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

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15

16

17 Abstract

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

26 (U)HT granulite, charnockites and enderbites. The three metamorphic complexes are intruded
27 by per-aluminous granite, and subordinate mafic plutons. In spite of local variations, the
28 foliation of the Ngoc Linh complex defines a bulk domal structure, and the stretching
29 lineation consistently trends NW-SE. The NW-SE lineation is also observed in the
30 tectonically overlying the Kan Nack complex. The Ngoc Linh and Kan Nack complexes are
31 interpreted here as parts of a metamorphic core complex (MCC), or "Ngoc Linh MCC",
32 exhumed by a top-to-the-NW detachment fault. Along the northern margin of the Ngoc Linh
33 MCC, upright folds with E-W striking axes, and E-W stretching lineation deform the
34 foliation. These structures are developed in a transpressive regime coeval with the activity of
35 plurikilometer-scale dextral strike-slip faults. Zircon and monazite U/Pb radiometric datings
36 document a 250-240 Ma age for the crustal melting, and the top-to-the-NW ductile shearing
37 coeval with the formation of the Ngoc Linh MCC. This extensional tectonics is followed by a
38 dextral strike-slip faulting, at ca 240-230 Ma, before the emplacement of the two-mica
39 granitic plutons at ca 240-224 Ma. Furthermore in the Ngoc Linh and Kan Nack complexes,
40 zircon and monazite yield U-Pb Early Paleozoic ages. In the Kham Duc complex, a ca 460
41 Ma MP/MT, garnet-biotite-staurolite-kyanite metamorphism, followed by migmatites at ca
42 450 Ma, is also recognized. The 420-400 Ma age of the Dai Loc plutonic suite, and the 450-
43 425 Ma age of the Dien Binh calc-alkaline granodiorite document an Early Paleozoic event.
44 The Early Paleozoic mafic and ultramafic masses of the Hiep Duc complex are ophiolites
45 included into a metasedimentary matrix. Thus, the Kham Duc complex is interpreted as a
46 tectonic mélangé formed during a collisional orogeny that subsequently underwent crustal
47 melting giving rise to the migmatites. A part of the Early Paleozoic rocks are enclosed as
48 xenoliths in the Triassic migmatite of the Ngoc Linh MCC. These petrologic, structural, and
49 chronological features allow us to propose the following geodynamic evolution for the
50 Kontum massif. During the Early Paleozoic, a continental collision, which was

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

62

63

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

66

67

68 1. Introduction

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

76 discussion of these issue see Faure et al., 2014, and enclosed references). Concerning the age
77 of the Indochina block-SCB collision, two main opinions are currently proposed. Some
78 authors (e.g. Lepvrier et al., 1997, 2004, 2008, 2011; Nakano et al., 2010; Liu et al., 2012;
79 Faure et al., 2014, 2016a) argue that the collision took place in Early to Middle Triassic (ca
80 250-230 Ma). The Ailaoshan-Song Ma-Song Chay-Hainan ophiolitic suture of SW China and
81 N. Vietnam represents the plate boundary along which the Paleotethys ocean was subducted
82 (Fig. 1). The collision was preceded by a South (or SW in the present geographic coordinate
83 frame) directed subduction giving rise to a magmatic arc on the Indochina block side, and
84 followed by a North (or NE) propagation of the folds and low-angle thrusts. In the Truong
85 Son belt of N. Vietnam (Fig. 1), the late collisional Triassic deformation was accommodated
86 by NW-SE striking dextral strike-slip faults (Lepvrier et al., 1997, 2004). Another group of
87 authors proposes the view that the collision occurred in Early Paleozoic on the basis of ca 400
88 Ma plutons, Devonian unconformity, and biostratigraphic correlations between Devonian
89 shallow water terrigenous deposits and similar fossil assemblages in NE Vietnam and South
90 China (e.g. Janvier et al., 1996, 1997; Thanh et al., 1996; Metcalfe, 1996, 2013; Findlay,
91 1997; Findlay and Pham, 1997; Carter et al., 2001; Carter and Clift, 2008; Roger et al., 2008,
92 2012; Tran and Vu, 2011). For these authors, the pre-Late Triassic tectonic-metamorphic and
93 plutonic events were interpreted as an intracontinental tectonics due to a far-field effect of the
94 collision between the Indochina and Sibumasu blocks.

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

101 Early to Middle Triassic ages have been documented there (Nam et al., 2001; Osanai et al.,
102 2004; Maluski et al., 2005; Roger et al., 2007; Usuki et al., 2009; Nakano et al., 2007, 2009,
103 2013). Our new field and laboratory analyses allow us to propose a crustal scale view of the
104 architecture of the Kon Tum massif. The place of the Kon Tum massif in the Paleozoic to
105 Triassic geodynamic evolution of the Indochina-South China collisional framework is also
106 discussed.

107

108 2. Regional setting

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

123

124 2.1. Lithotectonic units of the Kon Tum massif

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

131 *2.1.1. The Kham Duc complex.*

132 This unit is bounded to the North by a granitic intrusion belonging to the Ben Giang-
133 Que Son plutonic suite, and to the South by the E-W striking dextral Tra Bong strike-slip fault
134 (Lepvrier et al., 1997). The Kham Duc complex can be subdivided in two parts. The northern
135 one consists of metapelite, metagraywacke, quartz schist, and chlorite actinolite volcanic-
136 sedimentary rocks. Amphibolite, locally some of them preserving a gabbroic texture, and
137 serpentinized ultramafics are exposed as scattered blocks in the metasedimentary suite (Fig.
138 3A, B). The mafic-ultramafic rocks, called the Hiep Duc complex, are interpreted as a
139 dismembered ophiolitic series (Izokh et al. 2006; Pham et al., 2006; Tran and Vu, 2011). To
140 the South, the second part of the Kham Duc complex is characterized by the occurrence of
141 migmatites and anatectic granites, called the Chu Lai migmatitic complex. In these rocks, the
142 leucosomes are well foliated and folded (Fig 3C,D), and the amphibolite, and metagabbro
143 bodies represent xenoliths. Due to poor outcrop quality, and progressive transition from non-
144 melted to completely melted rocks, it is impossible to clearly delineate the boundary between
145 the two parts (Fig. 2). In the following, they will be collectively referred to as the Kham Duc
146 complex. The age of the protoliths is unknown, however the metapelite yields detrital zircon
147 grains dated at 558 ± 7 Ma (Usuki et al., 2009) showing that at least a part of the Kham Duc
148 complex is younger than Late Neoproterozoic. The Tra Bong fault system separates two
149 different migmatitic complexes, the Chu Lai and Ngoc Linh to the North and South,

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

152

153 2. 1. 2. *The Ngoc Linh complex.*

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

166

167 2. 1. 3. *The Kan Nack complex.*

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

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

177

178 2.2. The Northern Domain (South Truong Son area)

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

191

192 2.3. The plutonic rocks

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

195 2.3.1. *The post Ngoc Linh plutons.*

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

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

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

216

217 2.3.2. *The pre-Ngoc Linh plutons.*

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

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

225 2011). Zircon U-Pb (SHRIMP and LA ICP-MS) dating from granodiorite yields ages ranging
226 between 295 Ma and 261 Ma, with a peak at 294 Ma (Dinh, 2011; Nguyen Trong Giang
227 unpublished in Tran and Vu, 2011). Furthermore, zircon separated from a quartz diorite rock
228 in the large pluton that separated the southern part of the Truong Son belt) and the Kham Duc
229 complex, yields LA-ICP-MS age at 479 ± 3 Ma (Hieu and Trung, 2016a). On the basis of its
230 calc-alkaline geochemical features, the Ben Giang-Que Son plutonic suite is interpreted as
231 mantle derived magmas contaminated by crustal materials. These rocks are considered as
232 emplaced in a magmatic arc formed in a continental active margin (Tran et al., 2008; Hieu
233 and Trung, 2016a).

234 The Dai Loc magmatic suite is well developed SW of Da Nang in the northern
235 Domain, but it may also crop out as xenolith in the Ngoc Linh and Kan Nack complexes (Fig.
236 2). The dominant rocks are porphyritic biotite granite with subordinate two-mica granite,
237 syenogranite, and monzogranite. Most of the plutons of the northern domain exhibit a well
238 developed planar and linear fabric related to the dextral strike-slip fault system widespread
239 there (Lepvrier et al., 1997; 2008). The per-aluminous and subalkaline geochemical features
240 of these plutons indicate that they result of the partial melting of continental crust (Hieu et al.,
241 2016b). Zircon SHRIMP dating gives 418 ± 18 Ma and 407 ± 11 Ma ages (Carter et al., 2001),
242 whereas zircon LA-ICP-MS analyzes indicate 427 ± 10 Ma and 423 ± 2 Ma ages (Hieu et al.,
243 2016b). These late Silurian ages argue for an important Early Paleozoic magmatic event.

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

250 415±3 Ma (Nagy et al., 2001), and SHRIMP dating of a gneissic diorite gives an Early
251 Paleozoic age at 444±17 Ma (Carter et al., 200). The calc-alkaline geochemical character of
252 the Dien Binh plutons suggests that they formed in a magmatic arc setting (Nagy et al., 2001).

253

254 3. Structural analysis of the polyphase deformation

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

261

262 3.1. The syn-migmatitic D₁ main structural event.

263 3.1.1. *Fabric elements*

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

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

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

298 The same S_1 foliation is observed in the Kan Nack complex with variable attitude (Fig
299 5 stereogram H). Globally, S_1 is folded into a NW-SE trending structure with a general

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

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

318 *3.1.2. Kinematic analysis*

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

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

333 3.2. The post-migmatitic D₂ event.

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

347 Furthermore, north of the Tra Bong fault, the F₂ folds involve the Chu Lai migmatite, the
348 foliation of which is deformed by isoclinal folds coeval with melting (Fig. 8C, D) that must be
349 related to an older event.

350

351 3.3. The late D₃ event.

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

361

362 3.4. The pre-D₁ inherited structures in the Kham Duc complex.

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

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

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

378

379 4. Metamorphic and geochronological constraints

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

385 2.1. The Kham Duc complex.

386 Thermo-barometric investigations from metapelites and metagreywackes of the Kham
387 Duc complex indicate that these rocks underwent a polymetamorphic evolution (e.g. Nakano
388 et al., 2007, 2009, 2013; Osanai et al., 2008; Usuki, 2009; Yonemura et al., 2013). The main
389 metamorphic assemblage in metapelite is characterized by biotite-garnet-sillimanite, yielding
390 P and T conditions of 0.7 to 0.8 GPa, and 720-750°C, respectively. Monazite U-Th-Pb
391 chemical dating of the Kham Duc metapelite gives Middle Triassic ages ranging from 246±3
392 Ma to 236±9 Ma (Nakano et al., 2009, 2013). Similar Triassic ages, between 257±4 Ma and
393 245±3 Ma, have been obtained by LA-ICP-MS method on zircon and monazite from
394 paragneiss and orthogneiss around the Bong Mieu gold mine, between Tra My and Tam Ky
395 (Tran et al., 2014). Lastly, biotite, muscovite, and amphibole from the Kham Duc
396 metamorphic rocks, and the mylonites developed along the Tra Bong and Tam Ky shear
397 zones yield two biotite and muscovite ⁴⁰Ar/³⁹Ar ages at ca 245 Ma and 230 Ma that are
398 interpreted as those of the main D₁ metamorphic event, and the D₂ dextral shearing,
399 respectively (Lepvrier et al., 1997, 2004, Vu et al., 2007).

400 Moreover, garnet, kyanite, and staurolite inclusions in plagioclase document an older
401 MP/MT event under ca 1.2 GPa and 500-600°C P and T conditions. Furthermore, in this
402 metamorphic complex, quartz-feldspar aggregates, foliated and lineated during the D₁ event,
403 represent highly strained magmatic batches formed during an incipient stage of anatexis older
404 than D₁ (Fig. 3C). Near Phuoc Son, in these migmatitic rocks, zircon rims yield SHRIMP U-
405 Pb ages at 447±6 Ma, and 452±6 Ma interpreted as those of the migmatization (Usuki et al.,
406 2009). Thus the age of the HP/MT event took place before 450 Ma, but after 548±7 Ma,
407 which is the age of the youngest detrital zircon grain found in the metapelite (Usuki et al.,
408 2009). A Late Ordovician age, at ca 460 Ma, seems likely. An Early Paleozoic, pre-D₁,
409 tectonic and metamorphic event, represented by rare microstructures but with clear
410 metamorphic relicts, was overprinted by the D₁ Early to Middle Triassic event (Nakano et al.,
411 2009, 2013).

