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1 **Symmetry of the South China Sea conjugate margins in a rifting,**
2 **drifting and collision context**

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12

13 **Abstract**

14 The symmetry of conjugate rifted margins is a first-order observable feature reflecting the geodynamic
15 processes acting during and after continental rifting. The symmetry of the South China Sea (SCS) rifted
16 margins can be deduced from comprehensive geophysical datasets on a continental-margin scale. Here, we
17 combine three key approaches: (1) lateral fault distributions are delineated according to free-air gravity
18 anomalies, (2) crustal stretching styles are mapped based on gravity inversion constrained by deep seismic
19 profiles, and (3) total extensions of conjugate margins are estimated according to margin restorations and
20 tectonic settings. We infer a predominantly symmetric rifting style caused by pure shear extension, with only
21 narrow domains of asymmetric deformation in continent-ocean transition (COT) regions that have undergone
22 simple shear and where the lower crust of the highly thinned distal margin is embrittled before continental
23 breakup. However, our analysis also suggests that this symmetry has been modified by post-rift geodynamic
24 processes. Southward lower crustal flow, which occurred only on the southern margin due to the low viscosity
25 of the lower crust and the slab pull induced by the subducting Proto-SCS plate during seafloor spreading,
26 shifted the crustal stretching styles from symmetric to asymmetric. The collision between the southern margin
27 and Borneo thickened the lower crust more than the upper crust at the southern end of the southern margin
28 and shortened the southern margin. This event had a large impact on the SE margin but a small impact on the
29 SW margin. We conclude that (1) for the SE and NE margins, the crustal stretching styles shifted from
30 asymmetric to approximately symmetric, and the total extensions shifted from symmetric to asymmetric; (2) for
31 the SW and NW margins, the crustal stretching and total extensions remained asymmetric and symmetric,
32 respectively.

- 33 **Key Words:** South China Sea conjugate margins; symmetry and asymmetry; rifting and drifting processes; total
- 34 extension; crustal stretching style

35

36 1. Introduction

37 Classifying conjugate rifted margins in terms of their symmetry is a fundamental approach for analyzing the
38 geodynamics of rifted margin formation ([Huismans and Beaumont, 2003](#); [Nagel and Buck, 2004](#); [Reston, 2009](#);
39 [Brune et al., 2014](#); [Lescoutre et al., 2019](#)). The crustal rheology and extension rate control the rifting styles and
40 final architectures of margins ([Tetreault and Buitier, 2017](#)). However, different regions and layers in passive
41 margins at diverse evolution stages may have varying crustal rheologies and extension rates ([Bassi, 1991](#);
42 [Brune et al., 2016](#)). Thus, rift symmetry is not static during the rifting process, which is why margin symmetry
43 should be analyzed in the context of rifting.

44 Continental margin evolution can result in upper crust extension via faults, lower crust thinning via ductile
45 deformation and low-viscosity layer flow, transition from rifting to drifting, seafloor spreading, sedimentation
46 and others ([Lister et al., 1986](#); [Reston, 2007](#); [Sutra and Manatschal, 2012](#); [Clift et al., 2015](#); [Ding et al., 2019](#);
47 [Peron-Pinvidic et al., 2019](#)). Each of these observations can provide only a single perspective on the margin
48 evolution processes, and the characteristics of typical regions cannot represent the whole margin ([Direen et al.,](#)
49 [2011](#); [Espurt et al., 2012](#); [Dong et al., 2013](#); [Franke et al., 2014](#)). Therefore, examination of the symmetry of
50 conjugate margins from comprehensive aspects on a continental-margin scale should provide a more accurate
51 perspective.

52 During South China Sea (SCS) seafloor spreading, the southern margin experienced a southward pull
53 induced by the subduction of the Proto-SCS plate, whereas the northern margin did not. In addition, the
54 collision between the southern margin and Borneo (Fig. 1a) produced a modified crustal structure along the
55 southern margin ([Rangin et al., 1990](#); [Hutchison, 1996](#); [Metcalf, 2011](#)). Therefore, the evolution of the SCS

56 margin is distinctive; thus, in addition to rifting, drifting and collision processes should be considered when
57 assessing the symmetry of the SCS conjugate margins.

