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Early Paleozoic or Early-Middle Triassic collision between the South China and
Indochina Blocks: the controversy resolved? Structural insights from the Kon
Tum massif (Central Vietnam)

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Abstract

In Central Vietnam, the Kontum massif is subdivided from North to South into: i)
Kham Duc, ii) Ngoc Linh, iii) Kan Nack complexes. The Kham Duc complex consists of
metapelite, metapsammite, paragneiss, metagabbro, amphibolite, serpentized ultramafic,
and orthogneiss blocks. The southern part of this complex experienced an Early Paleozoic
crustal melting event responsible for migmatites and anatectic granites. The Ngoc Linh
complex, the largest one, is formed by metatexite and granitoid enclosing blocks of eclogite,
high pressure (HP) granulite, orthogneiss, metagabbro, amphibolite, granodiorite, and
migmatite. The Kan Nack complex is formed by migmatites with (ultra) high temperature

(U)HT granulite, charnockites and enderbites. The three metamorphic complexes are intruded by per-aluminous granite, and subordinate mafic plutons. In spite of local variations, the foliation of the Ngoc Linh complex defines a bulk domal structure, and the stretching lineation consistently trends NW-SE. The NW-SE lineation is also observed in the tectonically overlying the Kan Nack complex. The Ngoc Linh and Kan Nack complexes are interpreted here as parts of a metamorphic core complex (MCC), or "Ngoc Linh MCC", exhumed by a top-to-the-NW detachment fault. Along the northern margin of the Ngoc Linh MCC, upright folds with E-W striking axes, and E-W stretching lineation deform the foliation. These structures are developed in a transpressive regime coeval with the activity of plurikilometer-scale dextral strike-slip faults. Zircon and monazite U/Pb radiometric datings document a 250-240 Ma age for the crustal melting, and the top-to-the-NW ductile shearing coeval with the formation of the Ngoc Linh MCC. This extensional tectonics is followed by a dextral strike-slip faulting, at ca 240-230 Ma, before the emplacement of the two-mica granitic plutons at ca 240-224 Ma. Furthermore in the Ngoc Linh and Kan Nack complexes, zircon and monazite yield U-Pb Early Paleozoic ages. In the Kham Duc complex, a ca 460 Ma MP/MT, garnet-biotite-staurolite-kyanite metamorphism, followed by migmatites at ca 450 Ma, is also recognized. The 420-400 Ma age of the Dai Loc plutonic suite, and the 450-425 Ma age of the Dien Binh calc-alkaline granodiorite document an Early Paleozoic event. The Early Paleozoic mafic and ultramafic masses of the Hiep Duc complex are ophiolites included into a metasedimentary matrix. Thus, the Kham Duc complex is interpreted as a tectonic mélangé formed during a collisional orogeny that subsequently underwent crustal melting giving rise to the migmatites. A part of the Early Paleozoic rocks are enclosed as xenoliths in the Triassic migmatite of the Ngoc Linh MCC. These petrologic, structural, and chronological features allow us to propose the following geodynamic evolution for the Kontum massif. During the Early Paleozoic, a continental collision, which was

accommodated by a north-directed subduction of a southern block (S. Vietnam, or Viet-Cambodia block) below a northern block (N. Vietnam or Viet-Lao block), occurred along the Tam Ky-Phuoc Son suture. During the Early Triassic, at ca 250-245 Ma, the S. Vietnam block experienced a crustal melting giving rise to the Ngoc Linh MCC that reworked the Early Paleozoic orogen. Lastly, during the Middle Triassic, the dextral faulting superimposed upon the Ngoc Linh migmatite. The geodynamic significance of the Kontum massif is discussed in the general framework of Indochina- South China relationships. The Early Paleozoic collision in Vietnam is viewed as the driving force responsible for the development of the intracontinental orogeny of S. China. In order to account for the important heat flow required for the formation of UHT metamorphic rocks, a possible interaction between the SCB-Indochina collision, and the Emeishan mantle plume is proposed.

Keywords: Early Paleozoic orogeny, Triassic tectonics, South China-Indochina connection, Kon Tum massif, Metamorphic Core Complex, Plume-modified orogeny

1. Introduction

Continent or microcontinent collisions that follow the closure of oceanic basins played a major role in the formation of Asia since the Neoproterozoic. In this general frame, the collision between the Indochina block and the South China block (SCB) is an important feature that accounts for the Asian continental assembly. In North Vietnam, the Late Triassic (Norian) unconformity documents an Early Triassic tectonic event, called "Indosinian orogeny" (Fromaget, 1927, 1941). Nevertheless, the location of the ophiolitic suture, the age of the collision, and the subduction polarity have been debated for a long time (for a recent

discussion of these issue see Faure et al., 2014, and enclosed references). Concerning the age of the Indochina block-SCB collision, two main opinions are currently proposed. Some authors (e.g. Lepvrier et al., 1997, 2004, 2008, 2011; Nakano et al., 2010; Liu et al., 2012; Faure et al., 2014, 2016a) argue that the collision took place in Early to Middle Triassic (ca 250-230 Ma). The Ailaoshan-Song Ma-Song Chay-Hainan ophiolitic suture of SW China and N. Vietnam represents the plate boundary along which the Paleotethys ocean was subducted (Fig. 1). The collision was preceded by a South (or SW in the present geographic coordinate frame) directed subduction giving rise to a magmatic arc on the Indochina block side, and followed by a North (or NE) propagation of the folds and low-angle thrusts. In the Truong Son belt of N. Vietnam (Fig. 1), the late collisional Triassic deformation was accommodated by NW-SE striking dextral strike-slip faults (Lepvrier et al., 1997, 2004). Another group of authors proposes the view that the collision occurred in Early Paleozoic on the basis of ca 400 Ma plutons, Devonian unconformity, and biostratigraphic correlations between Devonian shallow water terrigenous deposits and similar fossil assemblages in NE Vietnam and South China (e.g. Janvier et al., 1996, 1997; Thanh et al., 1996; Metcalfe, 1996, 2013; Findlay, 1997; Findlay and Pham, 1997; Carter et al., 2001; Carter and Clift, 2008; Roger et al., 2008, 2012; Tran and Vu, 2011). For these authors, the pre-Late Triassic tectonic-metamorphic and plutonic events were interpreted as an intracontinental tectonics due to a far-field effect of the collision between the Indochina and Sibumasu blocks.

Indeed, most of the controversial points arose from a lack of detail knowledge, or from over-interpretations of a local geological record extrapolated to remote areas. As shown below, the divergent points can be easily reconciled if a polyorogenic evolution is considered. This paper presents new structural data from the Kon Tum massif of Central Vietnam that was first considered as the Precambrian core of Indochina (e.g. Hoffet, 1933; Saurin, 1935, Hutchison, 1989; Lan et al., 2003; Tran and Vu, 2011) but more recently, Early Paleozoic and

Early to Middle Triassic ages have been documented there (Nam et al., 2001; Osanai et al., 2004; Maluski et al., 2005; Roger et al., 2007; Usuki et al., 2009; Nakano et al., 2007, 2009, 2013). Our new field and laboratory analyses allow us to propose a crustal scale view of the architecture of the Kon Tum massif. The place of the Kon Tum massif in the Paleozoic to Triassic geodynamic evolution of the Indochina-South China collisional framework is also discussed.

2. Regional setting

Below the Late Triassic and younger formations, the study area (Fig. 2) can be divided into two domains, namely: i) a northern one, between Da Nang and Hue, forms the south Truong Son area (Lepvrier et al., 1997), or the Binh Tri Thien zone (Thanh et al., 2013), which is occupied by weakly or unmetamorphosed formations, and ii) the Kon Tum massif composed of metamorphic and plutonic rocks. Both domains also expose several generations of granitic plutons. The post-tectonic formations include, from the younger to the older, Quaternary to Cenozoic basaltic flows, and Cretaceous to Late Triassic terrigenous formations. SW of Da Nang, the Late Triassic to Jurassic sandstone, conglomerate, and siltstone deposits (Nong Son Formation) that unconformably overlie the folded Paleozoic formations in the northern domain provide an upper time limit for the tectono-metamorphic events of the study area. In the Kon Tum massif, Jurassic and Late Cretaceous red sandstones and conglomerates were deposited in N-S striking half-grabens that overlie the metamorphic rocks. The detailed structure of these formations that post-date the main tectonic events is not documented here.

2.1. Lithotectonic units of the Kon Tum massif

The granitic and metamorphic Kon Tum massif, formerly considered as the Precambrian nucleus of the Indochina block (Lan et al., 2003; Tran and Vu, 2011), is subdivided into three litho-tectonic units, namely from North to South, the Kham Duc, Ngoc Linh, and Kan Nack complexes (Tran and Vu, 2011; Fig. 2). The radiometric ages that are crucial to discuss the tectonic and geodynamic significance of the syn- to post-metamorphic events will be presented below in section 4.

2.1.1. The Kham Duc complex.

This unit is bounded to the North by a granitic intrusion belonging to the Ben Giang-Que Son plutonic suite, and to the South by the E-W striking dextral Tra Bong strike-slip fault (Lepvrier et al., 1997). The Kham Duc complex can be subdivided in two parts. The northern one consists of metapelite, metagraywacke, quartz schist, and chlorite actinolite volcanic-sedimentary rocks. Amphibolite, locally some of them preserving a gabbroic texture, and serpentized ultramafics are exposed as scattered blocks in the metasedimentary suite (Fig. 3A, B). The mafic-ultramafic rocks, called the Hiep Duc complex, are interpreted as a dismembered ophiolitic series (Izokh et al. 2006; Pham et al., 2006; Tran and Vu, 2011). To the South, the second part of the Kham Duc complex is characterized by the occurrence of migmatites and anatectic granites, called the Chu Lai migmatitic complex. In these rocks, the leucosomes are well foliated and folded (Fig 3C,D), and the amphibolite, and metagabbro bodies represent xenoliths. Due to poor outcrop quality, and progressive transition from non-melted to completely melted rocks, it is impossible to clearly delineate the boundary between the two parts (Fig. 2). In the following, they will be collectively referred to as the Kham Duc complex. The age of the protoliths is unknown, however the metapelite yields detrital zircon grains dated at 558 ± 7 Ma (Usuki et al., 2009) showing that at least a part of the Kham Duc complex is younger than Late Neoproterozoic. The Tra Bong fault system separates two different migmatitic complexes, the Chu Lai and Ngoc Linh to the North and South,

respectively. As they partly experienced the same deformation events, and in absence of precise dating, their distinction remains difficult.

2. 1. 2. The Ngoc Linh complex.

This rhombic shaped complex is limited to the North and South by the Tra Bong and Ba To faults, respectively. Westward, it probably extends into Laos (Fig. 2). The Ngoc Linh complex consists of metatexites and biotite-garnet-sillimanite gneiss (Fig. 4A, B) with foliated quartz-feldspar layers corresponding to leucosome. Mafic rocks, such as garnet amphibolite, eclogites, HP granulite, and biotite-hornblende orthogneiss, are widespread in the complex (Fig. 4C; Nakano et al., 2007; Osanai et al., 2008; Yonemura et al., 2013). These rocks are interpreted as refractory restites enclosed in the migmatite. The biotite-hornblende orthogneiss represent remnants of the pre-Ngoc Linh migmatite plutons, such as the Dai Loc or Ben Giang-Que Son bodies. Furthermore, South of Di Lang, along the Song Re, the Ngoc Linh migmatite encloses blocks of metatexite with a folded foliation unrelated to the deformation of the host rock migmatite (Fig. 4D). This feature argues for two generations of migmatites.

2. 1. 3. The Kan Nack complex.

This complex that crops out in the southeastern part of the Kon Tum massif, is composed of metagraywacke, metapelite, quartzite, marble, and mafic rocks metamorphosed under granulite facies conditions (Roger et al., 2007; Nakano et al., 2007, 2013). These HT metamorphic rocks, belonging to the khondalite-kinzigite series, are associated with garnet-orthopyroxene granite, or charnockites, and gabbro-tonalites, or enderbites, attesting to the melting of the lower continental crust under HT conditions (Roger et al., 2007). Zircon, monazite U-Pb, and biotite, muscovite radiometric datings document two metamorphic and

magmatic events at ca 465-422 Ma, and 255-240 Ma (Carter et al., 2001; Nagy et al., 2001; Maluski et al., 2005; Roger et al., 2007; Nakano et al., 2007, 2013).

2.2. The Northern Domain (South Truong Son area)

This area between Hue and Da Nang consists of Early Paleozoic to Triassic rocks. The Early Paleozoic (Cambrian-Ordovician) A Vuong Formation is composed of weakly metamorphosed quartz-sericite schist, sandstone and quartzite. It is unconformably covered by conglomerate, sandstone, and siltstone of Devonian age. Although globally non-metamorphic, these terrigenous formations are deformed by upright folds with the local development of an axial planar slaty cleavage. This event is related to the dextral strike-slip faulting widespread between Da Nang and Hue (Lepvrier et al., 1997). Permian and Triassic rocks crop out in the western part of the Northern Domain (Fig. 2). Similar rocks are also exposed in the southwestern part of the Kon Tum massif. These formations consist of unmetamorphosed terrigenous deposits and felsic and mafic volcanites. The basaltic rocks sometimes exhibit a pillowed structure. To the SW of the Kon Tum massif, near Sa Thay, Permo-Triassic felsic lava flows are also exposed.

2.3. The plutonic rocks

In the study area, the widely exposed plutonic rocks are gathered into two groups, namely the post-Ngoc Linh and the pre-Ngoc Linh suites (Fig. 2).

2.3.1. *The post Ngoc Linh plutons.*

These rocks are also collectively called the Hai Van complex. The Ba Na and Van Canh suites are included in this group (Tran and Vu, 2011). The Hai Van, Ba Na, and Van Canh plutons consist of biotite granite and two-mica cordierite \pm sillimanite \pm garnet granitoids with locally a migmatitic appearance and numerous aplitic dykes well exposed

North of Da Nang. Furthermore, the Hai Van granite intrudes migmatite in the central part of the Ngoc Linh Complex. Zircon yields LA-ICP-MS ages ranging between 242 Ma and 224 Ma (Hieu et al., 2015). Monazite U-Pb chemical ages distribute between 240 Ma and 220 Ma (Nakano et al., 2013). This range of ages is globally older than the Late Triassic sandstone, at ca 220-200 Ma that unconformably overlie the plutonic rocks. The peraluminous geochemical signature of these Middle to Late Triassic plutonism document an important crustal melting event. The presence of Early Paleozoic inherited zircon grains, dated at 438 ± 4 Ma, and 380 ± 4 Ma, also indicates the crustal contribution in the magma genesis (Shi et al., 2015). Small bodies of gabbro and diorite (Cha Val and Phu Loc magmatic suites) associated with the Hai Van plutons suggest that a mantle magmatic input might have triggered the crustal melting (Tran and Vu, 2011).

From a structural point of view, the Hai Van, Ba Na, and Van Canh plutons sometimes exhibit a planar mineral preferred orientation. Although a magmatic mineral fabric may be locally observed, a post-solidus one is lacking. In agreement with the radiometric ages, these plutons were emplaced after the development of the main foliation recorded in the Ngoc Linh, Kan Nack and Kham Duc metamorphic complexes.

