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1 Structural Control of Mesozoic Orogens on SE Asia Basin Opening

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7

8 **Abstract:**

9 A comparative study of basement structures, basins geometry and evolution, around SE Asia,
10 highlights an intrinsic relationship between crustal inherited structures, and deformation
11 through time from the Late Mesozoic to the Present. The present continental margin developed
12 alongside of a large magmatic arc active from the Permian to the middle of the Cretaceous
13 subsequently stretched during the Cenozoic. The Permo-Triassic crustal configuration was
14 affected by a regional compression during the middle to late Cretaceous which appears to be
15 mostly radial to the horse-shoe shape of the magmatic belt, and is best imaged by large regional
16 shear zones, broad folds and penetrative shear joints. A subsequent extension perpendicular to
17 the margin followed in the Paleogene, which is firstly marked by an early stretching
18 characterized by block faulting, dykes, and parallel extensional joint. We observed that the
19 main necking zones follow former sutures, and the direction of opening is interestingly also
20 perpendicular to them. The following thinning phase initiated with only minor discrepancies in
21 the timing of initiation from E to W of SE Asia, marked by large crustal tilted blocks
22 underlining a first thinning of the crust. This event was dominated by the occurrence of low
23 angle normal faults bounding basins which capture most of the clastics derived from the
24 formerly uplifted magmatic arc. These faults are frequently continent-dipping (counter-
25 regional). Rooted into the lower crust, they often reactivate former thrust faults and plutons

26 boundaries on the edges of the Mesozoic magmatic arc. Therefore, a link with the relaxation
27 of the Late Mesozoic thickened crust is invoked.

28 **In** a later stage, rifting developed across the outer edges of the previously thinned crust, outside
29 the magmatic arc and up to the final continent-ocean boundary (COB of the South China Sea
30 in the East and the Andaman Sea to the West). It is marked by distal low angle normal faults
31 mostly ocean dipping (regional) that do not seem to be sensitive to margin fabric but more
32 dependant to the thermal state and boundary stress conditions.

33 Therefore, the pattern of basin structure and development seems conditioned by the intrinsic
34 crustal configuration of **SE Asia**, specifically by the Triassic and Cretaceous orogenic
35 structures (suture, crustal faults, and crustal thickness variations). The Late Mesozoic margins
36 were indeed characterized by thickened crust which may have undergone collapse just before
37 the onset of rifting *sensus stricto*. As a consequence, the general **dip direction** of these major
38 crustal boundaries was often preserved during the Cenozoic extension that affected the
39 marginal regions. Where the crustal thinning was strong enough, the **fault plane dipped**
40 **oceanward** as a result from the crust/mantle relative motion. It is proposed that the rifting of
41 the Cenozoic basins was triggered and conditioned by the relaxation of the orogens that
42 assembled Sunda Plate in the past.

43

44

45

46 **1. Introduction**

47

48 Continental stretching and breakup processes have been studied extensively in the recent years,
49 due to a large amount of information coming from the exploration of rifted basins ([Ziegler,](#)
50 [1988](#), [Péron-Pindivic, 2007](#); [Whitmarsh et al. 2001](#)). The simple pattern which was the

51 reference for years showed a stretched continental crust with the upper crust affected by large
52 normal faults rooted to one or several décollement levels, which ultimately separate crustal
53 slivers (Le Pichon and Sibuet, 1981, Taylor et al., 1995, Péron-Pindivic et al., 2013). Many
54 factors control the mechanical behavior of the crust during extension. The boundary forces and
55 the coupling with the mantle are critical to explain the distribution – localized or diffuse - of
56 deformation and the classification of margins, notably into magmatic or non-magmatic is not
57 clear-cut (Franke, 2013, Tugend et al., 2020, Sapin et al., 2021). Traditionally, these normal
58 faults are ocean-dipping or “regional” faults (Figure 1). However, extension in continental
59 margin is often marked by systemic “counter regional” or “continent-dipping” normal faults
60 (CRNF).

61 In places where the crust is extremely thinned, such as near the continent-ocean transition
62 (COT), the normal faults are generally ocean-verging (Figure 1c) and more densely spaced.
63 Where they exist, CRNF are thought to be associated with the relative motion of the continental
64 crust versus the upper mantle (Clerc et al., 2017) along a detachment near the Moho (Figure
65 1b). In areas where the crust is only moderately thinned such as the South China Sea, CRNF
66 are dominant, it is suspected that reactivation of pre-existing large crustal heterogeneities
67 controls the location and the dip direction of normal faults. Therefore, the inherited crustal
68 thickness and/or the lithostatic pressure, adding to the rheological boundaries of the crust, may
69 also be factors intervening in the localization of the faults during the stretching (Savva et al.,
70 2014, Sapin et al., 2021). In this paper we explore the effects of the last orogenic event of the
71 continental core of SE Asia (between Sulawesi, Sumatra and South China, see Figure 2) and
72 the subsequent extension during the Cenozoic. The sharply curved geometry of the
73 Sunda/Philippine margin offers a wide range of compressional and extensional directions that
74 support the interpretation of a genetic link between them.

75 The present-day configuration of SE Asia (Fig. 2) reflects the long lasting evolution of this
76 plate which was separated from the rest of Eurasia starting from the Late Miocene (Fig. 2)
77 (Hamilton, 1979, Hall, 2002; Pubellier & Morley, 2014). The horseshoe shape of SE ASIA
78 finds its origin in the large Permian to Cretaceous magmatic arc bordering the core of its
79 thickened crust (Metcalf, 2017; Pubellier & Morley, 2014; Sautter et al. 2017; Zahirovic et
80 al., 2016). This granitic belt is fringed by numerous Cenozoic basins on its sides (Fig 3).
81 Therefore, the history of the deformation of SE Asia is inherent to the evolution of the
82 subductions which were taking place all around SE Asia. The pre-Cenozoic basement
83 complexity of SE Asia is itself the result of the amalgamation, since the Middle Triassic and
84 up to the Late Cretaceous, of several continental blocks whose migration is witnessed by the
85 occurrence of magmatic arcs, accretionary wedges and suture zones (Fig 2) (Hamilton, 1979,
86 Hutchison, 1977, Metcalfe, 1998, Cai & Zhang, 2009, Tran et al., 2020; Faure et al. 2018).
87
88 Many of the basins are likely to have developed during the Cenozoic in a back-arc setting with
89 geometries intrinsically influenced by the obliquity between SE Asia trench curvature and the
90 direction of convergence of the Neo-Tethys and Indian oceanic crusts (Pubellier and Morley,
91 2014). Despite a well characterized geodynamic setting, the existence of a major asymmetry in
92 the rifting structures remains poorly understood. Numerous studies have shown that structural
93 inheritance of pre-rifting crustal heterogeneities is likely to have influenced the accommodation
94 of the extension in the Cenozoic (Morley et al. 2004; Hall, 2009; Morley et al. 2011; Morley,
95 2014; Sautter et al., 2017; Ye et al., 2018).
96
97 Indicators of an active margin since the Late Palaeozoic are well documented and the geometry,
98 elevation, rheology and tectonic features observed today are a direct result from this
99 geodynamic configuration (Lepvrier et al., 2004, Carter and Clift, 2008, Faure et al., 2014),

100 although Cretaceous and Paleogene deformation may have disrupted the continuity of the
101 sutures as illustrated with the Red River Fault motion induced by the India-Eurasia collision
102 (Leloup et al., 1995, and references therein). It has been shown in various publications that the
103 basement rocks involved in the extension were affected by large normal faults reactivating the
104 metamorphic fabrics, ophiolitic sutures (Morley, 2012, 2016; Morley et al., 2004) or the
105 granitic plutons (Sautter et al., 2017; Savva et al., 2014). Polyphase inversion of the Palaeozoic
106 and Mesozoic basement resulted in a highly deformed and fractured pre-rifting basement. This
107 remarkable slivering of the plutons illustrated by penetrative fractures is observed at all scales
108 (Fig 4) (Sautter et al. 2017). The structures appear to have been reactivated during the Cenozoic
109 rifting that developed across a wide extensional domain with half-grabens opening between
110 reef-capped horsts, comparable to the Basin and Range province of the North American
111 continent (Franke et al., 2014).

