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#### 1 Structural Control of Mesozoic Orogens on SE Asia Basin Opening

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#### 8 Abstract:

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

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

33 Therefore, the pattern of basin structure and development seems conditioned by the intrinsic crustal configuration of SE Asia, specifically by the Triassic and Cretaceous orogenic 34 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 the onset of rifting *sensus stricto*. As a consequence, the general dip direction of these major 37 crustal boundaries was often preserved during the Cenozoic extension that affected the 38 39 marginal regions. Where the crustal thinning was strong enough, the fault plane dipped oceanward as a result from the crust/mantle relative motion. It is proposed that the rifting of 40 the Cenozoic basins was triggered and conditioned by the relaxation of the orogens that 41 assembled Sunda Plate in the past. 42

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### 46 **1. Introduction**

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

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

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

The present-day configuration of SE Asia (Fig. 2) reflects the long lasting evolution of this 75 plate which was separated from the rest of Eurasia starting from the Late Miocene (Fig. 2) 76 (Hamilton, 1979, Hall, 2002; Pubellier & Morley, 2014). The horseshoe shape of SE ASIA 77 finds its origin in the large Permian to Cretaceous magmatic arc bordering the core of its 78 thickened crust (Metcalfe, 2017; Pubellier & Morley, 2014; Sautter et al. 2017; Zahirowic et 79 al., 2016). This granitic belt is fringed by numerous Cenozoic basins on its sides (Fig 3). 80 Therefore, the history of the deformation of SE Asia is inherent to the evolution of the 81 subductions which were taking place all around SE Asia. The pre-Cenozoic basement 82 complexity of SE Asia is itself the result of the amalgamation, since the Middle Triassic and 83 up to the Late Cretaceous, of several continental blocks whose migration is witnessed by the 84 occurrence of magmatic arcs, accretionary wedges and suture zones (Fig 2) (Hamilton, 1979, 85 Hutchison, 1977, Metcalfe, 1998, Cai & Zhang, 2009, Tran et al., 2020; Faure et al. 2018). 86 87

Many of the basins are likely to have developed during the Cenozoic in a back-arc setting with 88 geometries intrinsically influenced by the obliquity between SE Asia trench curvature and the 89 direction of convergence of the Neo-Tethys and Indian oceanic crusts (Pubellier and Morley, 90 2014). Despite a well characterized geodynamic setting, the existence of a major asymmetry in 91 the rifting structures remains poorly understood. Numerous studies have shown that structural 92 inheritance of pre-rifting crustal heterogeneities is likely to have influenced the accommodation 93 of the extension in the Cenozoic (Morley et al. 2004; Hall, 2009; Morley et al. 2011; Morley, 94 2014; Sautter et al., 2017; Ye et al., 2018). 95

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Indicators of an active margin since the Late Palaeozoic are well documented and the geometry,
elevation, rheology and tectonic features observed today are a direct result from this
geodynamic configuration (Lepvrier et al., 2004, Carter and Clift, 2008, Faure et al., 2014),

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

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

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

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

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

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

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

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

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

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

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

- 201 <u>2.3. Cretaceous compression</u>
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After the Early to Middle Triassic Orogeny (Faure et al., 2018) and the Late Triassic to Jurassic 203 Cimmerian orogeny, the main tectonic event affecting SEAsia continental core is a Cretaceous 204 regional diffuse compression (Morley, 2012, Clements et al., 2011, Nanni et al., 2017). This 205 period was marked by the accretion of several blocks at the outer rim of SE Asia, (Barber, 206 2000, Morley, 2012, Hall, 2012), but the extent and the timing of accretion are still debated. In 207 eastern and south-eastern Asia, examples show that a Triassic tectonic event was reactivated 208 during the Cretaceous by alternating phases of compression and extension (Lin, 2015, Morley, 209 210 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), and erosional surfaces (Liang et al., 2019. The geodynamic environment included hot 212 geotherms in western Sunda (Watkinson et al. 2011) and could possibly be linked to the 213 subduction of a large Meso-Tethys ridge (Zahirovic et al., 2014) The area located along the 214 present-day position of the southern margin of the South China Sea is a re-entrant of the general 215 horse-shoe shape and is interpreted to be a consequence of the docking of the Luconia Block 216 (or Dangerous Grounds Block; Hall, 2012) during the Cretaceous, prior to the opening of the 217 South China Sea (Fig. 2). The location of the suture, although only poorly imaged at depth with 218 219 basement deformation on seismic lines, must be presently located offshore outward of the Cretaceous granites of the South China margin and South China (Fyhn et al., 2010, Pubellier 220

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

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

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

We hereafter consider that most of the deformations affecting the post-Triassic granitoids is 231 late Cretaceous and Cenozoic. The Cretaceous is marked by a regime of intense magmatism 232 and compression both in Western and Eastern Sunda. The terranes which might have accreted 233 at that time are still a matter of debate. The Burma block is represented by sporadic Cenozoic 234 sediments in Myanmar (Mitchell, 2017); the Woyla terrane is probably composed of an oceanic 235 arc (Advokaat et al. 2018; Wajzer et al., 1991); the Natuna block is debated in terms of location 236 and docking age. Only the Argo Block seems to be well identified. This tectono-magmatic 237 238 event may be related to the subduction of large oceanic ridges as suggested by the reconstruction of Setton and Muller and Zahirovic et al., (2014). In Eastern SE Asia, this event 239 is poorly dated due to lack of shallow marine deposits but is locally considered as late Early 240 Cretaceous as for instance around Hong Kong (Campbell and Sewell, 2007; Nanni et al., 2017). 241 The compression is marked by an angular unconformity on seismic lines blanketing broad folds 242 involving the Cretaceous sediments in the South China Sea (Yan et al., 2014, Huang et al., 243 244 2017). It results in a major sedimentary hiatus from the late Cretaceous to the Eocene in SE Asia (Hutchison et al., 1992; Clements et al., 2011). The Cenozoic basins that opened in SE
Asia are all located on the edge of the thickened crust following a post-Cretaceous relaxation
(Pubellier and Morley, 2014; Zahirowic et al., 2016).

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

#### 256 <u>3.1. Western SE Asia</u>

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

developed slickensides except for rare crystallisation of epidote, or Late Palaeozoic limestonewhich appears karstified preferentially along this fabric.

