic matrixof Late Permian- Early Triassic age (Co Noi formation) in the Song Da rift of the Son La-Lai Chau zone. C: Intrafolial fold with N-S striking axis coeval with top-to-the-N shearing (near Ta Khoa). D: Top-to-the-E shearing, indicated by arrow, of dolomitic layers in Middle Triassic limestone (N. of Dien Bien). E: Sigmoidal quartz vein in micaschist indicating top-to-the-NE shearing, shown by arrow. The foliation dips NE as it belongs to the northeastern limb of the Nam Co antiform (S. of Son La). F: well developped stretching lineation (L1) in micaschist in the southern limb of the Nam Co antiform (S. of Son La).

Fig. 5. Field pictures of ductile deformation structures in the NW Vietnam belt. A: upright NW-SE striking fold in Early Triassic mudstone (East of Son La). B: elongated vesicle in mafic lava showing the NE-SW L1 stretching lineation (NE of Son La). C: N-S L1 mineral and stretching lineation in phengite marble SW of Dien Bien. D: boudinaged mafic layers in marbles indicating a N-S stretching. E: Nam Su Lu migmatite with mafic restites.

Fig. 6. Evidence for polyphase deformation in the Son La- Lai Chau zone, North of Son La. The steeply dipping beds (S0) in Early Triassic sandstone form the southern limb of an upright fold. In its present situation, the North-dipping, low-angle cleavage (S1) is incompatible with an upright fold. If the beds are restaured to their initial flat lying attitude, the S0-S1 relationships, and the statigraphic polarity comply with a Northern vergence which is in agreemnt with a top-to-the NE ductile shearing observed in the mafic rocks to the NE.

Fig. 7. Field pictures of the NE Vietnam belt. A: Middle Triassic turbidite. B: Permian olistolith in the turbidite. C: General wiew of a Middle Triassic turbidite outcrop showing limestone olistoliths (white) and mafic rocks (dark). D: Detail of a Late Permian alkaline pillow basalt olistolith. Pictures A to D are from the N. of Cao Bang. E: Folded top-to-the-N Triassic decollement separating the overlying folded Middle Triassic turbidite from the underlying undeformed Devonian limestone (W. of Cao Bang). F: Diorite and gabbro boudins in the Day Nui Con Voi. The deformation developed during the Cenozoic shearing coeval with the Red River Fault. The mafic protoliths, dated of Permian to Triassic are interpreted here as formed in a magmatic arc (Near Fo Rang).

Fig. 8. Monazite U-Th-Pb chemical dating of a biotite-garnet-staurolite miscaschist in the inner part of the Song Chay nappe, SE of the Song Chay orthogneiss (GPS 22° 21.405N, 104° 29.245E). A: Back scattered electron image of representative monazite grain. B: average age of 246±10 Ma calculated from 67 measurements.

Fig. 9. Field pictures of the Song Chay ophiolitic mélange. A: General wiew of a block-in-matrix outcrop showing limestone blocks enclosed in a schistose mudstone-siltstone matrix. B: Exposure of a pluri-metrer scale serpentinized peridotite. The top of the hill consists of limestone block. C: Detail view of serpentinized peridotite surrounded by schistose black mudstone. D: Example of

coloured melange with red chert, white recrystallized limestone, greenish tuffaceous acidic volcanite, and siliceous mudstone. E: Sheared black mudstone matrix enclosing variously sized sandstone and limestone blocks. F: detail of serpentinite with a plagiogranite mass.

Fig. 10. Tentative geodynamic evolution model of the NE and NW Vietnam belts emphasizing the similar tectonic features in each belt. Tectonic elements are written in plain and italic letters for the NE and NW belts, respectively. Both belts can be interpreted as the result of continental collision. Note that in the NW Vietnam belt, the Early Paleozoic (pre-Devonian) orogen of S. China is absent (see text and Fig. 12 for discussion).

Fig. 11. Tectonic sketch of SE Asia showing the Jinshajiang Triassic suture (JSJS) and its possible correlations with the Song Ma suture (SMS) and Song Chay suture (SCS). Points 1 (Weixi) and 1' (Mojiang) and 2 and 2' are equivalent, but displaced by the sinistral motion along the Red River Fault (RRF). The NW Vietnam belt, between points 1' and 2', is the missing segment between points 1 and 2. The Late Permian Song Da intraplate basalts are equivalent to the Emeishan and Babu mafic rocks. BNS: Bangong-Nujiang suture.

Fig. 12. Late Permian-Early Triassic paleogeodynamic reconstruction of the Indochina- South China-East Tibet area showing a possible continuity of the Indochina and Qiangtang continents, and the Vietnamese Day Nui Con Voi and Sam Nua arcs overlying a S-directed subduction zone before the Middle Triassic closure of the northern branch of the Palaeo-Tethys Ocean. The Emeishan-Song Da intraplate magmatism develops only in the Southwestern part of the South China block. Double arrows in South China show the general strike of the Early Paleozoic orogen of South China, which is an intracontinental belt developed only in the southeastern part of the South China block.

Table 1. Radiometric ages of the N. Vietnam orogens. Locations are shown in Fig. 1

Table 2. Synoptic view of the radiometric constraints available for each zone. S, D, C, P1, P2, P3, T1, T2, and T3 correspond to Silurian, Devonian, Carboniferous, Early Permian, Middle Permian, Late Permian, Early Triassic, Middle Triassic, and Late Triassic, respectively. The absolute ages of the stratigraphy are from Gradstein et al. (2004). Numbers refer to Table 1