58 As the largest marginal basin in SE Asia, the SCS, especially its northern margin, has been explored for
59 several decades for both scientific and economic interests. Nevertheless, the symmetry of the SCS conjugate
60 margins is still controversial. Some early studies described asymmetric features, especially that compared with
61 the characteristics of the northern margin, those of the southern margin include (1) thinner crust, (2) smaller
62 and shallower sedimentary basins and (3) smaller thermal subsidence ([Zhou et al., 1995](#); [Yan et al., 2001](#)).
63 Recent studies on typical regions, however, demonstrate that the deformation structures of these conjugate
64 margins are mainly symmetric ([Wu et al., 2012](#); [Gao et al., 2016](#); [Ding and Li, 2016](#)). Here, we aim to reconcile
65 these two views by isolating the different aspects of symmetry and by discussing them in a geodynamic context
66 on a marginal scale.

67 The significant limitation of seismic imaging, which is one of the common ways of mapping passive margin
68 structures, is its low coverage due to high cost. In contrast, gravity inversion has the advantage of high
69 coverage in margin areas, and its accuracy has been increased greatly ([Smith and Sandwell, 1994](#); [Sandwell
70 et al., 2014](#)). A high-coverage and high-accuracy gravity field can be used to map crustal thickness variations
71 of passive margins, delineate fault distributions and estimate crustal stretching styles on a continental-margin
72 scale constrained by seismic profiles ([Wang et al., 2011](#); [Tenzer et al., 2015](#); [Oruç and Sönmez, 2017](#);
73 [Bagherbandi et al., 2017](#); [Bai et al., 2019](#)). Therefore, the gravitational method has unique advantages for
74 comprehensive margin-scale symmetry studies.

75 In this paper, we perform the following analytical steps: (1) major faults are delineated to identify crustal
76 structures, (2) upper and lower crustal stretching factors are mapped to deduce crustal stretching styles via

gravity inversion constrained by seismic profiles, and (3) conjugate margins are restored to estimate the total extensions. The northern and southern margins are compared comprehensively based on fault structures, crustal stretching styles and total extensions. Finally, based on well-known rifting processes and the seafloor spreading history, we attempt to use brittle faulting and ductile flow to infer the margin symmetry of the SCS in the context of its rift evolution, seafloor spreading, ridge jump and continental collision.

2. Previous studies and geological background

The opening of the SCS oceanic basin was mainly controlled by the slab pull of the subducting Proto-SCS plate ([Hutchison et al., 2000](#); [Zahirovic et al., 2014](#)) and the extrusion of the Indochina Block ([Briais et al., 1993](#); [Mazur et al., 2012](#)). The subduction of the Izanagi plate induced back-arc opening of the Proto-SCS starting at ~65 Ma ([Zahirovic et al., 2014](#); [Bai et al., 2015](#)). Some minor blocks, such as Semitau and Luconia, separated from the South China Block and drifted away with the opening of the Proto-SCS (Fig. 2a). The later southward subduction of the Proto-SCS plate induced slab pull on the South China Block ([Shao et al., 2017](#)). The slab pull and the extrusion of the Indochina Block induced further stretching of the South China Block (Fig. 2b) ([Tapponnier et al., 1990](#); [Leloup et al., 2001](#); [Mazur et al., 2012](#); [Zhang et al., 2013](#)). The continental breakup and opening of the SCS oceanic basin propagated from east to west ([Müller et al., 2008](#); [Li et al., 2014](#)). Seafloor spreading in the SCS ceased mainly at ~16 Ma ([Briais et al., 1993](#); [Sun et al., 2003](#)). The complete subduction of the Proto-SCS plate and the counterclockwise rotation of Borneo induced collision between the southern margin of the SCS and Borneo along the suture line (Fig. 2c and Fig. 2d).