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

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

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

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

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#### 321 <u>3.2. North-Eastern SE Asia</u>

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

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

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

352

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

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

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

379

380 3.2.2. Listric normal Faults

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

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

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- 392

#### 393 <u>3.3. Central-Eastern SE Asia</u>

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

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

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

423

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

432

#### 433 <u>3.4. Southern SE Asia</u>

In the southern part of SE Asia, the pre-rifting basement crops out exclusively in the Cretaceous granitoids of the Schwanner Mountains (Figure 2). In this region, the compression is also better illustrated on remotely sensed data than on direct field observations because morphologies are not well preserved in these low elevation granitic provinces. There, the set of pre-rifting 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.

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

464 basins, but also inverted the early normal faults in the Java Sea near Kangean Island and the465 Madura Peninsula.

466

467 **4. Synthesis** 

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

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

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

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

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

- 493
- 494 <u>4.2. A post late Cretaceous Orogeny relaxation</u>
- 495

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

509

510 <u>4.3. Large crustal scale normal faults (counter regional and regional)</u>

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

526

## 527 <u>4.4. Distal normal faults (DNF).</u>

528

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

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

540

541 **5 - Discussion:** 

#### 542 5.1. Tectonic inversion and outward migration of the rifting

543

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

553

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

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

#### 565 <u>5.2 Location of extension, necking and former suture zones</u>

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

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

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

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

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

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

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

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

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

646

#### 647 6. Conclusion

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

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

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

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

695

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# **References**

714	Advokaat, E.L., Bongers, M.L.M., Rudyawan, A., BouDagher-Fadel, M.K., Langereis, C.G.,
715	van Hinsbergen, D.J.J. 2018. Early Cretaceous origin of the Woyla Arc (Sumatra,
716	Indonesia) on the Australian plate, Earth and Planetary Science Letters, Volume 498,
717	Pages 348-361, https://doi.org/10.1016/j.epsl.2018.07.001.
718	Audley-Charles, M.G., 1977. Mesozoic evolution of the margins of Tethys in Indonesia and
719	the Philippines. Proc. of the Indon Petroleum Assoc. 5th Ann Conv., Jakarta, 1976, vol.
720	2, pp. 25–52.
721	Abdullah, C.I., Rampnoux, J.P., Bellon, H., Maury, R.C., Soeria-Atmadja, R., 2000. The
722	evolution of Sumba Island (Indonesia) revisited in the light of new data on the
723	geochronology and geochemistry of the magmatic rocks. J. Asian Earth Sci. 18, 533-
724	546. https://doi.org/10.1016/S1367-9120(99)00082-6
725	Ali, M.A., Willingshofer, E., Matenco, L., Francois, T., Daanen, T.P., Ng, T.F., Taib, N.I.,
726	Shuib, M.K., 2016. Kinematics of post-orogenic extension and exhumation of the Taku
727	Schist, NE Peninsular Malaysia. J. Asian Earth Sci. 127, 63–75.
728	https://doi.org/10.1016/j.jseaes.2016.06.020
729	Barber, A.J., 2000. The origin of the Woyla Terranes in Sumatra and the late Mesozoic
730	evolution of the SE Asia margin. J. Asian Earth Sci. 18, 713–738.
731	doi.org/10.1016/S1367-9120(00)00024-9
732	Barber, A.J and Crow, M.J, 2003, An Evaluation of Plate Tectonic Models for the
733	Development of Sumatra, Gondwana Research, Volume 6, Issue 1, January 2003, Pages
734	1-28
735	Barber, A.J., Crow, M.J., Milsom, J.S.S., 2005. Sumatra, Geological Society Memoir.
736	Geological Society. https://doi.org/10.1017/CBO9781107415324.004

737	Boillot, G., Beslier, M.O., Krawczyk, C.M., Rappin, D., Reston, T.J., 1995. The
738	formation of passive margins: constraints from the crustal structures and
739	segmentation of the deep Galicia Margin, Spain. In: Scrutton, R.A., Stoker, M.S.,
740	Schimmield, G.B., Tudhope, A.W. (Eds.), The Tectonics, Sedimentation and
741	Palaeoceanography of the North Atlantic Region. Geol. Soc. Sp. Pub. 90, 71-91.
742	Brune, S., Heine, C., Pérez-Gussinyé, M., Sobolev, S. V, 2014. Rift migration explains
743	continental margin asymmetry and crustal hyper-extension 1-9.
744	https://doi.org/10.1038/ncomms5014
745	Cai J-X, Zhang, K-J, 2009, A new model for the Indochina and South China collision during
746	the Late Permian to the Middle TriassicTectonophysics 467 (2009) 35–43
747	Campbell, S.D.G., Sewell, R.J., 2007. 40 Ar- 39 Ar Laser Microprobe Dating of Mafic Dykes
748	and Fault rocks in Hong Kong.
749	Cao, J., Xia, S., Sun, J., Zhao, F., Wan, K., & Xu, H. 2018. Offshore fault geometrics in the
750	Pearl River Estuary, southeastern China: Evidence from seismic reflection data. Journal
751	of Ocean University of China, 17(4), 799-810.
752	Carter, A., Clift, P.D., 2008. Was the Indosinian orogeny a Triassic mountain building or a
753	thermotectonic reactivation event? C. R. Geosci. 340, 83-93.
754	Chan, L. S., W. L. Shen, and M. Pubellier, 2010. Polyphase rifting of greater Pearl River
755	Delta region (South China) : Evidence for possible rapid changes in regional stress
756	configuration, J. Struct. Geol., v. 32(6), pp. 746-754, doi: 10.1016/j.jsg.2010.04.015

- 757 Choong C. M., Sautter, B., Pubellier, M., Menier, D., Weng Sum, C., Abd Kadir, A., 2015,
- 758 Geological Features of the Kinta Valley, Platform V. 10, N 2, July-Dec
- 759 Choong C. M., Pubellier, M., Sautter, B, Arshad Beg, M., 2021. New U-Pb ages of the
- 760 Benom Complex: Implications for a Late Triassic Uplift Event in Central Peninsular
- 761 Malaysia, Bulletin of the Geological Society of Malaysia volume 72, of Nov.