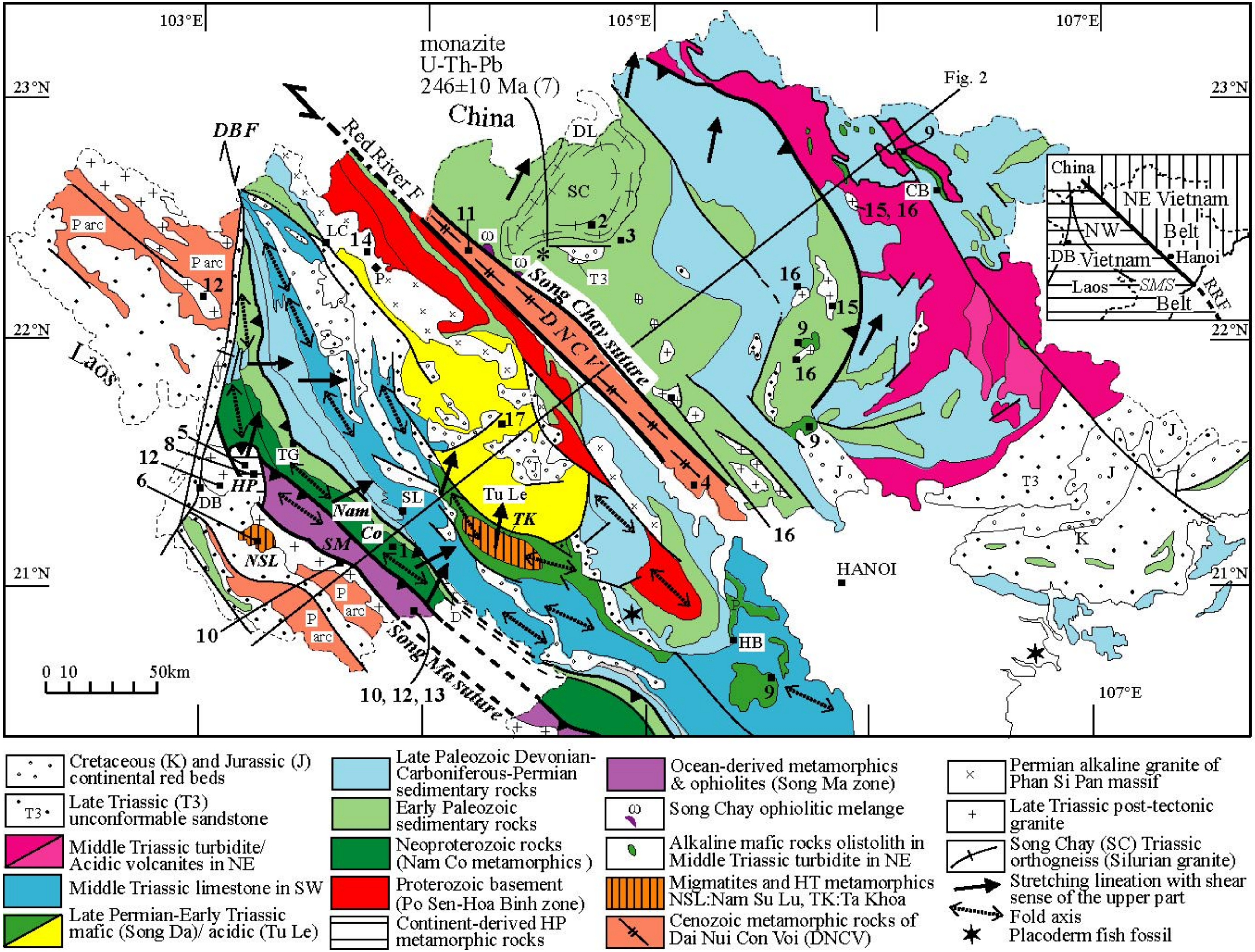

103°E
105°E
107°E
23°N
22°N
21°N
monazite
U-Th-Pb
246±10 Ma (7)
China
Laos
Red River F
DBF
Song Chay suture
DNCV
Song Ma suture
Fig. 2
HANOI
Tu Le
TK
Nam
Co
SM
NSL
HP
TG
SL
LC
DB
DL
SC
CB
HB
P arc
T3
J
K
0 10 50km
China
NE Vietnam
NW
Belt
DB Vietnam
Hanoi
Laos
SMS
Belt
RRF
Cretaceous (K) and Jurassic (J) continental red beds
Late Triassic (T3) unconformable sandstone
Middle Triassic turbidite/ Acidic volcanites in NE
Middle Triassic limestone in SW
Late Permian-Early Triassic mafic (Song Da)/ acidic (Tu Le)
Late Paleozoic Devonian-Carboniferous-Permian sedimentary rocks
Early Paleozoic sedimentary rocks
Neoproterozoic rocks (Nam Co metamorphics)
Proterozoic basement (Po Sen-Hoa Binh zone)
Continent-derived HP metamorphic rocks
Ocean-derived metamorphics & ophiolites (Song Ma zone)
Song Chay ophiolitic melange
Alkaline mafic rocks olistolith in Middle Triassic turbidite in NE
Migmatites and HT metamorphics NSL:Nam Su Lu, TK:Ta Khoa
Cenozoic metamorphic rocks of Dai Nui Con Voi (DNCV)
Permian alkaline granite of Phan Si Pan massif
Late Triassic post-tectonic granite
Song Chay (SC) Triassic orthogneiss (Silurian granite)
Stretching lineation with shear sense of the upper part
Fold axis
Placoderm fish fossil

Fig. 1

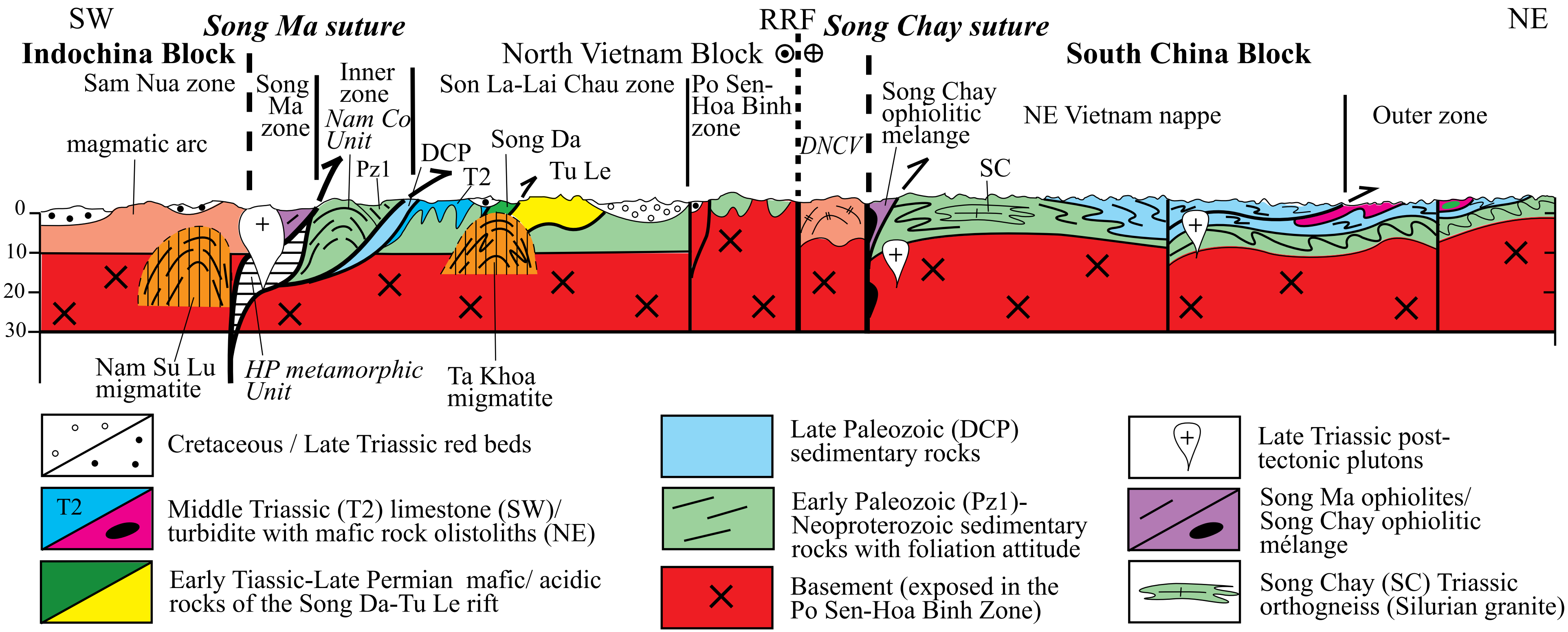

SW
Song Ma suture
Indochina Block
Sam Nua zone
Song Ma zone
Inner zone
Nam Co Unit
magmatic arc
Pz1
DCP
T2
Song Da
Tu Le
North Vietnam Block
Son La-Lai Chau zone
Po Sen-Hoa Binh zone
RRF
DNCV
Song Chay suture
Song Chay ophiolitic melange
SC
South China Block
NE Vietnam nappe
Outer zone
NE
0
10
20
30
Nam Su Lu migmatite
HP metamorphic Unit
Ta Khoa migmatite
Cretaceous / Late Triassic red beds
T2
Middle Triassic (T2) limestone (SW)/ turbidite with mafic rock olistoliths (NE)
Early Tiassic-Late Permian mafic/ acidic rocks of the Song Da-Tu Le rift
Late Paleozoic (DCP) sedimentary rocks
Early Paleozoic (Pz1)-Neoproterozoic sedimentary rocks with foliation attitude
Basement (exposed in the Po Sen-Hoa Binh Zone)
Late Triassic post-tectonic plutons
Song Ma ophiolites/ Song Chay ophiolitic mélange
Song Chay (SC) Triassic orthogneiss (Silurian granite)