112 In order to evaluate the impact of compressional structure reactivations on the extensional
113 pattern, we compiled and mapped surface expressions of inherited structures such as former
114 suture zones, fractured granitic belts and basins morphologies integrated in a detailed regional
115 structural map of SE Asia (Fig.2). In this respect we do not emphasize on the strike slip relative
116 motion between blocks when these do not parallel former orogens and because, being mostly
117 vertical, they are not prone to be reactivated during thinning. Based on a large database of
118 seismic lines and digital elevation models, we juxtapose the geometries of Mesozoic structures
119 with the emplacement of the basins to explore their consistency at different scales of
120 observation. We propose that the rifting evolution of margins may be significantly sensitive to
121 inherited structures, in agreement with previous studies (Liang et al. 2019; Morley et al. 2011;
122 Morley 2014), particularly the dip direction of the former crustal thrusts, and how the higher
123 lithostatic stress belonging to thickened margins can account for the trigger of a subsequent
124 extensional deformation.

125

126 2. A plate surrounded by subduction zones since the Permian

127 SE Asia was formed by successive accretions of continental blocks drifted away from
128 Gondwana (Audley Charles, 1977, Hutchison, 2013; Metcalfe, 2013a; C. K. Morley, 2012)
129 principally since the Permian (Figure 2 and 3a). We do not focus on the deformation which had
130 taken place during the Palaeozoic for which the rifting from Gondwana had certainly shaped
131 the geometry of SE Asia core but rather emphasize on the Late Mesozoic and Early Cenozoic
132 active margins of SE Asia. These are thought to have conditioned the stretching and thinning
133 of the plate's fringe during the Late Cenozoic. The docking of the large Argo block along the
134 Meratus suture zone ended a journey starting from the NW Australian margin (Hamilton, 1979,
135 Audley Charles, 1977, Pubellier et al., 1999, Granath et al., 2011, Metcalfe, 2013a), and has
136 been initially thought to be related to the amalgamation of the Woyla and Burma terranes along
137 western Sunda (Barber, 2000) despite poorly constrained geodynamic reconstructions.
138 However, more recent studies suggest that the Burma block collided with Southeast Asia in the
139 Cenozoic (Westerveel et al., 2019; Morley et al., 2021).

140 2.1 - Triassic to Cretaceous subductions and outward migration of magmatism

141 The western, southern and eastern magmatic margins of SE Asia evolved in a strikingly similar
142 way (Hall, 2002; Pubellier & Morley, 2014; Metcalfe 2017). Across SE Asia, Permian
143 granitoids were emplaced in the interior of the present-day plate configuration (Figure. 2 and
144 3), and we observe that the activity of the arcs migrated toward the outside of the plate during
145 the Mesozoic. The opening of the Paleogene and Neogene was later conditioned by the location
146 of the Mesozoic crust thickened by the successive shortening and the magmatism (Figure 3b
147 and 3c).

148 Most of the Permian granitoids known in Southeast Asian are concentrated inland Vietnam and
149 the Malay Peninsula until the East Himalayan Syntaxes (Figure 2) and are characterized by I-
150 Type arc-related chemical signature originating from the subduction of the Paleo-Tethys
151 (Hutchison, 1977, 1989, Ghani et al., 2013; Metcalfe, 2013b). On the eastern side of SE Asia
152 near the edges of the Indochina Block, Permian and Triassic subduction/collision belts
153 (Lepvrier et al., 2004, Faure et al., 2018, Gardner et al., 2017) shaped the gross geometry of
154 Eastern SE Asia. Younger arc-related granitoids migrated oceanward from the Late Jurassic to
155 the early Upper Cretaceous (Searle et al. 2012); the youngest magmatic indicators in the
156 continental core being the late Cretaceous coastal dykes (Sewell et al., 2012) as they are
157 observed near Hong Kong and the Guangdong Province of PRC (Li & Li, 2007, Yeh et al. ,
158 2017). To the west, the successive magmatic provinces defined three distinctive belts building
159 the Malay Peninsula's basement which is cored by the large Main Range Batholith (Hutchison,
160 1977; Metcalfe, 2013b; Sautter and Pubellier, 2015). These belts extend to the South to the
161 islands of Bangka and Belitung (G.J.J. et al., 1973; Katili, 1975, Schwartz et al., 1995). The
162 youngest arc-related granitoids are dated to the Late Cretaceous to Paleogene and are located
163 in Sumatra, Myanmar and Thailand (Figure 3b) (Gardiner et al., 2015). Upper Cretaceous
164 diorite dykes in eastern Peninsular Malaysia as well as Late Cenozoic basaltic lavas along the
165 northern shoreline of the Gulf of Thailand (Tjia, 2010) intruded the intensively fractured Late
166 Paleozoic Early Mesozoic eastern belt. On the other hand, the Upper Triassic-Lower Jurassic
167 Main Range granitic province is affected by numerous felsic dykes from southern Malaysia to
168 Northern Thailand, and accompanied by smaller isolated granitic intrusions, suspected to
169 represent a poorly constrained late Cretaceous thermal anomaly (Cottam et al. 2013, Sautter et
170 al., 2019). Subduction was still active as more sporadic pulses in the Eocene along the Mergui
171 ridge as evidenced by syn-rift volcanism in the Mergui basin (Sautter et al., 2017; Srisuriyon

172 and Morley, 2014), and later in the midst of the Andaman Sea during the Neogene (Morley et
173 al., 2015; Morley and Alvey, 2014).

174 In the southern part of the plate, the late Palaeozoic paleogeographic indicators are scarce
175 (Barber et al., 2005) but magmatism became increasingly important during the Cretaceous
176 (Figure 3a) as shown by the extensive granitic province of the Schwanner Mountains in
177 Kalimantan, and by intense volcanism developed during the Cenozoic along Sumatra, Java and
178 the eastern Sunda arc (Abdullah et al., 2000; Soeria-Atmadja and Noeradi, 2005).

179

180 2.2. Triassic and Cretaceous orogens; building the core of SE Asia

181 During the Triassic, the SE Asia core was subjected to the forces inherent to the termination of
182 the subduction (Hall and Wilson, 2000) which closed the different branches of the Paleotethys
183 in Asia. The first docking of Gondwanian blocks occurred during the Late Permian-Early
184 Triassic along the eastern side of the Indochina block (Faure et al., 2014,2016, Lepvrier et al,
185 2004), then in the Middle Triassic along the Ailao Shan and all the Red River system (Leloup
186 et al., 1995 Cai & Zhang, 2009, Metcalfe, 2000, 2013). Indicators of the Early to Middle
187 Triassic tectonics marked by a sharp angular unconformity are also seen to the South of the
188 South China Block (Faure et al., 2018, Cai & Zhong, 2017). This geodynamic configuration
189 embodies a large sheltered domain in the central part of SE Asia which became the locus of
190 massive continental sedimentation during the Mesozoic (Clements et al., 2011; Fyhn et al.,
191 2010; Tran and Vu, 2011). To the west of SE Asia, suture zones run from South China-Thailand
192 area to Peninsular Malaysia and Bangka-Belitung Island in Indonesia. Traces of a back-arc
193 closure onshore Thailand are evident but become poorly exposed southward suggesting that
194 less subducted crust was involved in the shortening (Choong et al., 2021). The southward
195 decrease in metamorphic grade and relics of ultramafic rocks along the suture zones, from

196 Thailand to Bangka-Belitung Island, may reflect a weaker orogenic event towards the southern
197 end of the Paleo-Tethys. The main elements associated with this large suture zone are the post
198 collision granitic bodies of Thailand and Peninsular Malaysia. These granites constitute the
199 backbone of the peninsula and conditioned the geometry of the rifting during Eocene and
200 Oligocene (Sautter et al., 2017).