762	Chu, Y., Lin, W., Faure, M., Xue, Z., Ji, W., & Feng, Z., 2019. Cretaceous episodic extension
763	in the South China Block, East Asia: Evidence from the Yuechengling Massif of central
764	South China. Tectonics, 38. https://doi.org/10.1029/2019TC005516
765	Clements, B., Burgess, P.M., Hall, R., Cottam, M. a., 2011. Subsidence and uplift by slab-
766	related mantle dynamics: a driving mechanism for the late Cretaceous and Cenozoic
767	evolution of continental SE Asia? Geol. Soc. London, Spec. Publ. 355, 37-51.
768	https://doi.org/10.1144/SP355.3
769	Clerc, C., Jolivet, L., Ringenbach, JC., Ballard, JF., 2017. Passive margins: ductile
770	deformation, boudinage, low-angle normal faults and the role of the weak lower crust.
771	Cuong, T.X., Warren, J.K., 2009. Bach Ho field , a fractured granitic basement reservoir, Cuu
772	Long Basin, offshore Vietnam : a "burried Hill" play Journal of Petroleum Geology
773	Volume 32, Issue 2 p. 129-156 doi.org/10.1111/j.1747-5457.2009.00440.x
774	Curray, J.R., 2005. Tectonics and history of the Andaman Sea region, Journal of Asian Earth
775	Sciences, Volume 25, Issue 1, Pages 187-232, ISSN 1367-9120,
776	https://doi.org/10.1016/j.jseaes.2004.09.001.
777	Ding, W.W., Li, M.B., Zhao, L.H., Ruan, A.G., Wu, Z.L., 2011. Cenozoic tectono
778	sedimentary characteristics and extension model of the Northwest Sub-basin, South
779	China Sea. Geoscience Frontiers 2 (4), 509-517.
780	Dupré, S., Cloetingh, S., Bertotti, G., 2011. Tectonophysics Structure of the Gabon Margin
781	from integrated seismic re flection and gravity data. Tectonophysics 506, 31-45.
782	https://doi.org/10.1016/j.tecto.2011.04.009
783	Emmel, F.J., Curray, J.R., 1982. A submerged late Pleistocene delta and other features related
784	to sea level changes in the Malacca Strait. Mar. Geol. 47. https://doi.org/10.1016/0025-
785	3227(82)90069-X

Faure, M., Shu,L., Wang,B., Charvet,J., Choulet, F., and , P., Monie., 2009.

787	Intracontinental subduction: a possible mechanism for the Early Palaeozoic Orogen of
788	SE China. 2009, Terra Nova, 21, 360–368, doi: 10.1111/j.1365-3121.2009.00888.x
789	Faure, M., Lepvrier, C., Nguyen, V.V., Vu, V.T., Lin, W., Chen, Z., 2014. The South China
790	block-Indochina collision: where, when, and how? J. Asian Earth Sci. 79, 260–274.
791	Faure, M., Nguyen, V.V., Thu Hoai, L.T., Lepvrier, C., 2018, Early Paleozoic or Early-
792	Middle Triassic collision between the South China and Indochina Blocks: The
793	controversy resolved? Structural insights from the Kon Tum massif (Central Vietnam).
794	Journal of Asian Earth Sciences 166 (2018) 162–180
795	Franke, D., 2013. Rifting, lithosphere breakup and volcanism: Comparison of magma-poor
796	and volcanic rifted margins, Marine and Petroleum Geology Volume 43, May 2013,
797	Pages 63-87
798	Franke, D., Savva, D., Pubellier, M., Steuer, S., Mouly, B., Auxietre, J., Meresse, F.,
799	Chamot-rooke, N., 2014. The final rifting evolution in the South China Sea 58, 704–720.
800	https://doi.org/10.1016/j.marpetgeo.2013.11.020
801	Fyhn, M. B. W., Boldreel, L. O., and Nielsen, L. H., 2009. Geological development of the
802	Central and South Vietnamese margin: Implications for the establishment of the South
803	China Sea, Indochinese escape tectonics and Cenozoic volcanism: Tectonophysics, v.
804	478, no. 3, 577 p. 184-214.
805	Fyhn, M.B.W., Pedersen, S.A.S., Boldreel, L.O., Nielsen, L.H., Green, P.F., Dien, P.T.,
806	Huyen, L.T., Frei, D., 2010. Palaeocene-early Eocene inversion of the Phuquoc-Kampot
807	Som Basin: SE Asian deformation associated with the suturing of Luconia. J. Geol. Soc.
808	London. 167, 281-295. https://doi.org/10.1144/0016-76492009-039
809	Gardiner, N.J., Searle, M.P., Robb, L., & Morley, C.K., 2015. Neo-Tethyan magmatism and
810	metallogeny in Myanmar - An Andean analogue? Journal of Asian Earth Sciences, 106,
811	197-215.

- Gardner, C.J., Graham, I.T., Belousova, E., Booth, G.W., Greig, A., 2017. Evidence for
- 813 Ordovician subduction-related magmatism in the Truong Son terrane, SE Laos:
- 814 Implications for Gondwana evolution and porphyry Cu exploration potential in SE Asia.
- Gondwana Research Volume 44, April 2017, Pages 139-156
- 816 G.J.J., A., H.E., B., J.J., N., W.J., S., 1973. A Contribution to the Geology of Part of the
- 817 Indonesian Tinbelt: the Sea Areas Between Singkep and Bangka Islands and Around the
  818 Karimata Islands. Bull. Geol. Soc. Malaysia 6, 257–271.
- 619 Ghani, A.A., Searle, M., Robb, L., Chung, S.L., 2013. Transitional IS type characteristic in
- the Main Range Granite, Peninsular Malaysia. J. Asian Earth Sci. 76, 225–240.
- 821 https://doi.org/10.1016/j.jseaes.2013.05.013
- Hall, R., Wilson, M.E.J, 2000. Neogene sutures in eastern Indonesia, Journal of Asian Earth
  Sciences 18 (2000) 781–808
- Hall, R., 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW
- Pacific: Computer-based reconstructions, model and animations. J. Asian Earth Sci. 20,