Fig. 2

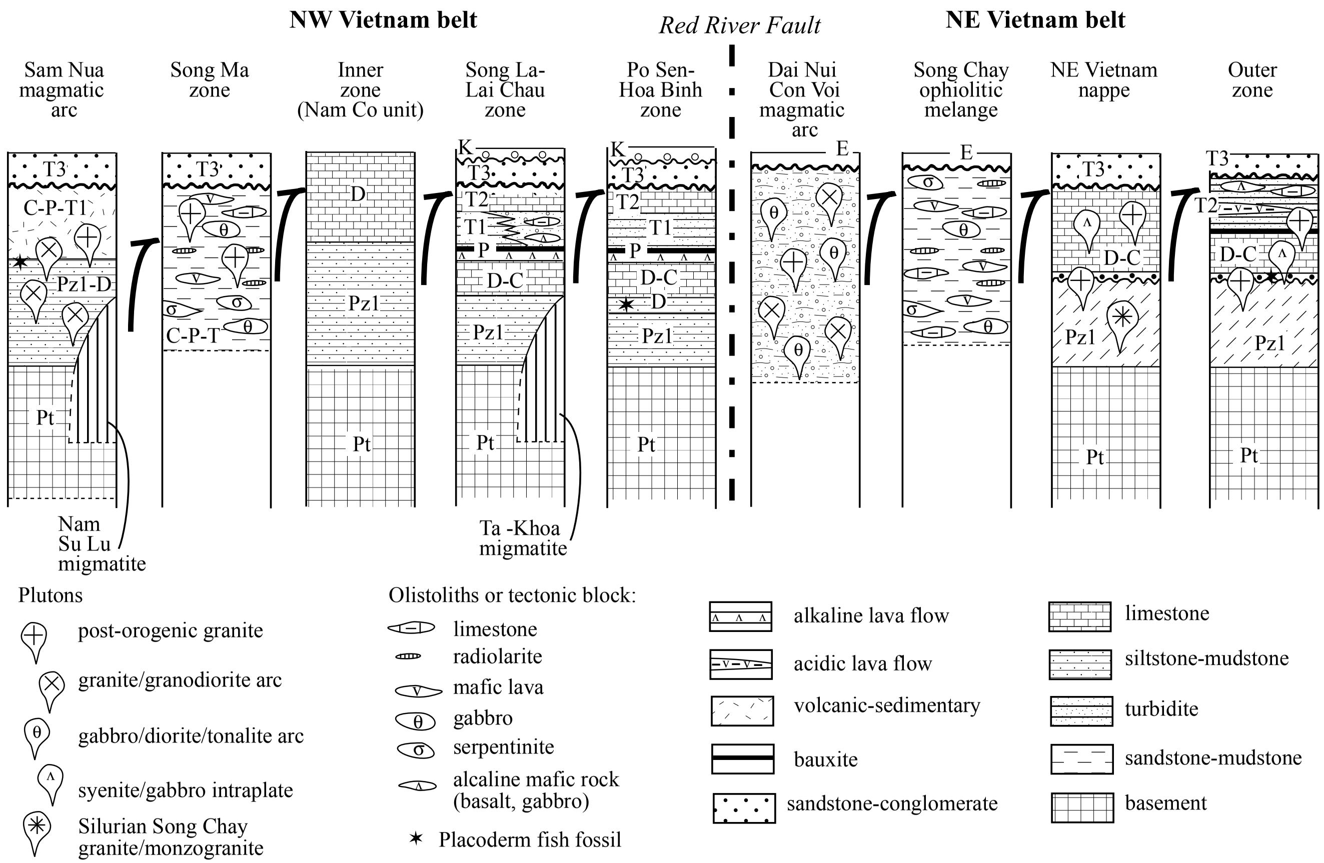

NW Vietnam belt
Red River Fault
NE Vietnam belt
Sam Nua magmatic arc
Song Ma zone
Inner zone (Nam Co unit)
Song La-Lai Chau zone
Po Sen-Hoa Binh zone
Dai Nui Con Voi magmatic arc
Song Chay ophiolitic melange
NE Vietnam nappe
Outer zone
T3
C-P-T1
Pz1-D
Pt
C-P-T
D
Pz1
K
T2
T1
P
D-C
E
Nam Su Lu migmatite
Ta -Khoa migmatite
Plutons
post-orogenic granite
granite/granodiorite arc
gabbro/diorite/tonalite arc
syenite/gabbro intraplate
Silurian Song Chay granite/monzogranite
Olistoliths or tectonic block:
limestone
radiolarite
mafic lava
gabbro
serpentinite
alcaline mafic rock (basalt, gabbro)
Placoderm fish fossil
alkaline lava flow
acidic lava flow
volcanic-sedimentary
bauxite
sandstone-conglomerate
limestone
siltstone-mudstone
turbidite
sandstone-mudstone
basement