2.3.2. *The pre-Ngoc Linh plutons.*

On the basis of their age and geochemistry, three earlier magmatic suites are distinguished. From the younger to the older they are the Ben Giang-Que Son, Dai Loc, Dien Binh, and Tra Bong suites (Tran and Vu, 2011):

The Ben Giang-Que Son granites are well exposed both in the Northern Domain, NW of Tam Ky, and in the Kon Tum metamorphic domain, where they are exposed as an unmelted blocks within the migmatite. Several petrographic facies including diorite, quartzdiorite, gabbro, porphyritic granodiorite, and syenite are recognized (Tran and Vu,

2011). Zircon U-Pb (SHRIMP and LA ICP-MS) dating from granodiorite yields ages ranging between 295 Ma and 261 Ma, with a peak at 294 Ma (Dinh, 2011; Nguyen Trong Giang unpublished in Tran and Vu, 2011). Furthermore, zircon separated from a quartz diorite rock in the large pluton that separated the southern part of the Truong Son belt) and the Kham Duc complex, yields LA-ICP-MS age at 479 ± 3 Ma (Hieu and Trung, 2016a). On the basis of its calc-alkaline geochemical features, the Ben Giang-Que Son plutonic suite is interpreted as mantle derived magmas contaminated by crustal materials. These rocks are considered as emplaced in a magmatic arc formed in a continental active margin (Tran et al., 2008; Hieu and Trung, 2016a).

The Dai Loc magmatic suite is well developed SW of Da Nang in the northern Domain, but it may also crop out as xenolith in the Ngoc Linh and Kan Nack complexes (Fig. 2). The dominant rocks are porphyritic biotite granite with subordinate two-mica granite, syenogranite, and monzogranite. Most of the plutons of the northern domain exhibit a well developed planar and linear fabric related to the dextral strike-slip fault system widespread there (Lepvrier et al., 1997; 2008). The per-aluminous and subalkaline geochemical features of these plutons indicate that they result of the partial melting of continental crust (Hieu et al., 2016b). Zircon SHRIMP dating gives 418 ± 18 Ma and 407 ± 11 Ma ages (Carter et al., 2001), whereas zircon LA-ICP-MS analyzes indicate 427 ± 10 Ma and 423 ± 2 Ma ages (Hieu et al., 2016b). These late Silurian ages argue for an important Early Paleozoic magmatic event.

The Dien Binh and Tra Bong magmatic suites are scattered in the Western and in the Northern parts of the Ngoc Linh metamorphic complex. They mainly crop out close to the Po Ko and Tra Bong faults, respectively (Fig. 2). These rocks are dominantly diorite, and porphyritic granodiorite with limited gabbro. The Tra Bong pluton experienced a pervasive post-solidus ductile deformation associated with the dextral strike-slip shearing (Lepvrier et al., 1997, 2004, 2008). Zircon fractions from a Dien Binh granodiorite yield a U-Pb age at

415±3 Ma (Nagy et al., 2001), and SHRIMP dating of a gneissic diorite gives an Early Paleozoic age at 444±17 Ma (Carter et al., 2000). The calc-alkaline geochemical character of the Dien Binh plutons suggests that they formed in a magmatic arc setting (Nagy et al., 2001).

3. Structural analysis of the polyphase deformation

In contrast to the numerous petrological and geochronological studies, the structural investigations of the Kon Tum massif remain rare (Lepvrier et al., 1997, 2004, 2008; Tran et al., 2014). Our study allows us to recognize three ductile and synmetamorphic events called in the following D₁, D₂, and D₃ in a younging relative chronological order. Furthermore, some rare lines of evidence argue for an early "pre-D₁" event, but the regional foliation, ascribed to the D₁ event, represents the main deformation observed in all metamorphic complexes.

3.1. The syn-migmatitic D₁ main structural event.

3.1.1. *Fabric elements*

The three metamorphic complexes exhibit a pervasive foliation (S₁) defined by the preferred orientation of platy minerals, such as biotite and muscovite, and also by the alternation of quartz and feldspar layers. This planar fabric is well developed in the Ngoc Linh complex where foliated migmatites exhibit a mylonitic foliation. S₁ often contains a mineral and stretching lineation, L₁, represented by elongated biotite streaks, and feldspar porphyroclasts. As observed by planar joints and triple junctions at ca 120° of the quartz and feldspar grains, a thermal annealing induced a static recrystallization that often erased L₁. In the eastern part of the Ngoc Linh complex, between Quang Ngai and Ba To, the foliation dips to the East or SE (Figs. 2, 5 stereograms G, I). In the southwestern part of the Ngoc Linh complex, from Kon Tum to Dak To, S₁ dips to the southwest, in its western part, North of Dak To, along the Po Ko fault, and up to the Laos border, S₁ dips westward (Fig. 2, 5

stereograms D, E). Therefore, as already recognized by Lepvrier et al., (2004, 2008), the foliation of the Ngoc Linh complex defines a domal structure. The antiformal geometry of S_1 clearly appears along the Song Re, between Di Lang and Ba To (Fig. 2, 5). Along the northern boundary of the Ngoc Linh dome, S_1 dips alternatively northward or southward due to the post-folial folding ascribed to the D_2 event. In several places, S_1 is folded by NE-trending, and NW-verging folds. Although obviously post-dating the S_1 formation, these structures are distinct from the upright folds ascribed below to the D_2 event. They are interpreted here as a late increment of the D_1 top-to-the NW sense of shear, and shown as F_{1-2} folds in Fig. 5 stereograms D and J. Furthermore, the variable dip and strike attitude of S_1 suggests that the Ngoc Linh dome may be composed by several sub-domes, however the present state of knowledge does not allow us to precisely depict the geometry.

In contrast to the domal architecture of the Ngoc Linh complex defined by the variously oriented S_1 , the L_1 stretching and mineral lineation presents a well organized pattern, since whatever the attitude of S_1 , L_1 trends NW-SE (Figs 2, 5). However, SW of Tra My, and in the NE corner of the dome, the stretching lineation trends NE-SW (Figs. 2, 5 stereogram K). This local feature is interpreted as the result of recumbent folding, in which the dominantly NW-SE trending lineation trends locally NE-SW in the inverted limb (Fig. 6). Indeed, in the NE part of the Ngoc Linh dome, small-scale folds, overturned to the NW, and associated to a low angle axial plane, are recognized (Fig. 7C). They correspond to NW-verging collapse folds indicating a subvertical shortening. These folds deform S_1 , but as their NW-ward vergence is consistent with the syn- S_1 ductile shearing, they are ascribed here to a late increment of the D_1 event. As a matter of fact, when S_1 is overturned, L_1 strikes NE-SW instead of NW-SE (Fig. 6).

The same S_1 foliation is observed in the Kan Nack complex with variable attitude (Fig 5 stereogram H). Globally, S_1 is folded into a NW-SE trending structure with a general

southward or southeastward dip, well observed in the SE part of the Kan Nack complex (Fig. 2). Geometrically, in spite of undulation of S_1 , the Kan Nack complex appears as a multi-km scale migmatitic and granulitic gneiss slice dipping to the SE. Most of the present boundaries between the Kan Nack and Ngoc Linh complexes are late high-angle faults (Fig. 2), and thus the syn-folial tectonic contact between the two units is not observed. From the field observation of the SE-ward dip of the S_1 foliation in both complexes, we infer that the Kan Nack complex overlies the Ngoc Linh complex, in agreement with previous works (Nagy et al., 2001; Cau et al., 2004; Lepvrier et al., 2004; Tran et al. 2006). Due to the jump in the metamorphic grade between the two complexes, a flat-lying tectonic contact should separate them, however, this boundary is not precisely recognized in the field since the two units are presently separated by NE-SW striking high angle faults. Alike for the Ngoc Linh complex, the Kan Nack complex contains a E-W to NW-SE striking mineral and stretching lineation, also ascribed to L_1 (Figs. 2, 5 stereogram H). Due to the intense recrystallization, L_1 is less developed than in the Ngoc Linh complex.

The Kham Duc complex exhibits also a pervasive foliation S_1 globally striking E-W or NE-SW but with a variable dip due to the late D_2 folding (Fig. 5 stereograms B, and L). Near Phuoc Son, L_1 is well developed, however, eastwards, the D_1 event is no more observed and D_2 predominates (Fig. 5 stereogram L).

3.1.2. Kinematic analysis

In spite of the static recrystallization that often erased the kinematic indicators, in section perpendicular to S_1 and parallel to L_1 , (i.e. in the XZ plane of the finite strain ellipsoid), ductile shear criteria, coeval with the development of the SL fabric, can be recognized both in the field and in thin sections. In the field, the most common criteria are sigmoidal leucosomes, asymmetric boudins, and drag folds (Figs 7A,B, C, E, F, 8A, B). In thin section, cut in the XZ plane of the finite strain ellipsoid, sigmoidal biotite and muscovite,

sigma-type porphyroclast systems, oblique quartz shape fabric, and pressure shadows are the commonest kinematic indicators (Fig. 9). From these observations, a top-to-the-NW shearing is widely distributed in the migmatites, gneiss, amphibolites, micaschists and quartzites of the Ngoc Linh, Kan Nack, and Kam Duc complexes. The D₁ ductile shearing is coeval with the HT/MP metamorphism and migmatization recorded in the Ngoc Linh and Kan Nack complexes. It is worth to note that when L₁ strikes NE-SW, due to the recumbent folding, as observed at the cm- and m-scale (Fig. 7C), and inferred for larger scale, the same kinematic indicators show a top-to-the-NE sense of shear can be observed in the inverted limb (Fig. 6).

3.2. The post-migmatitic D₂ event.

As mentioned above, the domal geometry of the Ngoc Linh migmatite is modified along its northern boundary by a set of ductile dextral strike-slip faults, collectively called the Tra Bong fault system (Fig. 2, Lepvrier et al., 1997, 2004). In this area, the S₁ foliation is deformed by E-W striking upright folds (F₂, Fig. 5 stereogram L, 7D). Locally an axial planar foliation may develop. These F₂ folds formed during a transpressional component of the strike-slip faulting. It is worth to note that the Tra Bong fault system belongs to an important network of dextral strike-slip faults well developed in the entire Truong Son belt (Lepvrier et al., 1997, 2004). In the study area, the Dai Loc orthogneiss, and their country rocks, west of Da Nang, are intensely deformed by the dextral shearing (Fig. 5 stereograms A and M, see Lepvrier et al., 1997, 2004 for details). From a structural point of view, the D₁ features (S₁, L₁, and the top-to-the-NW shearing) are clearly deformed by the dextral shearing D₂ event. As indicated by the ⁴⁰Ar/³⁰Ar radiometric ages at ca 245 Ma, and 230 Ma for D₁ and D₂, the two events developed successively but in a short time span (Lepvrier et al., 2007, 2004). Furthermore, north of the Tra Bong fault, the F₂ folds involve the Chu Lai migmatite, the foliation of which is deformed by isoclinal folds coeval with melting (Fig. 8C, D) that must be related to an older event.

3.3. The late D₃ event.

The S₁ foliation of the Ngoc Linh dome is also locally cut by high angle normal faults. These structures are well documented to the NE of Kon Tum and in the southeastern part of the dome (Lepvrier et al., 2004, 2008). Since the Hai Van two mica granites are involved in the faulting, the deformation should have occurred in the Late Triassic or after. Furthermore, the eastern side of the N-S to NNE-SSW striking normal fault that reworks the Ngoc Linh and Kan Nack complexes is moving downward. The hangingwall of the fault is a half-graben filled by Jurassic continental deposits (Fig. 2). Thus, a Jurassic age is tentatively assumed for these brittle-ductile normal faults. In the following, this post-migmatitic tectonic event will not be considered.

3.4. The pre-D₁ inherited structures in the Kham Duc complex.

E-W striking upright folding, attributed to the D₂ event, is well developed in the Kham Duc complex (Fig. 8B,C). In the southern part of the complex, upright or NW-verging folds deform the isoclinally folded leucosomes parallel to the migmatitic foliation of the Chu Lai migmatite (Figs. 3D, 8D). Near Tra My, the axes of the isoclinal folds trends N-S with variable dip, depending on their location within F₂ (Fig. 10). Since these intrafolial folds are coeval with the crustal melting, the formation time of this isoclinal folding is that of the Chu Lai migmatite. Several lines of evidence argue for an Early Paleozoic age (ca 450 Ma) for the Chu Lai migmatite. Therefore, these structures have to be ascribed to a pre-D₁ tectonic-metamorphic event. This interpretation is supported by petrological and geochronological constraints presented in the next section.

Another line of evidence for a pre-D₁ event is provided by the Song Re section, south of Di Lang (Fig. 2). There, the Ngoc Linh migmatite, coeval with the D₁ event, encloses

highly foliated and folded migmatitic blocks, the block internal foliation and fold axes oblique to the regional ones (Fig 4D) indicate that they belong to an older pre-D₁ event, in agreement with zircon U-Pb ages.

4. Metamorphic and geochronological constraints

The knowledge of the thermo-barometric conditions and ages of the tectonic-metamorphic events described in the previous section is a key issue in attempting to understand the tectonic evolution of the Kon Tum massif. This section synthesizes the available radiometric and metamorphic constraints available in the literature for the Kham Duc, Ngoc Linh, and Kan Nack complexes.

2.1. The Kham Duc complex.

Thermo-barometric investigations from metapelites and metagreywackes of the Kham Duc complex indicate that these rocks underwent a polymetamorphic evolution (e.g. Nakano et al., 2007, 2009, 2013; Osanai et al., 2008; Usuki, 2009; Yonemura et al., 2013). The main metamorphic assemblage in metapelite is characterized by biotite-garnet-sillimanite, yielding P and T conditions of 0.7 to 0.8 GPa, and 720-750°C, respectively. Monazite U-Th-Pb chemical dating of the Kham Duc metapelite gives Middle Triassic ages ranging from 246±3 Ma to 236±9 Ma (Nakano et al., 2009, 2013). Similar Triassic ages, between 257±4 Ma and 245±3 Ma, have been obtained by LA-ICP-MS method on zircon and monazite from paragneiss and orthogneiss around the Bong Mieu gold mine, between Tra My and Tam Ky (Tran et al., 2014). Lastly, biotite, muscovite, and amphibole from the Kham Duc metamorphic rocks, and the mylonites developed along the Tra Bong and Tam Ky shear zones yield two biotite and muscovite ⁴⁰Ar/³⁹Ar ages at ca 245 Ma and 230 Ma that are interpreted as those of the main D₁ metamorphic event, and the D₂ dextral shearing, respectively (Lepvrier et al., 1997, 2004, Vu et al., 2007).