826 353–431. https://doi.org/10.1016/S1367-9120(01)00069-4

- 827 Hall, R., 2012. Late Jurassic–Cenozoic reconstructions of the Indonesian region and the
- 828 Indian Ocean. Tectonophysics s 570–571:1–41 DOI: 10.1016/j.tecto.2012.04.021
- 829 Hamilton, W., 1979. Tectonics of the Indonesian Region. Geological Survey professional
- paper 1078, 345.Heggemann, H., Helmcke, D., Tietze, K.-W., 1994. Sedimentary
- evolution of the Khorat Group in Thailand 57–58.
- 832 Huang, C.-D., T.-Y. Lee, C.-H. Lo, S.-L. Chung, J.-C. Wu, C.-L. Tien, M.-W. Yeh, S.-C.
- 833 Chen, Y.-L. Chan, and C.-Y. Hu, 2017. Structural inversion in the northern South China
- 834 Sea continental margin and its tectonic implications. Terr. Atmos. Ocean. Sci., 28, 891-
- 835 922, doi: 10.3319/TAO.2017.03.27.01
- 836 Hutchison, C.S., 2013. Tectonic evolution of Southeast Asia. Tecton. Evol. Southeast Asia

- 837 27. https://doi.org/10.1016/S0264-8172(97)81119-1
- Hutchison, C.S., 1977. Granite emplacement and tectonic subdivision of Peninsular Malaysia.
  Geol. Soc.
- 840 Huy X. N, , Bae W, San T., Xuan V.T, Sung Min J, Kim D.Y, 2012. Fractured Basement
- 841 Reservoirs and Oil Displacement Mechanism in White Tiger Field, Offshore Vietnam,
- 842 AAPG Datapages, Search and discovery, Tulsa, US, 2012
- 843 Kanjanapayont, P., 2014. Deformation style of the Mesozoic sedimentary rocks in southern
- 844 Thailand. J. Asian Earth Sci. 92, 1–9. https://doi.org/10.1016/j.jseaes.2014.06.010
- Jammes, Suzon & Lavier, Luc., 2019. Effect of contrasting strength from inherited crustal
- fabrics on the development of rifting margins. Geosphere. 15. 10.1130/GES01686.1.
- Kosa, Eduard., 2015. Sea-level changes, shoreline journeys, and the seismic stratigraphy of
- 848 Central Luconia, Miocene-present, offshore Sarawak, NW Borneo. Marine and
- Petroleum Geology. 59. 35-55. 10.1016/j.marpetgeo.2014.07.005.
- 850 Lacassin, R., Maluski, H., Leloup, P.H., Tapponnier, P., Hinthong, C., Siribhakdi, K.,
- 851 Chuaviroj, S., Charoenravat, A., 1997. Cenozoic diachronic extrusion and deformation
- of western Indochina: Structural and 40Ar/39Ar evidence from NW Thailand. J.
- 853 Geophys. Res. 102, 10013–10037.
- Larsen, H.C., Mohn, G., Nirrengarten, M., Sun, Z., Stock, J., Jian, Z., Klaus, A., Alvarez-
- Zarikian, C.A., Boaga, J., Bowden, S.A., Briais, A., Chen, Y., Cukur, D., Dadd, K.,
- Ding, W., Dorais, M., Ferré, E.C., Ferreira, F., Furusawa, A., Gewecke, A., Hinojosa, J.,
- 857 Höfig, T.W., Hsiung, K.H., Huang, B., Huang, E., Huang, X.L., Jiang, S., Jin,
- 858 H., Johnson, B.G., Kurzawski, R.M., Lei, C., Li, B., Li, L., Li, Y., Lin, J., Liu, C., Liu,
- 859 C., Liu,Z., Luna, A.J., Lupi, C., McCarthy, A., Ningthoujam, L., Osono, N., Peate,
- B60 D.W., Persaud, P., Qiu, N., Robinson, C., Satolli, S., Sauermilch, I., Schindlbeck, J.C.,
- 861 Skinner, S., Straub, S., Su, X., Su, C., Tian, L., van der Zwan, F.M., Wan, S., Wu, H.,

862	Xiang, R.,	Yadav, R.,	Yi, L., Y	(u, P.S., Zl	hang, C.,	Zhang, J.,	Zhang, Y	Y., Zhao, N	J.,
-----	------------	------------	-----------	--------------	-----------	------------	----------	-------------	-----

263 Zhong, G., Zhong, L., 2018d. Rapid transition from continental breakup to igneous

oceaniccrust in the South China Sea. Nat. Geosci. 11, 782–789.

865 https://doi.org/10.1038/s41561-018-0198-1.

Lavier LL, Manatschal G., 2006. A mechanism to thin the continental lithosphere at magmapoor margins. Nature. Mar 16; 440(7082):324-8. doi: 10.1038/nature04608. PMID:
16541070.

Lei, C., Ren. J., 2016. Hyper-extended rift systems in the Xisha Trough, northwestern

870 SouthChina Sea: Implications for extreme crustal thinning ahead of apropagating ocean

871 Marine and Petroleum Geology 77 (2016) 846e864

- Lei, C., Ren, J., Pang, X., Chao, P., Han, X., 2018. Continental rifting and sediment infill in
- the distal part of the northern South China Sea in the Western Pacific region: challenge

on the present-day models for the passive margins. Mar. Pet. Geol. 93, 166–181

Eloup, P.H., Lacassin, R., Tapponnier, P., Schärer, U., Zhong, D.L., Liu, X.H., Zhang, L.S.,

Ji, S.C., Phan, T.T., 1995. The Ailao Shan-Red River shear zone (Yunnan, China),

877 Cenozoic transform boundary of Indochina. Tectonophysics 251, 3–84

- Le Pichon, X., and Sibuet, J. C., 1981. Passive margins: a model of formation. JGR 86, 3708–
  3720. doi: 10.1029/JB086iB05p03708
- 880 Lepvrier, C., Maluski, H., Vu, V.T., Leyreloup, A., Phan, T.T., Nguyen, V.V., 2004. The

Early Triassic Indosinian orogeny in Vietnam (Truong Son Belt and Kontum Massif):

- implications for the geodynamic evolution of Indochina. Tectonophysics 393, 87–118.
- Liang, Y., Delescluse, M., Qiu, Y., Pubellier, M., Chamot-Rooke, N., Wang, J., 2019.
- 884 Décollements, detachments, and rafts in the extended crust of Dangerous Ground, South
- 885 China Sea: The role of inherited contacts. Tectonics, 38.
- 886 https://doi.org/10.1029/2018TC005418