201 2.3. Cretaceous compression

202

203 After the Early to Middle Triassic Orogeny (Faure et al., 2018) and the Late Triassic to Jurassic
204 Cimmerian orogeny, the main tectonic event affecting SE Asia continental core is a Cretaceous
205 regional diffuse compression (Morley, 2012, Clements et al., 2011, Nanni et al., 2017). This
206 period was marked by the accretion of several blocks at the outer rim of SE Asia, (Barber,
207 2000, Morley, 2012, Hall, 2012), but the extent and the timing of accretion are still debated. In
208 eastern and south-eastern Asia, examples show that a Triassic tectonic event was reactivated
209 during the Cretaceous by alternating phases of compression and extension (Lin, 2015, Morley,
210 2016; Chu et al., 2019) with a deformation involving folds, thrusts and metamorphism (Chan
211 et al., 2008, Nanni et al., 2016) resulting in local highs (Yan et al., 2014, Huang et al., 2017),
212 and erosional surfaces (Liang et al., 2019). The geodynamic environment included hot
213 geotherms in western Sunda (Watkinson et al. 2011) and could possibly be linked to the
214 subduction of a large Meso-Tethys ridge (Zahirovic et al., 2014) The area located along the
215 present-day position of the southern margin of the South China Sea is a re-entrant of the general
216 horse-shoe shape and is interpreted to be a consequence of the docking of the Luconia Block
217 (or Dangerous Grounds Block; Hall, 2012) during the Cretaceous, prior to the opening of the
218 South China Sea (Fig. 2). The location of the suture, although only poorly imaged at depth with
219 basement deformation on seismic lines, must be presently located offshore outward of the
220 Cretaceous granites of the South China margin and South China (Fyhn et al., 2010, Pubellier

221 et al., 2017). The deformation includes, on either side of the internal orogenic zone, a thick-
222 skinned fold and thrust belt with ductile exhumation along metamorphic domes (François et
223 al., 2017, Chan et al., 2008, Sautter et al. 2019; Wei et al., 2015; Nanni et al. 2017; Yan et al.,
224 2014).

225 Finally, the extreme outer edges of the system were subjected to the Cenozoic docking of the
226 eastern Philippine Arc carried by the Philippine Sea Plate in the east (Karig, 1983, McCabe
227 and Almasco, 1985, Pubellier et al., 1998), and the formation of thick accretionary wedges
228 involving debated pieces of ocean floor (Wajzer, 1991, Barber and Crow, 2003, Barber et al.,
229 2005) in the west (Fig 2).

230 3. Deformation regimes around SE Asia from Late Mesozoic to recent.

231 We hereafter consider that most of the deformations affecting the post-Triassic granitoids is
232 late Cretaceous and Cenozoic. The Cretaceous is marked by a regime of intense magmatism
233 and compression both in Western and Eastern Sunda. The terranes which might have accreted
234 at that time are still a matter of debate. The Burma block is represented by sporadic Cenozoic
235 sediments in Myanmar (Mitchell, 2017); the Woyla terrane is probably composed of an oceanic
236 arc (Advokaat et al. 2018; Wajzer et al., 1991); the Natuna block is debated in terms of location
237 and docking age. Only the Argo Block seems to be well identified. This tectono-magmatic
238 event may be related to the subduction of large oceanic ridges as suggested by the
239 reconstruction of Setton and Muller and Zahirovic et al., (2014). In Eastern SE Asia, this event
240 is poorly dated due to lack of shallow marine deposits but is locally considered as late Early
241 Cretaceous as for instance around Hong Kong (Campbell and Sewell, 2007; Nanni et al., 2017).
242 The compression is marked by an angular unconformity on seismic lines blanketing broad folds
243 involving the Cretaceous sediments in the South China Sea (Yan et al., 2014, Huang et al.,
244 2017). It results in a major sedimentary hiatus from the late Cretaceous to the Eocene in SE

245 **Asia** (Hutchison et al., 1992; Clements et al., 2011). The Cenozoic basins that opened in **SE**
246 **Asia** are all located on the edge of the thickened crust following a post-Cretaceous relaxation
247 (Pubellier and Morley, 2014; **Zahirovic et al., 2016**).

248 We selected five principal synthetic cross-sections (**Figure 4 to 8**) out of the database compiled
249 on the map of **Figure 2**. These sections integrate published seismic lines in each area and were
250 supported by other unpublished lines in order to extrapolate observations located outside the
251 strip which is presented. Two E-W sections are located in the west, one NW-SE composite
252 section in the south and two NW-SE sections in the east of **SE Asia**. Each of these sections is
253 accompanied by a selected enlargement of a detailed structural map in order to show the lateral
254 extent of the geological indicators of the Mesozoic compression, and the later extension which
255 opened marginal basins.

256 3.1. Western SE Asia

257 In Western Sunda, pre-rifting compression has been documented extensively. The Mesozoic
258 deformation involved high temperature conditions and a large amount of wrench motion
259 (Lacassin et al., 1997; Morley, 2004). There was possibly a partitioning between N-S striking
260 thrust faults and fold axis, and a synchronous activity of sinistral NW-SE and dextral NE-SW
261 wrench faults (**Figure 2 and 4**) (Emmel and Curray, 1982; **Morley, 2012; Sautter et al., 2017**).
262 Southward, in Peninsular Malaysia, a dextral shear is suspected in the midst of the Main Range
263 batholith (Fig 5) (Harun et al., 2002; Sautter and Pubellier, 2015). The observed directions of
264 shear joints are strikingly homogeneous as for instance in the granites of southern Thailand,
265 and well imprinted on the morpho-structures along the coast of Southern Myanmar (Figure 5),
266 although field observations are still lacking in the southernmost part. The fractures are indeed
267 expressed mainly in very competent rocks, particularly in granite which do not record well

268 developed slickensides except for rare crystallisation of epidote, or Late Palaeozoic limestone
269 which appears karstified preferentially along this fabric.

270 In Peninsular Malaysia, field evidence includes remarkable sets of joints oriented NW-SE and
271 NE-SW (Figure 7). A convincing example is present in granites surrounding the Kinta Valley
272 in northern Malaysia (Choong et al., 2015, Figure 7). They are often clogged by massive quartz
273 dykes that pre-date the rifting stage (Sautter et al., 2017). Broad folds are also present in
274 Peninsular Malaysia (Tjia 1994; Metcalfe, 2013b). These large folds, which affect de granites,
275 are indicative of an E-W shortening (Figure 6).

276 In terms of extensional structures, Western Sunda is characterized principally by large normal
277 faults cutting the Palaeozoic basement and the Mesozoic granites. The early extensional
278 deformation is mostly visible along the edges of the Mesozoic granites in Malaysia and
279 Southern Thailand. There is however no spectacular normal fault onshore. The extension is
280 marked only offshore on the margins of the Andaman Sea (Figure 6), particularly on the Mergui
281 ridge (Sautter et al., 2017). The normal faults reactivate pluton flanks and pre-existing
282 conjugate shear joint sets and are marked by stockwerk-like cataclasite of quartz porphyric
283 material with clasts of the host rock, running parallel to the axis of the granitic belt.
284 Aforementioned porphyric felsic dykes are exhumed through the ductile-brittle transition at the
285 shift from compression to extension, as seen in the field by ductile shear in agreement with a
286 and E-W compression and brittle open fractures following a later undated E-W extension. The
287 edge of the granites acted as a decollement surface which stacks up carbonate platform slices
288 under high temperature conditions evidenced in ductily deformed limestone (Choong et al.,
289 2015). The precise discrimination between the last stages of the compressional deformation
290 and the early stages of the extensional conditions is yet to be assessed.