Fig. 3

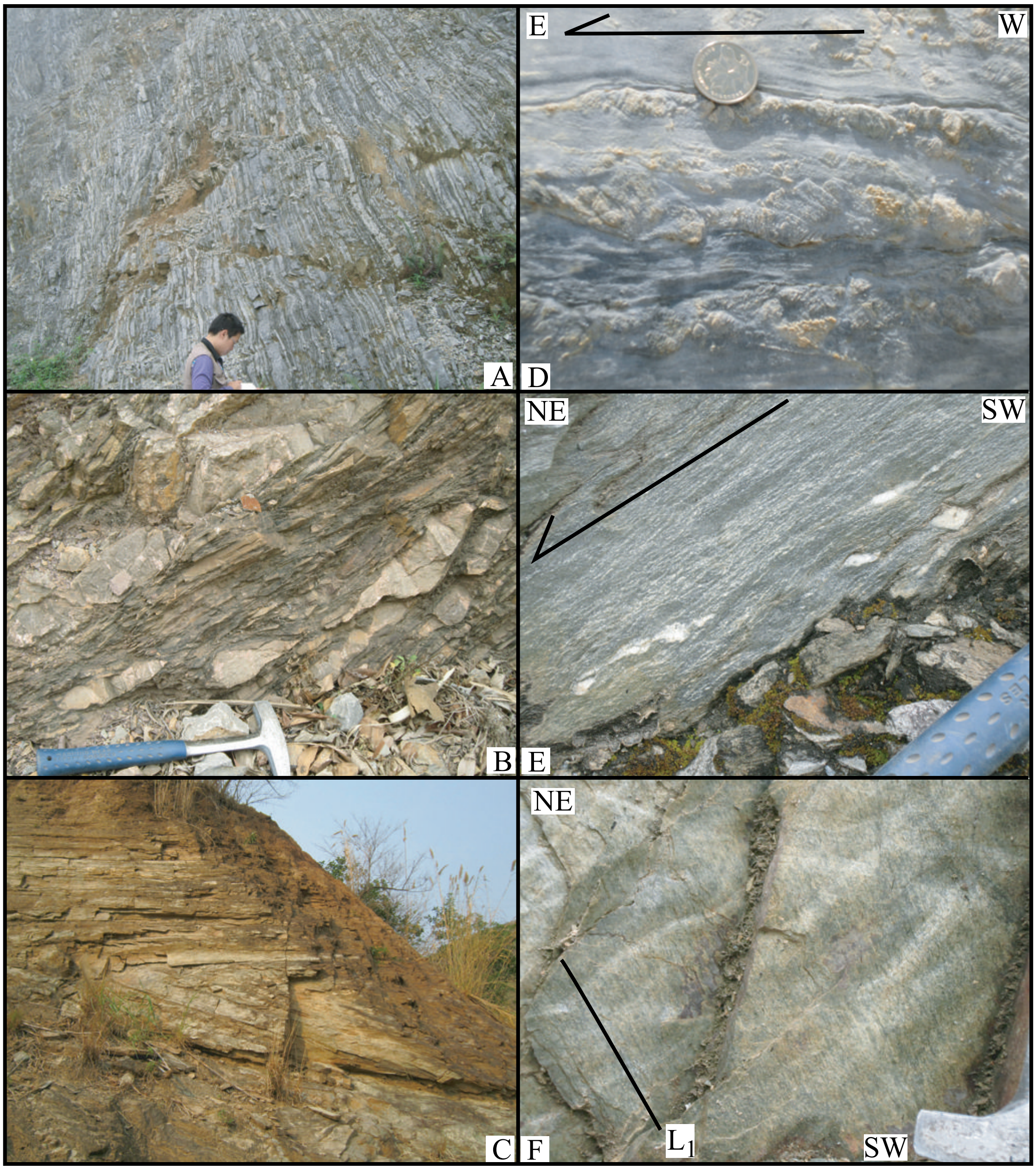


Fig. 4

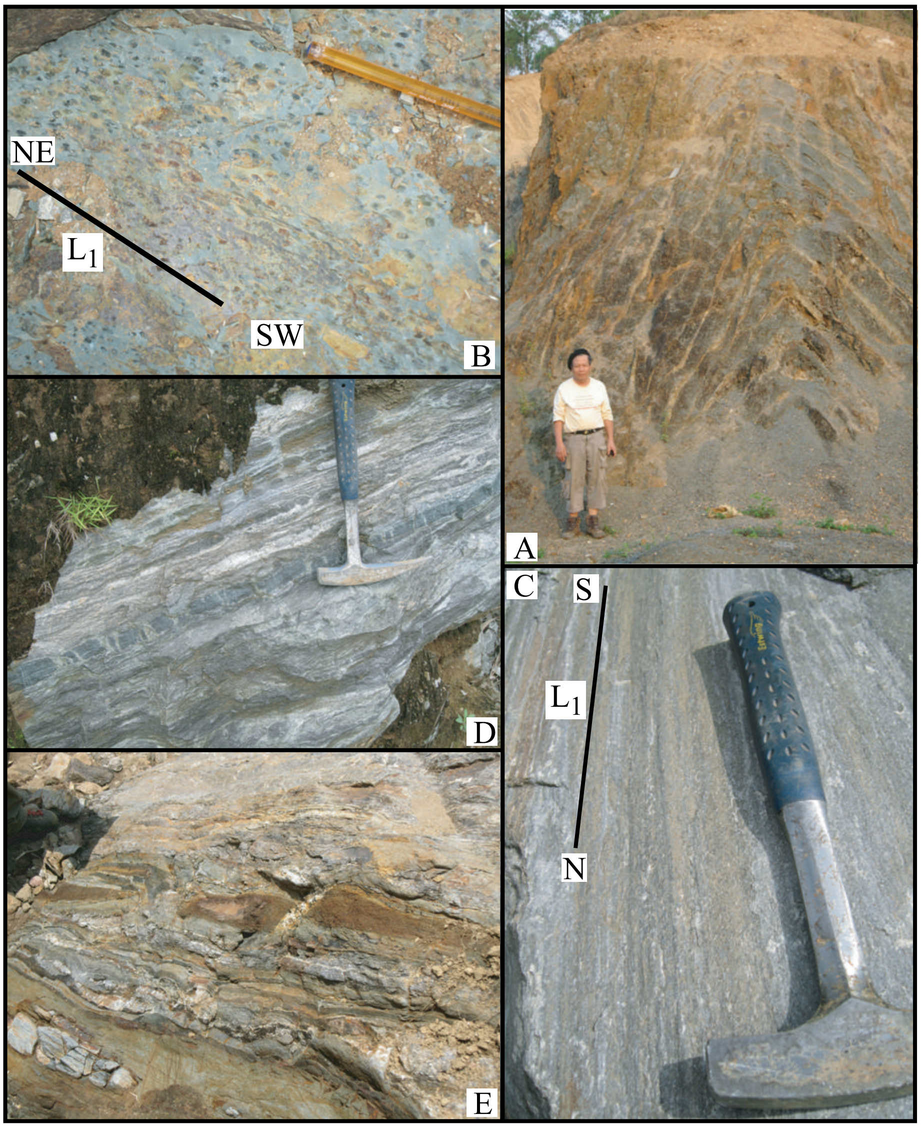


Fig.5

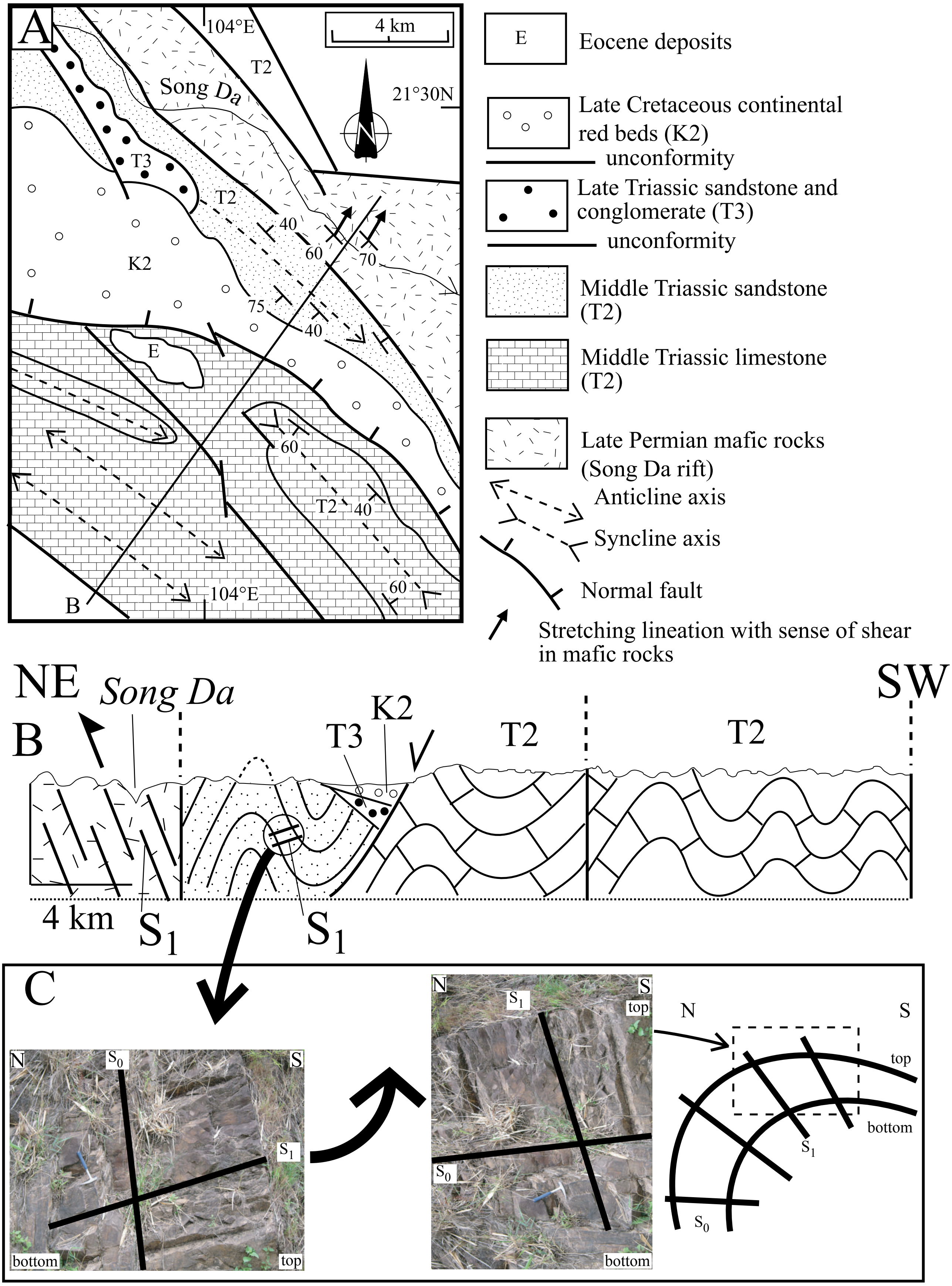

A
4 km
104°E
21°30N
Song Da
T2
T3
K2
E
40
60
70
75
40
60
40
60
104°E
B
Eocene deposits
Late Cretaceous continental red beds (K2)
unconformity
Late Triassic sandstone and conglomerate (T3)
unconformity
Middle Triassic sandstone (T2)
Middle Triassic limestone (T2)
Late Permian mafic rocks (Song Da rift)
Anticline axis
Syncline axis
Normal fault
Stretching lineation with sense of shear in mafic rocks
NE
Song Da
SW
B
T3
K2
T2
T2
4 km
S1
S1
C
N
S
S0
S1
bottom
top
N
S
S1
top
S0
bottom
N
S
top
bottom
S1
S0