412

413 4.2. The Ngoc Linh complex.

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

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

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

429

430 4.3. The Kan Nack complex.

431 The thermo-barometric conditions for the formation of the Kan Nack metamorphic
432 rocks have been estimated at ca 1000°C and 1.2 GPa for the mafic granulite (Nakano et al.,
433 2007, 2013), and 750°C and 0.3-0.4 GPa for the granulitic migmatite (Roger et al., 2007). As
434 for the Ngoc Linh complex, two groups of ages are recognized there. The central and western
435 parts of the complex yield Triassic ages. Zircon U-Pb, biotite $^{40}\text{Ar}/^{39}\text{Ar}$, and monazite U-Pb
436 chemical ages range from 255 Ma to 240 Ma (e.g. Maluski et al., 2005; Roger et al., 2007;
437 Nakano et al., 2007, 2013). Furthermore, in the eastern part of the Kan Nack complex (Song
438 Bien area), zircon and monazite from migmatites and gneiss yield Early Paleozoic ages,
439 ranging from 465 Ma to 422 Ma (Roger et al., 2007; Nakano et al., 2013 and enclosed
440 references).

441

442 4.4. A polycyclic metamorphic evolution of the Kon Tum massif

443 The petrological and geochronological studies from the three metamorphic complexes
444 allow us to draw their representative P-T-t paths, although the prograde parts of the paths are
445 poorly documented (Fig. 11A, B). The Kham Duc metamorphic rocks document a kyanite-
446 garnet-staurolite assemblage indicative of a MP/MT event, followed by a HT one, associated
447 with crustal melting. This metamorphic evolution occurred during the Early Paleozoic, from
448 460 Ma to 445 Ma. Moreover, a late Early Triassic thermal event, dated around 250-246 Ma,

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

451 High temperature, even ultra-high temperature (UHT), metamorphic rocks, coeval
452 with migmatites, are widespread in the Ngoc Linh and Kan Nack complexes. The later
453 complex reached higher temperatures (ca 1000°C) than the former. The UHT event was coeval
454 with melting of the lower crust under HP conditions that produced charnockite and enderbite
455 (Fig. 11B). The migmatite encloses mafic granulite and eclogite xenoliths that document an
456 early HP event. The numerous multi-method geochronological studies support a late Early
457 Triassic to early Middle Triassic age, at ca 250-230 Ma, for the crustal melting. Moreover,
458 some migmatites also yield Early Paleozoic ages, between 460 and 430 Ma. Thus, the
459 existence of a polycyclic evolution, as in the Kham Duc complex, is well documented in the
460 Ngoc Linh and Kan Nack complexes. The accuracy of both the thermo-barometric estimates,
461 and the radiometric dating, does not allow us to discriminate between the Triassic and Early
462 Paleozoic migmatites on the basis of their P-T conditions of formation. The two P-T paths
463 superimposes on the Fig. 11A and B. Moreover, the Early Paleozoic deformed xenolith
464 migmatite enclosed in the Early Triassic migmatite, observed in the Song Re section (Fig.
465 4D), provides a field evidence for a polycyclic evolution.

466

467 5. Tectonic and geodynamic interpretations

468 5.1. The architecture of the Kon Tum massif

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

474 metamorphic core complex (MCC) exhumed in the footwall of the Ngoc Linh detachment
475 fault. In spite of some post-S₁ folds, the Kan Nack complex is interpreted as a flat lying unit
476 exhumed from the granulitic lower crust, as indicated by the HT (or UHT) migmatite,
477 charnockite, and enderbite overlying the Ngoc Linh complex. The Kan Nack complex
478 exhumed from the deepest crust overlies the Ngoc Linh migmatitic complex. This extensional
479 tectonics occurred between 250 Ma and 230 Ma. Both the Ngoc Linh and Kan Nack Triassic
480 migmatite encloses Early Paleozoic xenoliths of migmatite, HP granulite, and Dai Loc or Ben
481 Giang-Que Son granitoids. The northern boundary of the Ngoc Linh dome is cut by the D₂
482 dextral strike-slip faults of the Tra Bong fault system that mylonitized the Early Paleozoic Tra
483 Bong granodiorite, and erased the microstructures related to the Ngoc Linh detachment.

484 More to the North, the Kham Duc complex is interpreted as an Early Paleozoic
485 accretionary complex containing mafic and ultramafic blocks. The southern part of the
486 complex experienced an Early Paleozoic anatexis, represented by the Chu Lai migmatite. As a
487 whole, the Kham Duc metamorphic rocks, and the Chu Lai migmatite belong to the Tam Ky-
488 Phuoc Son suture (Lepvrier et al., 2008; Tran and Vu, 2011; Tran et al., 2014). North of the
489 Tam Ky-Phuoc Son suture, the Early Paleozoic sedimentary formations are devoid of any
490 significant metamorphism. A Devonian unconformity, though often reworked by the Triassic
491 tectonics, argues for an Early Paleozoic folding event (Tran and Vu, 2011; Than et al., 2012).
492 Upright folds, associated to the Middle Triassic D₂ dextral ductile shearing, deform the entire
493 Paleozoic succession. The Early Paleozoic Dai Loc plutons are also changed into orthogneiss
494 during this D₂ shearing (Lepvrier et al., 1997, 2004). Therefore, the Kon Tum massif, and its
495 northern domain, resulted from a polycyclic evolution. A HT/UHT extensional event,
496 responsible for the late Early to early Middle Triassic exhumation of the Ngoc Linh and Kan
497 Nack complexes, followed by a Middle Triassic strike-slip faulting, overprinted the Early
498 Paleozoic orogen. At the crust-scale, the Tam Ky-Phuoc Son suture separates two different

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

503 On the western side of the Kon Tum massif, an Early Paleozoic ophiolitic suture has
504 been proposed along the Po Ko fault (Lepvrier et al., 2008). Mafic and ultramafic rocks are
505 exposed SW of Kon Tum in the Plei Wak complex, and Early Paleozoic Dien Binh
506 granodiorite crops out west of the fault (Nagy et al., 2011). Our field observations suggest that
507 the Po Ko fault is a Neogene sinistral strike-slip fault, but older ductile and synmetamorphic
508 structures are not identified yet. Moreover, migmatite widely develops west of the Po Ko fault
509 at least up the Laos border. Furthermore, the chemical composition of the main constitutive
510 minerals (olivine, clinopyroxene, spinel) of the Plei Wak ultramafic body does not support an
511 ophiolitic setting for this massif (Pham et al., 2006). More detailed work is necessary to
512 clarify this point. In the following, the Po Ko suture will not be considered. NE of Dak To
513 (Fig. 2), a dextral Dak To Kan shear zone was proposed (Osanai et al., 2008, Nakano et al.,
514 2007, 2012). North of Dak To, the NW-SE striking, SW dipping S_1 foliation contains a
515 subhorizontal mineral and stretching L_1 lineation (Fig.5, stereogram E). This structure appears
516 different from the other strike-slip faults described in the northern domain both by its "old"
517 age, around 250 Ma, at variance with the ca 230 Ma age of the Tra Bong shear zone, and by
518 its HT metamorphic conditions. An alternative interpretation can be proposed if considering
519 that the present SW dip of the S_1 foliation is not primary but due to the late normal faulting D_3
520 event. In this case, if S_1 is restored to its subhorizontal initial geometry, the apparent dextral
521 sense of shear becomes a top-to-the-NW one, consistent with the D_1 kinematics observed in
522 other parts of the Ngoc Linh dome (Fig. 5).

523

524 5.2. The place of the Kon Tum massif in the Triassic (Indosinian) orogeny.

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

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

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

554 A late orogenic thermal overprint is common in many collisional orogens such as the
555 Variscan belt of Western Europe (e. g. Ledru et al., 2001; Martinez-Catalan et al., 2009;
556 Schulman et al., 2008; Faure et al., 2010; Lardeaux et al. 2014), the Himalaya (Le Fort et al.,
557 1987), or the Qinling-Dabie belt of central China (e.g. Lin et al., 2015; Ji et al., 2017). The
558 collision related crustal thickening is often acknowledged as the source of the radiogenic heat
559 responsible for the crustal melting, and subsequent MCC development in the subducted
560 continental crust of the lower plate. In such a setting, an UHT metamorphism is rare. It also
561 does not account for the Ngoc Linh MCC as this structure developed in the upper plate of the
562 collision system. Another proposed case is heat advection in the upper plate lower crust
563 triggered by asthenospheric mantle upwelling in a subduction setting. There, a slab breakoff
564 of the subducting lithosphere is a prerequisite to promote UHT granulite facies metamorphism
565 and crustal melting (e. g. Kelsey and Hand, 2015; Touret et al., 2016, and enclosed
566 references). In this respect, the Kon Tum massif appears as unusual, as a linear trend of the
567 UHT metamorphic rocks, parallel to the Triassic belt that would better comply with a slab
568 breakoff mechanism is expected instead of the "punctual" occurrence observed for the Ngoc
569 Linh MCC.

570 It is worth noting that during the Late Permian, between 263 Ma and 257 Ma, the
571 Emeishan-Song Da-Tu L  Large Igneous Province (LIP, Ali et al., 2005; Schellnutt et al.,
572 2015; Fig 14) was emplaced in the western part of the SCB. The present separation between
573 the Emeishan LIP and the Song Da-Tu L  area is a consequence of the Cenozoic sinistral

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

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

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

607

608 5.3. The Early Paleozoic evolution of the Kon Tum massif.

609 Early Paleozoic ages are widespread in the Ngoc Linh MCC, but contemporaneous
610 structures are rare, except in the Kham Duc complex where intrafolial folds might be ascribed
611 to the pre-D₁ event. In the Kham Duc complex, various blocks of sedimentary or volcani-
612 clastic rocks, amphibolite, metagabbro, and serpentinites enclosed into a metasandstone matrix
613 has been recognized as an Early Paleozoic accretionary complex, also called the Tam Ky-
614 Phuoc Son suture (Izokh et al., 2006; Pham et al., 2006; Lepvrier et al., 2008; Tran and Vu,
615 2011; Tran et al., 2014). This plate boundary represents the place where the N. Vietnam (or
616 Viet-Lao) block and the S. Vietnam (or Viet-Cambodia) block were welded together. Thus
617 the question of the subduction polarity arises. The existence of an Early Paleozoic magmatic
618 arc is supported by the calc-alkaline granodiorites of the Dien Binh and Tra Bong suites (Fig.
619 2), though the available ages, between 445 Ma and 415 Ma (Nagy et al., 2001; Carter et al.,
620 2001), are younger than the late orogenic crustal melting of the Kham Duc, and Ngoc Linh
621 complexes dated at ca 450 Ma (Roger et al., 2007; Usuki et al., 2009; Nakano et al., 2013). In
622 Laos, close to the study area, a calc-alkaline granodiorite similar to the Dien Binh suite
623 yielded a zircon U-Pb LA-ICP-MS age of 470 Ma (Gardner et al., 2017). Moreover, a zircon

624 LA-ICP-MS age at 479 ± 3 Ma (Pham and Huynh, 2016) from a calc-alkaline quartz diorite in
625 an Early Permian Ben Giang-Que Son pluton could be interpreted as a relict grain inherited
626 from an Early Paleozoic magmatic arc formed in a continental active margin (Tran et al.,
627 2008; Pham and Huynh, 2016).

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

636 The Early Paleozoic (ca 450 Ma) late orogenic anatexis is documented by the Chu Lai
637 migmatite in the southern part of the Kham Duc complex (Usuki et al., 2009). The Early
638 Paleozoic age, at 436 ± 10 Ma, of the foliated migmatite xenoliths (Fig 4D; Nam et al. 2004)
639 enclosed in the Triassic Ngoc Ling dome is also considered here as an evidence for the Early
640 Paleozoic orogeny. During the late orogenic stage, after the collision, the melting of
641 metapelites that formed the Dai Loc S-type plutons is dated between 427 Ma and 423 Ma
642 (Fig. 16). In the same way, the Early Paleozoic HP rocks, granulitic and eclogitic relics,
643 enclosed in the Ngoc Linh and Kan Nack complexes (Roger et al., 2007; Nakano et al., 2004,
644 2007, 2013), might represent remnants of the deep-seated part of the Early Paleozoic belt of
645 Central Vietnam. In most of orogens in the world, the highly metamorphosed and deformed
646 rocks belong to the lower plate that underwent subduction. In Central Vietnam, the Early
647 Paleozoic migmatites and metamorphic rocks are located to the south of the Tam Ky-Phuoc
648 Son suture, whereas, north of the suture, the pre-Devonian rocks are represented by

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

655

656 5.4. A possible interaction between the Early Paleozoic belts of Indochina and South China.