- 887 Lin, W., Ji, W., Faure, M., Wu, L., Li, Q., Shi, Y., Scharer, U., Wang, F., Wang, Q., 2015.
- Early Cretaceous extensional reworking of the Triassic HP-UHP metamorphic orogen in
  Eastern China. Tectonophysics 662, 256–270
- 890 Mahattanachai, T., Morley, C. K., Charusiri, P., & Kanjanapayont, P., 2021. The Andaman
- 891 Basin Central Fault Zone, Andaman Sea: Characteristics of a major deepwater strike-slip
- fault system in a polyphase rift. Marine and Petroleum Geology, 128, 104997.
- 893 Manatschal, G., 2004. New models for evolution of magma-poor rifted margins based on a
- review of data and concepts from West Iberia and the Alps. Int. J. Earth Sci. 93, 432–
- 466. https://doi.org/10.1007/s00531-004-0394-7
- 896 Manatschal, G., Lavier, L., Chenin, P., 2015. The role of inheritance in structuring
- 897 hyperextended rift systems: Some considerations based on observations and numerical
- 898 modeling. Gondwana Res. 27, 140–164. https://doi.org/10.1016/j.gr.2014.08.006
- Mathew, M., Makhankova, A., Menier, D., Sautter, B., Betzler, C., & Pierson, B.J., 2020.
- 900 The emergence of Miocene reefs in South China Sea and its resilient adaptability under
- 901 varying eustatic, climatic and oceanographic conditions. Scientific Reports, 10.
- 902 Metcalfe, I., 1998. Palaeozoic and Mesozoic geological evolution of the SE Asian region:
- 903 multidisciplinary constraints and implications for biogeography. Biogeogr. Geol. Evol.
- Southeast Asia 25–41.
- 905 Metcalfe, I., 2000. The Bentong Raub Suture Zone. J. Asian Earth Sci. 18, 691–712.
- 906 https://doi.org/10.1016/S1367-9120(00)00043-2
- 907 Metcalfe, I., 2013a. Gondwana dispersion and Asian accretion: Tectonic and
- palaeogeographic evolution of eastern Tethys. J. Asian Earth Sci. 66, 1–33.
- 909 https://doi.org/10.1016/j.jseaes.2012.12.020
- 910 Metcalfe, I., 2013b. Tectonic evolution of the Malay Peninsula. J. Asian Earth Sci. 76, 195–
- 911 213. https://doi.org/10.1016/j.jseaes.2012.12.011

- Metcalfe, I., 2017. Tectonic evolution of SE Asia. Bulletin of the Geological Society of
  Malaysia. 63. 27-60. 10.7186/bgsm63201702.
- 914 Mitchell, A., 2017. Geological belts, plate boundaries, and mineral deposits in Myanmar.
  915 Elsevier.
- 916 Morley, B.C.K., Program, P.G., Mai, C., Morley, C.K.K., 2015. Cenozoic structural
- evolution of the Andaman Sea: evolution from an extensional to a sheared margin. Geol.
- 918 Soc. London, Spec. Publ. 431, 8550–8550. https://doi.org/10.1144/SP431.1
- 919 Morley, C.K, A. Alvey, A., 2015. Is spreading prolonged, episodic or incipient in the
- 920 Andaman Sea? Evidence from deepwater sedimentation, Journal of Asian Earth
- 921 Sciences, Volume 98, Pages 446-456, ISSN 1367-9120,
- 922 https://doi.org/10.1016/j.jseaes.2014.11.033.
- 923 Morley, C.K., 2016. The impact of multiple extension events, stress rotation and inherited
- fabrics on normal fault geometries and evolution in the Cenozoic rift basins of Thailand.
- 925 GSL Spec. 439. https://doi.org/10.1144/SP439.3
- 926 Morley, C.K., 2012. Late Cretaceous-Early Palaeogene tectonic development of SE Asia.
- 927 Earth-Science Rev. 115, 37–75. https://doi.org/10.1016/j.earscirev.2012.08.002
- 928 Morley, C.K., 2009. Geometry and evolution of low-angle normal faults (LANF) within a
- 929 Cenozoic high-angle rift system, Thailand: Implications for sedimentology and the
- 930 mechanisms of LANF development. Tectonics 28, 1–30.
- 931 https://doi.org/10.1029/2007TC002202
- 932 Morley, C.K., 2004. Nested strike-slip duplexes, and other evidence for Late Cretaceous-
- 933 Palaeogene transpressional tectonics before and during India–Eurasia collision, in
- Thailand, Myanmar and Malaysia. J. Geol. Soc. London. 161, 799–812.
- 935 https://doi.org/10.1144/0016-764903-124
- 936 Morley, C.K., Charusiri, P., Watkinson, I., Christopher K. Morley, P.C.& I.A.N.M.W., 2011.

- 937 Structural geology of Thailand during the Cenozoic. Geol. Thail. 273–334.
- 938 Morley, C.K.K., Alvey, A., 2014. Is spreading prolonged, episodic or incipient in the
- Andaman Sea? Evidence from deepwater sedimentation . J. Asian Earth Sci. 98, 446–
- 940 456. https://doi.org/10.1016/j.jseaes.2014.11.033
- 941 Morley, C.K., 2014. The widespread occurrence of low-angle normal faults in a rift setting:
- 942 Review of examples from Thailand, and implications for their origin and evolution,
- Earth-Science Reviews, Volume 133, Pages 18-42, ISSN 0012-8252,
- 944 https://doi.org/10.1016/j.earscirev.2014.02.007
- 945 Morley, C. K., Chantraprasert, S., Kongchum, J., & Chenoll, K., 2021. The West Burma
- 946 Terrane, a review of recent paleo-latitude data, its geological implications and
- 947 constraints. Earth-Science Reviews, 220, 103722. doi:10.1016/j.earscirev.2021.10372
- 948 Nanni, U., Pubellier, M., Chan, L.S., J. Sewell, R., 2017. Rifting and reactivation of a
- 949 Cretaceous structural belt at the northern margin of the South China Sea. J. Asian Earth
  950 Sci., Vol 136, (2017) 110-133, doi.org/10.1016/j.jseaes.2017.01.008
- 951 Nirrengarten, M., Mohn, G., Kusznir, N. J., Sapin, F., Despinois, F., Pubellier, M., Chang, S.
- 952 P., Larsen, H. C., and Ringenbach, J. C., 2020, Extension modes and breakup processes
- 953 of the southeast China-Northwest Palawan conjugate rifted margins: Marine and
- 954 Petroleum Geology, v. 113, p. 104123. , DOI: 10.1016/j.marpetgeo.2019.1041
- 955 Palin, R.M., Searle, M.P., Morley, C.K., Charusiri, P., Horstwood, M.S.A., Roberts, N.M.W.,
- 2013. Timing of metamorphism of the Lansang gneiss and implications for left-lateral
- 957 motion along the Mae Ping (Wang Chao) strike-slip fault, Thailand. J. Asian Earth Sci.
- 958 76, 120–136. https://doi.org/10.1016/j.jseaes.2013.01.021
- 959 Pérez-Gussinyé, M., Reston, T.J., 2001. Rheological evolution during extension at non
- 960 volcanic rifted margins: Onset of serpentinization and development of detachments
- leading to continental breakup. J. Geophys. Res. 106(B3), 3961-3975.