Fig. 6

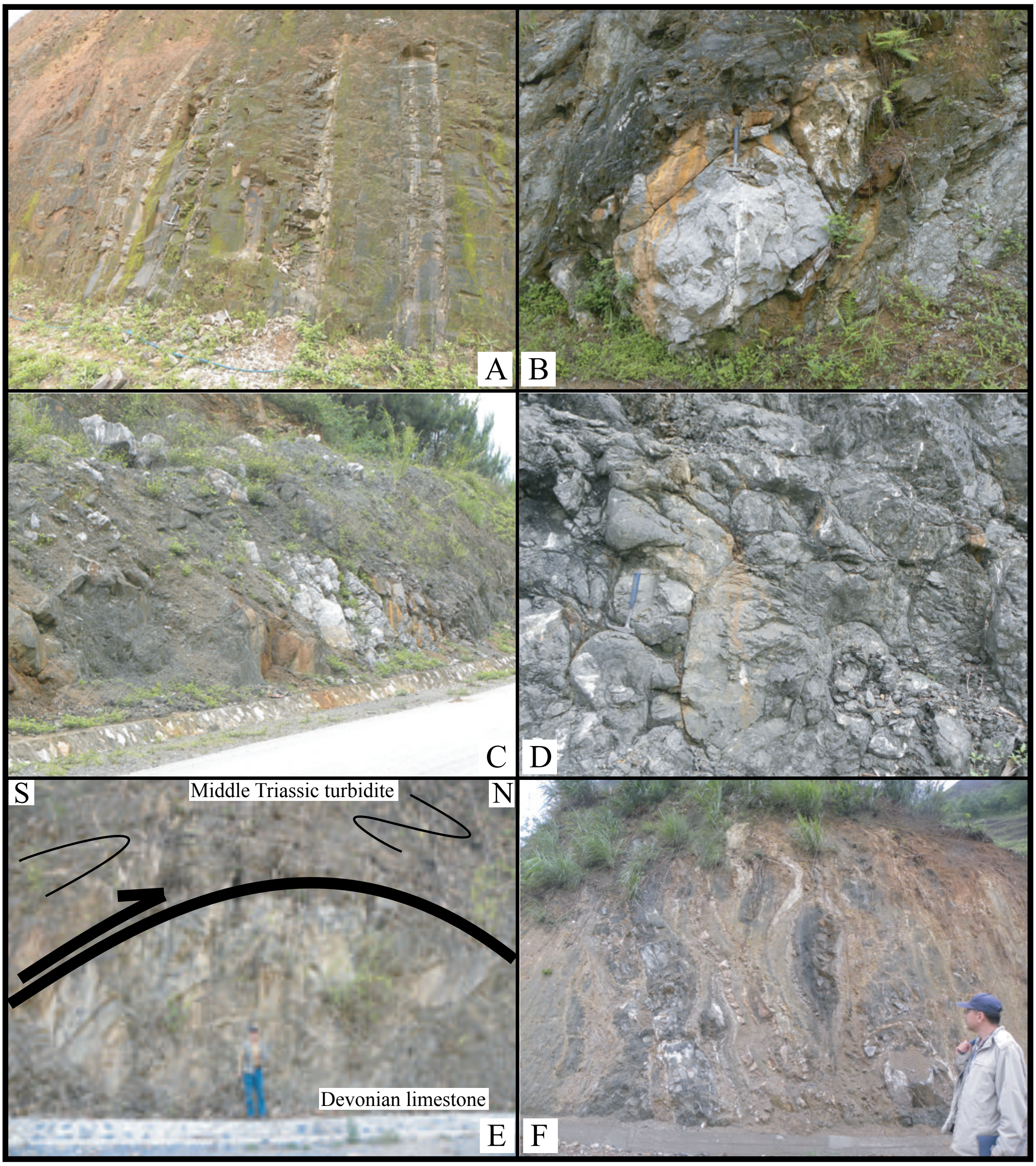
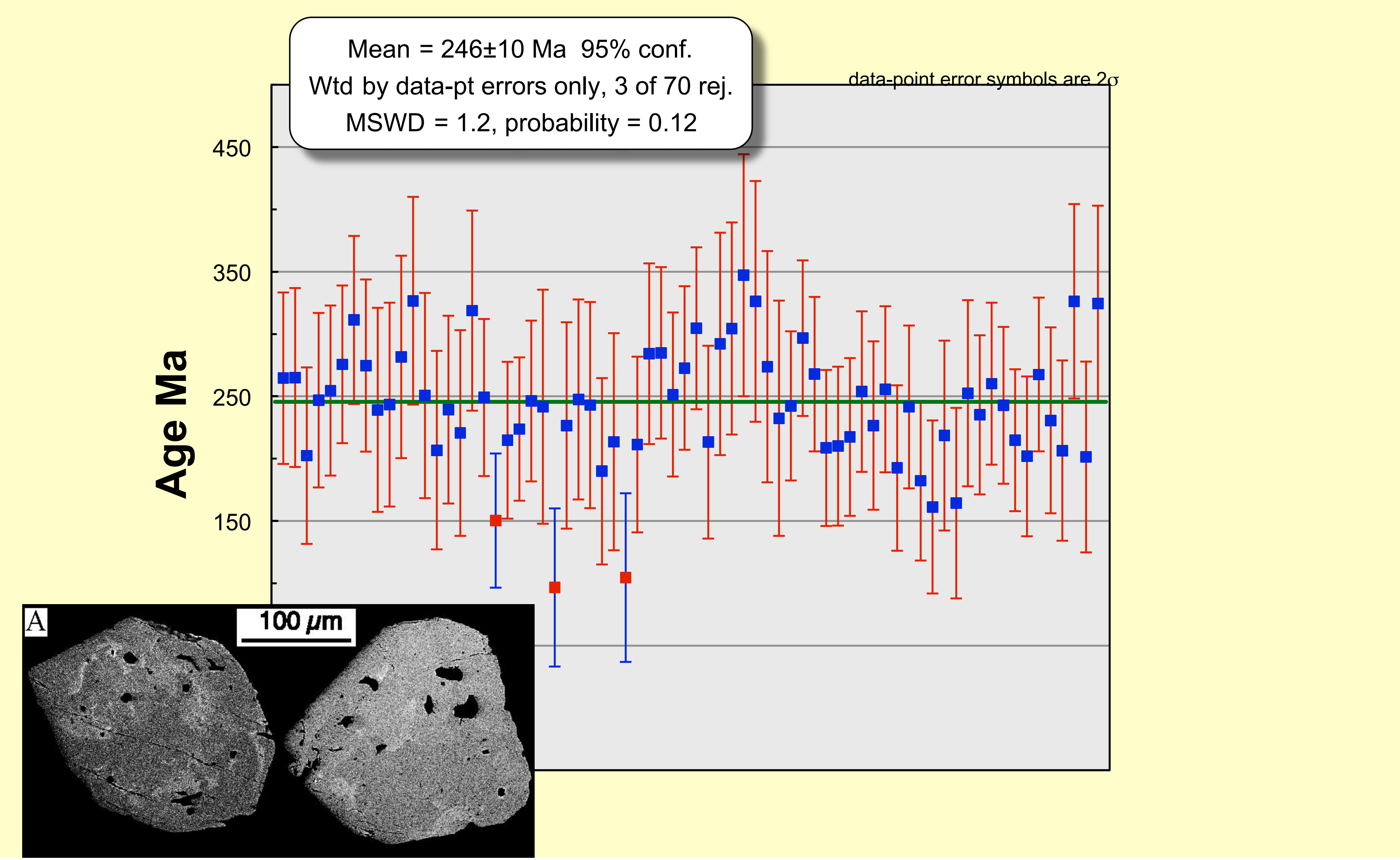


Fig. 7



Mean = 246±10 Ma 95% conf.
Wtd by data-pt errors only, 3 of 70 rej.
MSWD = 1.2, probability = 0.12
data-point error symbols are 2σ
450
350
250
150
Age Ma
A
100 μm