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

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

674 2009; Charvet et al., 2010, Li et al. 2010). This belt, devoid of ophiolites, subduction
675 complex, and magmatic arc is an intracontinental orogen that resulted from the closure of a
676 Neoproterozoic-Cambrian rift accommodated by a North-directed continental subduction
677 (Faure et al., 2009; Charvet et al., 2010). The cause of this intracontinental orogeny was not
678 understood yet. A collision between the main part of SCB and Australia, a piece of which is
679 supposed to be located in Hainan island, has been proposed (Xu et al., 2016). However, the
680 geological record for Early Paleozoic arc magmatism, and ophiolitic suture are missing in
681 Hainan island. As no other Early Paleozoic ophiolitic suture is recognized between the SCB
682 intracontinental orogen and the Tam Ky-Phuoc Son suture, the SCB and N. Vietnam block
683 belonged to the same continent until the Devonian (Metcalf, 2013). In late Cambrian-Early
684 Ordovician, the S. Vietnam (Viet-Khmer) continent subducted below the N. Vietnam (Viet-
685 Lao) that was a part of the SCB, within which an intracontinental rift developed (Fig. 16). The
686 Middle to Late Ordovician (460-450Ma) collision between the N. Vietnam and the S.
687 Vietnam blocs led to the closure of the intracontinental rift of the SCB. During the Silurian,
688 the late- to post-collisional evolution was responsible for the crustal melting experienced by
689 the S. Vietnam block, and SCB. Therefore, we propose here that the collision between the N.
690 Vietnam (Viet-Lao) and S. Vietnam (Viet-Cambodia) blocks induced stress propagation in the
691 SCB, and was responsible for the closure of the Neoproterozoic-Cambrian rift of SCB, and
692 the related deformation and metamorphism. The Early Paleozoic intracontinental orogeny of
693 South China may be considered as a consequence of a far-field effect of the central Vietnam
694 collision (Fig. 16), in the same way as the Central Asia Cenozoic structures resulted from the
695 Himalayan collision. This SCB-Viet-Lao continental mass was split during the Carboniferous
696 by the opening of a branch of the Paleotethys Ocean (Nguyen et al., 2013) that was closed in
697 the late Early to early Middle Triassic by the Indosinian orogeny.
698

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

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

736

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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

1120 Fig. 5. Structural elements of the Kon Tum massif. Stereoplots (Schmidt net, lower
 1121 hemisphere) showing the statistical preferred orientation of the structural elements: S_1 , L_1 , S_2 ,
 1122 L_2 , F_2 . The stereogram with grey back compiles the total L_1 measurements for the Ngoc Linh
 1123 complex. The foliation trajectory outlines the domal shape of the Ngoc Linh complex, and the
 1124 dominantly S-ward dip of the Kan Nack complex. Arrow indicates the top-to-the NW sense of
 1125 shear related to the D_1 event.

1126

1127 Fig. 6. Sketch of collapse fold, similar to the one shown in Fig. 7C, responsible for the
 1128 reorientation of L_1 . The NW-SE trend of L_1 in the normal limb is changed to NE-SW in the
 1129 inverted one. The top-to-the NW sense of shear becomes top-to-the-NE.

1130

1131 Fig. 7. Kinematic indicators related to the D_1 and D_2 events in the Ngoc Linh complex. A:
 1132 Sigmoidal leucosome with top-to-the-NW sense of shear in a subhorizontal foliation (W. of
 1133 Quang Ngai; GPS N14.92498; E108.67458); B: top-to-the-NW sigmoidal leucosome in a
 1134 South dipping foliation (S. of Di Lang; GPS N14.82420; E108.54218); C: NW verging
 1135 "collapse" fold (N. of Nam Tra My; GPS N15.23340; E108.09438); D: D_2 upright fold
 1136 developed in the Ngoc Linh migmatite (S. of Tra My; GPS N15.29946; E108.12762); E:
 1137 sigmoidal leucocratic boudins in metatexite (W. of Quang Ngai; GPS N15.20117;
 1138 E108.10903); F: pluri-meter sized retort-shaped leucosomic boudin indicating a top-to-the-
 1139 NW sense of shear (N. of Nam Tra My; GPS N15.18497; E108.11713).

1140

1141 Fig. 8. Field-scale kinematic indicators in the Phuoc Son complex and Chu Lai migmatite. A:
 1142 asymmetric amphibolite boudin indicating a top-to-the-NW sense of shear (Phuoc Son; GPS
 1143 N15.51221; E107.81304); B: NW verging F_2 folds refolding a D_1 or pre- D_1 isoclinal fold
 1144 (Phuoc Son; GPS N15.46803; E107.83970); C: Upright F_2 fold developed in the Early

1145 Paleozoic Chu Lai migmatite (GPS N15.35611; E108.23472); D: Intrafolial pre-D₁ fold
 1146 coeval with the Early Paleozoic Chu Lai migmatite (GPS N15.35611; E108.23472).

1147

1148 Fig. 9. Thin section-scale kinematic indicators of the D₁ event showing a top-to-the NW sense
 1149 of shear in the Ngoc Linh and Phuoc Son complexes. A: D₁ sigmoidal biotite aggregate in
 1150 paragneiss (Phuoc Son; GPS N15.53013; E107.81676); B: pre-D₁ kyanite relict enclosed in a
 1151 sigmoidal plagioclase porphyroblast deformed during D₁ (GPS N15.49237; E107. 82388) C:
 1152 pre-D₁ kyanite relict enclosed in a sigmoidal plagioclase porphyroblast (Phuoc Son; GPS
 1153 N15.49237; E107.82388); D, E: sigmoidal muscovite in micaschist (GPS N14.92548;
 1154 E108.60463, N15.22334; E108.43497, respectively); F: quartz grain with an oblique shape
 1155 fabric (dashed line) due to synkinematic recrystallization (N15.20898; E108.41955).

1156

1157 Fig. 10. Geometric relationships between the Early Paleozoic Chu Lai migmatite, and the
 1158 Triassic Ngoc Linh migmatite. The S₁ foliation, and L₁ stretching lineation formed during the
 1159 D₁ event in the Ngoc Linh migmatite are folded by the D₂ event, coeval with the right lateral
 1160 strike-slip faulting along the Tra Bong fault. The Chu Lai migmatite, containing intrafolial
 1161 folds with high-angle dipping axes, is deformed by the post-folial D₂ upright folds (see Fig.
 1162 8C, D for a natural example).

1163

1164 Fig. 11. P-T-t paths for the Kan Nack (KN), Ngoc Linh (NL), and Kham Duc (KD)
 1165 metamorphic complexes (modified from Roger et al., 2007, and Nakano et al., 2013). A:
 1166 Early Paleozoic event. The rocks of the Kham Duc and Ngoc Linh complexes reached their
 1167 maximum pressure around 460 Ma. The retrograde paths were coeval with HT and crustal
 1168 melting around 450-420 Ma. B: Early to Middle Triassic event. The rocks of the Ngoc Linh
 1169 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.

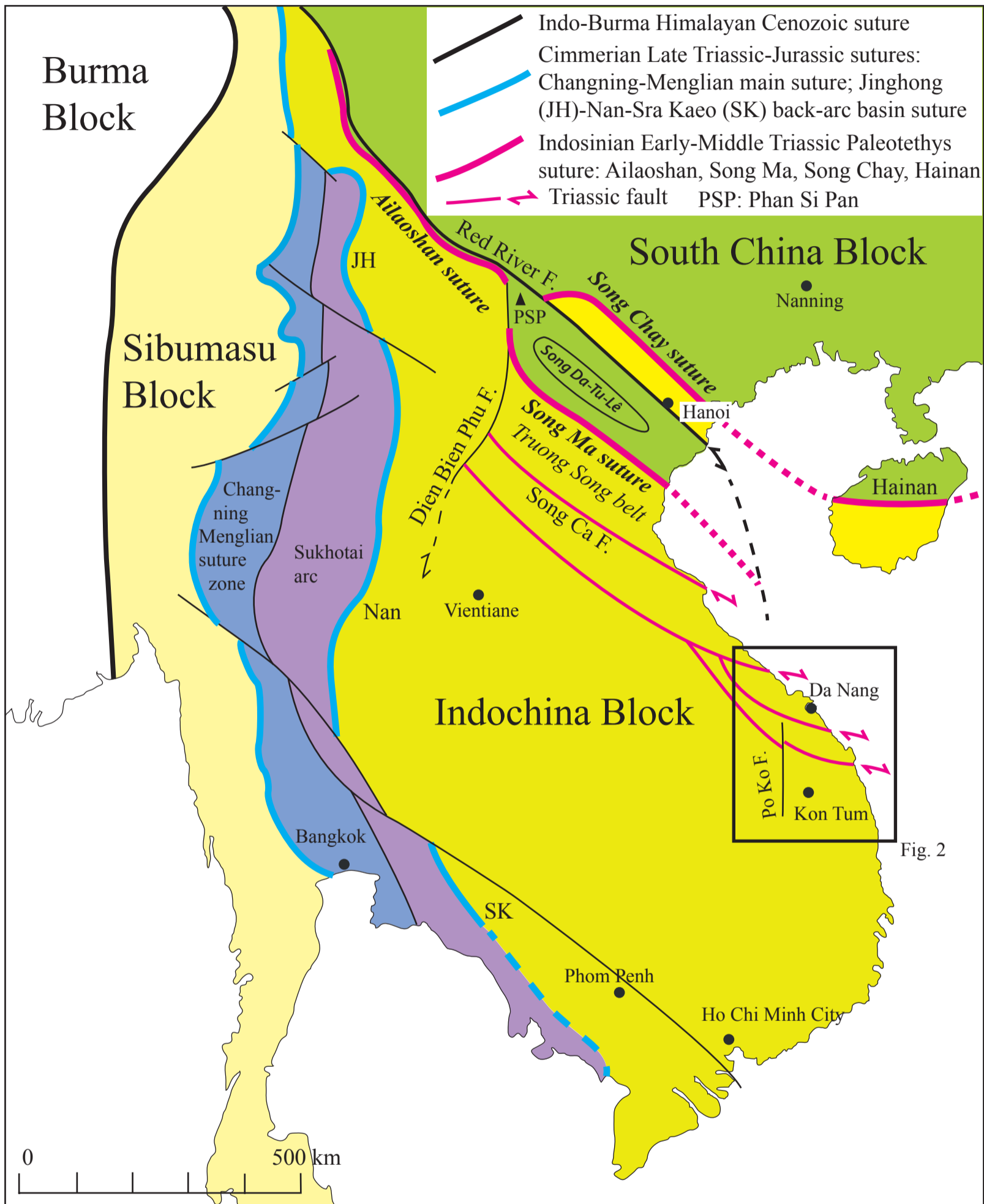
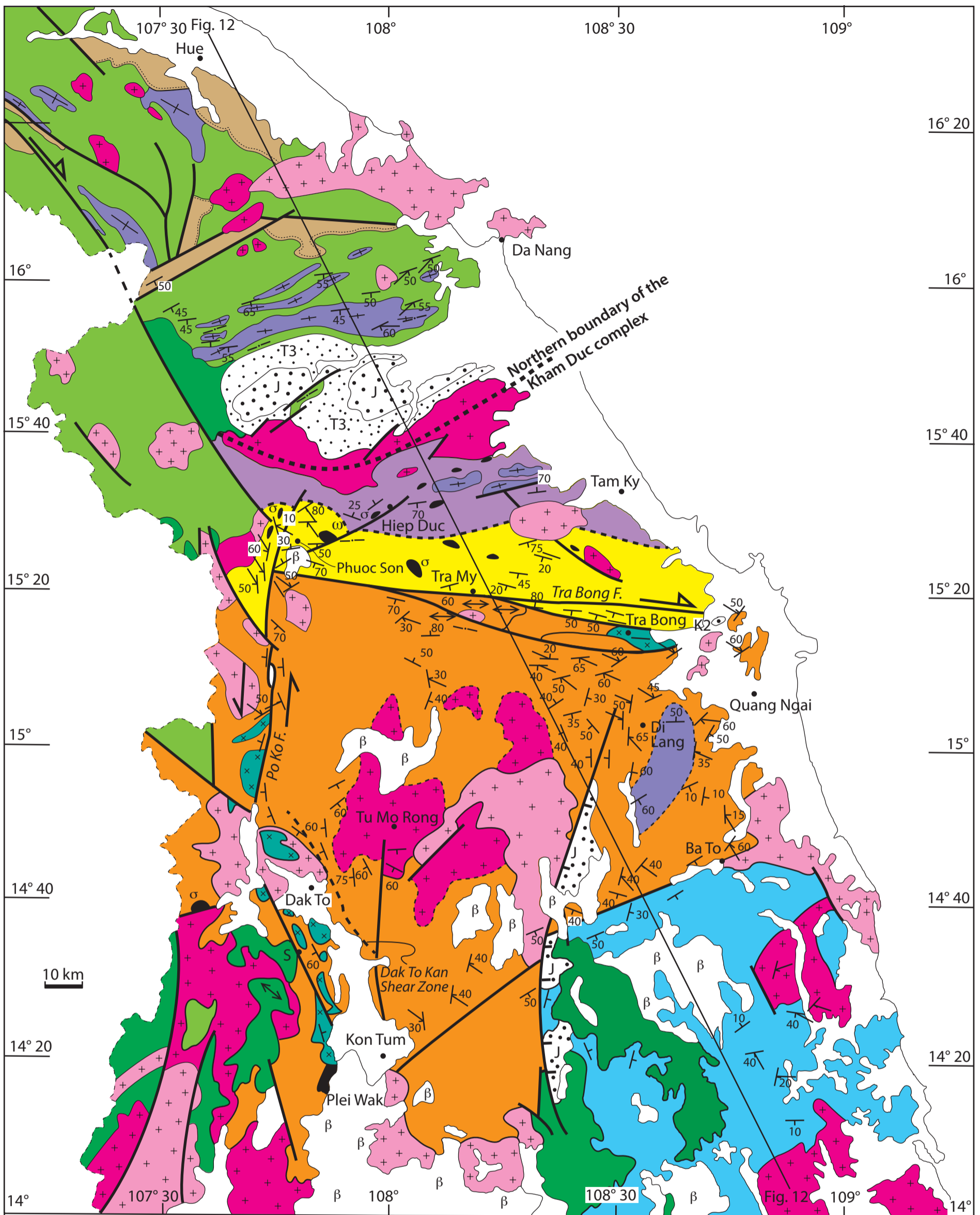