Moreover, garnet, kyanite, and staurolite inclusions in plagioclase document an older MP/MT event under ca 1.2 GPa and 500-600°C P and T conditions. Furthermore, in this metamorphic complex, quartz-feldspar aggregates, foliated and lineated during the D₁ event, represent highly strained magmatic batches formed during an incipient stage of anatexis older than D₁ (Fig. 3C). Near Phuoc Son, in these migmatitic rocks, zircon rims yield SHRIMP U-Pb ages at 447±6 Ma, and 452±6 Ma interpreted as those of the migmatization (Usuki et al., 2009). Thus the age of the HP/MT event took place before 450 Ma, but after 548±7 Ma, which is the age of the youngest detrital zircon grain found in the metapelite (Usuki et al., 2009). A Late Ordovician age, at ca 460 Ma, seems likely. An Early Paleozoic, pre-D₁, tectonic and metamorphic event, represented by rare microstructures but with clear metamorphic relicts, was overprinted by the D₁ Early to Middle Triassic event (Nakano et al., 2009, 2013).

4.2. The Ngoc Linh complex.

The main metamorphic event in the Ngoc Linh complex is a HT/MP one, represented by biotite-garnet-sillimanite-cordierite migmatite that encloses mafic blocks of HP granulite with a garnet-clinopyroxene-orthopyroxene-plagioclase-quartz assemblage, and rare eclogites, (Osanai et al., 2004, 2009; Nakano et al., 2004, 2007, 2009, 2013). The thermo-barometric conditions for these two metamorphic facies are estimated at ca 900 to 1000°C and 1.3 to 1.6 GPa, for the HT/MP crustal melting, and 900°C-1.6 GPa for the preceding HP/MT one.

A wealth of radiometric ages is available for the Ngoc Linh complex (e.g. Nakano et al., 2013, and enclosed references). Monazite yields U-Pb chemical ages ranging from 247 Ma to 228 Ma. However, old ages between 462 Ma and 432 Ma are also measured in migmatitic gneiss from the western and southwestern parts of the Ngoc Linh complex. Zircon from this migmatite yields U-Pb SHRIMP ages at 436±10 Ma (Tran, 2004). Thus, two

migmatitic events, namely an Early Paleozoic, and a late Early Triassic one are recognized in the Ngoc Linh complex. Moreover, NE of Dak To, at Tu Mo Rong, Sm-Nd dating of HT granulite and gneiss gives isochron ages at 240 ± 26 Ma, and 247 ± 11 Ma, respectively (Nakano et al., 2007).

4.3. The Kan Nack complex.

The thermo-barometric conditions for the formation of the Kan Nack metamorphic rocks have been estimated at ca 1000°C and 1.2 GPa for the mafic granulite (Nakano et al., 2007, 2013), and 750°C and 0.3-0.4 GPa for the granulitic migmatite (Roger et al., 2007). As for the Ngoc Linh complex, two groups of ages are recognized there. The central and western parts of the complex yield Triassic ages. Zircon U-Pb, biotite $^{40}\text{Ar}/^{39}\text{Ar}$, and monazite U-Pb chemical ages range from 255 Ma to 240 Ma (e.g. Maluski et al., 2005; Roger et al., 2007; Nakano et al., 2007, 2013). Furthermore, in the eastern part of the Kan Nack complex (Song Bien area), zircon and monazite from migmatites and gneiss yield Early Paleozoic ages, ranging from 465 Ma to 422 Ma (Roger et al., 2007; Nakano et al., 2013 and enclosed references).

4.4. A polycyclic metamorphic evolution of the Kon Tum massif

The petrological and geochronological studies from the three metamorphic complexes allow us to draw their representative P-T-t paths, although the prograde parts of the paths are poorly documented (Fig. 11A, B). The Kham Duc metamorphic rocks document a kyanite-garnet-staurolite assemblage indicative of a MP/MT event, followed by a HT one, associated with crustal melting. This metamorphic evolution occurred during the Early Paleozoic, from 460 Ma to 445 Ma. Moreover, a late Early Triassic thermal event, dated around 250-246 Ma,

overprinted the Early Paleozoic cycle. These two different events argue for a polycyclic evolution of the Kham Duc complex.

High temperature, even ultra-high temperature (UHT), metamorphic rocks, coeval with migmatites, are widespread in the Ngoc Linh and Kan Nack complexes. The later complex reached higher temperatures (ca 1000°C) than the former. The UHT event was coeval with melting of the lower crust under HP conditions that produced charnockite and enderbite (Fig. 11B). The migmatite encloses mafic granulite and eclogite xenoliths that document an early HP event. The numerous multi-method geochronological studies support a late Early Triassic to early Middle Triassic age, at ca 250-230 Ma, for the crustal melting. Moreover, some migmatites also yield Early Paleozoic ages, between 460 and 430 Ma. Thus, the existence of a polycyclic evolution, as in the Kham Duc complex, is well documented in the Ngoc Linh and Kan Nack complexes. The accuracy of both the thermo-barometric estimates, and the radiometric dating, does not allow us to discriminate between the Triassic and Early Paleozoic migmatites on the basis of their P-T conditions of formation. The two P-T paths superimposes on the Fig. 11A and B. Moreover, the Early Paleozoic deformed xenolith migmatite enclosed in the Early Triassic migmatite, observed in the Song Re section (Fig. 4D), provides a field evidence for a polycyclic evolution.

5. Tectonic and geodynamic interpretations

5.1. The architecture of the Kon Tum massif

The structural, petrological, and geochronological data presented in the previous sections allow us to draw an interpretative crustal scale cross section of the Kon Tum massif, and the northern domain (Fig. 12, located in figure 2). The metamorphic rocks of the Ngoc Linh and Kan Nack complexes document a retrograde P-T path coeval with crustal melting, and top-to-the-North ductile shearing. These two complexes are interpreted here as forming a

metamorphic core complex (MCC) exhumed in the footwall of the Ngoc Linh detachment fault. In spite of some post- S_1 folds, the Kan Nack complex is interpreted as a flat lying unit exhumed from the granulitic lower crust, as indicated by the HT (or UHT) migmatite, charnockite, and enderbite overlying the Ngoc Linh complex. The Kan Nack complex exhumed from the deepest crust overlies the Ngoc Linh migmatitic complex. This extensional tectonics occurred between 250 Ma and 230 Ma. Both the Ngoc Linh and Kan Nack Triassic migmatite encloses Early Paleozoic xenoliths of migmatite, HP granulite, and Dai Loc or Ben Giang-Que Son granitoids. The northern boundary of the Ngoc Linh dome is cut by the D_2 dextral strike-slip faults of the Tra Bong fault system that mylonitized the Early Paleozoic Tra Bong granodiorite, and erased the microstructures related to the Ngoc Linh detachment.

More to the North, the Kham Duc complex is interpreted as an Early Paleozoic accretionary complex containing mafic and ultramafic blocks. The southern part of the complex experienced an Early Paleozoic anatexis, represented by the Chu Lai migmatite. As a whole, the Kham Duc metamorphic rocks, and the Chu Lai migmatite belong to the Tam Ky-Phuoc Son suture (Lepvrier et al., 2008; Tran and Vu, 2011; Tran et al., 2014). North of the Tam Ky-Phuoc Son suture, the Early Paleozoic sedimentary formations are devoid of any significant metamorphism. A Devonian unconformity, though often reworked by the Triassic tectonics, argues for an Early Paleozoic folding event (Tran and Vu, 2011; Than et al., 2012). Upright folds, associated to the Middle Triassic D_2 dextral ductile shearing, deform the entire Paleozoic succession. The Early Paleozoic Dai Loc plutons are also changed into orthogneiss during this D_2 shearing (Lepvrier et al., 1997, 2004). Therefore, the Kon Tum massif, and its northern domain, resulted from a polycyclic evolution. A HT/UHT extensional event, responsible for the late Early to early Middle Triassic exhumation of the Ngoc Linh and Kan Nack complexes, followed by a Middle Triassic strike-slip faulting, overprinted the Early Paleozoic orogen. At the crust-scale, the Tam Ky-Phuoc Son suture separates two different

basements. The northern block, tentatively called here the "North Vietnam" or "Viet-Lao block" underlies the northern domain, and to the South, a southern block, called here the "South Vietnam" or "Viet-Cambodia" block underlies the suture zone and was partly melted to form the Ngoc Linh and Kan Nack complexes during the Triassic.

On the western side of the Kon Tum massif, an Early Paleozoic ophiolitic suture has been proposed along the Po Ko fault (Lepvrier et al., 2008). Mafic and ultramafic rocks are exposed SW of Kon Tum in the Plei Wak complex, and Early Paleozoic Dien Binh granodiorite crops out west of the fault (Nagy et al., 2011). Our field observations suggest that the Po Ko fault is a Neogene sinistral strike-slip fault, but older ductile and synmetamorphic structures are not identified yet. Moreover, migmatite widely develops west of the Po Ko fault at least up the Laos border. Furthermore, the chemical composition of the main constitutive minerals (olivine, clinopyroxene, spinel) of the Plei Wak ultramafic body does not support an ophiolitic setting for this massif (Pham et al., 2006). More detailed work is necessary to clarify this point. In the following, the Po Ko suture will not be considered. NE of Dak To (Fig. 2), a dextral Dak To Kan shear zone was proposed (Osanai et al., 2008, Nakano et al., 2007, 2012). North of Dak To, the NW-SE striking, SW dipping S_1 foliation contains a subhorizontal mineral and stretching L_1 lineation (Fig.5, stereogram E). This structure appears different from the other strike-slip faults described in the northern domain both by its "old" age, around 250 Ma, at variance with the ca 230 Ma age of the Tra Bong shear zone, and by its HT metamorphic conditions. An alternative interpretation can be proposed if considering that the present SW dip of the S_1 foliation is not primary but due to the late normal faulting D_3 event. In this case, if S_1 is restored to its subhorizontal initial geometry, the apparent dextral sense of shear becomes a top-to-the-NW one, consistent with the D_1 kinematics observed in other parts of the Ngoc Linh dome (Fig. 5).

5.2. The place of the Kon Tum massif in the Triassic (Indosinian) orogeny.

In order to discuss the Paleozoic and Mesozoic evolution of the Indochina block, it is necessary to reconstruct its Early Triassic paleogeography with respect to South China. Presently, the Indochina block is bounded to the North by the Ailaoshan-Song Ma ophiolitic suture that can be correlated to the Song Chay-Hainan, and Jinshajiang suture to the East and Northwest, respectively (Fig. 13; Faure et al., 2014, 2016b; Xu et al., 2015). Several lines of evidence lead us to argue that the Indosinian collision occurred in Early to Middle Triassic. It was preceded by a southwestward (in the present coordinate) subduction, that is to say that the South China Block (SCB) subducted below the Indochina block that represented the upper plate of the collision system (see Faure et al., 2014, 2016a, b for details). During the late orogenic evolution of the Indosinian belt, a series of NW-SE striking dextral shear zones developed (Lepvrier et al., 1997, 2004).

It is well acknowledged that the Indian collision was responsible for an important disturbance in the Triassic architecture of Indochina. The left-lateral Red River fault (RRF) accommodated the SE-ward extrusion of Sundaland with respect to the SCB (Tapponnier et al., 1990). A controversy remains on the amount of displacement along the RRF. Our field based tectonic reconstruction suggests an offset of ca 500 km close to that proposed by many authors on geological and paleomagnetic bases (e. g. Leloup et al., 1995; Royden et al., 2008; Otofuiji et al., 2012; Li et al., 2017). Furthermore, the total amount of Triassic dextral motion that widely distributes between the Song Ma fault, Song Ca, Truong Son, and Tra Bong fault system, can be estimated to ca 250 to 350 km on the basis of the offset of geological markers, the km-scale width of each ductile shear zone, and the pervasive deformation associated to each shear zone. Thus, an Early Triassic palinspastic reconstruction of the Indochina and SCB relative position just after the collision, but before the late Middle to Early Triassic dextral faulting, is proposed in figure 14. The ca 500 km Cenozoic sinistral offset along the RRF is

partly balanced by the ca 300 km Triassic dextral one. In this qualitative reconstruction, the Kon Tum massif appears in the upper plate of the Indochina orogen, about 600 km southward of the Song Ma-Song Chay ophiolitic suture zone. The question of the heat source able to supply a sufficient temperature elevation to generate the UHT granulite facies metamorphism must be addressed.

A late orogenic thermal overprint is common in many collisional orogens such as the Variscan belt of Western Europe (e. g. Ledru et al., 2001; Martinez-Catalan et al., 2009; Schulman et al., 2008; Faure et al., 2010; Lardeaux et al. 2014), the Himalaya (Le Fort et al., 1987), or the Qinling-Dabie belt of central China (e.g. Lin et al., 2015; Ji et al., 2017). The collision related crustal thickening is often acknowledged as the source of the radiogenic heat responsible for the crustal melting, and subsequent MCC development in the subducted continental crust of the lower plate. In such a setting, an UHT metamorphism is rare. It also does not account for the Ngoc Linh MCC as this structure developed in the upper plate of the collision system. Another proposed case is heat advection in the upper plate lower crust triggered by asthenospheric mantle upwelling in a subduction setting. There, a slab breakoff of the subducting lithosphere is a prerequisite to promote UHT granulite facies metamorphism and crustal melting (e. g. Kelsey and Hand, 2015; Touret et al., 2016, and enclosed references). In this respect, the Kon Tum massif appears as unusual, as a linear trend of the UHT metamorphic rocks, parallel to the Triassic belt that would better comply with a slab breakoff mechanism is expected instead of the "punctual" occurrence observed for the Ngoc Linh MCC.

It is worth noting that during the Late Permian, between 263 Ma and 257 Ma, the Emeishan-Song Da-Tu L  Large Igneous Province (LIP, Ali et al., 2005; Schellnutt et al., 2015; Fig 14) was emplaced in the western part of the SCB. The present separation between the Emeishan LIP and the Song Da-Tu L  area is a consequence of the Cenozoic sinistral

faulting along the RRF (Fig. 13). Assuming that the mantle plume that produced the Emeishan-Song Da-Tu L^ê LIP at ca. 260 Ma (e.g. Schellnutt et al., 2015) remained fixed with respect to the asthenospheric mantle, and that the SCB-Indochina lithospheric system moved northward with a 80 km/Ma velocity, as currently measured for the present Pacific or Philippine Sea plates (e.g. Gripp and Gordon, 2002), the Kon Tum massif was overlying the mantle plume in late Early Triassic, at ca 245 Ma (Fig. 15). The mantle plume-related heat flow triggered the melting of the lower crust, giving rise to the charnockite and enderbites of the Kan Nack complex, and subsequently the middle crustal melting in the Ngoc Linh complex. The tectonically assisted upward migration of the melted continental crust led to the extensional emplacement of the Ngoc Linh MCC. The top-to-the-NW sense of shear might be a consequence of the N-dipping Early Paleozoic inherited crustal structure. The importance of a mantle source for the heat flux required to produce the UHT metamorphism of the Kon Tum massif was also documented by petrography and geochemistry (Owada et al., 2006, 2016; Osanai et al., 2008). Thus, the role of the Emeishan-Song Da LIP, related to a mantle plume, as a possible heat source for the melting of the continental crust in the Kon Tum massif must be seriously considered.