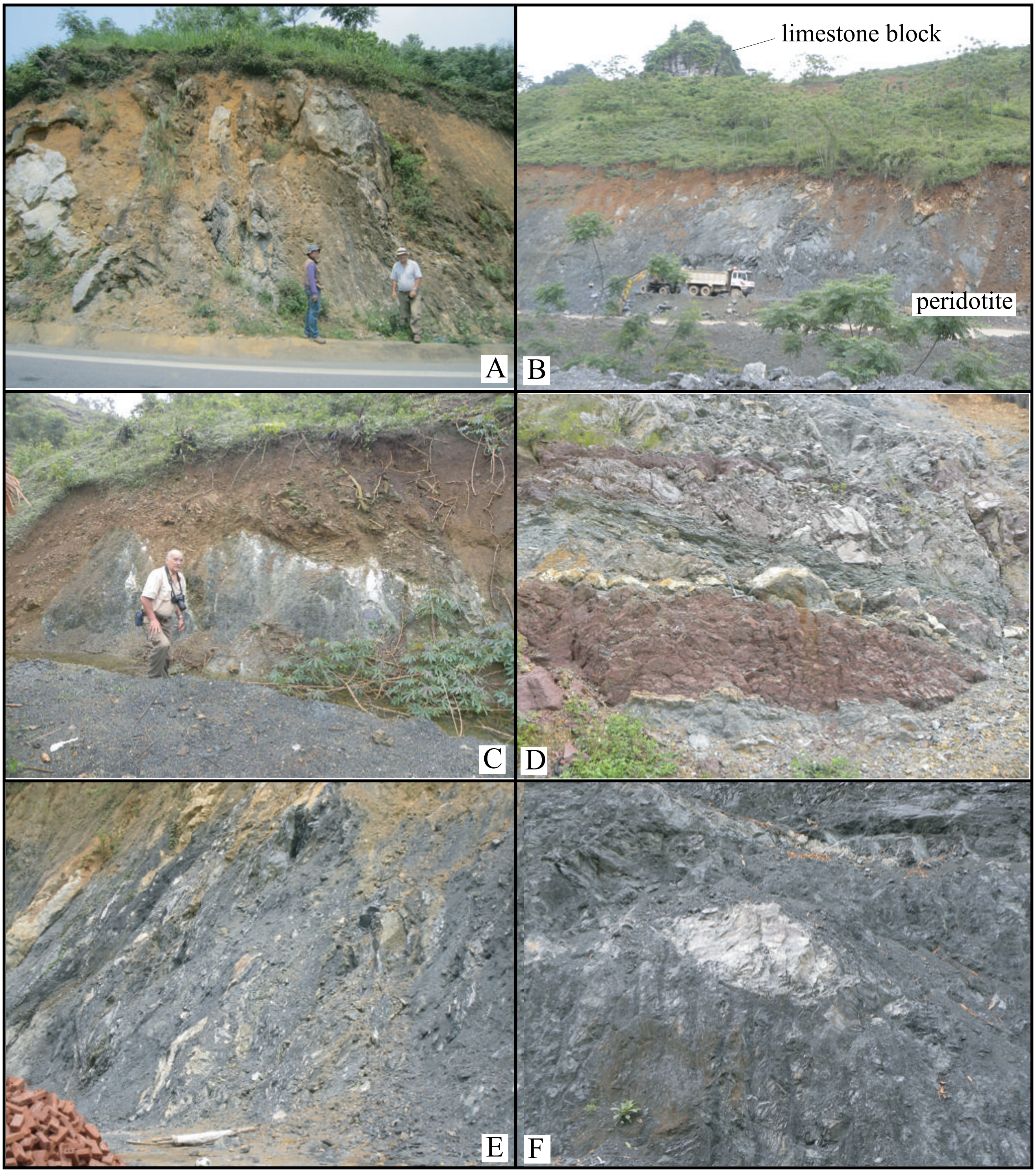
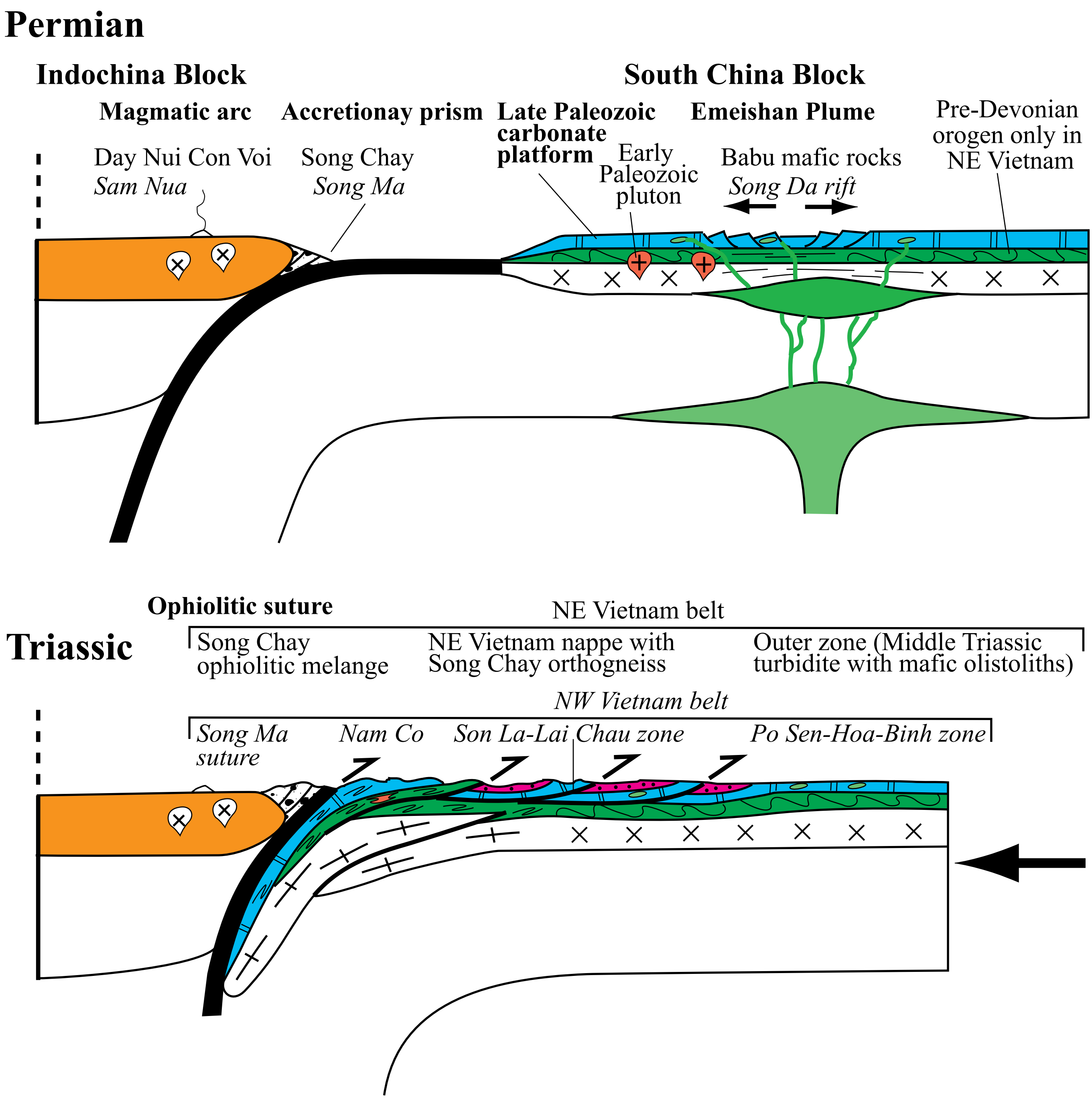