962	Péron-Pinvidic, G., Manatschal, G., Dean, S.M., Minshull, T.A., 2008. Compressional
963	structures on the West Iberia rifted margin: controls on their distribution. Geol. Soc.
964	London, Spec. Publ. 306, 169–183. https://doi.org/10.1144/sp306.8
965	Peron-Pinvidic, G., Manatschal, G., and Osmundsen, P. T., 2013. Structural comparison of
966	archetypal Atlantic rifted margins: a review of observations and concepts. Mar. Pet.
967	Geol. 43, 21–47. doi: 10.1016/j.marpetgeo.2013.02.002
968	Gwenn Péron-Pinvidic, Gianreto Manatschal, Emmanuel Masini, Emilie Sutra, Jean Marie
969	Flament, Isabelle Haupert and Patrick Unternehr, 2015. Unravelling the along-strike
970	variability of the Angola-Gabon rifted margin: a mapping approach. Geological Society,
971	London, Special Publications, 438, 49-76, 2 December 2015,
972	https://doi.org/10.1144/SP438.1
973	Pigott, J.D., Ru, K., 1994. Basin superposition on the northern margin of the South China Sea
974	235, 27–50.
975	Polachan, S., Pradidtan, S., Tongtaow, C., Janmaha, S., Intarawijitr, K., Sangsuwan, C., 1991.
976	Development of Cenozoic basins in Thailand. Mar. Pet. Geol. 8, 84-97.
977	https://doi.org/10.1016/0264-8172(91)90047-5
978	Polachan, S., Racey, A., 1994. Stratigraphy Of The Mergui Basin, Andaman Sea:
979	Implications For Petroleum Exploration. J. Pet. Geol. 17, 373–406.
980	Pubellier M., Girardeau J., Tjashuri I., 1998. Accretion history of Borneo inferred from the
981	polyphase structural features in the Meratus mountains, in Gondwana dispersion and
982	Asian accretion- Final results of IGCP 321, edited by I. Metcalfe, AA Balkema
983	Publishers, Rotterdam, p141-160
984	Pubellier, M., Ego, F., Chamot-Rooke, N., Rangin, C., 2003. The building of pericratonic
985	mountain ranges : structural and kinematic constraints applied to GIS-based
986	reconstructions of SE Asia. Bull. la Soc. Geol. Fr. 174, 561–584.

- Pubellier, M., Morley, C.K., 2014. The basins of SE Asia (SE Asia): Evolution and boundary
  conditions. Mar. Pet. Geol. 58, 555–578.
- 989 https://doi.org/10.1016/j.marpetgeo.2013.11.019
- 990 Pubellier, Manuel & Savva, Dimitri & Aurelio, Mario & Sapin, F., 2017. Structural Map of
- the South China Sea; scale 1:3M, Commission for the Geological Map of the World.
- 992 10.14682/2017STRUCTUSCS.
- 993 Putthapiban, P., 1992. The Cretaceous-Cenozoic Granite Magmatism in the West Coast of
- 994 Peninsular Thailand and the Mergui Archipelago of Myanmar/Burma, in: Thailand, D.
- of M.R. of (Ed.), National Conference on Geologic Resources of Thailand: Potential for
- 996 Futur Development. Bangkok, Thailand, pp. 75–88.
- 997 Racey, A., Ridd, M. F., 2015. Petroleum Geology of the Tanintharyi Region, Myanmar",
- 998 Petroleum Geology of Myanmar, Geological Society of London, 45
- 999 Ran, W., Luan, X., Lu, Y., Wei, X., Zhang, H., Wang, K., Wang, J., Wang, X., Zhang, D.,
- 1000 Islam, M.S., 2020. Seismic characteristics and strontium isotope ages of the Middle
- 1001 Miocene Ngrayong Formation in the Madura Strait Basin: Implications for the
- 1002 paleogeographic reconstruction of East Java, Journal of Asian Earth Sciences, Volume
- 1003 190, 104109, ISSN 1367-9120, https://doi.org/10.1016/j.jseaes.2019.104109.
- 1004 Rangin, C., Huchon, P., Le Pichon, X., Bellon, H., Lepvrier, C., Roques, D., Nguyen, D.H.,
- 1005 Phan, V.Q., 1995. Cenozoic deformation of central and south Vietnam, Tectonophysics
- 1006 Volume 251, Issues 1–4, 15 December 1995, Pages 139-152
- 1007 Ru, K. & Pigott, J.D., 1986. Episodic rifting and subsidence in the South
- 1008 China Sea. American Association of Petroleum Geologists Bulletin, 70, 1136–1155
- 1009 Satyana, A. H., Edward Erwanto, E., Prasetyadi, C., 2004. Rembang-Madura-Kangean-
- 1010 Sakala (RMKS) Fault Zone, East Java Basin : The Origin and Nature of a Geologic
- 1011 Border. Indon. Assoc Geologists, 33<sup>rd</sup> Ann. Conc., Bandung, 2004