291 The early extensional event also includes an early stretching accommodated through discrete
292 E-W faults that presently follow the edge of the Malay Peninsula thickened crust (figure 3b).
293 This event is clearly antecedent to the opening of isolated N-S half grabens in the Late Eocene
294 to Oligocene. Ubiquitous in the Penyu Basin and the deep section of the Malay Basin, this set
295 of faults is also retrieved from fault tensor analysis onshore despite the absence of major dip
296 slip movements (Sautter et al. 2017, 2019; Choong et al. 2021). After the development of
297 numerous small scale continental basins oriented NNW-SSE and NNE-SSW, the basins
298 experienced strong thinning as seen on seismic profiles, forming deep half-grabens from the
299 Earliest Oligocene (Morley et al., 2011; Raj et al., 1998). In the southern region (around
300 Peninsular Malaysia), the syn-rift sequences (Figure 6) were deposited mainly during the
301 Oligocene and are characterized by a grading from continental shales to thick deltaic marine
302 sandy sequences in the middle to late Oligocene (Sautter et al., 2017), merging former isolated
303 grabens into larger basins (Figure 6) whereas northward, in the Andaman Sea-Mergui region,
304 syn-rift sequences are marine influenced (Polachan et al., 1991). (The major syn-rift faults are
305 predominantly deep rooted low angle normal faults (Morley, 2009) mostly dipping eastward
306 (CRNF). These are restricted to the East of the Mergui ridge (Sautter et al., 2017) within the
307 westernmost occurrences of the Upper Cretaceous magmatic arc and to the east of the Triassic
308 granitic belts in the Gulf of Thailand (Figure 2, Polachan and Racey, 1994; Putthapiban, 1992).
309 In western SE Asia, the Andaman Sea (Figure 2 and 4) is the only domain that suffered extreme
310 stretching leading to oceanic spreading in the Late Miocene (Curry 2005; Morley and Alvey,
311 2015). A recent study suggested that the East Andaman Basin depression would have
312 originated from a to-top-the-west detachment in the Oligocene and subsequently controlled by
313 a N-S right lateral transtensional system (Mahattanachai et al., 2021). However, our data
314 suggest that this region was affected by two successive rifting episodes; the first one in the
315 Oligocene generated CRNF presently located in the deepest sections (see section on Figure 6).

316 Following an abrupt change in the obliquity of the convergence in the Miocene, the second
317 rifting is defined by ductile distal normal faults verging towards the oceanic crust (Figure 4).
318 In the East Andaman basin, the two generations of faults are preserved with deep CRNF
319 dipping eastward overlaid by shallower DNF dipping westward (Figure 2).

320

321 3.2. North-Eastern SE Asia

322 The northern margin of the South China Sea is marked by crustal stretching and thinning which
323 took place mostly in the Paleogene (Ru and Pigott 1986; Savva et al., 2014). Similarly to the
324 history of Western Sunda, the extension is followed in the Miocene by an extreme crustal
325 thinning and mantle uplift that sometimes places sediments in contact with the Moho
326 discontinuity (Savva et al., 2012, Lei and Ren, 2016). Most of the large faults responsible for
327 the thinning are CRNF, particularly in the Pearl River Basin which was mostly affected by the
328 Eocene to Early Oligocene rifting

329 The Late Mesozoic to Present evolution of the eastern Sunda area similarly began with a
330 Cretaceous compression. A remarkable early insight of the succession of events was given for
331 the Pearl River delta by Pigott and Ru, (1994) and Pinglu and Chuntao, (1994). These authors
332 noticed that in the coastal region of the South China Sea, an early compression is oriented NW-
333 SE and marked by a penetrative set of conjugate faults which is developed on top of broad
334 folds and was attributed to an Early Paleozoic deformation. Although Palaeozoic deformation
335 exists, the last important folding event has since then been attributed to late Cretaceous on the
336 basis of seismic interpretation (Yan, 2014) and onshore mapping (Campbell and Sewell, 2007;
337 Nanni et al., 2017). The Cretaceous deformation is also marked by broad folds and thrusts in
338 the coastal region of SE China particularly around the Pearl River delta (Chan et al., 2010) and
339 along the shelf of the northern margin of the South China Sea (Yan et al. 2014; Ye et al., 2020).

340 These fractures are also present in the Tonkin region (N. Vietnam), where they are intersected
341 by Eocene to Miocene wrench faults responsible for the opening of the Baise (China) and Cao
342 Bang (Vietnam) basins (Pubellier et al, 2004). Towards the centre of the plate, fractured
343 reservoirs are present in the coastal strip of granites offshore Vietnam and are controlled by a
344 similar set of first order regional fractures striking WNW-ESE and NE-SW (Cuong and
345 Warren, 2009). This penetrative conjugate shear joints remarkably affected the Mesozoic
346 granites along the South China Sea in Guangdong and Guangxi provinces of China as well as
347 in Southeast Vietnam coast (Figure 8 and 9). They are compatible with an E-W compression
348 that is evidenced on remotely sensed data as well as fault tensors analyses. In the offshore
349 region, Cretaceous folds within the shelf have been interpreted in seismic data (Yan et al. 2014),
350 with axes of compression oriented NNE-SSW to NW-SE on late Cretaceous thrusts faults (Ye,
351 2020), but also on field data onshore in Hong Kong (Nanni et al., 2017).

352

353 3.2.1. Early extension; close set of faults and joints

354 In the coastal strip from Southern China and Vietnam, parallel extensional joints and normal
355 faults affect the late Cretaceous series in the Pearl River region (Cuong and Warren, 2009; Cao
356 et al., 2018; Chan et al., 2010), and large faults delineating half-grabens offshore (Franke et al.,
357 2014). The pre-Cenozoic basement, where it crops out on land, is affected by numerous
358 fractures which appear well on remote sensing images and can be easily observed in the field
359 onshore (Pubellier et al., 2017). They are unfortunately almost systematically buried under
360 thick Cenozoic clastic series and carbonate platforms offshore. They appear clearly on seismic
361 lines such as the section 1555 (Larsen et al., 2018) (figure 8). 2D seismic lines reveal relatively
362 simple structures with a clear pattern of normal faults with moderate offsets resulting in diffuse
363 block faulting (Fig 6, 7). Although these fractures are characteristic of Sunda Plate pre-rifting
364 basement (Tg in the South China Sea, Ding et al., 2013), we rarely have a clear picture of their

365 3D **geometry**, and it can be argued that they strike in the same direction as the older set of
366 conjugate shear joints described above. However, these have a clear dip-slip motion indicating
367 classical “block-faulting” pattern and the spacing is in favour of a regular set of fractures and
368 faults related to the early stretching stage of extension (Figure 8 left of section). Others have
369 been shown by [Lei and Ren \(2016\)](#). The apparent spacing on seismic data is 5 to 10 Km, but it
370 does not preclude that a shorter wavelength also exists beyond the detection of the seismic
371 profiles. These fractures pre-date the main stage of thinning as they always appear along
372 basement surfaces subsequently tilted by rotational faults (figure 6). In the field, many localities
373 show an early phase of extension prior to the tilting as for instance in the Guangdong Province
374 NE of Shenzhen (Donggan Basin, [Shen, 2008](#), [Chan et al., 2010](#)). Along most of the coastal
375 region of the South China Sea, the early extension is oriented NW-SE with faults generally
376 parallel to both the coastline and the trend of the **Triassic to Cretaceous arc** and tectonic belt
377 (Figures 8 and 9). These early faults are characterized by minor offset as compared to the
378 subsequent large listric faults responsible for most of the thinning.

379

380 3.2.2. Listric normal Faults

381 This second system is a middle Eocene to early Oligocene rift event characterized all across
382 the wide margins of the South China Sea, showing a succession of rift basins with thinned
383 continental crust associated with large extensional detachment faults soling on top of the lower
384 crust ([Ding et al., 2013](#), [Savva et al., 2012](#), [Franke et al., 2014](#), [Lei et al., 2016, 2018](#),
385 [Nirrengarten et al., 2020](#)). They are responsible for the tilting of the blocks and create the large
386 half-grabens of the Pearl River Mouth Basin. They appear in some places to broadly bend the
387 top basement surface in addition, suggesting that the thinned crust could have suffered from a
388 roll-over at a crustal scale (**Figure8**). The majority of these rifting faults are counter regional

389 beneath the shelf. As we look closer to the COT where the continental crust is thin, they are
390 systematically ocean-verging (regional).