The interaction between the rise of a mantle plume, and a subduction zone is a complex issue, still poorly documented. This question has been addressed for an oceanic subduction in several natural examples, such as the Cordilleran Laramide belt of western US (Murphy et al., 1998), in the W. Gondwana region (Dalziel et al., 2000), and in the Central Asia Orogenic Belt (Betts et al., 2015). Numerical and analogue modelings shed light on the active thermo-mechanical processes (Fletcher and Wyman, 2015; Betts et al., 2015, Mériaux et al., 2016). These studies emphasize the development of extensional tectonics in the upper crust of the upper plate overlying the plume. The case of continental subduction, as in SCB-Indochina area, is more complex than that of an oceanic subduction, as asthenospheric magma

upwelling must cross through the subducting continental lithosphere. A slab break off, as also assumed in the Western US (Murphy et al., 1988), would probably permit heat transfer from the mantle plume to the lithosphere necessary to enhance the magmatic underplating. Osanai et al., (2008) already suggested such a mechanism, but the northward subduction of Indochina block below SCB invoked by the authors is not in agreement with the magmatic arc on the Indochina block side. Presently, the geochemical and geophysical records that would allow us to test this interpretation are lacking. Thus, this geodynamic scenario, schematically depicted in Figure 15, must be considered as a working hypothesis.

5.3. The Early Paleozoic evolution of the Kon Tum massif.

Early Paleozoic ages are widespread in the Ngoc Linh MCC, but contemporaneous structures are rare, except in the Kham Duc complex where intrafolial folds might be ascribed to the pre-D₁ event. In the Kham Duc complex, various blocks of sedimentary or volcaniclastic rocks, amphibolite, metagabbro, and serpentinites enclosed into a metasandstone matrix has been recognized as an Early Paleozoic accretionary complex, also called the Tam Ky-Phuoc Son suture (Izokh et al., 2006; Pham et al., 2006; Lepvrier et al., 2008; Tran and Vu, 2011; Tran et al., 2014). This plate boundary represents the place where the N. Vietnam (or Viet-Lao) block and the S. Vietnam (or Viet-Cambodia) block were welded together. Thus the question of the subduction polarity arises. The existence of an Early Paleozoic magmatic arc is supported by the calc-alkaline granodiorites of the Dien Binh and Tra Bong suites (Fig. 2), though the available ages, between 445 Ma and 415 Ma (Nagy et al., 2001; Carter et al., 2001), are younger than the late orogenic crustal melting of the Kham Duc, and Ngoc Linh complexes dated at ca 450 Ma (Roger et al., 2007; Usuki et al., 2009; Nakano et al., 2013). In Laos, close to the study area, a calc-alkaline granodiorite similar to the Dien Binh suite yielded a zircon U-Pb LA-ICP-MS age of 470 Ma (Gardner et al., 2017). Moreover, a zircon

LA-ICP-MS age at 479 ± 3 Ma (Pham and Huynh, 2016) from a calc-alkaline quartz diorite in an Early Permian Ben Giang-Que Son pluton could be interpreted as a relict grain inherited from an Early Paleozoic magmatic arc formed in a continental active margin (Tran et al., 2008; Pham and Huynh, 2016).

From the litho-stratigraphic point of view, south of Hue (Fig. 2), in the Binh Tri Thien zone, or South Truong Son area, the Ordovician rocks of the Long Dai Formation consist of rhythmic alternations of sandstone, siltstone, mudstone, with intercalations of radiolarian chert, and andesitic layers (Tran and Vu, 2011, Thanh et al., 2013). The Early Silurian deposits consist of sandstone and tuffaceous shales, but lack andesitic rocks. Lastly, the Late Silurian (Ludlow, 423-419 Ma) Dai Giang Formation unconformably covers the Ordovician-Early Silurian rocks. Thus, an Ordovician-Early Silurian magmatic arc located to the North of the Kon Tum massif seems likely, although its precise location remains uncertain yet.

The Early Paleozoic (ca 450 Ma) late orogenic anatexis is documented by the Chu Lai migmatite in the southern part of the Kham Duc complex (Usuki et al., 2009). The Early Paleozoic age, at 436 ± 10 Ma, of the foliated migmatite xenoliths (Fig 4D; Nam et al. 2004) enclosed in the Triassic Ngoc Ling dome is also considered here as an evidence for the Early Paleozoic orogeny. During the late orogenic stage, after the collision, the melting of metapelites that formed the Dai Loc S-type plutons is dated between 427 Ma and 423 Ma (Fig. 16). In the same way, the Early Paleozoic HP rocks, granulitic and eclogitic relics, enclosed in the Ngoc Linh and Kan Nack complexes (Roger et al., 2007; Nakano et al., 2004, 2007, 2013), might represent remnants of the deep-seated part of the Early Paleozoic belt of Central Vietnam. In most of orogens in the world, the highly metamorphosed and deformed rocks belong to the lower plate that underwent subduction. In Central Vietnam, the Early Paleozoic migmatites and metamorphic rocks are located to the south of the Tam Ky-Phuoc Son suture, whereas, north of the suture, the pre-Devonian rocks are represented by

sedimentary and volcanic formations. Therefore, in agreement with the presence of an Early Paleozoic andesitic magmatism North of the Tam Ky-Phuoc Son suture, a north-directed subduction is preferred here (Fig. 16). In the present state of knowledge, except the N-S striking mineral lineation observed in the Chu Lai migmatite, the microstructures and associated kinematic indicators related to the Early Paleozoic orogen have not been recognized yet.

5.4. A possible interaction between the Early Paleozoic belts of Indochina and South China.

The collision between the N. Vietnam (or Viet-Lao) block and the S. Vietnam (or Viet-Cambodia) block was responsible for the development of the Tam Ky-Phuoc Son suture (Fig. 13). This event might have also an important significance for the geodynamic evolution of Asia. This section explores some possible relationships between the pre-Devonian belts of South China and the Tam Ky-Phuoc Son belt. In South China, two Early Paleozoic orogenic belts are recognized (Figs. 13, 14). To the north, the Qinling-Qilian orogen resulted of the collision between the North China and South China blocks. The age of the collision remains disputed, although a Triassic collision is often put forward, several lines of evidence argue for a pre-Devonian collisional event, at ca 420 Ma (e.g. Mattauer et al., 1985; Faure et al., 2008, Dong et al., 2015; Shi et al., 2016). Nevertheless, whatever its real age, the SCB-NCB collision is younger than the Early Paleozoic tectonics in Indochina, and it will not be considered in the following.

On the contrary, the central part of the SCB is occupied by a NE-SW striking intracontinental orogen characterized by a south-directed fold-and-thrust belt, a top-to-the-South ductile decollement, and a polyphase metamorphism. An Early MP/MT event, dated at ca 460-455 Ma, reworked by a HT/LP event coeval with migmatites and peraluminous granites, dated between 440 Ma and 400 Ma, has been identified (for details see Faure et al.,

2009; Charvet et al., 2010, Li et al. 2010). This belt, devoid of ophiolites, subduction complex, and magmatic arc is an intracontinental orogen that resulted from the closure of a Neoproterozoic-Cambrian rift accommodated by a North-directed continental subduction (Faure et al., 2009; Charvet et al., 2010). The cause of this intracontinental orogeny was not understood yet. A collision between the main part of SCB and Australia, a piece of which is supposed to be located in Hainan island, has been proposed (Xu et al., 2016). However, the geological record for Early Paleozoic arc magmatism, and ophiolitic suture are missing in Hainan island. As no other Early Paleozoic ophiolitic suture is recognized between the SCB intracontinental orogen and the Tam Ky-Phuoc Son suture, the SCB and N. Vietnam block belonged to the same continent until the Devonian (Metcalf, 2013). In late Cambrian-Early Ordovician, the S. Vietnam (Viet-Khmer) continent subducted below the N. Vietnam (Viet-Lao) that was a part of the SCB, within which an intracontinental rift developed (Fig. 16). The Middle to Late Ordovician (460-450Ma) collision between the N. Vietnam and the S. Vietnam blocks led to the closure of the intracontinental rift of the SCB. During the Silurian, the late- to post-collisional evolution was responsible for the crustal melting experienced by the S. Vietnam block, and SCB. Therefore, we propose here that the collision between the N. Vietnam (Viet-Lao) and S. Vietnam (Viet-Cambodia) blocks induced stress propagation in the SCB, and was responsible for the closure of the Neoproterozoic-Cambrian rift of SCB, and the related deformation and metamorphism. The Early Paleozoic intracontinental orogeny of South China may be considered as a consequence of a far-field effect of the central Vietnam collision (Fig. 16), in the same way as the Central Asia Cenozoic structures resulted from the Himalayan collision. This SCB-Viet-Lao continental mass was split during the Carboniferous by the opening of a branch of the Paleotethys Ocean (Nguyen et al., 2013) that was closed in the late Early to early Middle Triassic by the Indosinian orogeny.

699

700 6. Conclusion

701 The Kon Tum massif of Central Vietnam provides important clues for understanding
 702 the restless geodynamic movements between the SCB and Indochina block. The Kon Tum
 703 massif of Central Vietnam cannot be simply considered as the Precambrian nucleus of
 704 Indochina. This massif experienced a polycyclic evolution. Although structural evidence is
 705 poorly preserved, the geochronological and petrological records indicate that an Early
 706 Paleozoic (at ca 460-450 Ma) collision, along the Tam Ky-Phuoc Son suture. The syn-
 707 metamorphic structures preserved in the Kon Tum massif developed during Early Triassic (at
 708 ca 250-240 Ma) within an extensional tectonic setting, giving rise to pervasive crustal melting
 709 and the formation of the Ngoc Linh metamorphic core complex.

710 The Early Paleozoic collision was responsible for the welding of the S. Vietnam (or
 711 Viet-Cambodia) block and the N. Vietnam (or Viet-Lao) block that was at that time a part of
 712 the SCB. This collision is also interpreted here as the driving force that closed the
 713 Neoproterozoic-Early Paleozoic Nanhua continental rift basin, and triggered the formation of
 714 the intracontinental orogen of South China. Since the Early Devonian, the SCB, Viet-Lao, and
 715 Viet-Cambodia blocks formed a single continental mass characterized by similar faunistic and
 716 floristic fossil assemblages and sedimentary facies (Thanh et al., 1996; Janvier et al., 1997,
 717 1998; Metcalfe, 2002, 2013). This continent was subsequently disrupted by the opening of the
 718 Paleotethys ocean in Carboniferous times (Nguyen et al., 2013). Since that time, the SCB and
 719 Indochina became separated. The Indochina block appears as a composite continent formed,
 720 at least by the Viet-Lao and Viet-Cambodia blocks. The Ailaoshan-Song Ma-Song Chay-
 721 Hainan ophiolitic suture is now acknowledged as the plate boundary, the collision age is no
 722 longer a matter of debate. The closure of the Paleotethys ocean was accommodated by a
 723 south-directed subduction, as shown by the Permian Sam Nua magmatic arc, followed by the

continental subduction of the SCB below Indochina. The Song Ma and Song Chay ophiolitic sutures belong to a thousands of km long collisional belt that extends, at least, from Eastern Tibet to Hainan, and probably farther East (see discussion in Faure et al., 2016a). Within this general scenario, the tectonic survey of the Kon Tum massif indicates that the Early to Middle Triassic Ngoc Linh MCC developed in the upper plate of the collision system. The radiogenic crust of Indochina thickened by the Early Triassic collision was not able to supply the important heat input required to form the UHT metamorphic rocks, such as granulites, charnockites, and enderbites, in the lower continental crust. The mantle plume that formed the Emeishan LIP in Late Permian might have represented the main heat source, as this plume afterwards underlain Indochina in late Early to early Middle Triassic. Forthcoming structural, petrological, and geochemical investigations will provide new lines of evidence to refine the geodynamic scenario of this continental ballet.

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1095 Figure Captions

1096

1097 Fig. 1. Tectonic sketch of SE Asia with emphasis of the Early-Middle Triassic (Indosinian),
1098 and Late Triassic-Early Jurassic (Cimmerian) sutures. Modified from Sone and Metcalfe,
1099 2008; and Lepvrier et al., 1997).

1100

1101 Fig 2. Simplified litho-structural map of the Kontum Massif and the northern area (South
1102 Truong Son). The dashed line between Dak To and Tu Mo Rong is the Dak To Kan shear
1103 zone proposed by Nakano et al. (2007, 2012); and Osanai et al. (2008).

1104

1105 Fig. 3. Field pictures of the Kham Duc complex. A: pillow basalts (GPS N15.60017;
1106 E107.43735); B: partially melted metagabbro (GPS N15.44366; E107.84521); C: partly
1107 melted mylonitic paragneiss, the white layers are Early Paleozoic quartz-feldspar aggregates
1108 corresponding to leucosomes deformed by the Triassic D₁ deformation (GPS N15.51322;
1109 E107.81195); D: isoclinally folded leucosomes formed during the D₁ or pre-D₁ event (GPS N
1110 15.53013; E107.81676).

1111

1112 Fig. 4. Field pictures of the Ngoc Linh complex. A: Triassic metatexite derived from a
1113 graywacke protoliths (W. of Quang Ngai; GPS N.14.99382; E108.78465); B: Garnet-biotite-
1114 sillimanite-cordierite gneiss, the K-feldspar megacrysts suggest that it derived from an
1115 orthogneiss (near Tu Mo Rong; GPS N14.99383; E107.89547); C: metatexite with mafic
1116 xenolith (N. of Di Lang; GPS N14.92865; E108.64905); D: Early Paleozoic folded metatexite
1117 block with a pre-D₁ foliation enclosed in the Triassic migmatite (S. of Di Lang; GPS
1118 N15.00483; E108.50844).

1119

Fig. 5. Structural elements of the Kon Tum massif. Stereoplots (Schmidt net, lower hemisphere) showing the statistical preferred orientation of the structural elements: S_1 , L_1 , S_2 , L_2 , F_2 . The stereogram with grey back compiles the total L_1 measurements for the Ngoc Linh complex. The foliation trajectory outlines the domal shape of the Ngoc Linh complex, and the dominantly S-ward dip of the Kan Nack complex. Arrow indicates the top-to-the NW sense of shear related to the D_1 event.

Fig. 6. Sketch of collapse fold, similar to the one shown in Fig. 7C, responsible for the reorientation of L_1 . The NW-SE trend of L_1 in the normal limb is changed to NE-SW in the inverted one. The top-to-the NW sense of shear becomes top-to-the-NE.

Fig. 7. Kinematic indicators related to the D_1 and D_2 events in the Ngoc Linh complex. A: Sigmoidal leucosome with top-to-the-NW sense of shear in a subhorizontal foliation (W. of Quang Ngai; GPS N14.92498; E108.67458); B: top-to-the-NW sigmoidal leucosome in a South dipping foliation (S. of Di Lang; GPS N14.82420; E108.54218); C: NW verging "collapse" fold (N. of Nam Tra My; GPS N15.23340; E108.09438); D: D_2 upright fold developed in the Ngoc Linh migmatite (S. of Tra My; GPS N15.29946; E108.12762); E: sigmoidal leucocratic boudins in metatexite (W. of Quang Ngai; GPS N15.20117; E108.10903); F: pluri-meter sized retort-shaped leucosomic boudin indicating a top-to-the-NW sense of shear (N. of Nam Tra My; GPS N15.18497; E108.11713).