Fig. 1



Sedimentary-volcanic formations

- Quaternary (Q) and Neogene basalt (β)
- K2 Late Cretaceous red beds
- J Jurassic sandstone
- T3 Late Triassic sandstone
- unconformity*
- Permian-Early Triassic (T1) terrigenous and felsic volcanics
- Devonian terrigenous rocks
- unconformity*
- Early Paleozoic rocks

Metamorphic-migmatitic complexes in Kon Tum massif

- Kham Duc Complex: HP/MT Early Paleozoic ophiolitic melange (σ: serpentinite, ω: gabbro) with a Triassic HT/LP metamorphic overprint
- Chu Lai migmatite and partly melted rocks
- Ngoc Linh complex: Early Triassic (ca 250 Ma) migmatite with Early Paleozoic restites
- Kan Nack complex: Early Triassic (ca 250 Ma) migmatite, granulite and charnockite with Early Paleozoic restites
- Foliated granitoid
- Isotropic granitoid
- Foliation and mineral lineation with dip

Post-T1 Ngoc Linh granitoids

- Two mica granite: Hai Van, Ba Na, Van Canh, and Cha Val, Phu Loc mafic plutons (ca 240-225 Ma)

Pre-T1 Ngoc Linh granitoids

- Ben Giang-Que Son diorite-gabbro-granodiorite (ca 260 Ma)
- Dai Loc porphyritic biotite-granite, two mica granite (ca 410 Ma)
- Dien Binh granodiorite (ca 450-444 Ma)
- Tra Bong granodiorite