391

392

393 3.3. Central-Eastern SE Asia

394 Toward the South, along the coast of Vietnam (Figure 2), the set of conjugate shears constitute
395 the main argument for a middle to late Cretaceous deformation as the folding event is difficult
396 to date onshore due to the scarcity of reliable ages in the overlying sediments. The conjugate
397 set of fractures is also compatible with an E-W compression (Figure 11) and reflects the set of
398 conjugate strike-slip faults described by (Rangin et al., 1995). The evolution of the large faults
399 was affected during the Paleogene by the slip of the Vietnam Fault during the opening of the
400 South China Sea (Fyhn et al., 2009). Few normal faults exist on the narrow shelf, but the
401 extension offshore is stronger starting from the shelf break (Figure 2 and 10). Two large graben
402 opened; the Cuu Long Basin and the Nam Con Son Basin. They also are characterised by a
403 number of CRNF close to the coastline (Savva et al., 2014, Franke et al, 2014, Clerc et al,
404 2017). While the Cuu Long basin was affected by the displacement of the Mae Ping Fault
405 (Schmidt et al., 2019), the more distal the Nam Con Son Basin is located at the tip of the SCS
406 propagator and displays numerous overlying oceanward distal normal faults (DNF) which
407 occur just prior to the breakup.

408 The conjugate (southern) margin of the South China Sea does not permit to observe the
409 basement fractures indicative of the Cretaceous compression. The rifting structures are only
410 visible on seismic lines in front of the North Borneo accretionary wedge, large crustal
411 Paleogene faults dip to the northwest (Fix 2). They clearly pre-date the late normal faults
412 occurring closer to the oceanic crust (figure 10) and they created large half graben being the
413 locus of important clastic sedimentation, mostly continental and shallow marine lacustrine but

414 also sub-tidal (Kosa 2015; Mathew et al. 2020). If the faults are in an ocean-dipping position
415 (toward SCS oceanic crust) at Present, reconstructions prior to the complete opening of the
416 South China Sea show that they were formed as large CRNF (toward South China and
417 Indochina blocks) in the Paleogene rifting stage (Lei and Ren, 2016). In the Luconia Basin and
418 offshore NW Palawan (Schlütter et al., 1996), both Regional (RNF, Yao et al., 2018) and
419 Counter Regional (CRNF) are observed. This implies that the CRNF were formed on both
420 margins of the SCS in the period of intense rifting during the Eocene and the Early Oligocene
421 at a time where the margin was shorter and juxtaposed to the South China and Indochina blocks
422 (figure 2).

423

424 It is a general characteristic for distal parts of continental margins to be affected by normal
425 faults cutting through thinned continental crust (Franke et al., 2014, Ranero, 2020, Chang et
426 al., in press). IODP drilling results emphasize the complexity of the crustal thinning next to the
427 COT where breccias have been found (Larsen et al, 2018). These seaward dipping faults affect
428 even margins where CRNF dominate (Clerc et al. 2017). In the South China Sea, distal normal
429 faults are well expressed and appear with a low angle in most places near the COB (Fig 6 and
430 7). Interestingly, they appear steeper where they affect the Cretaceous granites as for instance
431 at the edge of the Spratlys or the Paracel margins (Figure 6).

432

433 3.4. Southern SE Asia

434 In the southern part of SE Asia, the pre-rifting basement crops out exclusively in the Cretaceous
435 granitoids of the Schwanner Mountains (Figure 2). In this region, the compression is also better
436 illustrated on remotely sensed data than on direct field observations because morphologies are
437 not well preserved in these low elevation granitic provinces. There, the set of pre-rifting
438 conjugate joints indicates a N-S (N10°E) direction of maximum principal stress (Figure 13).

439 Interestingly, the sharp angle is small (25°) between the conjugate fractures, thus constraining
440 accurately the main horizontal compression.

441 The extension in the southern Sunda is localized within a narrow zone of less than 100km width
442 on the margins of the Makassar basin (Figure 2), but it still dramatically thins the continental
443 crust. Along the coast of Makassar, east of the Meratus Mountains, conjugate joints indicate a
444 NW-SE extension in addition to a NE-SW one (Pubellier et al., 1998). In the Makassar Basin
445 of SE Sunda, the rifting is marked by faults dipping mainly toward the north (CRNF),
446 particularly the deep-rooted ones which account for most of the thinning. Some CRNF
447 affecting the pre-rifting basement of the basin are located along the flanks of the Cretaceous
448 Schwanner Mountains granites (Figure 2 and 12), but are not spectacular or poorly documented
449 Further south, in the Java basin, N-S extension was initiated just after the late Cretaceous where
450 most of the syn-rift section is Eocene (Figure 3b and 12). The finite extension is not as strong
451 as that of the Western and Eastern Sunda and is oriented N-S, creating basins orthogonal to the
452 previous compressional axis observed in the Schwanner Mountains of South Kalimantan.
453 These early Paleogene E-W are predominant in southern Sunda but interestingly occur locally
454 further North in the Gulf of Thailand and in the South China Sea (Figure 2 and 3b). Both CRNF
455 and RNF are seen on seismic lines (Fig X) (Granath et al., 2011). The difficulty to match the
456 observations in the Southern Sunda with those of Eastern and Western Sunda, is that most of
457 the rifting faults which are observed South and SE of the Meratus/Argo suture zone are actually
458 inherited from the rifting of the Australian margin (Hall, 2012, Granath et al., 2011) (Figure 2
459 and 12). Yet, it is clear that the early faults initiate on the edges of the Schwanner granite in
460 the Barito Basin, and end as distal normal faults in the Makassar Basin. The CRNF are mostly
461 located on the edge of the Bawean arch (Bawean Trough) and the Central Deep north of Madura
462 Island (Satyana et al., 2004). The extension is mostly Eocene, but the whole region was
463 shortened in the middle Miocene (Figure 12). The shortening affected the Makassar and Kutei

464 basins, but also inverted the early normal faults in the Java Sea near Kangean Island and the
465 Madura Peninsula.

466

467 **4. Synthesis**

468 In spite of the large extent of **SE Asia**, every region in **SE Asia** witnessed similar evolutions
469 and share comparable structural features. A large subduction zone surrounded the margin
470 which created a backbone of granites developed from the Permian to the end of the Early
471 Cretaceous. Compression in the late Cretaceous is **documented** through a series of shear joints
472 indicating a radial maximum stress imprinted in the granites but also broad folds and thrusts
473 which reactivate Triassic and Early Cretaceous sutures. Starting from the Cretaceous-
474 Paleogene boundary, the margins entered an extensional regime (Pubellier and Morley, 2014)
475 that began with shear zones and cataclastic deformation at the boundaries of the granites, and
476 counter regional normal faults often reactivating former Mesozoic folds and pluton edges. The
477 accommodation of the extension migrated towards the plate margins with a critical thinning of
478 the crust restricted to **SE Asia** edges which are marked by distal regional normal faults (DNS)
479 dipping towards the newly formed oceanic crust.

480 4.1. Indicators of Cretaceous compression, broad folds and shear joints

481 The striking aspect of the deformation observed within the **Permian to Cretaceous** granites is
482 represented by a set of conjugate shear fractures which are ubiquitous and well expressed
483 particularly in competent rocks around **SE Asia** (figure 4 to 8). We observe that the formation
484 of shear joints always pre-date the Cenozoic extensional joints.