Fig. 8. Field-scale kinematic indicators in the Phuoc Son complex and Chu Lai migmatite. A: asymmetric amphibolite boudin indicating a top-to-the-NW sense of shear (Phuoc Son; GPS N15.51221; E107.81304); B: NW verging F_2 folds refolding a D_1 or pre- D_1 isoclinal fold (Phuoc Son; GPS N15.46803; E107.83970); C: Upright F_2 fold developed in the Early

Paleozoic Chu Lai migmatite (GPS N15.35611; E108.23472); D: Intrafolial pre-D₁ fold coeval with the Early Paleozoic Chu Lai migmatite (GPS N15.35611; E108.23472).

Fig. 9. Thin section-scale kinematic indicators of the D₁ event showing a top-to-the NW sense of shear in the Ngoc Linh and Phuoc Son complexes. A: D₁ sigmoidal biotite aggregate in paragneiss (Phuoc Son; GPS N15.53013; E107.81676); B: pre-D₁ kyanite relict enclosed in a sigmoidal plagioclase porphyroblast deformed during D₁ (GPS N15.49237; E107. 82388) C: pre-D₁ kyanite relict enclosed in a sigmoidal plagioclase porphyroblast (Phuoc Son; GPS N15.49237; E107.82388); D, E: sigmoidal muscovite in micaschist (GPS N14.92548; E108.60463, N15.22334; E108.43497, respectively); F: quartz grain with an oblique shape fabric (dashed line) due to synkinematic recrystallization (N15.20898; E108.41955).

Fig. 10. Geometric relationships between the Early Paleozoic Chu Lai migmatite, and the Triassic Ngoc Linh migmatite. The S₁ foliation, and L₁ stretching lineation formed during the D₁ event in the Ngoc Linh migmatite are folded by the D₂ event, coeval with the right lateral strike-slip faulting along the Tra Bong fault. The Chu Lai migmatite, containing intrafolial folds with high-angle dipping axes, is deformed by the post-folial D₂ upright folds (see Fig. 8C, D for a natural example).

Fig. 11. P-T-t paths for the Kan Nack (KN), Ngoc Linh (NL), and Kham Duc (KD) metamorphic complexes (modified from Roger et al., 2007, and Nakano et al., 2013). A: Early Paleozoic event. The rocks of the Kham Duc and Ngoc Linh complexes reached their maximum pressure around 460 Ma. The retrograde paths were coeval with HT and crustal melting around 450-420 Ma. B: Early to Middle Triassic event. The rocks of the Ngoc Linh and Kan Nack complexes experienced a decompression melting event at UHT conditions.

1170

1171 Fig. 12. Crustal scale cross section of the S. Truong Son belt, and Kon Tum Massif. The Early
 1172 Paleozoic Tam Ky-Phuoc Son suture zone separates a northern block (N. Vietnam or Viet-
 1173 Lao block) from a southern block (S. Vietnam or Viet-Cambodia block). The weakly
 1174 deformed Paleozoic series of the Viet-Lao block argues for a north-directed subduction. The
 1175 Early to Middle Triassic Ngoc Linh metamorphic core complex (MCC) superimposes on the
 1176 Early Paleozoic belt. The northern border of the Ngoc Linh MCC is cut by E-W striking
 1177 dextral fault of the Tra Bong shear zone; the detachment fault is interpreted.

1178

1179 Fig. 13. Present tectonic map showing the different orogenic belts of S. China and Indochina
 1180 blocks: Neoproterozoic (Jiangnan), Early Paleozoic, and Triassic (simplified from Faure et
 1181 al., 2016a). JSJ: Jin Sha Jiang; AS: Ailaoshan, SM: Song Ma, SC: Song Chay; PKF: Po Ko
 1182 Fault, DBF: Bien Bien Fu Fault; RRF: Red River Fault, TS: Truong Son, XFS: Xuefengshan.

1183

1184 Fig. 14. Reconstruction of the Indochina-South China blocks tectonic framework in Early
 1185 Triassic. A: Palinspastic map after removing the Cenozoic sinistral strike-slip motion, and the
 1186 Triassic dextral strike-slip along the late Indosinian faults. In this reconstruction, the
 1187 Emeishan-Song Da LIP is about 1200 km from the Ngoc Linh MCC. B: schematic crustal
 1188 scale cross section from N. China to Kon Tum massif.

1189

1190 Fig. 15. Permian-Triassic geodynamic evolution of the SCB-Indochina lithosphere with
 1191 respect to the Emeishan plume fixed. In the Late Permian, a post-collisional slab break off is
 1192 inferred to allow heat transfer from the mantle plume to the Indochina lithosphere.

1193

1194 Fig. 16. Early Paleozoic to Late Carboniferous geodynamic evolution model from the North
1195 China block (NCB) to South Vietnam. The Middle to Late Ordovician (around 460 Ma)
1196 continental collision between the N. Vietnam (Viet-Lao) and S. Vietnam (Viet-Cambodia)
1197 blocks is interpreted as the driving force for the intracontinental belt of S. China. The NCB-
1198 SCB collision took place later, around 420 Ma. The Paleotethys ocean opened in Late
1199 Carboniferous.