Fig. 9



Permian
Indochina Block
South China Block
Magmatic arc
Accretionay prism
Late Paleozoic carbonate platform
Emeishan Plume
Pre-Devonian orogen only in NE Vietnam
Day Nui Con Voi
Sam Nua
Song Chay
Song Ma
Early Paleozoic pluton
Babu mafic rocks
Song Da rift
Ophiolitic suture
NE Vietnam belt
Triassic
Song Chay ophiolitic melange
NE Vietnam nappe with Song Chay orthogneiss
Outer zone (Middle Triassic turbidite with mafic olistoliths)
NW Vietnam belt
Song Ma suture
Nam Co
Son La-Lai Chau zone
Po Sen-Hoa-Binh zone

Fig. 10

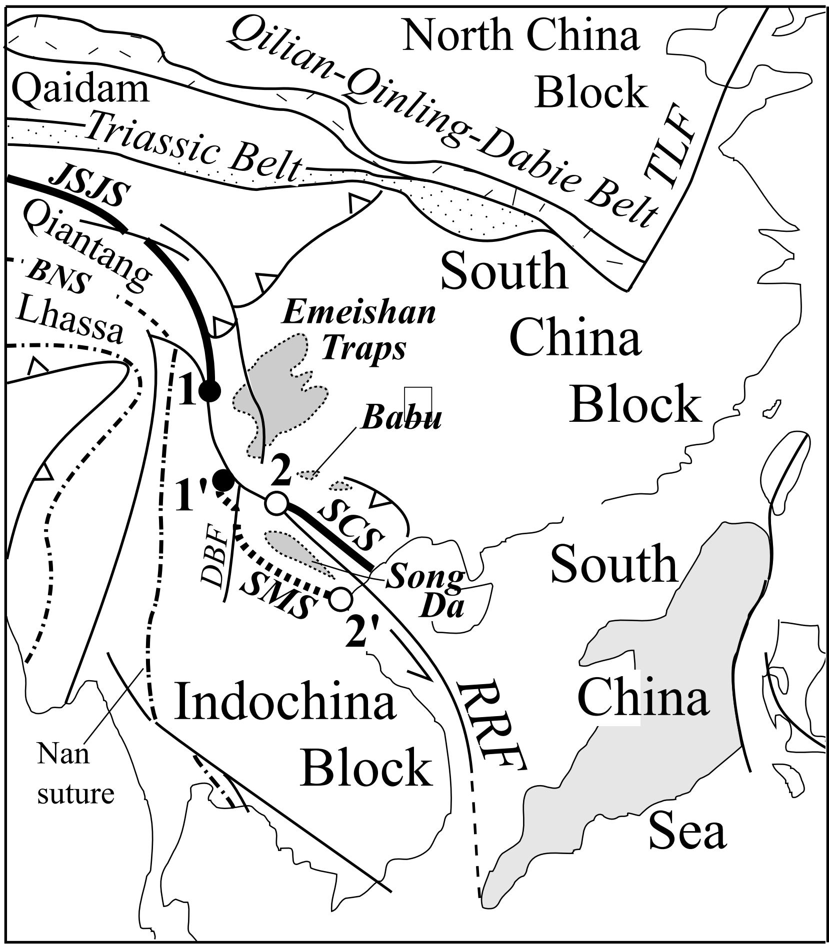

North China
Block
Qilian-Qinling-Dabie Belt
TLF
Qaidam
Triassic Belt
JSJS
Qiantang
BNS
Lhassa
South
China
Block
Emeishan
Traps
Babu
1
1'
2
2'
SCS
DBF
SMS
Song
Da
South
China
Sea
RRF
Indochina
Block
Nan
suture

Fig. 11

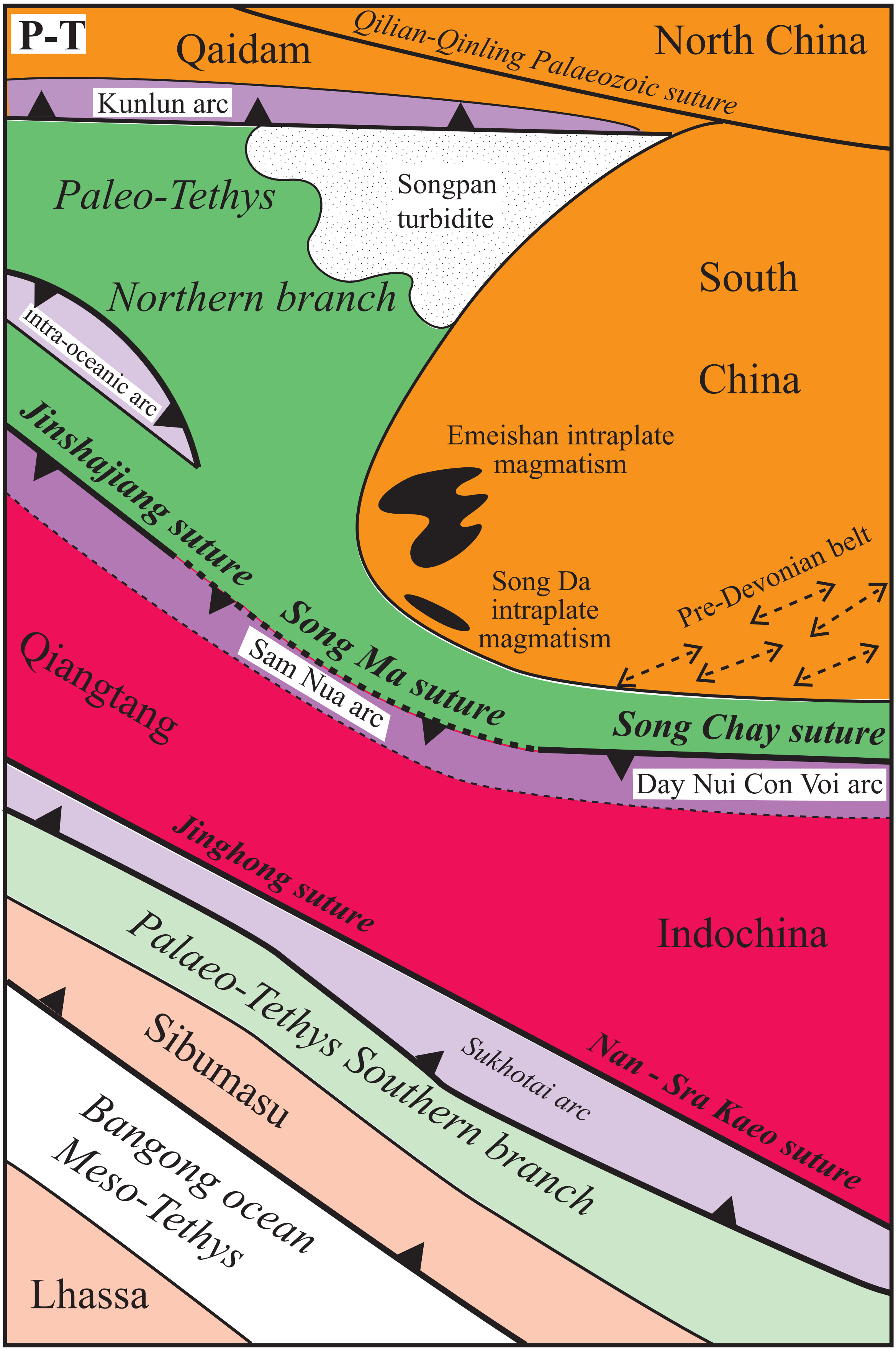

P-T
Qaidam
Qilian-Qinling Palaeozoic suture
North China
Kunlun arc
Paleo-Tethys
Songpan
turbidite
South
China
Northern branch
intra-oceanic arc
Emeishan intraplate
magmatism
Jinshajiang suture
Song Da
intraplate
magmatism
Pre-Devonian belt
Song Ma suture
Sam Nua arc
Qiangtang
Song Chay suture
Day Nui Con Voi arc
Jinghong suture
Indochina
Palaeo-Tethys Southern branch
Sukhotai arc
Sibumasu
Nan - Sra Kaeo suture
Bangong ocean
Meso-Tethys
Lhassa