- Sautter, B., 2017. Influence de l'héritage structural sur le rifting : exemple de la marge Ouest
  de La Sonde, PhD Thesis, PSL University.
- 1014 Sautter, B., Pubellier, M., 2015. Did the Malaysian Main Range record a weak hot Mega
- 1015 Shear ? Geophys. Res. Abstr. Vol. 17, EGU2015-5167-1, 2015 17, 5167.
- 1016 Sautter, B., Pubellier, M., Jousselin, P., Dattilo, P., Kerdraon, Y., Choong, C.M., Menier, D.,
- 1017 2017. Late Paleogene rifting along the Malay Peninsula thickened crust. Tectonophysics

1018 710–711. https://doi.org/10.1016/j.tecto.2016.11.035

- 1019 Sautter, B., Pubellier, M., Králiková Schlögl, S., Matenco, L., Andriessen, P., & Mathew, M.,
- 1020 2019. Exhumation of west SE Asia: A record of the path of India? Earth-Science

1021 Reviews, 198, 1-16. [102933]. https://doi.org/10.1016/j.earscirev.2019.102933

- 1022 Savva, D., Pubellier, M., Franke, D., Chamot-Rooke, N., Meresse, F., Steuer, S., Auxietre,
- 1023 J.L., 2014. Different expressions of rifting on the South China Sea margins. Mar. Pet.

1024 Geol. 58, 579–598. https://doi.org/10.1016/j.marpetgeo.2014.05.023

- 1025 Savva, D., Pubellier, M., Franke, D., Chamot-Rooke, N., Meresse, F., Steuer, S., & Auxietre,
- J. L., 2014. Different expressions of rifting on the South China Sea margins. Marine and
  Petroleum Geology, 58, 579-598.
- 1028 Shu, L.S., Zhou, X.M., Deng, P., Wang, B., Jiang, S.Y., Yu, J.H., Zhao, X.X., 2009.
- 1029 Mesozoic tectonic evolution of the Southeast China Block : New insights from basin
- 1030 analysis. J. Asian Earth Sci. 34, 376–391. https://doi.org/10.1016/j.jseaes.2008.06.004
- 1031 Sone, M., Metcalfe, I., 2008. Parallel Tethyan sutures and the Sukhothai Island-arc system in
- 1032 Thailand and beyond. Proc. Int. Symp. Geosci. Resour. Environ. Asian Terranes
- 1033 (GREAT 2008), 4th IGCP 516,and 5th APSEG; 132–134.
- 1034 Srisuriyon, K., Morley, C.K., 2014. Pull-apart development at overlapping fault tips: Oblique
- 1035 rifting of a cenozoic continental margin, northern mergui basin, and aman sea. Geosphere
- 1036 10, 80–106. https://doi.org/10.1130/GES00926.1

- 1037 Lisa Tannock, Marco Herwegh, Alfons Berger, Jie Liu, Pierre Lanari, Klaus Regenauer-Lieb,
- 1038 2020. Microstructural analyses of a giant quartz reef in south China reveal episodic
- brittle-ductile fluid transfer, Journal of Structural Geology, Volume 130, 103911, ISSN

1040 0191-8141, https://doi.org/10.1016/j.jsg.2019.103911.

- 1041 Sapin, F., 2010. Impact du couple érosion/sédimentation sur la structuration d'un prisme
- 1042 d'accrétion : L'exemple du prisme NO Bornéo : approche géologique, sismique et
- 1043 thermique. PhD Thesis, Pierre et Marie Curie University.
- 1044 Sapin, F., Ringenbach, J.C., Clerc, C., 2021. Rifted margins classification and forcing
- 1045 parameters, Scientific Reports | (2021) 11:8199 | https://doi.org/10.1038/s41598-0211046 87648-3
- Taylor, B.L., Goodliffe, A.M., Martínez, F., & Hey, R.N., 1995. Continental rifting and
  initial sea-floor spreading in the Woodlark basin. Nature, 374, 534-537.
- 1049 Savva, D. 2013. Variabilité de processus d'extension continentale en mer de Chine du sud.
  1050 PhD thesis, ENS Paris.
- 1051 Tjia, H.D., 2010. Growing evidence of active deformation in the Malay basin region. Bull.
- 1052 Geol. Soc. Malaysia 56, 35–40. https://doi.org/10.7186/bgsm2010005
- 1053 Tjia, H.D., 1995. Tectonics of deformed and undeformed Jurassic- Cretaceous strat of
- 1054 Peninsular Malaysia. Geol. Soc. Malaysia- Pet. Geol. Conf. 1995 33.
- 1055 Tran, T.V., Faure, M., Nguyen, V.V., Bui, H.H., Fyhn, M.B.W., Nguyen, T.Q., Lepvrier, C.,
- 1056 Thomsen, T.B., Tani, K., Charusiri, P., 2020. Neoproterozoic to Early Triassic tectono-
- 1057 stratigraphic evolution of Indochina and adjacent areas: A review with new data, Journal
- 1058 of Asian Earth Sciences doi: https://doi.org/10.1016/j.jseaes.2020.104231
- 1059 Tran, V.T., Vu, K. (Eds.), 2011. Geology and Earth Resources of Vietnam, 2011th ed.
- 1060 Vietnam Public House for Science and Technology, Hanoi, pp.646.
- 1061 Tugend, J., Gillard, M., Manatschal, G., Nirrengarten, M., Harkin, C., Epin, M. E., Sauter, D.,

- 1062 Autin, J., Kusznir, N. & McDermott, K., 2020. Reappraisal of the magma-rich versus
- 1063 magma-poor rifted margin archetypes. Geol. Soc. Lond. Spec. Publ. 476(1), 23–47.