Fig. 2



Fig. 3

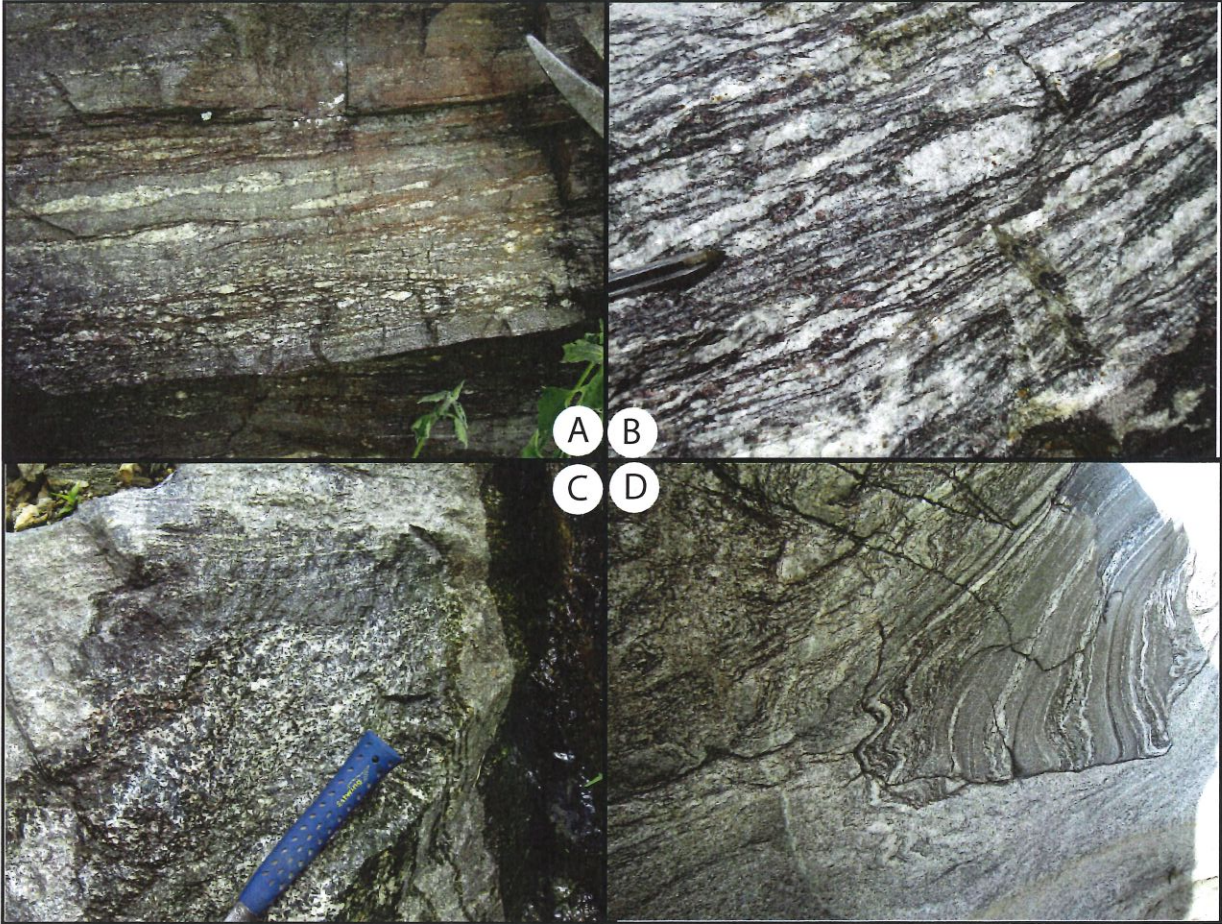


Fig. 4

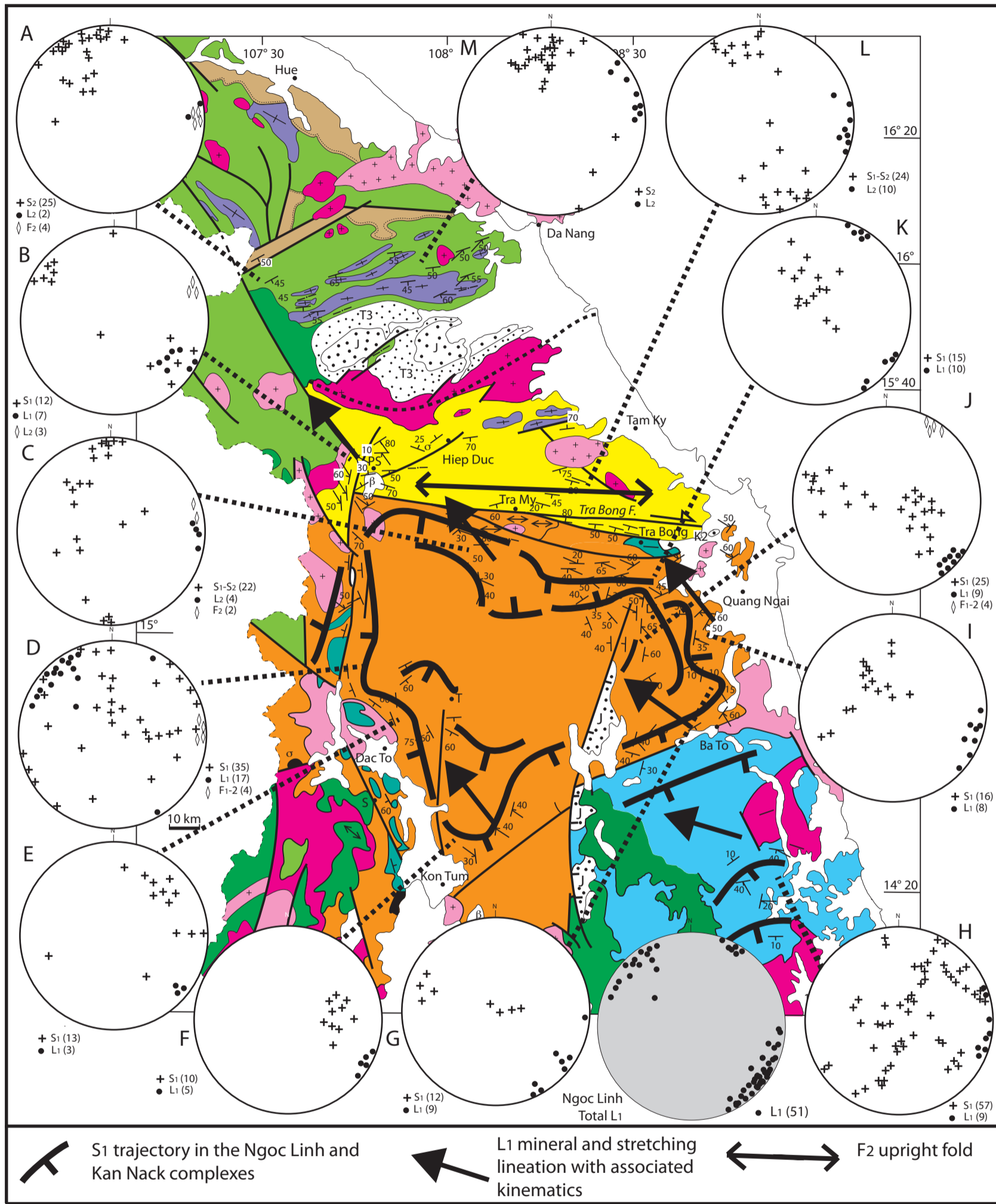


Fig. 5

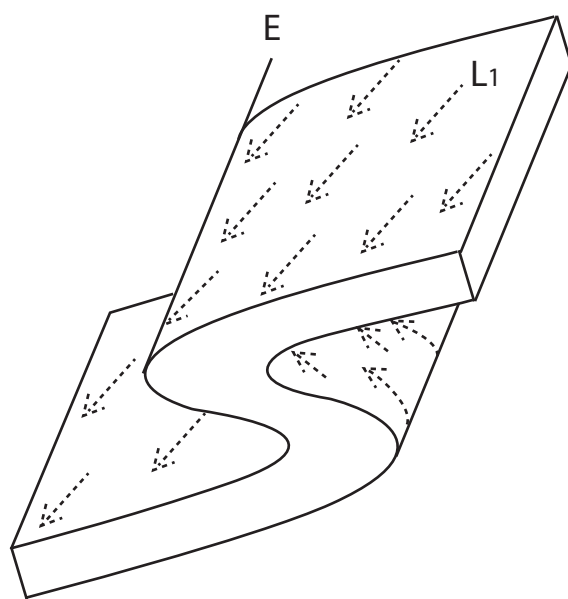


Fig. 6

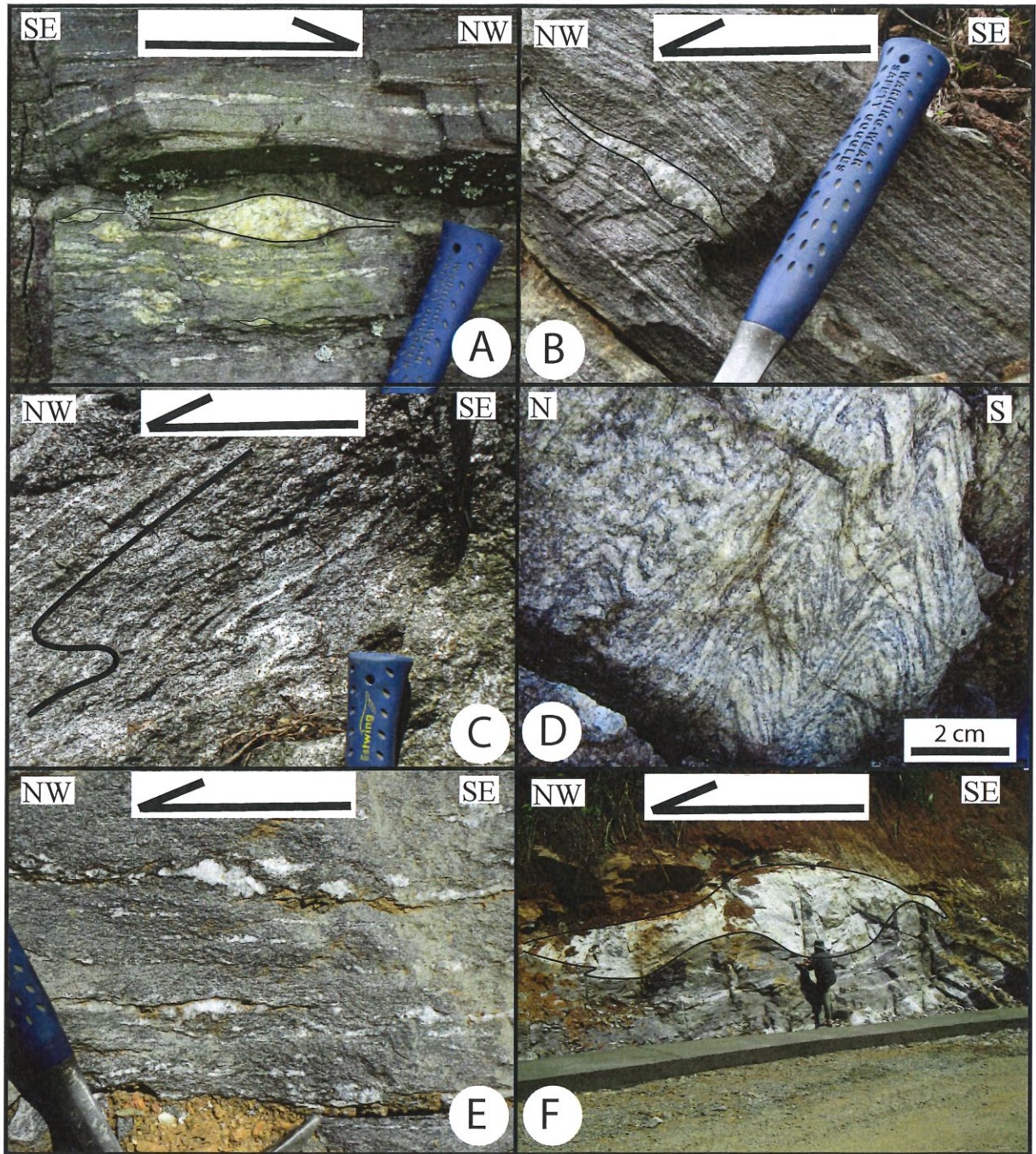


