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► **To cite this version:**

Benjamin Sautter, Manuel Pubellier. Structural control of Mesozoic orogens on SE Asia Basin opening. Journal of Asian Earth Sciences, 2022, 230, pp.105207. 10.1016/j.jseaes.2022.105207 . hal-04290154

**HAL Id: hal-04290154**

**<https://hal.science/hal-04290154>**

Submitted on 17 Nov 2023

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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; Zahirowic 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 ( $25^\circ$ ) 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

## 696 **Acknowledgements**

697 The authors would like to thank the handling editor Prof Michel Faure, and reviewer Prof  
698 Christopher Morley as well as an anonymous reviewer for their suggestions, critical and  
699 constructive reviews that greatly helped improve the scientific quality of the manuscript. The  
700 work on the construction would not have been possible without funding from Total E&P, the  
701 Ecole Normale Supérieure in Paris, and a cooperation with the Universiti Teknologi Petronas.  
702 Benjamin Sautter was funded by the Geological Mapping group of Deep-time Digital Earth  
703 (DDE) and hosted in the Commission for the Geological map of the World (CGMW) while  
704 Manuel Pubellier was supported by the CNRS (France) and hosted by the Ecole Normale  
705 Supérieure during the compilation of the data and redaction of this manuscript.

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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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