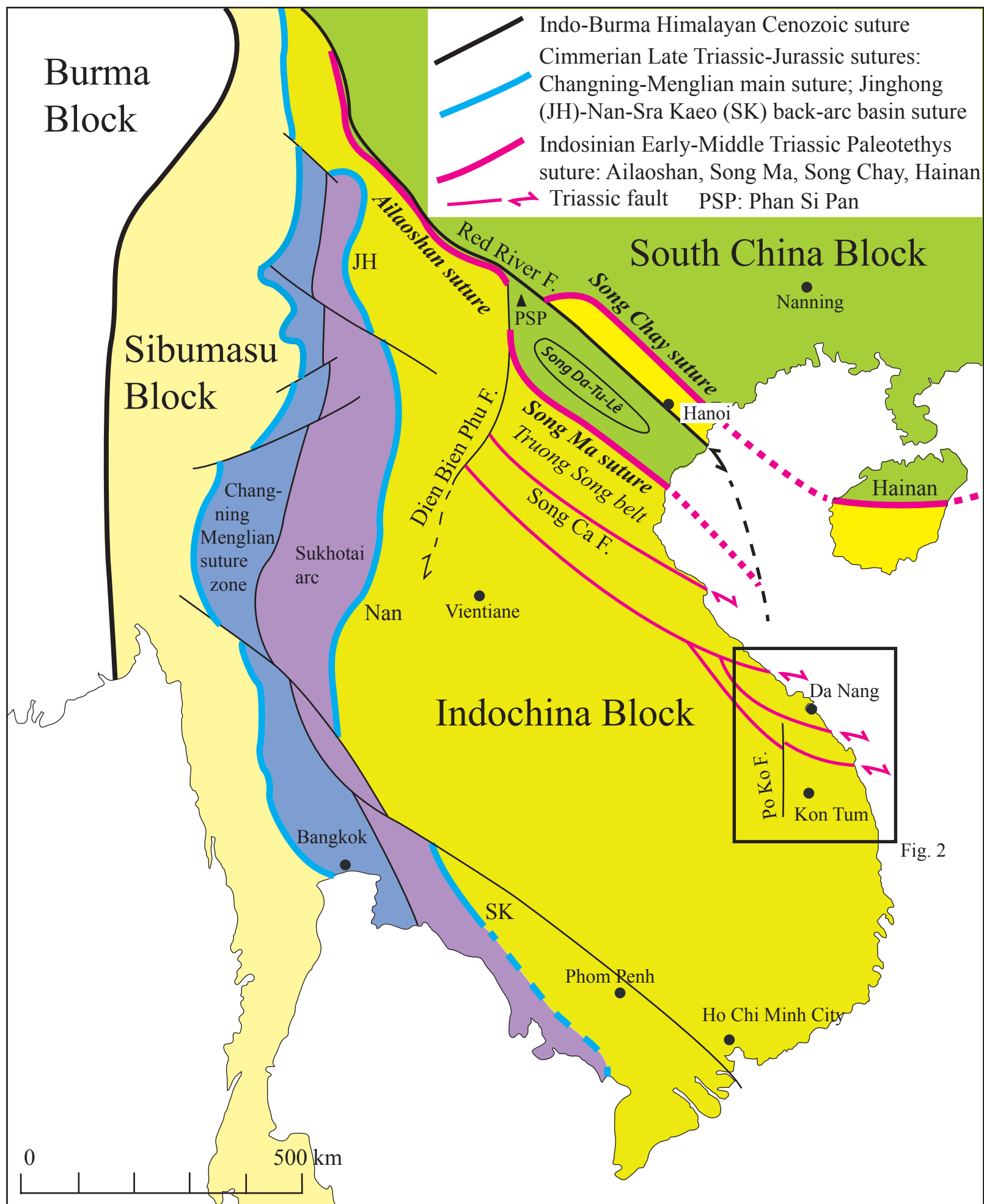


Fig. 1

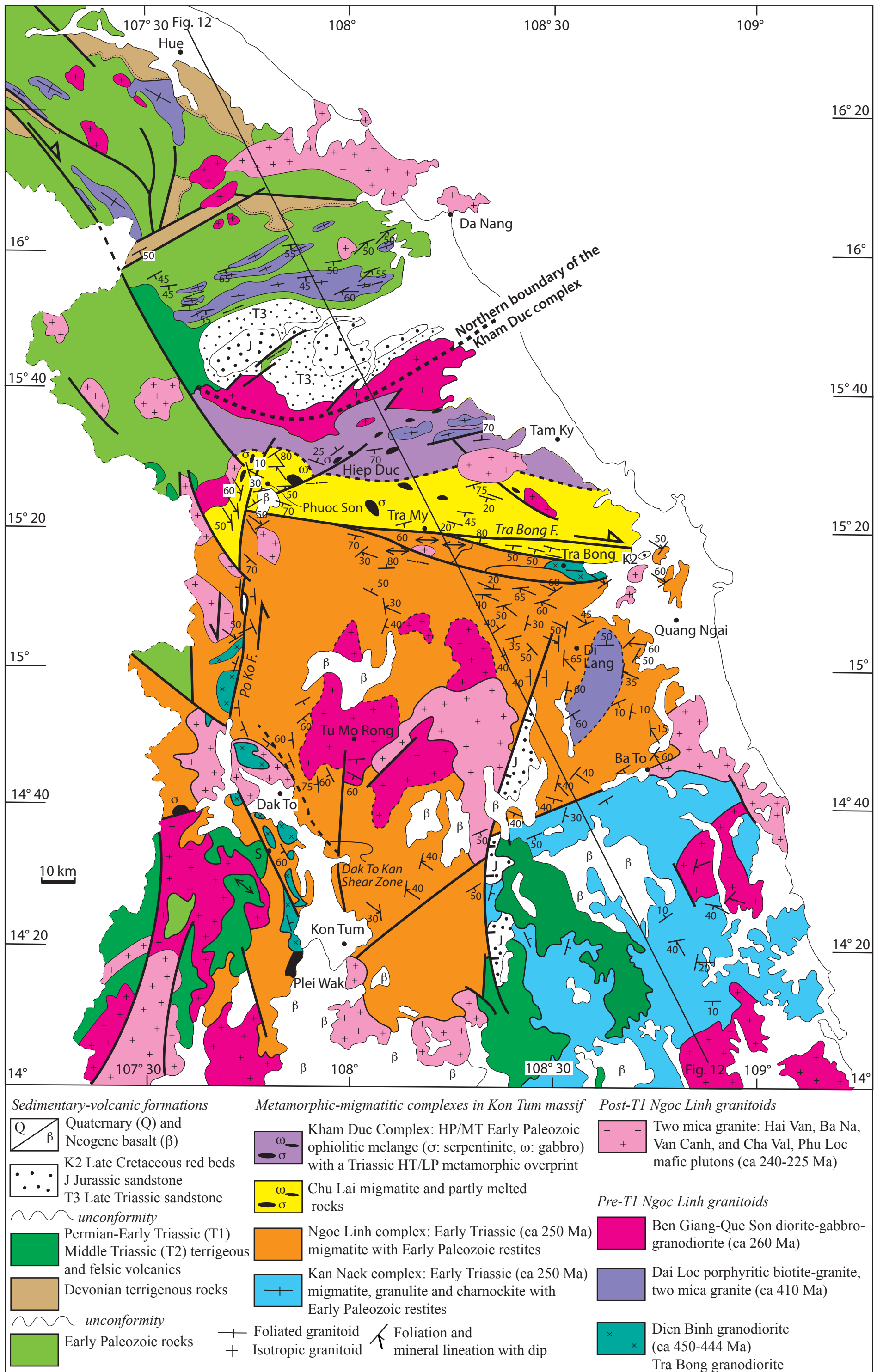


Fig. 2



Fig. 3

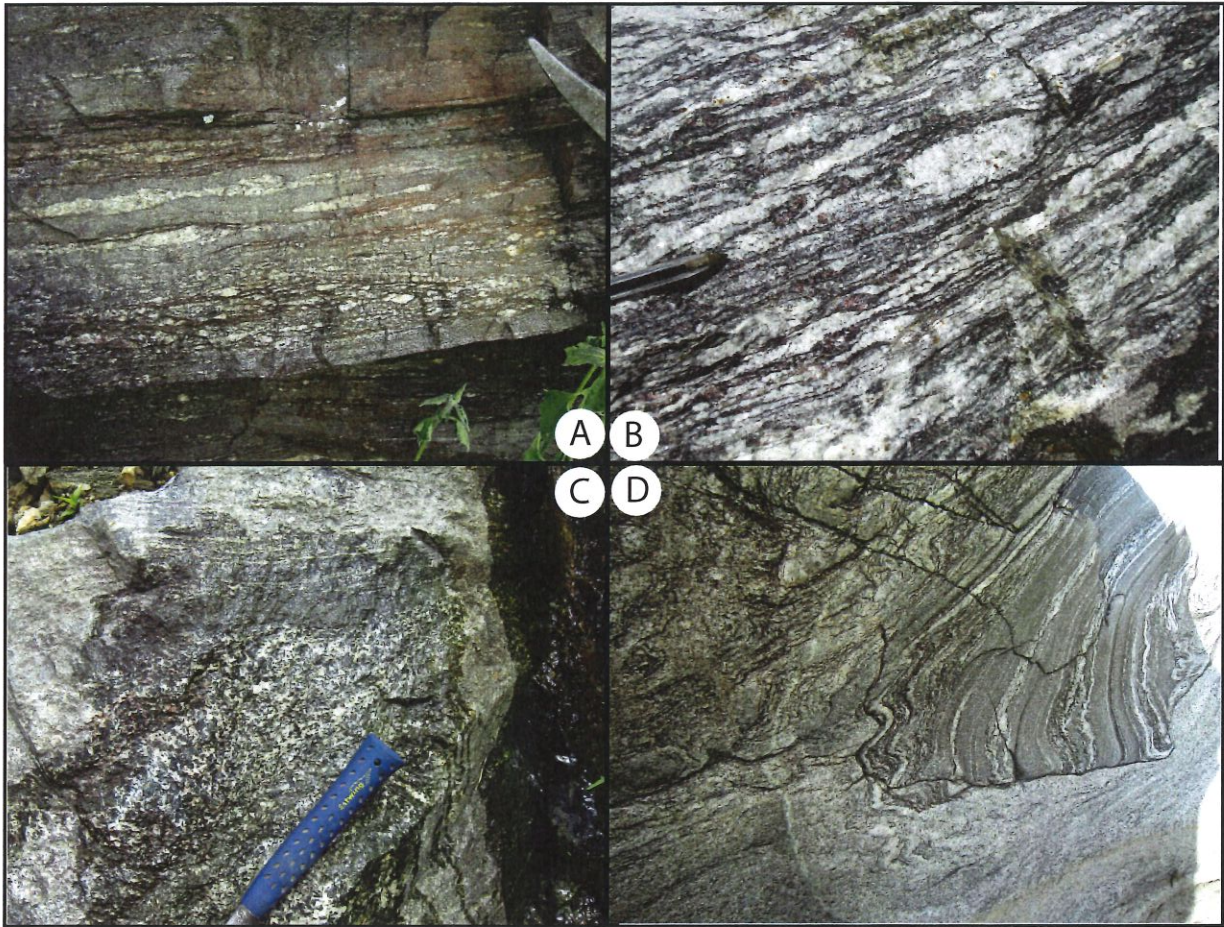


Fig. 4

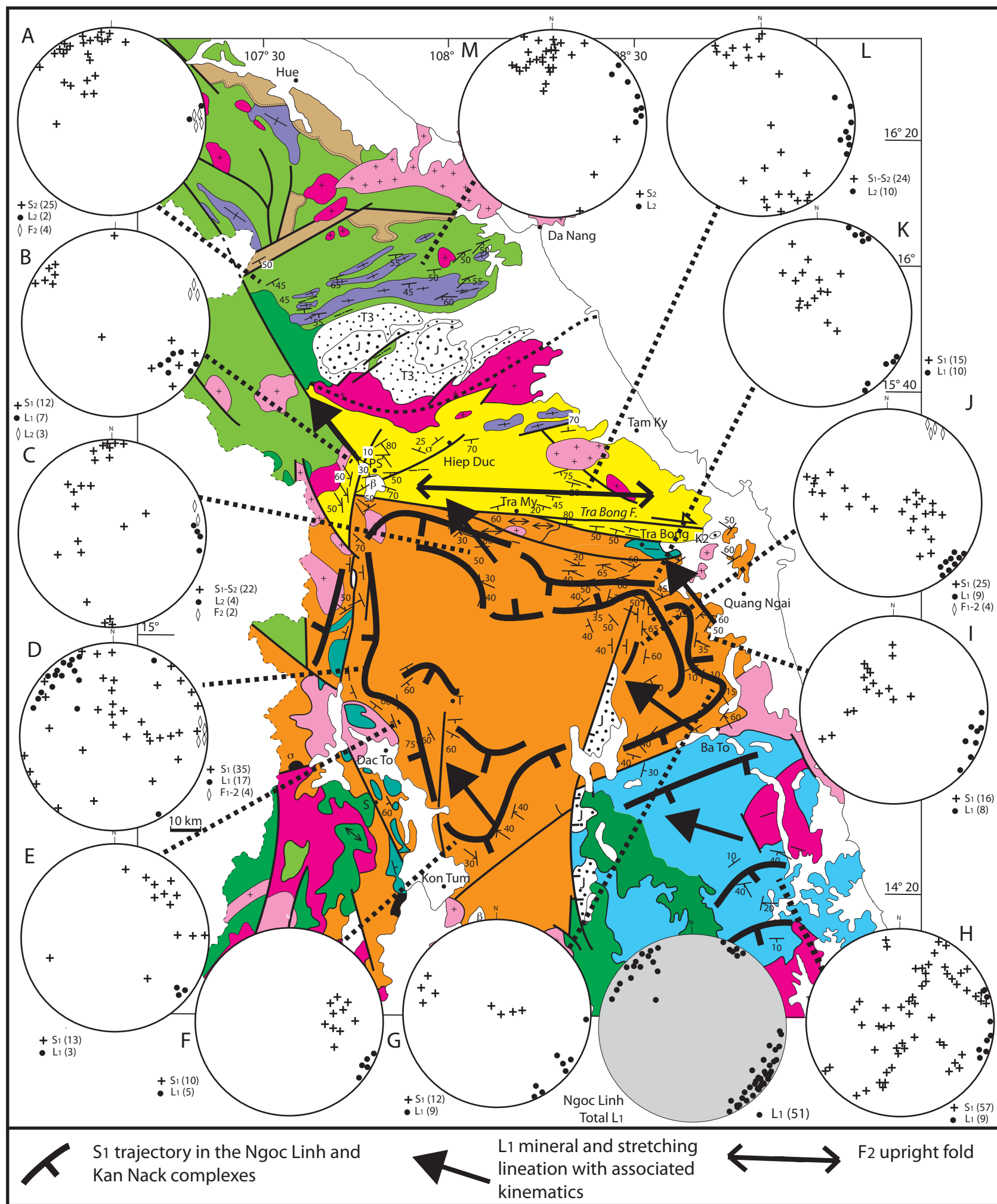


Fig. 5

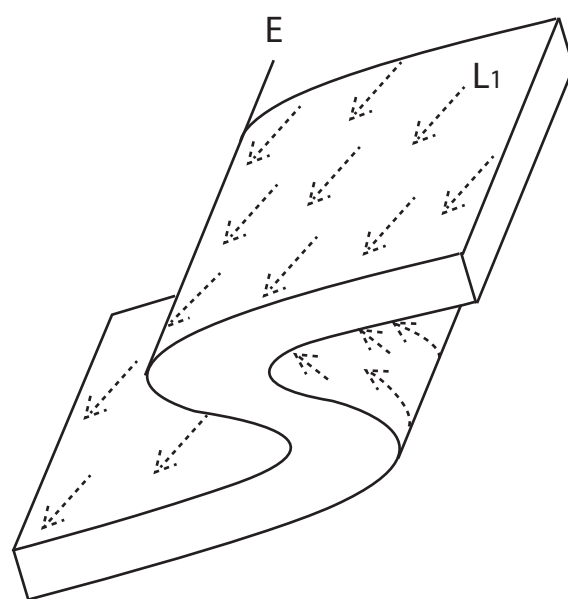


Fig. 6

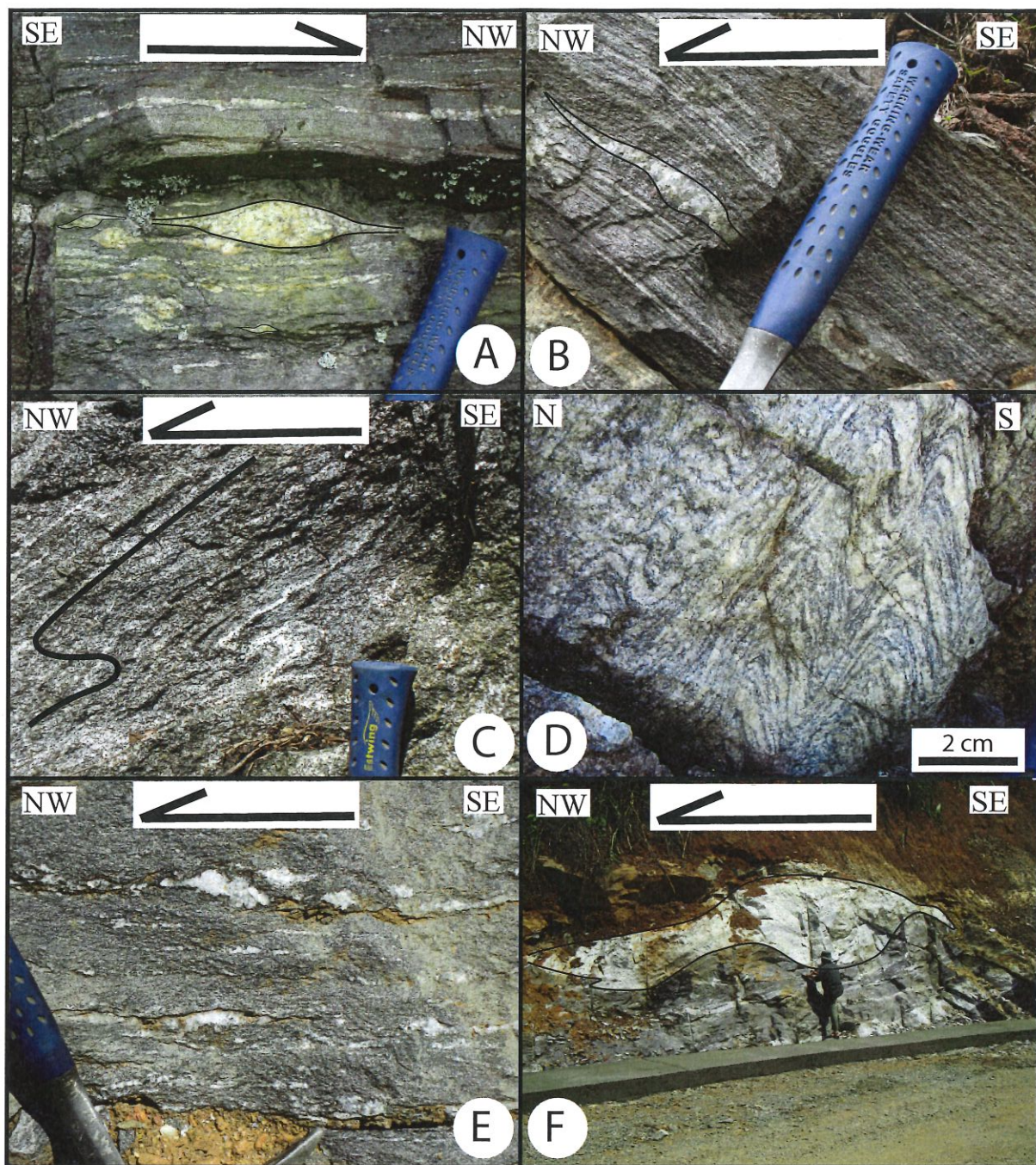


Fig. 7