Fig. 7

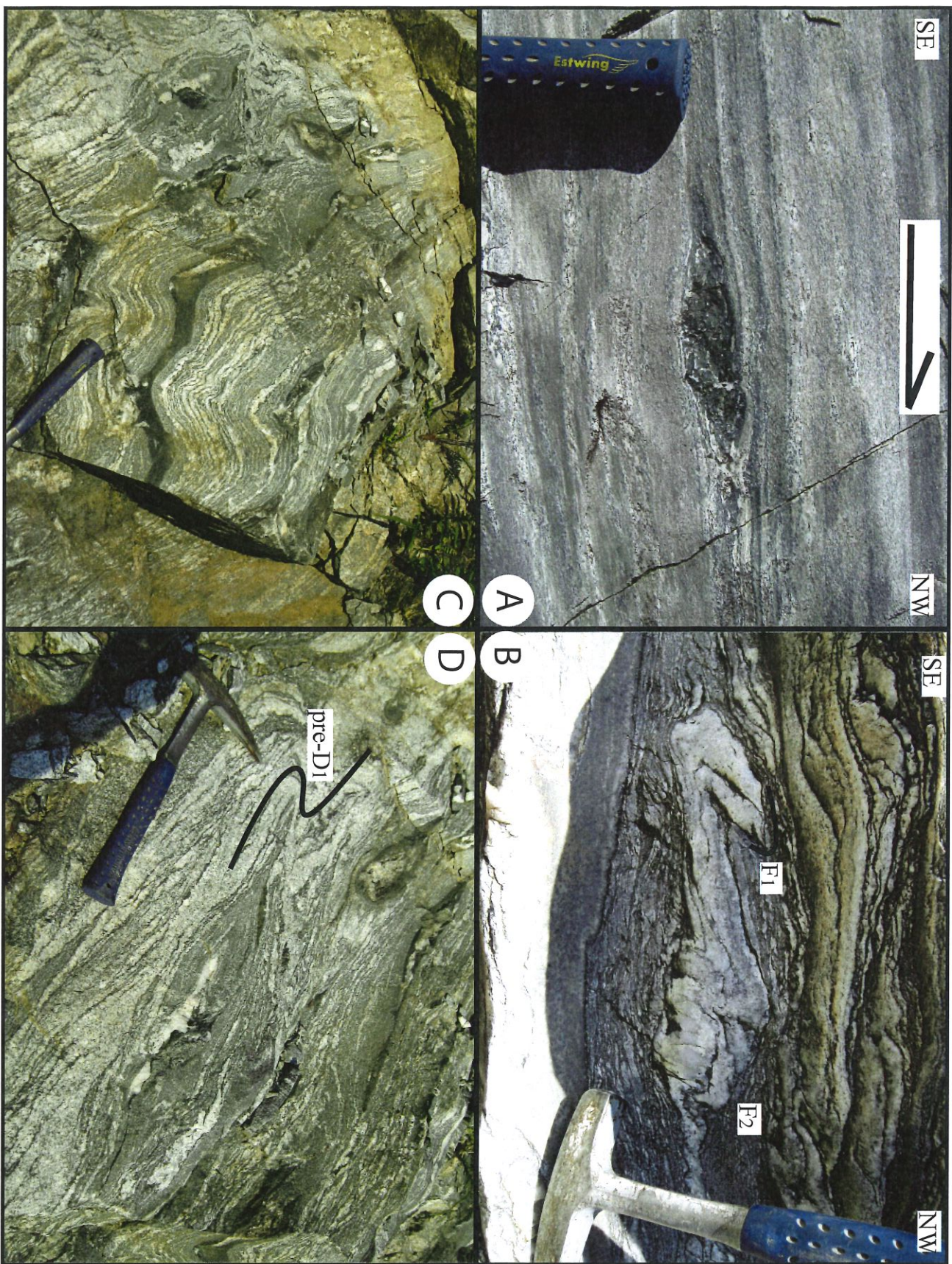


Fig. 8

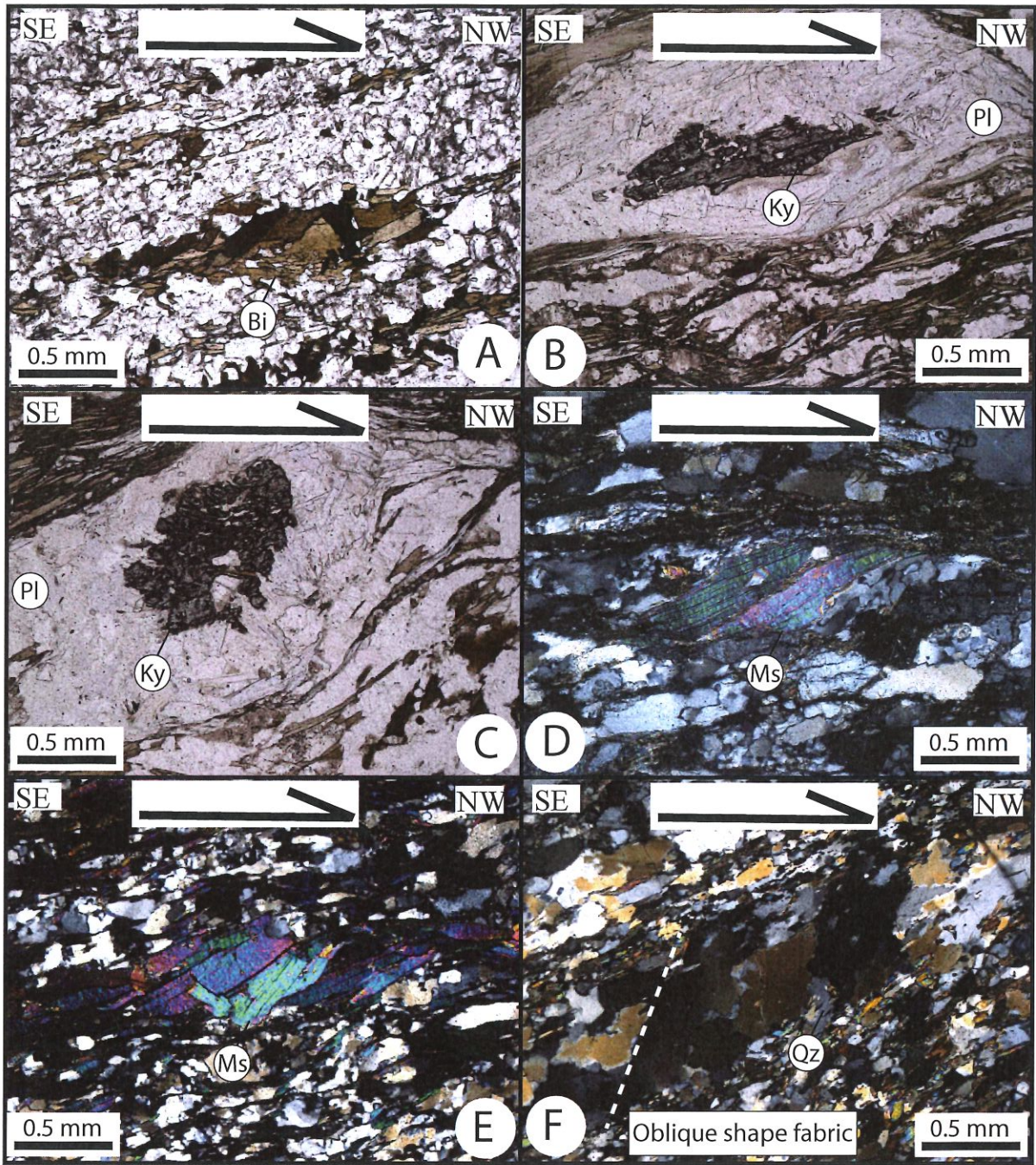


Fig. 9

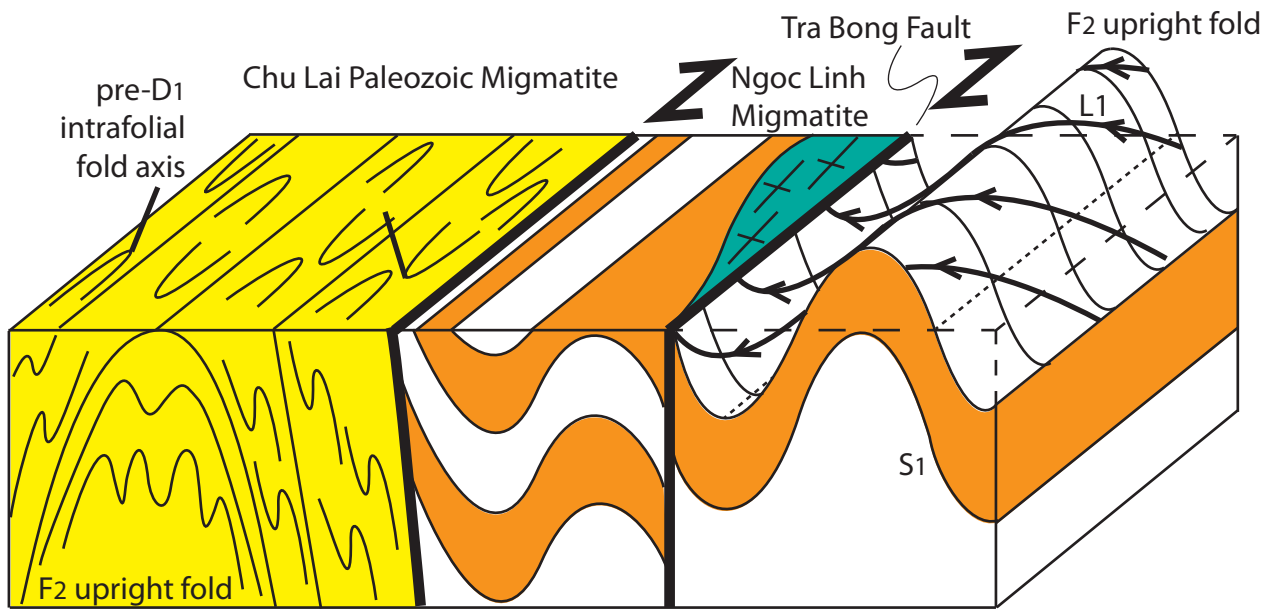
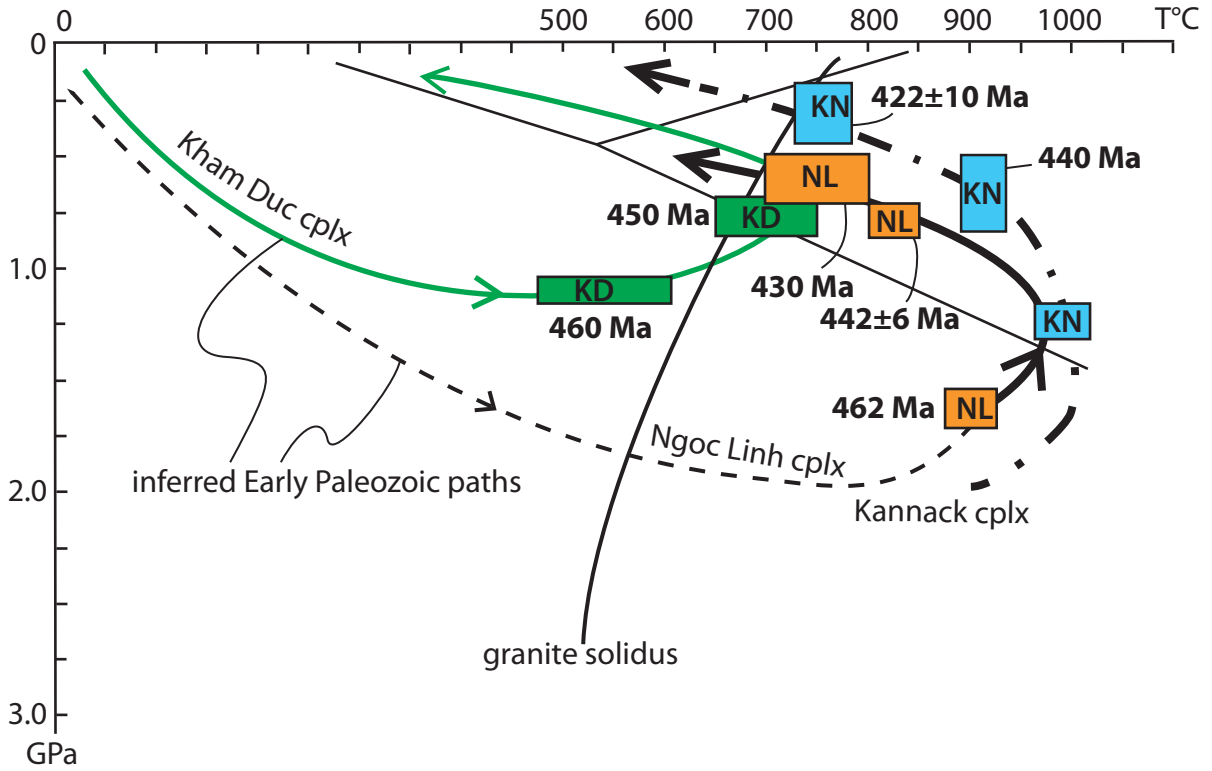