485 Therefore, the average measurements both on outcrops and on SAR images (ERS-1, JERS-1,
486 Space Shuttle Radar) may be complex, but a clear set of conjugate fractures indicative of
487 varying E-W to NW-SE compression is always dominant all along the eastern and the western

488 sides of SE Asia (Ye et al., 2020), whereas it is N-S in the south (Southern Borneo). To all the
489 sites which were studied in the field, similar directions were observed and they systematically
490 pre-date the Cenozoic extension (Sautter et al. 2017; Morley 2004). The folds may be several
491 kilometres in width such as in the Pearl River in Guangdong Province of China (Chan et al.,
492 2010).

493

494 4.2. A post late Cretaceous Orogeny relaxation

495

496 The early stages of extension are difficult to assess in continental margins. They are generally
497 diffuse and as a result tend to be sensitive to small variations of rheology or crustal thickness
498 (Jammes and Lavier 2019). The initial stretching stage is widely distributed (Peron-Pindivic et
499 al., 2015) as evidenced on many seismic lines by pre-rift sets of normal faults without specific
500 vergency and limited offsets. They are tilted together with the rest of the pre-rift units.
501 However, we observe that the faults, usually low-angle normal faults tend to also localize at
502 the boundary of the more cohesive and resistant granites. Spectacular examples are found
503 across the Malay Peninsula where “roof pendant” structures are reactivated with a normal dip-
504 slip motion (Sautter et al. 2017; 2019). Reactivation of pluton edges involves important silica-
505 rich fluid circulation and is expressed in the field by development of quartz-porphyric dykes at
506 the contact between the granites and the host rock (Sautter et al 2017; Tannock et al. 2020).
507 These penetrate by a few meters in the granites by a dense “stockwerk-like” network of tension
508 gashes and hydro-fractures.

509

510 4.3. Large crustal scale normal faults (counter regional and regional)

511

512 The domains affected by major crustal thinning are concentrated in the more distal regions of
513 the plate, under the continental shelf, and affects largely the granitic belts which are sliced-off
514 in a series of parallel normal faults with large offsets. These faults are mostly rooted within the
515 lower crust (Lei et al., 2016, Franke et al., 2014) and often closely spaced. They accommodate
516 a higher stretching factor (Ding et al, 2011), and constitute the “thinning stage” (Lavier and
517 Manatschall, 2006). Around the Sunda block, many of the normal faults dipping towards the
518 core of SE Asia (CRNF) (Figures 4,6,8,10,12), and thus created a large asymmetry within the
519 thinned margin with series of half grabens rotated continentward. While some of these faults
520 may originate from major horizontal shear episodes along large-scale strike slip fault (Figure
521 2), it is worth noticing that a majority of these faults are systematically parallel to the alignment
522 of the granitic plutons in the proximal regions but also to the shelf break in the more distal parts
523 (Figure 2 and 3). Hence, the trigger for the initial extension could be linked to the excess of
524 crustal thickness or topography in the granitic arc region, suggesting a strong influence of
525 lithostatic stress compared to the actual boundary forces (Figure 14).

526

527 4.4. Distal normal faults (DNF).

528

529 DNF are common at the extremity of most margins in the world and correspond to the region
530 where the stretching factor is the highest near the COT. Rafts of continental crust may exist
531 atop of the serpentized mantle (Boillot et al, 1995, Pérez-Gussinyé, and Reston, 2001, Péron-
532 Pinvidic and Manastchal, 2008). However, in the South China Sea and the Andaman Sea, they
533 have been considered as resulting from a second rifting episode in the Neogene linked to a re-
534 organisation of the boundary forces resulting in a different orientation of extension (Morley et
535 al. 2016; Sautter 2017). Although this may be a coincidence, our data suggest that the DNF on
536 both sides of SE Asia represent the late stages of a single regional extensional phase throughout

537 **the Cenozoic.** The different directions of extension may indicate that hyper-thinned continental
538 crust is more sensitive to a change in the boundary conditions. The DNF are almost always
539 ocean-verging (regional faults).

540

541 **5 - Discussion:**

542 5.1. Tectonic inversion and outward migration of the rifting

543

544 The basins of **SE Asia** developed on both sides of the relic of a large orogenic domain inherited
545 from successive cycles of subduction-collision. This pre-rifting structural fabric can be outlined
546 by a series of granitic belts, subduction-related, syn and post collision, and the subsequent
547 collisional features of a large magmatic arc active from the Permian to the middle of the
548 Cretaceous which was later affected by a regional compression during the middle to late
549 Cretaceous. Generally, it appears that the deformation began with shear joints (**Figures**
550 **5,7,9,11,13**) and broad folds radial to the horse-shoe shape of the magmatic belt (**Figures 4-9**).
551 Extension followed in the Paleogene, firstly with an early stretching marked by limited block
552 faulting and sets of extensional joints perpendicular to the margin (**Figures 4,6,8,10,12**).

553

554 The extension seems conditioned by the presence of an anomalously thickened crust at the edge
555 of the continental masses (**Figure 14**). All around **SE Asia**, these crustal thickness anomalies
556 originate from the subduction-accretion processes which took place during the Triassic and the
557 middle Cretaceous. Tectonic inversion is marked by the reactivation of former thrusts both in
558 the west of Sunda (**Morley, 2009, 2016**) and to the east (**Savva et al., 2014, Yeh et al., 2018**),
559 and penetrative conjugate shear joints into tension faults and gashes. The rifting is later marked
560 by the development of larger listric faults located along the edges of the granites or broad folds'
561 flanks. These later faults are generally continent dipping (CRNF) and are responsible for most

562 of the crustal thinning. The DNF only appear at the end of the extension process, where
563 magmatic processes are dominant and the crust is very thin, that eventually ends up with crustal
564 breakup.

565 5.2 Location of extension, necking and former suture zones

566 Narrow basins with molassic sediments developed during the late Cretaceous prior to the main
567 rifting event (Savva et al., 2014; Shu et al., 2009; Chan et al., 2010) and correspond to the
568 stretching phase (Figure 8-9). The initiation of this extensional deformation is clearly expressed
569 since the Early Eocene (Ypresian) in the South China Sea but is suspected in the latest
570 Cretaceous and the Paleocene while it appears slightly later from the Late Eocene-Early
571 Oligocene in Western Sunda (Figure 6). The direction of extension is dominantly N-S but
572 actually varies to NNW depending if the reactivation of earlier morpho-structures is involved
573 (Franke et al., 2014; Savva et al., 2014) in the east Sunda plate and E-W in the west. It is
574 important to note that the place where the Cenozoic extension is well expressed falls outward
575 of the Late Paleozoic suture zone. In western SE Asia, pronounced rift systems developed on
576 both sides of the Triassic suture zone (Figure 2, 3b,3c,4), and even along its trace in northern
577 Thailand (Morley et al. 2011). However, extreme crustal stretching and oceanic spreading only
578 developed outside the Sibumasu block in the Andaman Sea (Figure 3c,4).

579 The transitions between localized early stretching, pronounced rift systems and extremely
580 stretched crust illustrated by major crustal necking are interestingly located along inherited
581 orogenic fabrics revealing the importance of former crustal thickness heterogeneities in the
582 thinning processes (Figure 15). The crust supporting the Late Permian to Cretaceous arc is
583 relatively unaffected by the rifting with only isolated shallow deposits in its core, whereas on
584 each of its edges pronounced rift systems developed (Figure 2, 3b,c). This is particularly
585 obvious in the west and south of the plate, while in the east the southern part of the arc was
586 affected by the rifting. Another major crustal necking occurs at the COT, which is often defined

587 in SE Asia by younger plutonic rocks. In the SCS, the last fringe of continental crust is also
588 cored by numerous late Cretaceous plutons while in the south, the deep Makassar basin
589 developed on the edges of the Schwanner and Meratus Upper Cretaceous granitoids. In the
590 west, the relatively undeformed Mergui ridge marks the western edge of a late Cretaceous to
591 Paleogene volcanic arc stretching from onshore Myanmar to Sumatra (Morley, 2015a; Morley,
592 2014; Polachan and Racey, 1994; Sautter, 2017), and marks the transition from the pronounced
593 rift system of the Mergui basins and the extremely stretched crust of the Andaman Sea.