Fig. 12

n° in Fig. 1	Tectonic unit & Rock type	Dated Mineral	Method	Age in Ma	Reference
1	Inner zone Nam Co unit micaschist	biotite	$^{40}Ar/^{39}Ar$	246±0.5 245±4 240±2	Lepvrier et al. (1997)
		muscovite	$^{40}Ar/^{39}Ar$	253±1 246±4 241±4 237±4	
		amphibole	$^{40}Ar/^{39}Ar$	266±4	
2	Song Chay Orthogneiss	zircon	TIMS	428±1	Roger et al. (2000)
		whole rock muscovite biotie	Rb/Sr	206±10	
		biotite	$^{40}Ar/^{39}Ar$	190±8	
	Du Long orthogneiss (chinese part of Song Chay)	muscovite	$^{40}Ar/^{39}Ar$	210±9	Yan et al. (2006)
		zircon	SHRIMP	402±10 436-402	
		zircon	SHRIMP	237±15	
		amphibole	$^{40}Ar/^{39}Ar$	237±5	
3	Song Chay micaschists	biotite	$^{40}Ar/^{39}Ar$	201±2	Maluski et al. (2001)
		muscovite	$^{40}Ar/^{39}Ar$	228±1 234±1 236±1	
4	Song Chay micaschists	monazite	U-Th-Pb	246±8 203±5	Gilley et al. (2003)
	Dai Nuy Con Voi micaschists	monazite	U-Th-Pb	220±4	
5	Inner zone HP unit micaschist	monazite	U-Th-Pb	243±4	Nakano et al. (2010)
6	Nam Su Lu micaschist	monazite	U-Th-Pb	233±5	Nakano et al. (2008)
7	Song Chay micaschists	monazite	U-Th-Pb	246±8	This study
8	Song Ma eclogite	zircon	SHRIMP	230±8	Zhang et al. (2013)
9	Nui Chua gabbro	zircon	SHRIMP	251±4	Tran et al. (2008b)
	Suoi Cun massif gabbro-dolerite	zircon	SHRIMP	266±4	
	rhyolite	zircon	SHRIMP	248±4.5	
	Ban Phuc granite	biotite	$^{40}Ar/^{39}Ar$	251±1	
	Kim Boi granite	zircon	SHRIMP	242.5±2	

10	Chieng Khuong plagiogranite	zircon	LA-ICP-MS	263±8	Pham T.H. et al. (2008)
	Metabasalt	zircon	LA-ICP-MS	254±12	
	Song Ma granite	zircon	LA-ICP-MS	257±6	
11	Dai Nuy Con Voi micaschists	zircon	SIMS	263-240	Zelazniewicz et al. (2012)
12	Dien Bien granite	zircon	LA-ICP-MS	224±3 (206±7)	Liu et al. (2011)
	“Chieng Khuong quartz-diorite”	zircon	LA-ICP-MS	271±3	
	Gabbro diorite	zircon	LA-ICP-MS	280±3 247±3	
13	Chieng Khuong plagiogranite	zircon	TIMS	222±4	Nguyen et al. (2012)
	Song Ma metagabbro-amphibolite	zircon	TIMS	265±4	
				241±5	
		titanite amphibole pyroxene whole rock	Sm-Nd	313±32 315±92 322±45 338±24 387±56	
14	Phan Si Pan Alkaline granite	zircon	LA-ICP-MS	253-251	Pham et al. (2012)
15	Phia Bioc granite	zircon	LA-ICP-MS	245±5	Roger et al. (2012)
	Phia Oac leucogranite	zircon	LA-ICP-MS	87±1	
16	granite	zircon	SIMS	228±1	Chen et al. (in press)
	leucogranite	zircon	SIMS	90±1	
	quartz-syenite	zircon	SIMS	246±2	
	granodiorite	zircon	SIMS	252±2	
17	Tu Lê rhyolite Phu Sa Phin Alkaline granite	zicon zircon	SHRIMP SHRIMP	256±4 248±4	Tran and Vu (2011)

Table1. Main radiometric ages available in N Vietnam, locations shown in Fig.1

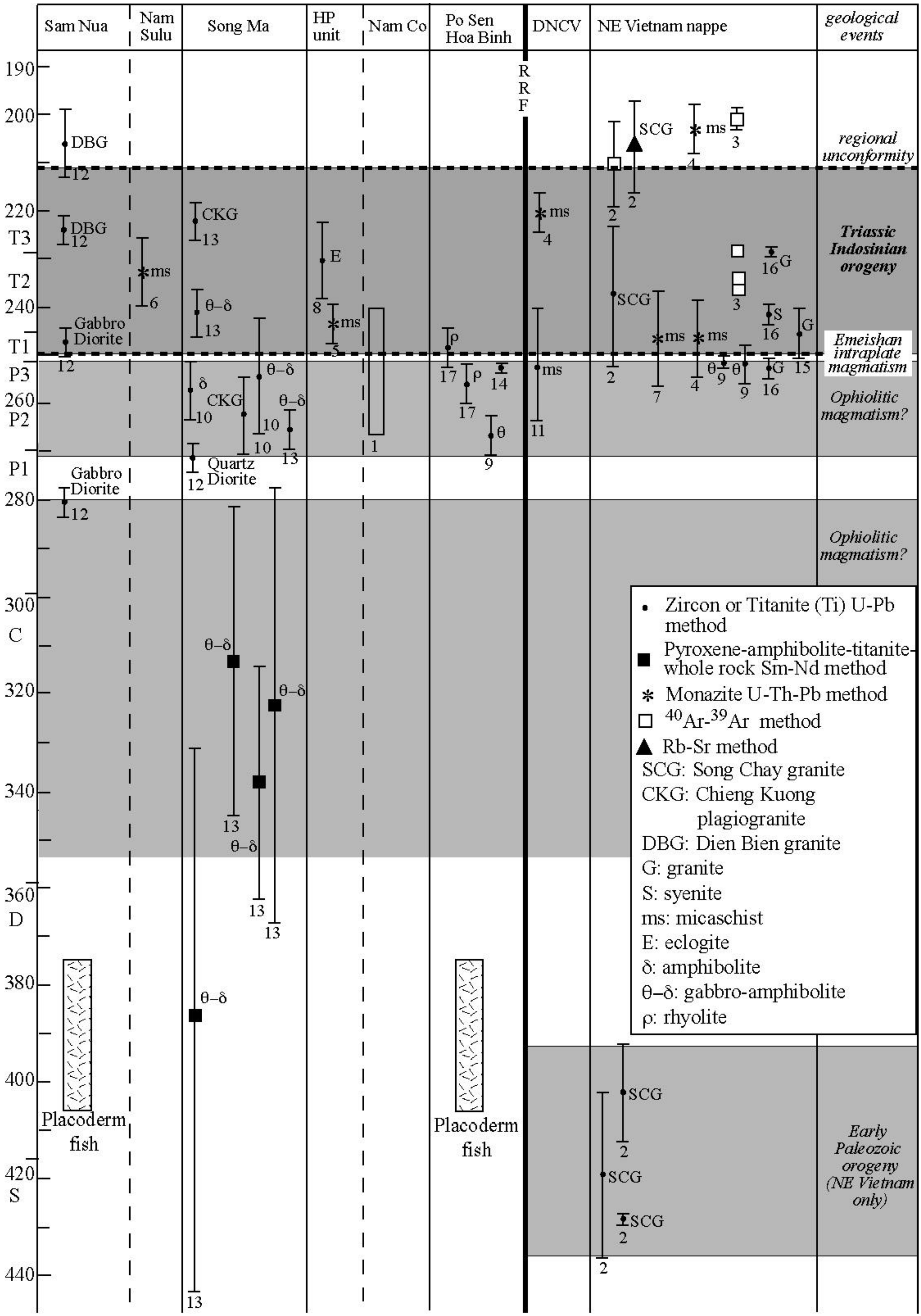


Table 2. Synoptic view of the radiometric constraints available for each zone numbers refers to Table 1