1064 https://doi.org/10.1144/SP476.9

- 1065 van der Broek, J.M., and Gaina, C., 2020. Microcontinents and Continental Fragments
- Associated With Subduction Systemsdoi: 10.1029/2020TC006063Vendeville, B., 1987.
- 1067 Champs de failles et tectonique en extension : Modélisation expérimentale. Mémoires et
- 1068 Documents du Centre Armoricain d'Etude Structurale des Socles n°15, 392p. ISBN : 21069 905532-14-9, Université Rennes 1.
- Wei, W., Faure, M., Chen, Y., Ji, W., Lin, W., Wang, Q., et al., 2015. Back-thrusting response
  of continental collision: Early Cretaceous NW-directed thrusting in the Changle-Nan'ao
  belt (Southeast China). J. Asian Earth Sci. 100, 98–114
- 1073 Wajzer, M.R., Barber, A.J., Hidayat, S., Suharsono, 1991. Accretion, collision and strike-slip
  1074 faulting: the Woyla Group as a key to the tectonic evolution of North Sumatra. J. Southeast
  1075 Asian Earth Sci. 6 (3/4), 447e461.
- Watkinson, I., Elders, C., Batt, G., Jourdan, F., Hall, R., and McNaughton, N. J., 2011. The
  timing of strike-slip shear along the Ranong and Khlong Marui faults, Thailand, J.
  Geophys. Res., 116, B09403, doi:10.1029/2011JB008379.
- Westerweel, J., Roperch, P., Licht, A., Dupont-Nivet, G., Win, Z.A., Poblete, F., Ruffet, G.,
  Swe, H.H., Thi, M.K., & Aung, D.W., 2019. Burma Terrane part of the Trans-Tethyan Arc
  during collision with India according to palaeomagnetic data. Nature geoscience, 12, 863
   868.
- Whitmarsh, R. B., Manatschal, G., and Minshull, T. A., 2001. Evolution of magma-poor
  continental margins from rifting to seafloor spreading. Nature 413, 150–154. doi:
  10.1038/35093085

- Winardi, S., Erlangga, G., Surjono, S. S., Husein, S., Akmaluddin, Isnani, D. K., Agustin, M.
  V., Prihantono, W., Krisnayadi, M. N., Gunawan, A., Rahmadi, D., 2019. Post Mortem as
  the First Step to Increase Success Rate of Next Exploration in Barito Basin. Proceedings
- 1089 Joint Convention Yogyakarta 2019, Hagi Iagi Iafmi- Iatmi (Jcy 2019), TBA Hotel,
- 1090 Yogyakarta, November 25th 28th, 2019.
- 1091 Yan, P., Wang, L. & Wang, Y., 2014. Late Mesozoic compressional folds in Dongsha
- 1092 Waters, the northern margin of the South China Sea. Tectonophysics. 615-616.
- 1093 10.1016/j.tecto.2014.01.009.
- 1094 Ye, Q., Mei, L., Shi, H., Shu, Y., Camanni, G.i, Wu, J., 2018. A low-angle normal fault and
- 1095 basement structures within the Enping Sag, Pearl River Mouth Basin: Insights into late
- 1096 Mesozoic to early Cenozoic tectonic evolution of the South China Sea area.
- 1097 Tectonophysics. 731. 10.1016/j.tecto.2018.03.003.
- 1098 Ye, Q., Mei, L., Shi, H., Wu, J., Du, J., Deng, P., Shu, Y., and Giovanni Camanni, G.I., 2020.
- 1099 The Influence of Pre-existing Basement Faults on the Cenozoic Structure and Evolution
- of the Proximal Domain, Northern South China Sea Rifted Margin. Tectonics, 39.
- 1101 https://doi.org/10.1029/2019TC005845
- 1102 Zahirovic, S., Seton, M., and Müller, D.M., 2014. The Cretaceous and Cenozoic tectonic
- 1103 evolution of Southeast Asia. Solid Earth, 5, 227–273, 2014. doi:10.5194/se-5-227-2014
- 1104 Zahirovic, S., Flament, N., Dietmar Müller, R., Seton, M., and Gurnis, M., 2016. Large
- fluctuations of shallow seas in low-lying Southeast Asia driven by mantle flow,
- 1106 Geochem. Geophys. Geosyst., 17, 3589–3607, doi:10.1002/2016GC006434.
- 1107 Zhao, F., Alves, T.M., Xia, S., Li, W., Wang, L., Mi, L., Wu, S., Cao, J., & Fan, C., 2020.
- 1108 Along-strike segmentation of the South China Sea margin imposed by inherited pre-rift
- 1109 basement structures. Earth and Planetary Science Letters, 530, 115862.
- 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

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

directions represented with arrows. b) distribution of basins during the Paleogene withstretching direction represented with arrows, c) distribution of basins during the Neogene

1135 with stretching direction represented with arrows, c) distribution of

1136

1137 Figure 4 : A) Extract of the structural map of SE Asia modified after Sautter 2017 showing

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

maps. C) Interpreted seismic profile across the Andaman shelf break modified after Sautter etal. (2017). D) Interpreted seismic profile of the East Tanintharyi Basin modified from Racey

1143 and Ridd (2015).

1144

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

1148

Figure 6 : A) Extract of the structural map of SE Asia modified after Sautter 2017 showing
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
- seismic profile across the Mergui Basin modified after Sautter et al. (2017). D) Interpreted
- 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  $\hat{F}$
- Malaysia. See the grey rectangle in Figure 6a for location. B) Digital elevation model built
   from SRTM30 showing conjugate fracture sets striking NW-SE and NE-SW. Important syn-
- 1158 from SRTM30 showing conjugate fracture sets striking NW-SE and NE-SW. Impor 1159 kinematic fluid intrusions are present and illustrated with elongated red polygons.
- Figure 8 : A) Extract of the structural map of the South China Sea modified after Pubellier et al. (2017) showing the main faults related to the Cenozoic rifting in northeastern SE Asia. B) Synthetic cross-section across main structural features of eastern Sunda built from field observations, seismic profile interpretation and regional maps. C) Interpreted seismic profile across the Zhu-3 Trough modified after Zhao et al. (2020). D) Interpreted seismic profile of 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
- China. See the grey rectangle in Figure 8a for location. B) Digital elevation model built fromSRTM30 showing conjugate fracture sets striking WNW-ESE and NNW-SSE. Post-
- 1168 SK 1930 showing conjugate fracture sets striking with w-ESE and NTW-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
- 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
- across the Cuu Long basin modified after Fyhn et al. (2019). D) Interpreted seismic profile of
- 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.
- Figure 12 : A) Extract of the structural map of Borneo modified after Sapin (2010) showing
  the main faults related to the Cenozoic rifting in central SE Asia. B) Synthetic cross-section
  across main structural features of central Sunda built from field observations, seismic profile
  interpretation and regional maps. C) Interpreted seismic profile across the Barito Basin
  modified after Winardi et al. (2019). D) Interpreted seismic profile of the East Java Basin
  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.
- Figure 14: Style of extension when controlled by A) CRNF and DNF, and load excess on the 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
- 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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- 1208