594

595 5.3 Position of Counter Regional Normal Faults relative to previous orogens.

596 The observation that low angle faults are generally typical occurrences of the much thinned
597 crust in the vicinity of the COT is common but the CRNF are often omitted in the syntheses.
598 Although it is a classical aspect of the Coulomb wedge principle and can be modelled with
599 varying taper and slope angles (Vendeville, 1987), the dip direction of the faults may reflect
600 the actual motion of the mantle relative to the crust (Clerc et al., 2017). However, we note that
601 the CRNF are also located at the edge of the former mountain ranges where the crust has been
602 previously thickened and they commonly reactivate former thrusts during tectonic inversion.
603 A striking point regarding the extensional structures around SE Asia is that the style of faulting
604 varies similarly along any section from a proximal to a distal setting of the margin.

605 As mentioned in previous parts, the CRNF of eastern, central and western Sunda developed
606 earlier than the distal regional normal faults. They also control most of the large half-grabens
607 of the northern margin of the South China Sea (Franke et al., 2014). However, they often
608 coexist with large regional normal faults. We observe that they are mostly located among the
609 magmatic arc and on the edges of thickened crust suggesting that the presence of numerous
610 granite plutons could be a parameter conditioning their occurrence and location (Figure 14).
611 Recently Clerc et al., (2017) showed that thick-skinned CRNF are typical of passive margins

612 such as the Angola and Gabon margins (Dupré et al., 2011) and proposed a model dependant
613 on the upward motion of the mantle. Besides, thin-skinned CRNF have been documented on
614 margins such as the SW African margin where thick accumulation of sediments is present due
615 to extended and long-lasting deltas. This suggests that the load on the lithosphere of the margin
616 is a significant parameter for the style of deformation, and that it may be due to tectonic load
617 (former orogenic root) or sedimentary load (excess of sedimentary infill). In sedimentary rocks,
618 particularly in gravity-controlled provinces such as W Africa or NW Borneo (e.g. offshore
619 Brunei), it has been shown that CRNF faults are structures activated easily in response to the
620 increase of sediments weight (Sapin et al., 2012). These authors point out the importance of a
621 low viscosity layer at the base of the sedimentary pile where faults are rooted. In these
622 examples, the decollement layer rheology (salt or shale) is primordial and depends on its
623 composition and its pore pressure (Cobbold et al., 2009). In the case of passive margins, the
624 weak decollement layer is likely to be located in the lower crust. Therefore, the location of the
625 CRNF could be influenced by the presence of a low viscosity layer related to magma rich crust
626 and to a higher lithostatic pressure compared to adjacent regions due to a margin anomalously
627 thick as a result of tectonic or sedimentary load.

628 However, the CRNF are not exclusively present within the Cretaceous magmatic arc or at its
629 boundary; they are also present in the Dangerous Grounds, offshore West Sabah and in the East
630 Andaman basin. The rheological behavior of the magmatic arc may not be the main cause for
631 their existence. Another option is that the excessively thick crust at the edge of SE Asia, could
632 account for bulk forces collapsing the crust toward the core of the SE Asia. In fact, the
633 magmatic arc is associated with a thickening that took place during the Middle Triassic and the
634 Upper Cretaceous orogens. In the internal zones of SE Asia, presently occupied by the Khorat
635 Plateau, the plate was characterized by a depression devoid of important deformation and
636 associated with a thick accumulation of sediments particularly during the Mesozoic (Clements

637 et al., 2011; Heggemann et al., 1994; Racey and Goodall, 2009, Morley, 2012, Pubellier and
638 Morley, 2014).

639 The presence of a free edge along the subduction zones may have been a suitable setting for
640 the development of faults dipping toward this central subsiding depression, thus influencing
641 them in a “counter-regional” orientation. Moreover, the migration of large basin deposition
642 with time towards the edges of SE Asia is an indicator for an evolution driven by the relaxation
643 of a regional dynamic topographic low. Later, during the following phases of the rifting,
644 extension located outward would be less prone to this style of faulting and more influenced by
645 the plate boundary geodynamics and the faults would become oceanic dipping (Figure 16).

646

647 **6. Conclusion**

648 The parameters that control the tectonic evolution of SE Asia from the last major orogen during
649 the Cretaceous are explored in this paper. Based on a similar geodynamic setting all around the
650 former SE Asia, we consider SE Asia continental core as a relatively simple rheological
651 structure and observe the variations/migration of structural style of large joints and major
652 faults. Most of the tectonic features observed in SE Asia result from post-Cretaceous
653 extensional forces which acted on a heterogeneous basement mainly structured during the
654 Triassic and the Cretaceous. They are commonly large half-grabens developed by tectonic
655 inversion on the sides of the Mesozoic orogens and have in turn suffered tectonic inversion
656 mostly in the South of SE Asia (inversion of the Java Basins or in the Eastern Sunda). We
657 recognized a radial compression in the late Cretaceous that affected a large magmatic arc which
658 was active from Permian to early late Cretaceous, and subsequent phases of extension during
659 the Cenozoic. Deformation was mostly brittle and marked by sets of joints expressed in the
660 granites, which indicate compressional forces radial to SE Asia. The following extension was
661 continuous from the late Cretaceous to the Present except in place where local compression

662 occurred. We observe that the premises of this extension are very sensitive to the lithology
663 contrasts since the earliest fractures reactivated the edges of granitic plutons and broad folds.
664 They are therefore parallel to the **contact** between the granite and the host rocks. As such, they
665 can also be low angle normal faults if they tend to rest above magma chambers, on the limbs
666 of Triassic and Cretaceous folds, or thrust faults of the previous shortening event (Morley,
667 2009; Palin et al., 2013).

668 The early structures mostly expressed on land are narrow grabens filled with red sandstone and
669 conglomerate (Chan et al., 2008). Faults are often steep and the compartments are weakly tilted
670 characteristics of the stretching stage (Péron-Pindivic et al., 2008). They affect the basement
671 structural surfaces seen on seismic lines, which were later tilted during the thinning stage. The
672 following stage corresponds to large crustal boudinage with formation of half grabens filled
673 with terrestrial, fluvial, lacustrine or shallow marine deposits. Faults root to the top of the
674 Lower crust and participate intense crustal thinning. If some faults are ocean dipping, many of
675 them are actually CRNF on all sides of the thick Sunda Plate. They affect mostly the granitic
676 arc and cease in the distal parts of the margins. Finally, a late stage characterised by distal
677 normal faults (DNF) appear in the hyper-stretched crust in the final stage of extension. These
678 faults are low angle and generally **dipping ocean-ward, or toward the oceanic** crust of the new
679 marginal basins. Contrarily to the rifting which affects the thickened crust, the late stage
680 affecting very thin crust seems to be independent of the pre-existing structures, and depend
681 strongly on the direction of convergence at plate boundaries. This is particularly well illustrated
682 in the Andaman Sea which underwent E-W extension with faults parallel to the former orogens
683 and their magmatic arcs during the Oligocene and the Early Miocene, followed sharply by a
684 N-S extension in the Late Miocene to Present which reflects the extremely oblique motion of
685 India related to Sunda (Morley et al., 2015, Sautter, 2016).

686

687 Despite small discrepancies in timing, basin structures are interestingly similar all around SE
688 Asia. The basins develop on the edge of older orogens and reactivate the associated structures.
689 Because the orogens are also places where the crust was thickened, and because the opening of
690 the marginal basins often brings the crust-mantle boundary close to the surface, it is likely that
691 the location and structure of the basins is due to orogenic collapse of the thickened crust along
692 the main suture zones, which reactivated the thickening structures. When the extension
693 continues, the extensional faults seem to lose the memory of the orogen, and be driven mostly
694 by the plate boundary forces.