Fig. 10

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

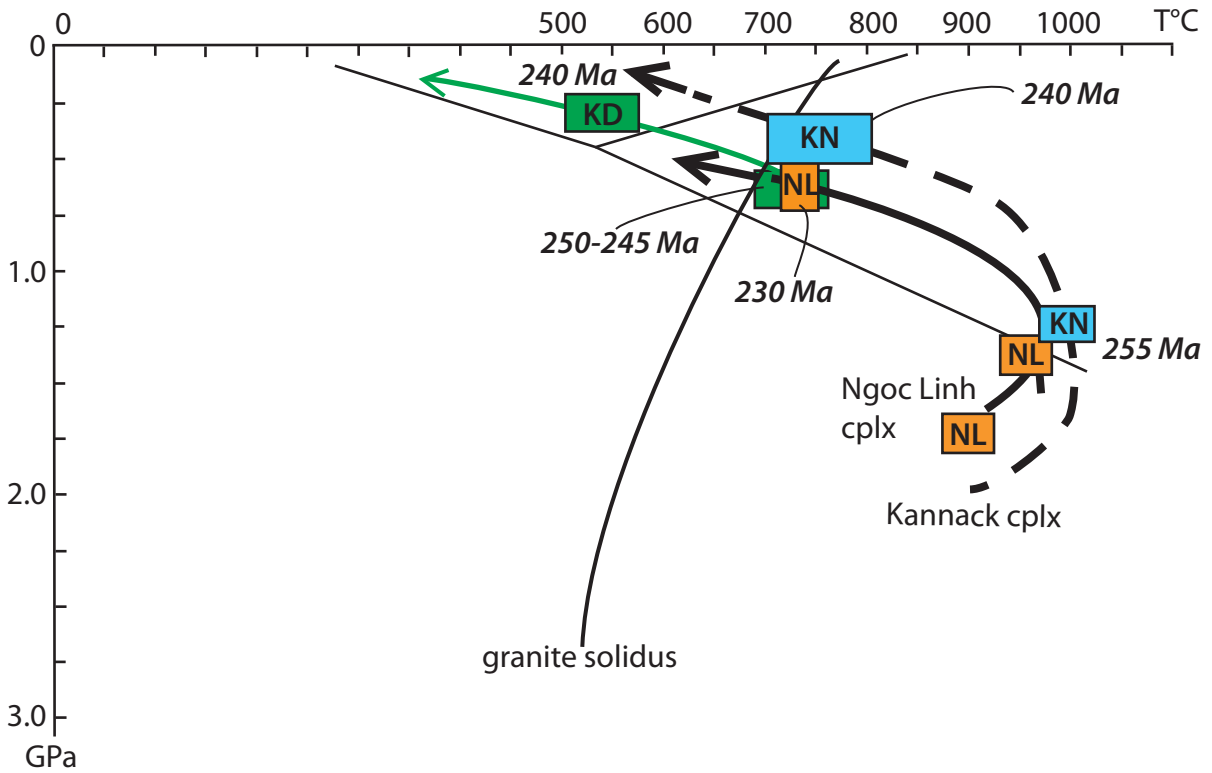


Fig. 11

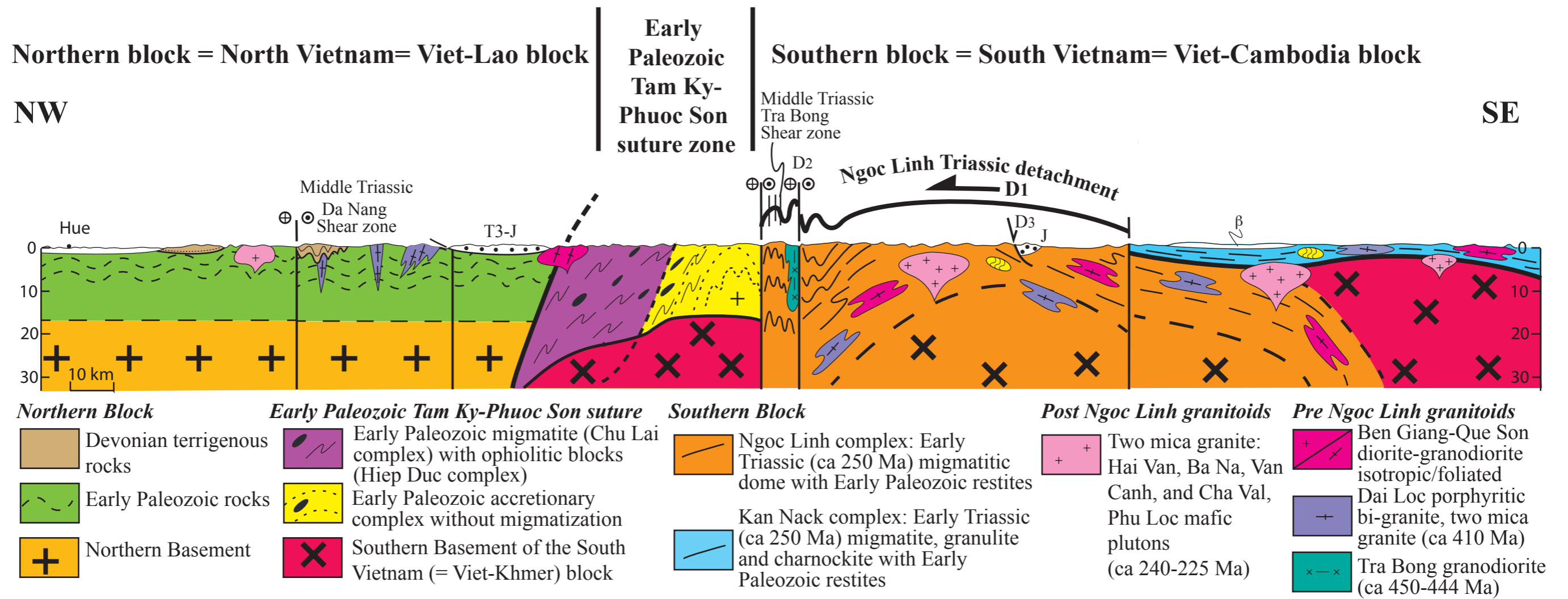


Fig. 12

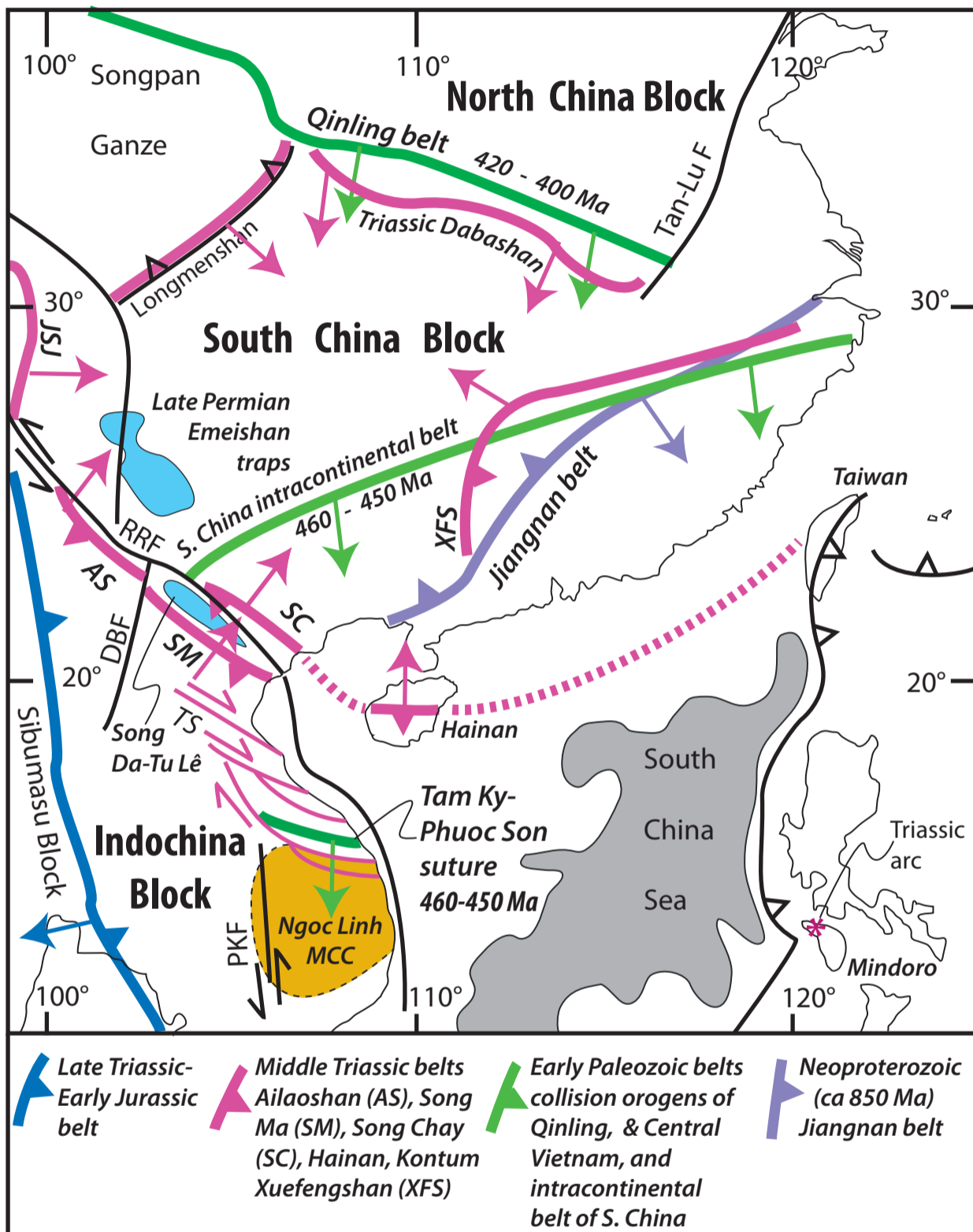


Fig. 13

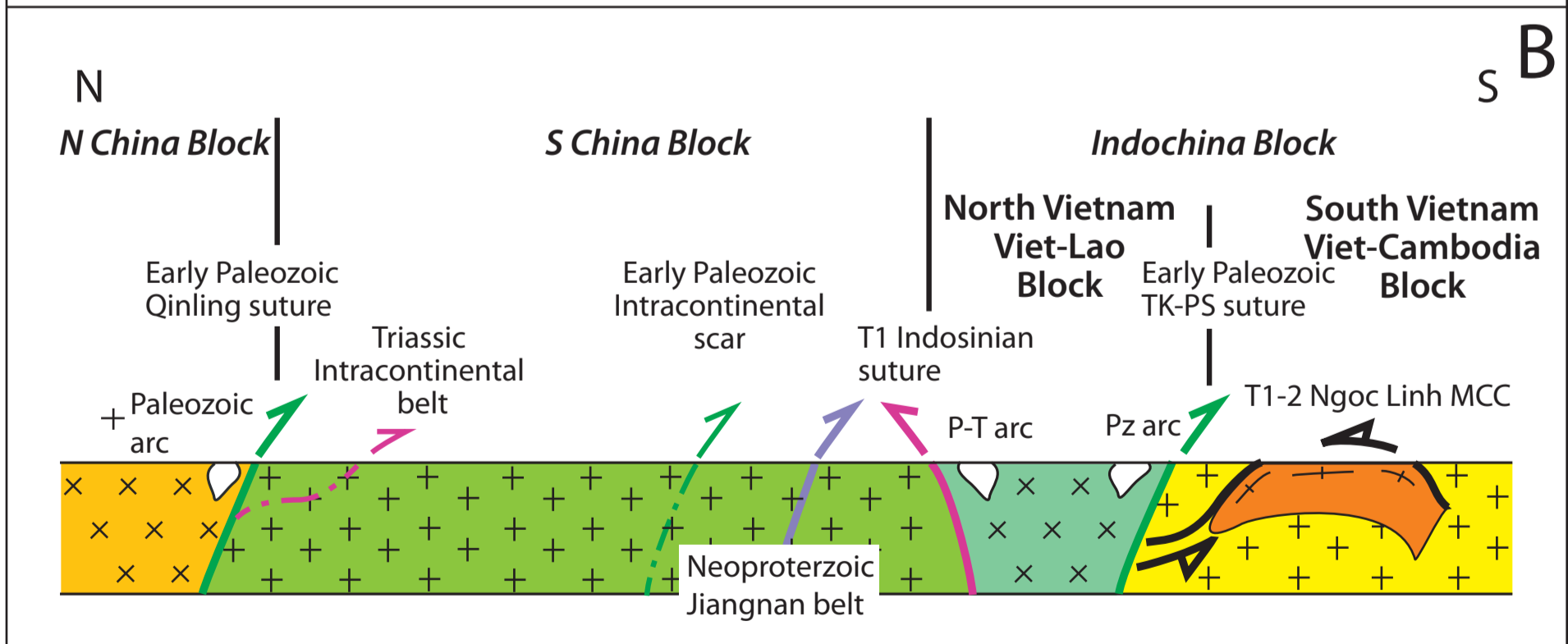
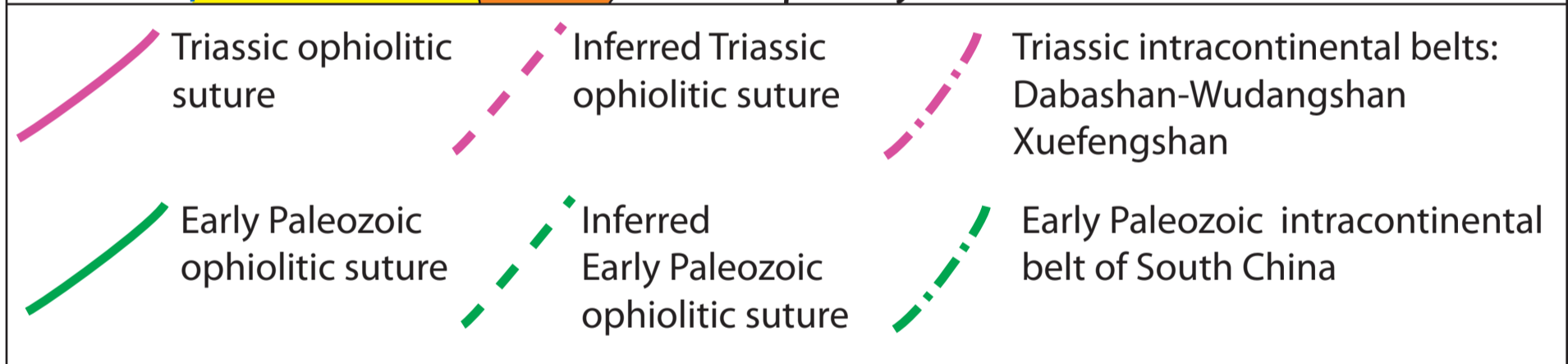
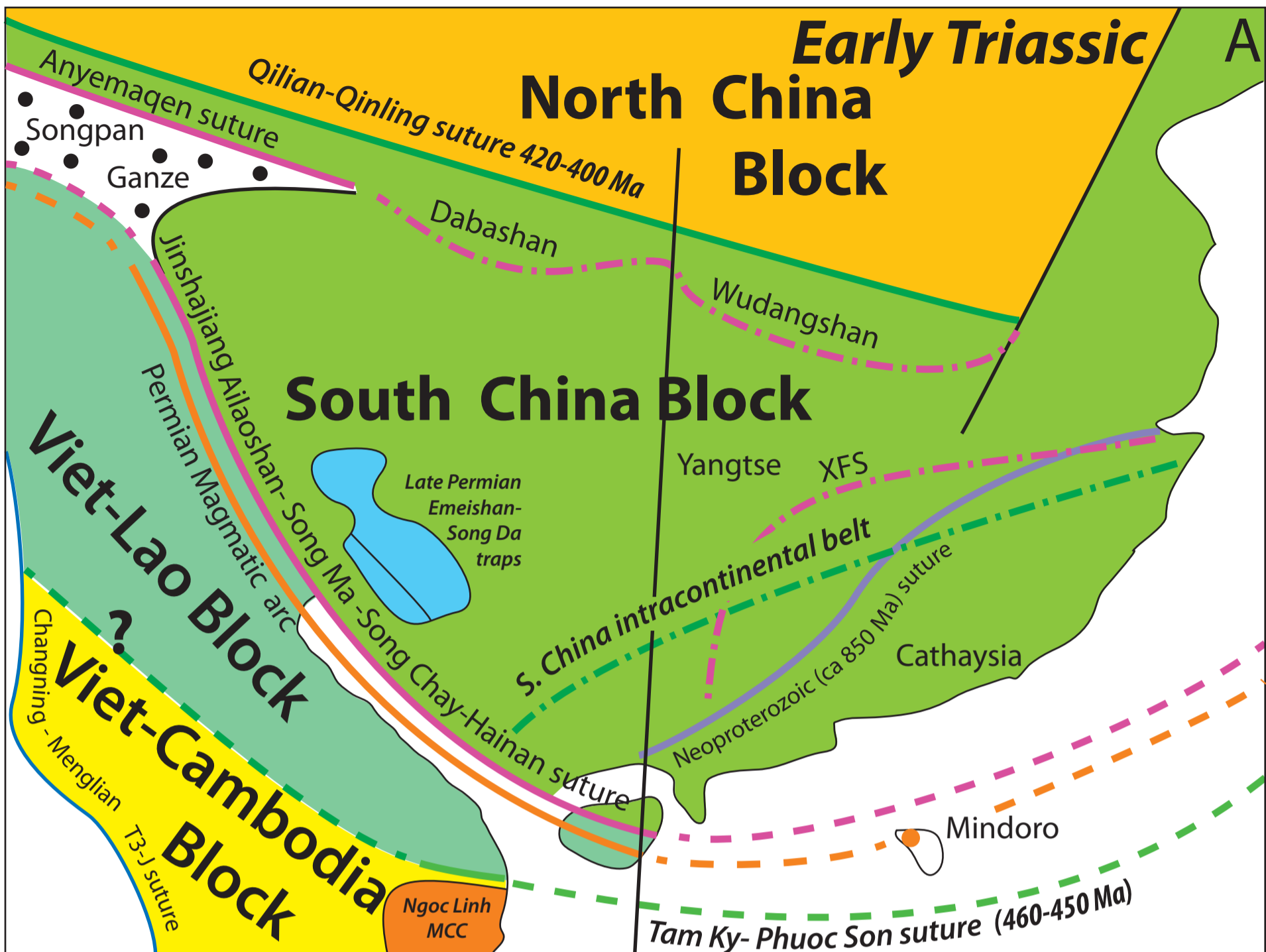