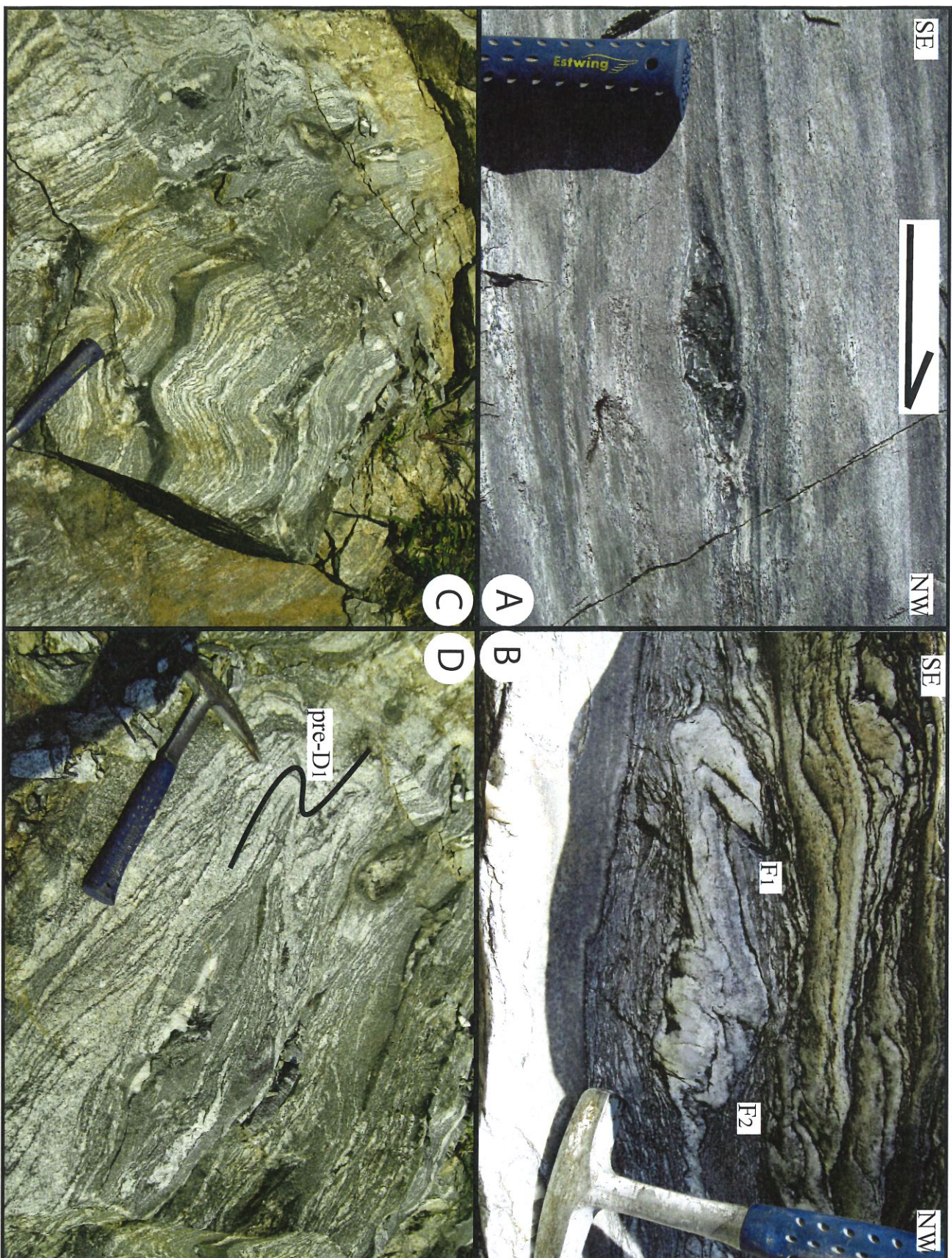


Fig. 8

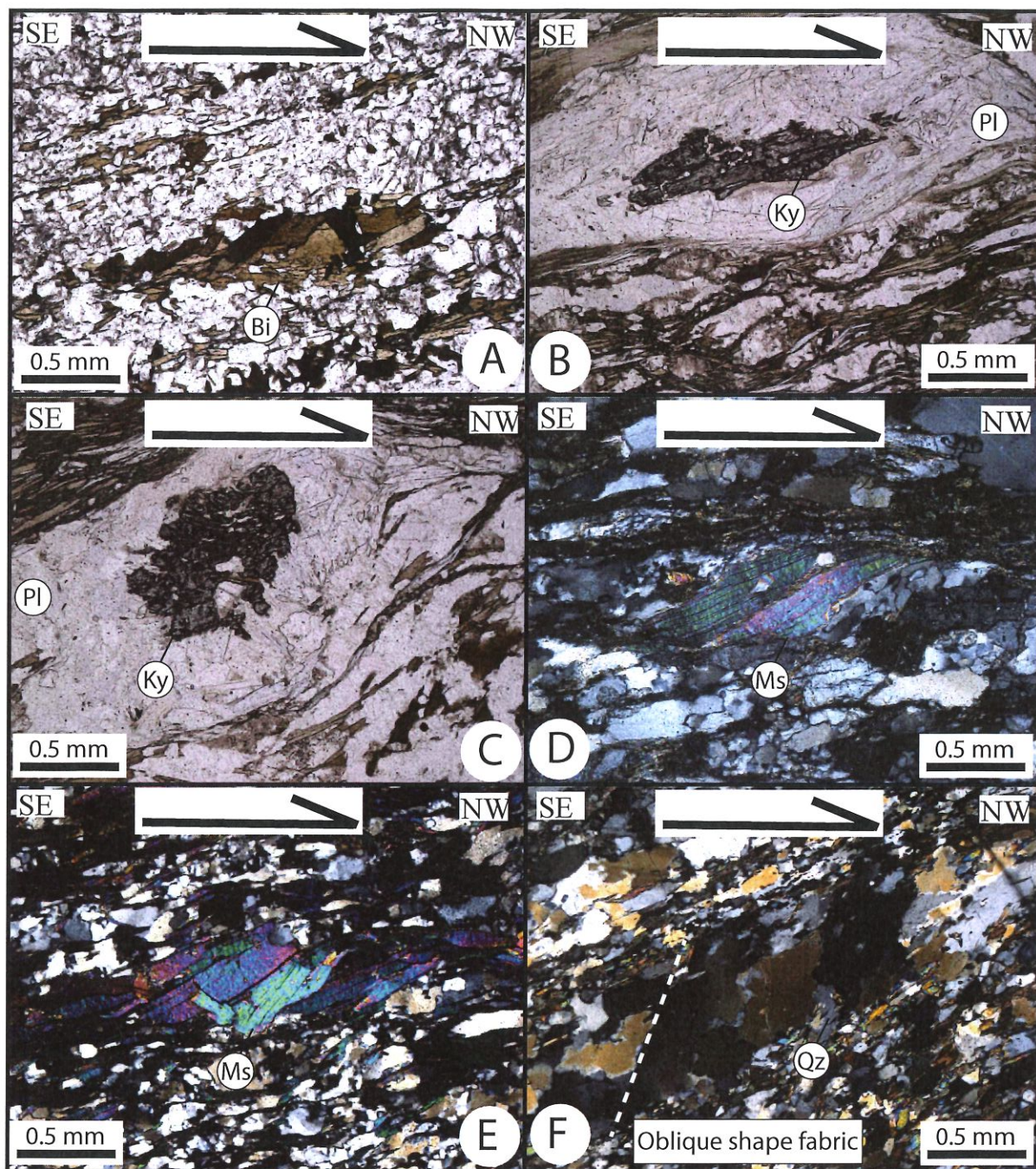


Fig. 9

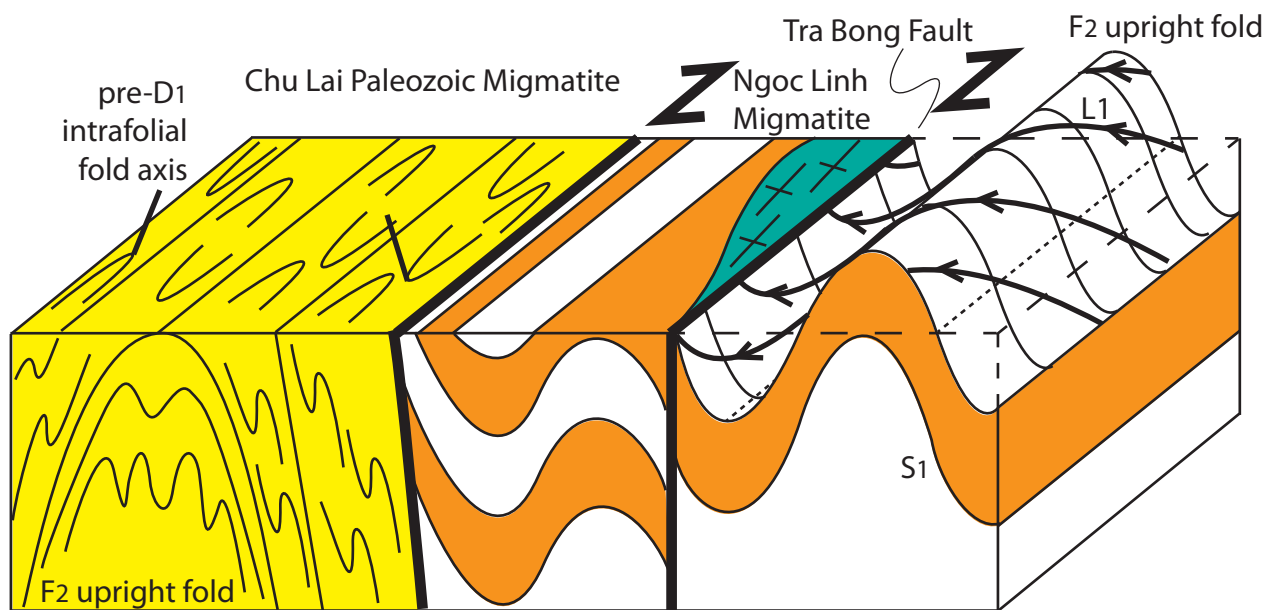
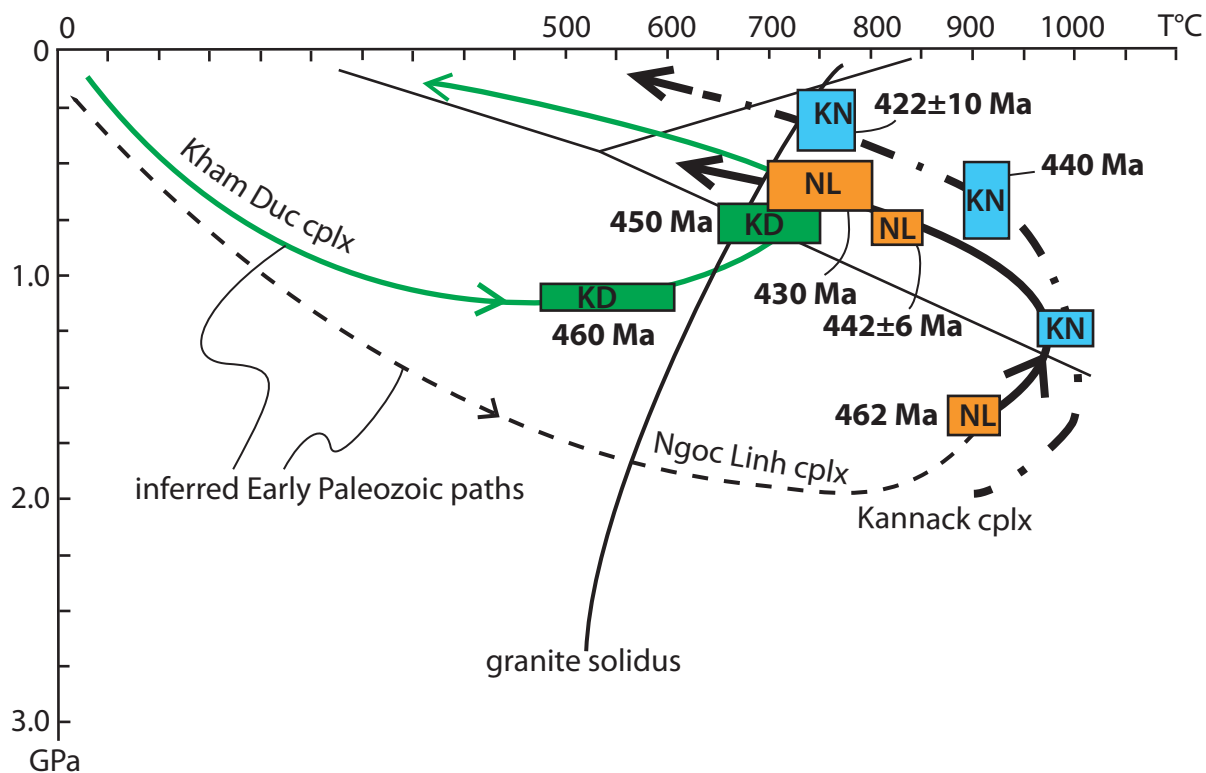


Fig. 10

A: Early Paleozoic event

i) ca 460 Ma - HP/MT (Kham Duc) to UHP/MT (Ngoc Linh)

ii) ca 450-420 Ma - HT (Kham Duc, Ngoc Linh, Kannack) to UHT (Kannack)