695

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1110

1111 **Figure Captions:**

1112 Figure 1 : a) mantle-crust relationship in the context of passive margin formation. IB: Igneous
1113 Body; UC: Upper Crust; LC: Lower Crust; UM: Upper Mantle. b) occurrence of Counter
1114 Regional Normal Faults (CRNF) associated with a hot upper mantle, c) occurrence of
1115 Regional Normal Faults (RNF) in a Cold margin setting.

1116

1117 Figure 2 : Structural map of SE Asia with emphasis on Cenozoic rift basins and pre-Cenozoic
1118 compressive fabrics. Basins developed dominantly on the sides of Mesozoic orogens leaving
1119 the magmatic arcs devoid of sedimentary cover. The rifting migrated through time towards
1120 the edges of SE Asia where extremely stretched crust and oceanic spreading took place.

1121 Basin names: CL: Cuu Long, CM: Central Myanmar, CS: Central Sumatra, DG: Dangerous
1122 Grounds, EA: East Andaman, EJ: East Java, EN: East Natuna, L: Luconia, Ma: Malay, Me:
1123 Mergui, Mk: Makassar, NCS: Nam Con Son, NS: North Sumatra, Pa: Pattani, Pe: Penyu, PK:
1124 Phu Khan, PRM: Pearl River Mouth, S: Sabah, SS: South Sumatra, WJ: West Java, WN:
1125 West Natuna. Sutures: ASZ : Ailaoshan Suture Zone, BRSZ: Bentong Raub Suture Zone,
1126 ISZ : Inthanon Suture Zone, MSZ: Meratus Suture Zone. **The Ailoshan is an Early to Middle
1127 Triassic Suture while the Bentong Raub represents a Late Triassic collision. The Meratus and
1128 Woyla sutures are Lower Cretaceous whereas the Burma and Andaman sutures are thought to
1129 be Late Cretaceous in age.**

1130

1131 Figure 3 : Main structural domains of SE Asia. A) Paleozoic core of Sunda and Yanshanian
1132 magmatic arc and blocs accreted during the Cretaceous (green) with induced shortening
1133 directions represented with arrows. b) distribution of basins during the Paleogene with
1134 stretching direction represented with arrows, c) distribution of basins during the Neogene
1135 with stretching directions represented with arrows.

1136

1137 Figure 4 : A) Extract of the structural map of SE Asia modified after Sautter 2017 showing
1138 the main faults related to the Upper Cretaceous compression and Cenozoic rifting in
1139 northwestern SE Asia. B) Synthetic cross-section across main structural features of
1140 northwestern Sunda built from field observations, seismic profile interpretation and regional
1141 maps. C) Interpreted seismic profile across the Andaman shelf break modified after Sautter et
1142 al. (2017). D) Interpreted seismic profile of the East Tanintharyi Basin modified from Racey
1143 and Ridd (2015).

1144

1145 Figure 5 : A) simplified structural map of a fractured Cretaceous granite in peninsular
1146 Myanmar. See the grey rectangle in Figure 4a for location. B) Digital elevation model built
1147 from SRTM30 showing conjugate fracture sets striking WNW-ESE and ENE-WSW.
1148

1149 Figure 6 : A) Extract of the structural map of SE Asia modified after Sautter 2017 showing
1150 the main faults related to the Upper Cretaceous compression and Cenozoic rifting in western

1151 SE Asia. B) Synthetic cross-section across main structural features of western Sunda built
1152 from field observations, seismic profile interpretation and regional maps. C) Interpreted
1153 seismic profile across the Mergui Basin modified after Sautter et al. (2017). D) Interpreted
1154 seismic profile of the Central Graben of the Malacca Straits modified after Sautter (2017).
1155 See Figure 4 for the legend.

1156 Figure 7 : A) simplified structural map of fractured Triassic-Jurassic granitoids in peninsular
1157 Malaysia. See the grey rectangle in Figure 6a for location. B) Digital elevation model built
1158 from SRTM30 showing conjugate fracture sets striking NW-SE and NE-SW. Important syn-
1159 kinematic fluid intrusions are present and illustrated with elongated red polygons.

1160 Figure 8 : A) Extract of the structural map of the South China Sea modified after Pubellier et
1161 al. (2017) showing the main faults related to the Cenozoic rifting in northeastern SE Asia. B)
1162 Synthetic cross-section across main structural features of eastern Sunda built from field
1163 observations, seismic profile interpretation and regional maps. C) Interpreted seismic profile
1164 across the Zhu-3 Trough modified after Zhao et al. (2020). D) Interpreted seismic profile of
1165 the Pearl River Mouth Basin modified after Ye et al. (2020). See Figure 4 for the legend.

1166 Figure 9 : A) simplified structural map of fractured Permian-Triassic granitoids in southern
1167 China. See the grey rectangle in Figure 8a for location. B) Digital elevation model built from
1168 SRTM30 showing conjugate fracture sets striking WNW-ESE and NNW-SSE. Post-
1169 compression basins developed in the Late Cretaceous to Early Cenozoic reactivating the
1170 edges of the plutons.

1171 Figure 10 : A) Extract of the structural map of the South China Sea modified after Pubellier
1172 et al. (2017) showing the main faults related to the Cenozoic rifting in central SE Asia. B)
1173 Synthetic cross-section across main structural features of central Sunda built from field
1174 observations, seismic profile interpretation and regional maps. C) Interpreted seismic profile
1175 across the Cuu Long basin modified after Fyhn et al. (2019). D) Interpreted seismic profile of
1176 the East Natuna Basin modified after Savva (2013). See Figure 4 for the legend.

1177 Figure 11 : A) simplified structural map of fractured Cretaceous granitoids in southern
1178 Vietnam. See the grey rectangle in Figure 10a for location. B) Digital elevation model built
1179 from SRTM30 showing conjugate fracture sets striking NW-SE and NE-SW. Important syn-
1180 kinematic fluid intrusions are present and illustrated with elongated red polygons.

1181 Figure 12 : A) Extract of the structural map of Borneo modified after Sapin (2010) showing
1182 the main faults related to the Cenozoic rifting in central SE Asia. B) Synthetic cross-section
1183 across main structural features of central Sunda built from field observations, seismic profile
1184 interpretation and regional maps. C) Interpreted seismic profile across the Barito Basin
1185 modified after Winardi et al. (2019). D) Interpreted seismic profile of the East Java Basin
1186 modified after Ran et al. (2020). See Figure 4 for the legend.

1187 Figure 13 : A) simplified structural map of fractured Cretaceous granitoids in southern
1188 Borneo. See the grey rectangle in Figure 12a for location. B) Digital elevation model built
1189 from SRTM30 showing conjugate fracture sets striking NNW-SSE and N-S.

1190 Figure 14: Style of extension when controlled by A) CRNF and DNF, and load excess on the
1191 lithosphere due to the presence of a peri-cratonic orogen cored with large plutons (case of W
1192 Sunda and N. SCS margins), or B) excess of sediments (NW Borneo, SW Africa)

1193 Figure 15: A) Simplified cross section across SE Asia showing the pre-Cenozoic accretion of
1194 continental blocks and terranes marked with purple polygons for the Triassic orogeny and
1195 green polygons for the Cretaceous orogeny. Sutures are shown in bright colors whereas
1196 accreted sediments are in faded colors. B) Setting in the Late Cenozoic showing the
1197 reactivation of former compressive structures during the rifting. Black faults are CRNF
1198 whereas red faults are DNF.

1199 Figure 16: Conceptual model of the evolution of the fault systems forming basins at the edge
1200 of SE Asia. Gradient of greys represent the continental crustal layers: lightest grey for the
1201 continental crust affected by extension (tilted blocks), then the upper crust, lower crust and
1202 finally the mantle in the darkest grey. The purple shape represents the oceanic crust. Set of
1203 conjugate fractures (shear joints) mostly visible in the Mesozoic granites (red shape).
1204 Reactivation of the granite edges and development of counter-regional normal faults (CRNF).
1205 Late evolution of the basins near the COT, with regional distal normal faults (DNF).

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