Fig. 14

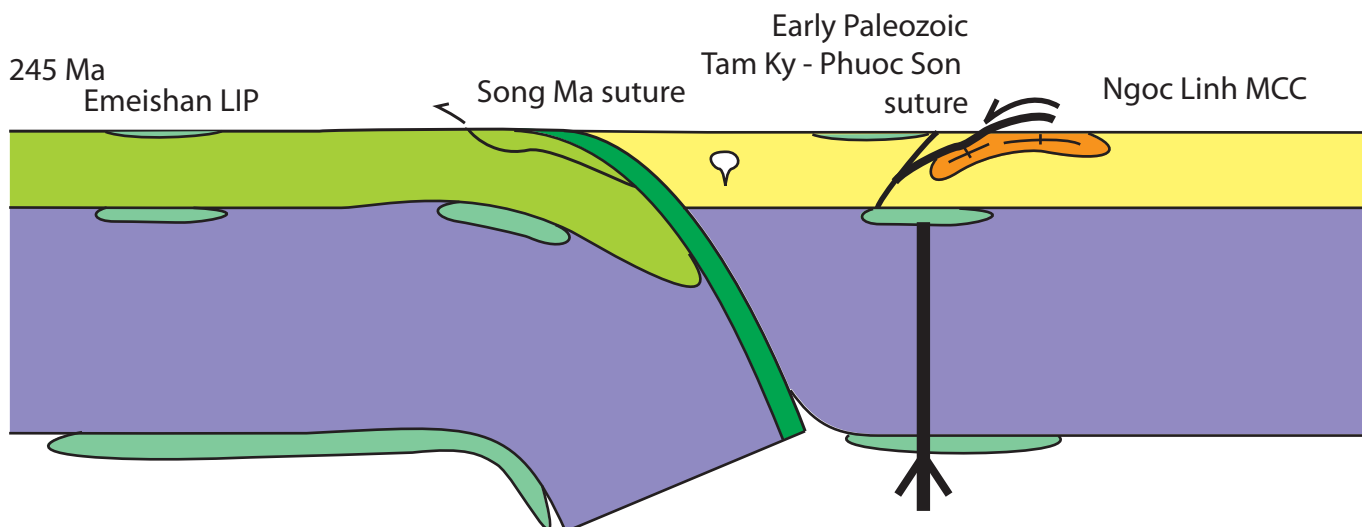
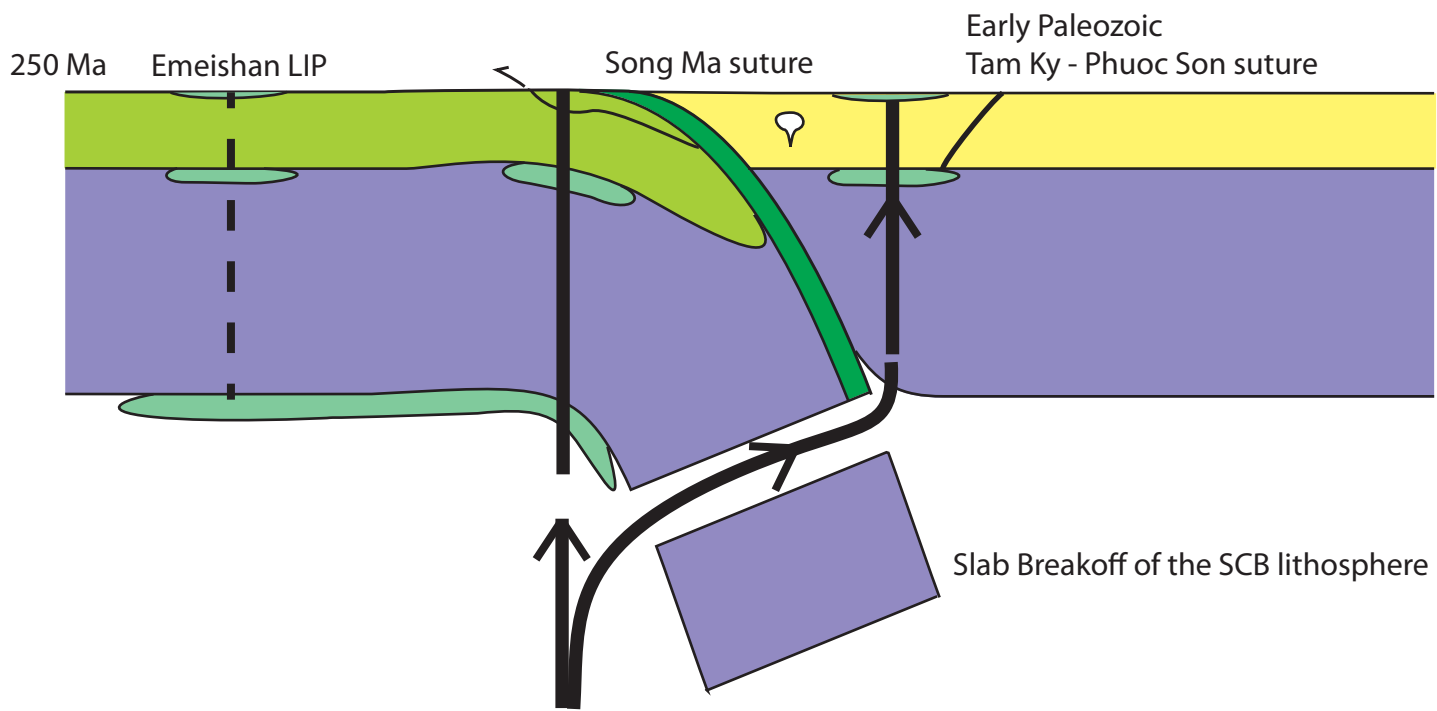
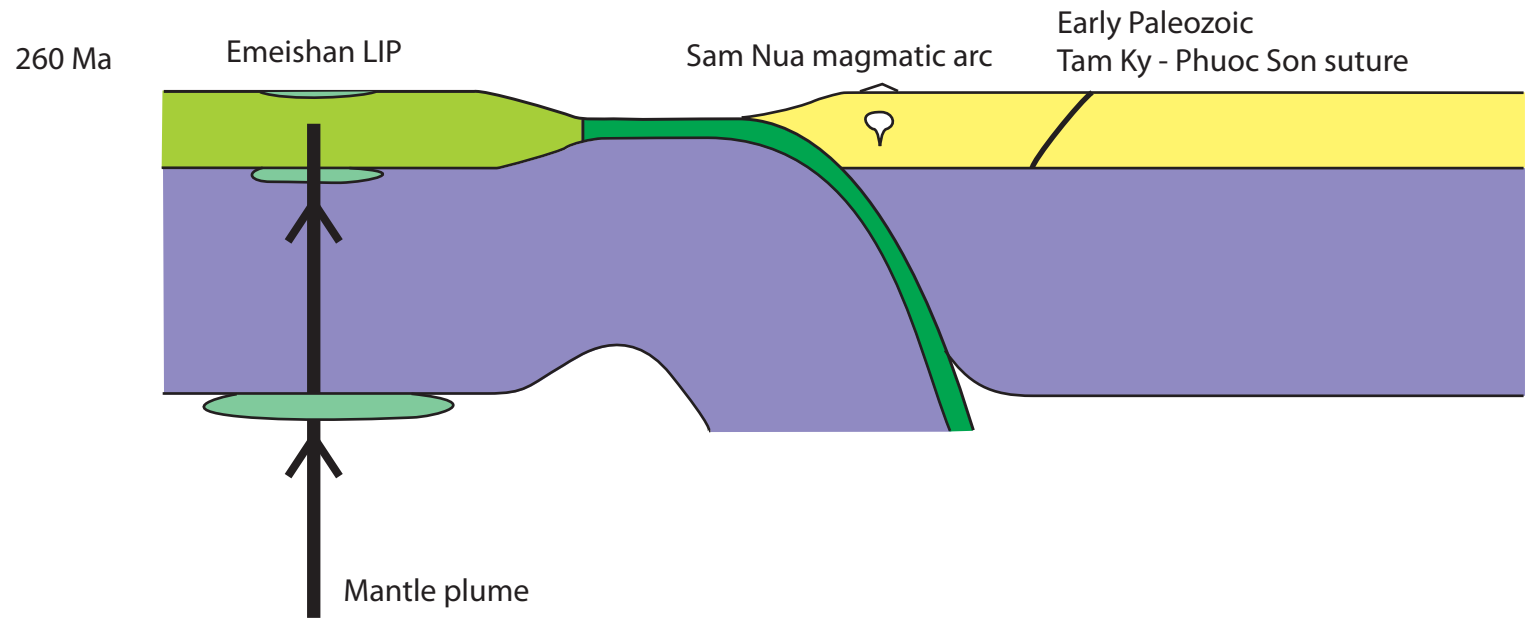


Fig. 15

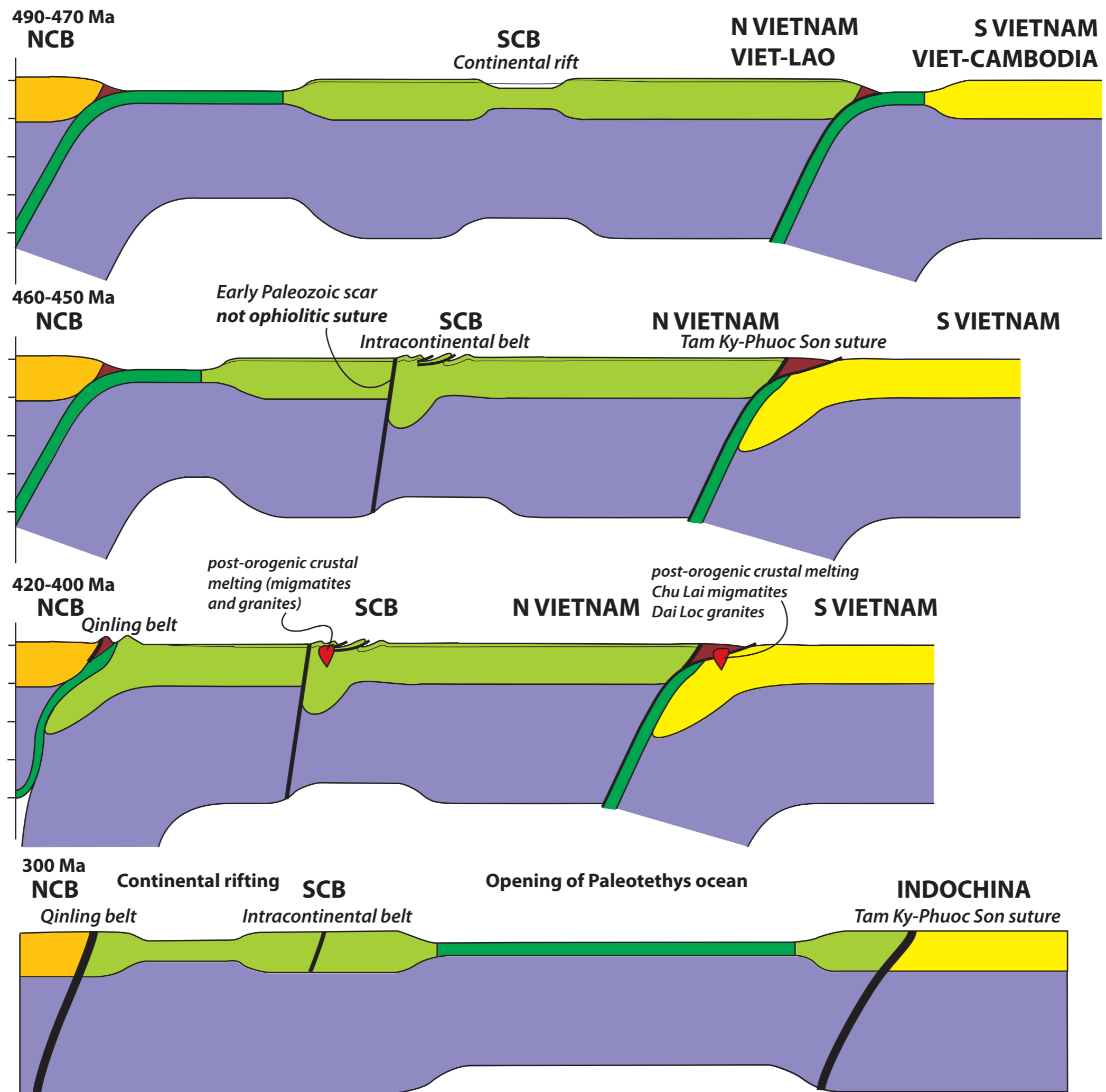


Fig. 16