B: Early - Middle Triassic event HT to UHT coeval with extensional tectonics

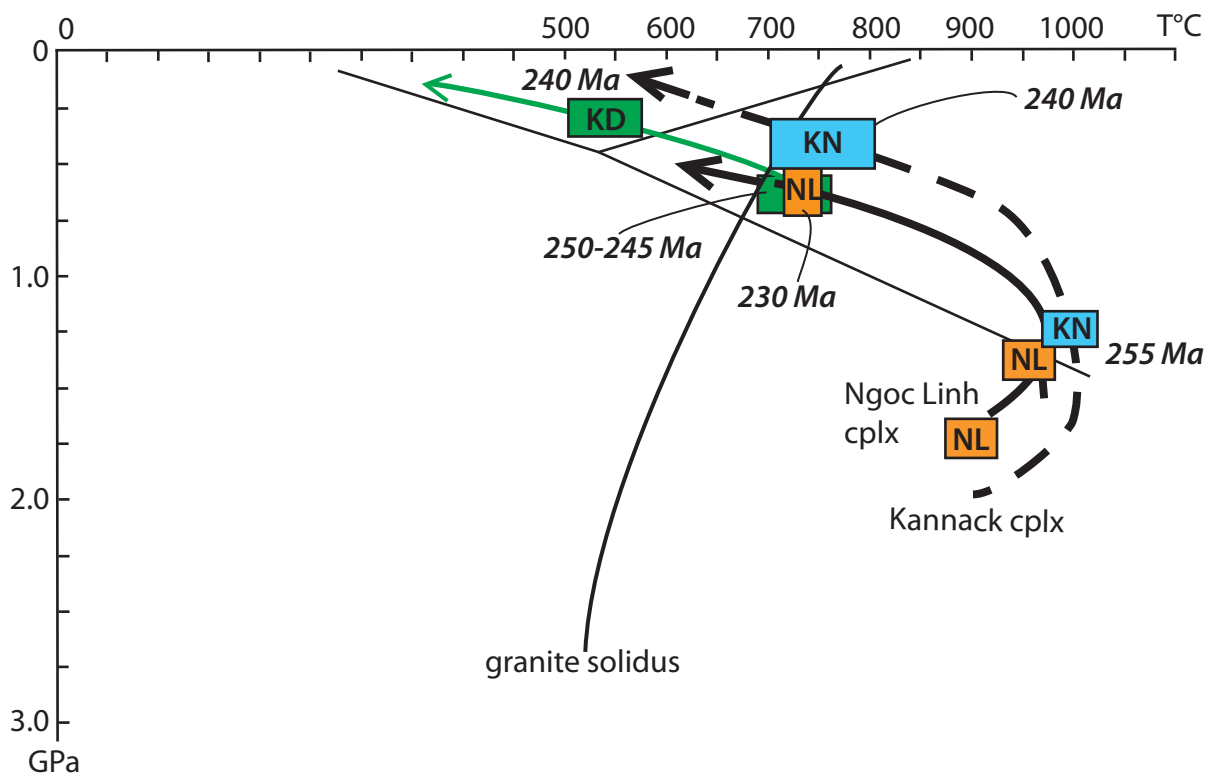


Fig. 11

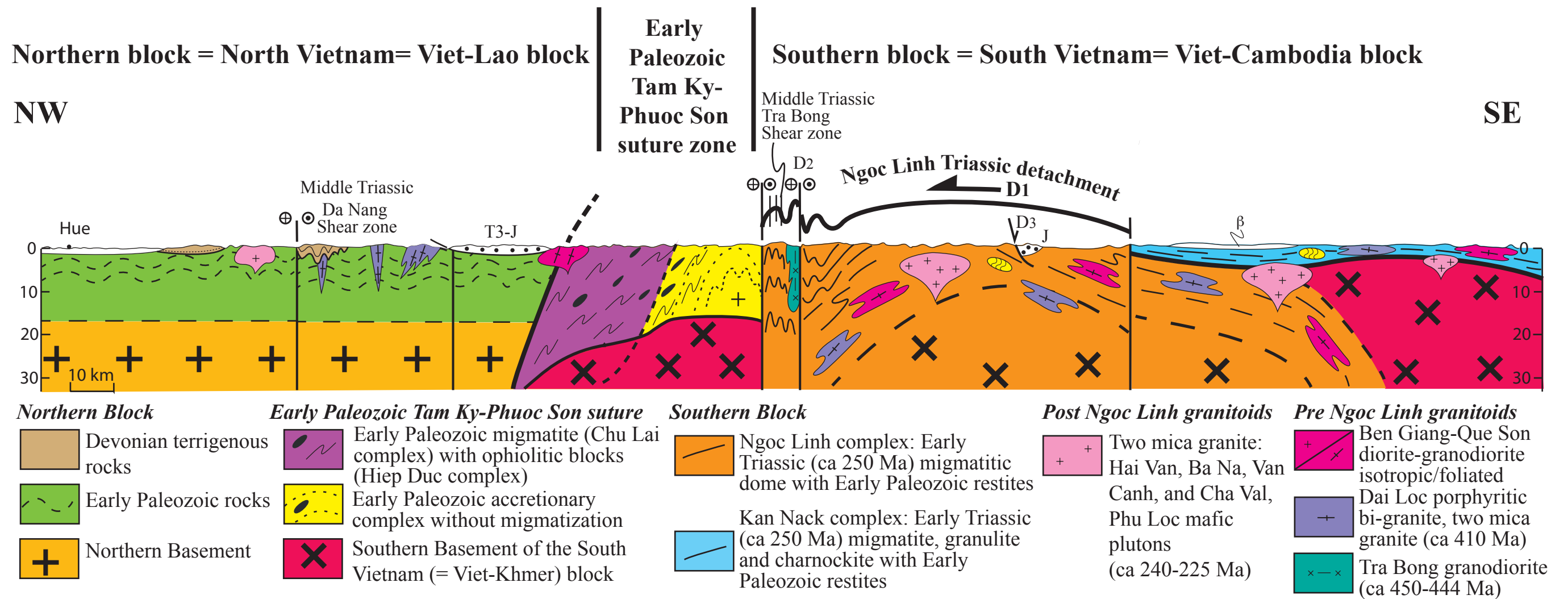


Fig. 12

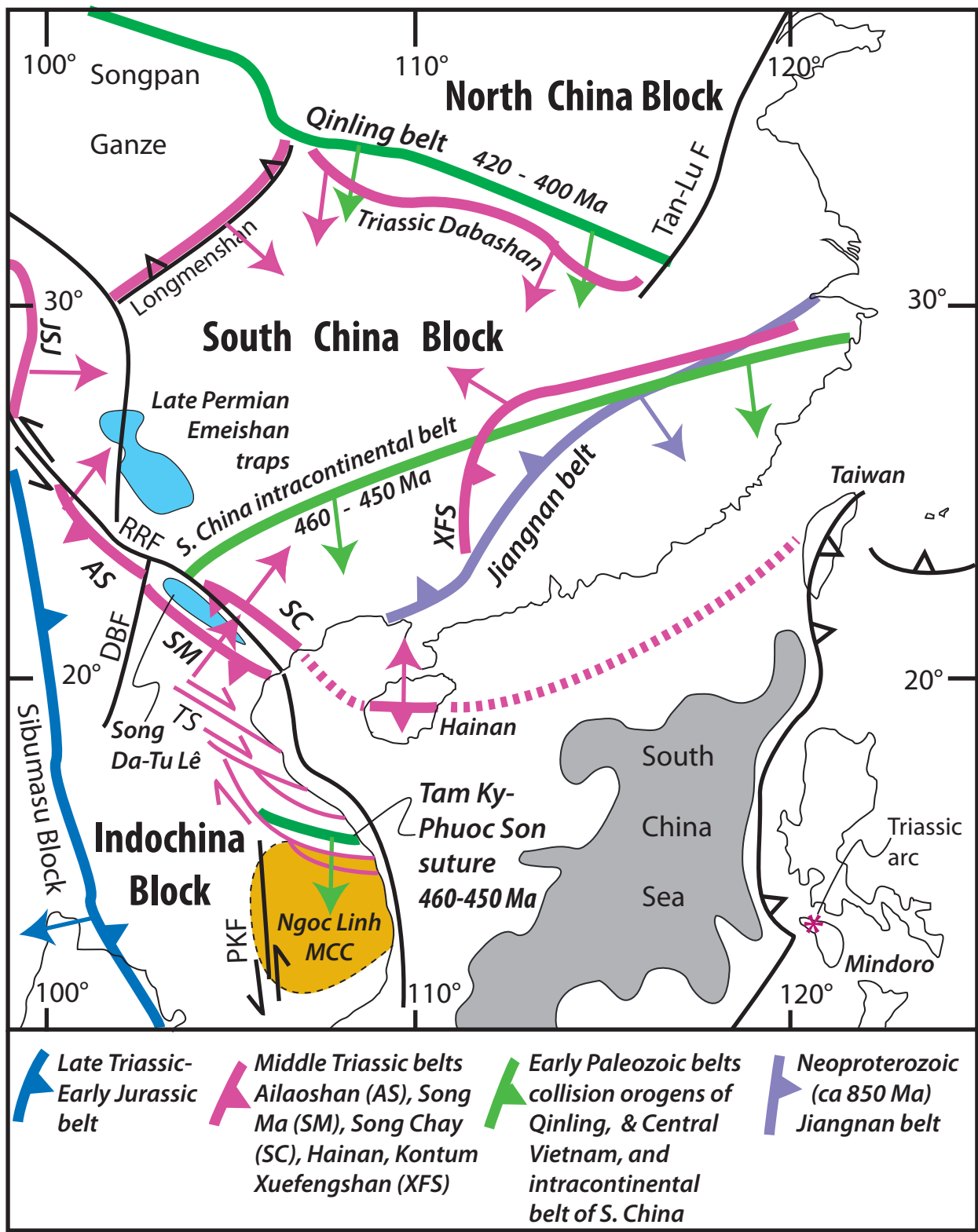


Fig. 13

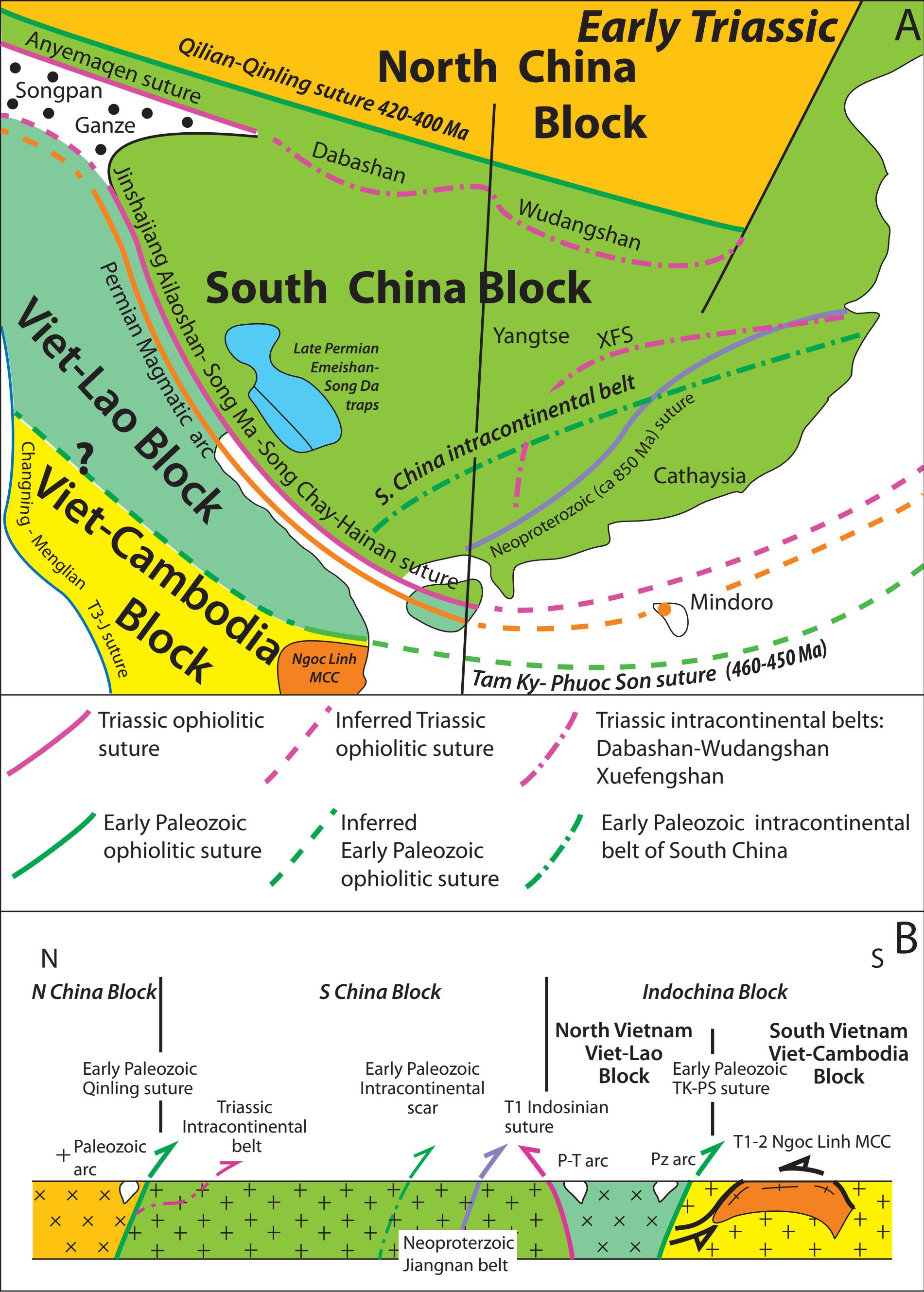


Fig. 14

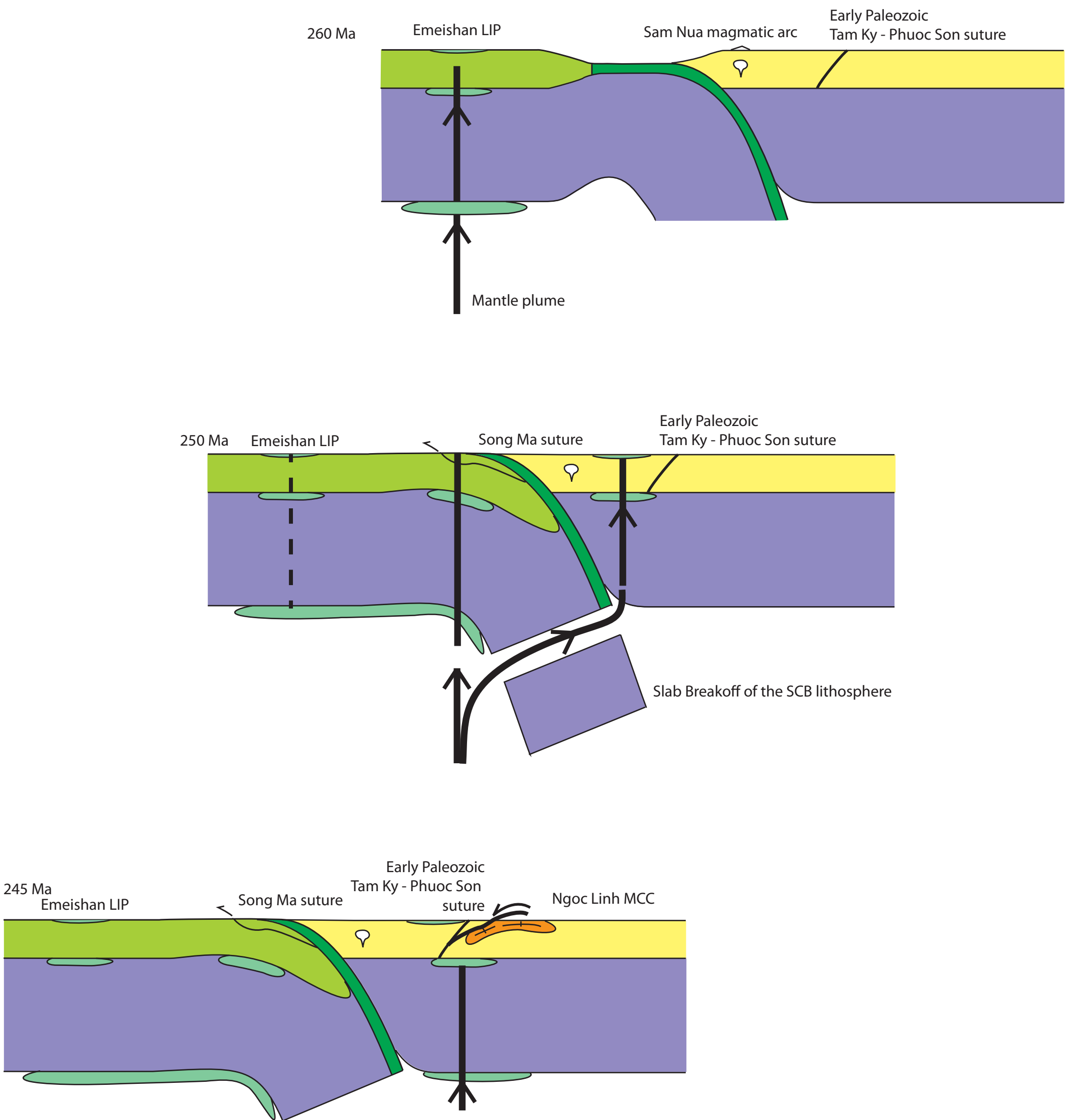


Fig. 15

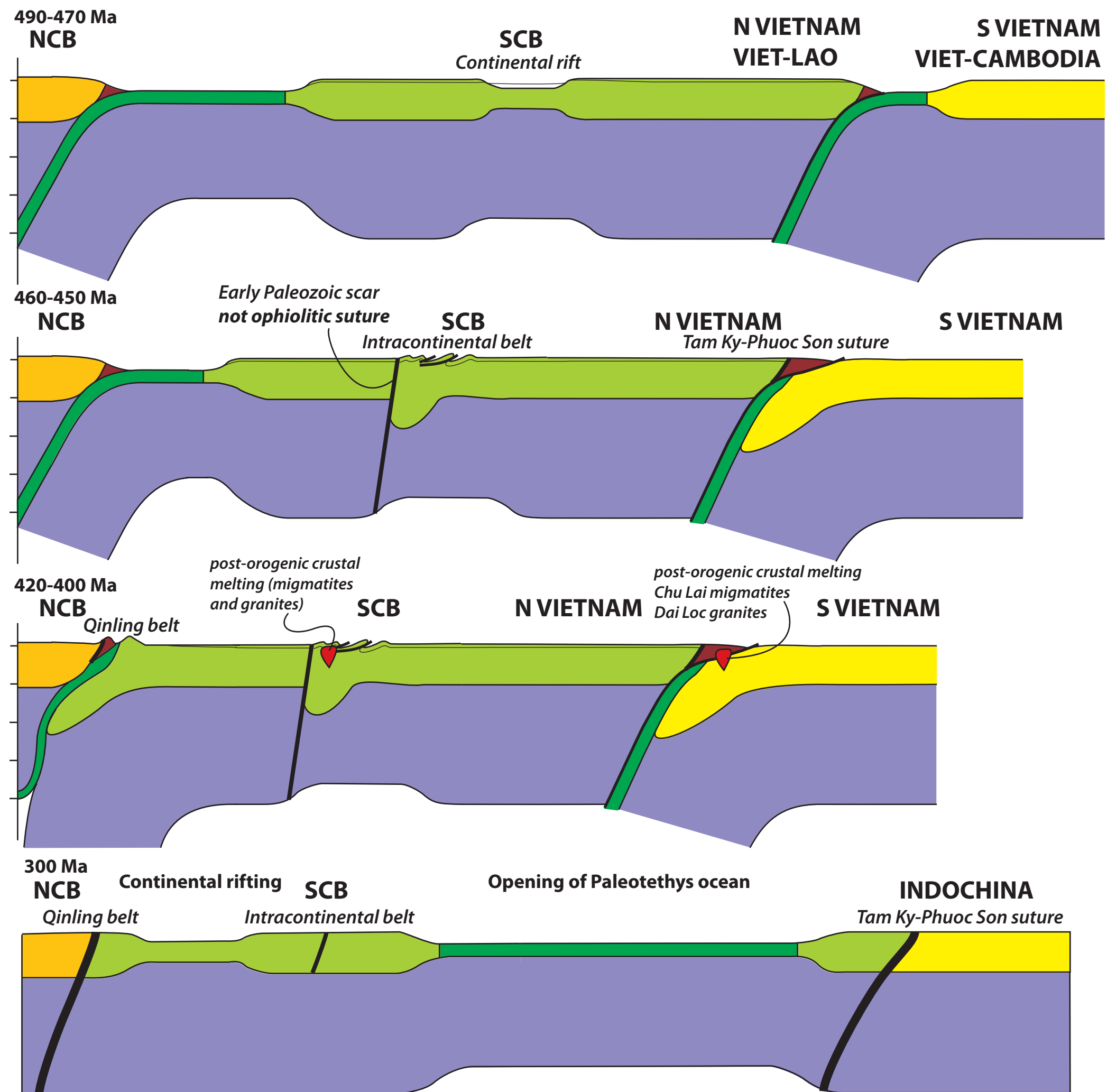


Fig. 16