Continental crustal stretching is the first-order result of rifting; therefore, the amount of stretching is a key input for inferring margin formation processes. Two main parameters can provide insight into stretching: (1) the stretching factor, which demonstrates thinning in the vertical direction ([McKenzie, 1978](#); [Davis and Kuszniir,](#)

98 [2004](#)), and (2) the extension length, which indicates elongation in the lateral direction ([Anderson et al., 2000](#);
99 [Huismans and Beaumont, 2008](#)). Seismic studies of sedimentary basins on the northern margins, such as the
100 Pearl River Mouth Basin and the Qiongdongnan Basin, indicate depth-dependent stretching ([Clift et al., 2002](#);
101 [Davis and Kuszniir, 2004](#); [Zhang et al., 2008](#); [Lei et al., 2015](#); [Lei and Ren, 2016](#); [Li et al., 2016](#)). A recent
102 gravity study shows that the stretching styles vary with tectonic setting on the northern margin of the SCS: (1)
103 the upper crust is stretched more than the lower crust in major sedimentary basins, (2) the lower crust is
104 stretched more than the upper crust in the distal margin and (3) almost depth-uniform stretching occurs in the
105 main proximal northern margin ([Luo et al., 2018](#)). Compared with the northern margin, however, the southern
106 margin has been poorly explored.

107 The extension rate, which is a key parameter of rifting, is commonly assumed to be constant for simplicity
108 ([Naliboff et al., 2017](#); [Beniest et al., 2017](#); [Chenin et al., 2018](#)). However, recent studies suggest a
109 characteristic velocity evolution that involved slow rifting at the beginning of extension followed by an abrupt
110 increase before continental breakup that was controlled by strength reduction during strain localization in the
111 distal margin at the end of rifting ([Brune et al., 2016](#); [Ulvrova et al., 2019](#)). According to the plate reconstruction
112 analysis in these studies, the extension rate of the SCS conjugate margins was ~3 mm/yr when rifting initiated,
113 and the maximum value reached an estimated 43 mm/yr before continental breakup.

114 3. Methodology

115 Fault distributions, crustal stretching styles, and margin extension lengths/rates are the three main
116 parameters for margin symmetry study in the context of whole-margin evolution processes. Here, we estimate
117 these parameters based on the gravity anomaly field along with the constraints provided by deep seismic
118 profiles.

119 3.1 Fault delineation

120 The structure of the surface of the crystalline basement along passive margins is covered by sediments
121 and water. Thus, faults are difficult to identify on bathymetry maps. However, the gravitational signal produced
122 by the relative height difference between the hanging wall and footwall of a fault cannot be obscured
123 completely by sediments, so gravitational measurements are a powerful tool for identifying tectonic structures
124 beneath sediments ([Sandwell et al., 2014](#)). The gravity anomalies in the dataset produced by [Sandwell et al.](#)
125 [\(2014\)](#) (version 27) show obvious NE-trending lineations on both conjugate margins. Interpretations of large
126 faults on different seismic profiles of the NE-trending gravity lineations confirm the existence of these
127 NE-trending major faults.

128 3.2 Crustal stretching style mapping

129 Fault geometries on seismic profiles are used to calculate the crustal stretching factor ([Davis and Kuszniir,](#)
130 [2004](#); [Chen, 2014](#)). However, seismically imaged fault geometries can be used to estimate only the upper
131 crustal stretching factor, and this process is associated with large uncertainties because approximately 50% of
132 faults may not be recognizable in seismic data ([Walsh and Watterson, 1991](#); [Davis and Kuszniir, 2004](#); [Reston,](#)
133 [2007](#)). The gravity inversion method not only can estimate both the upper and lower crustal stretching factors
134 but also can identify variations in the stretching factor on a regional scale instead of only along specific profiles
135 such as those produced by the seismic method.

136 Details of the gravity-based method and parameters have been provided in a previous paper ([Luo et al.,](#)
137 [2018](#)), and only a brief description of the concept is given here. The observed gravity anomalies are mainly
138 contributed by variations in the density of the lithosphere ([Chappell and Kuszniir, 2008](#); [Wang et al., 2011](#)).
139 There are four main interfaces with obvious density contrasts in the lithosphere under an ocean: the sea

140 bottom, the sediment bottom, the Conrad discontinuity between the upper and lower crust, and the Moho
141 discontinuity between the lower crust and the mantle. After density variations of the sediment layer, the crust
142 and the mantle have been modeled and the initial depths of each interface have been set, the gravity effects of
143 these layers can be removed from the observed free-air gravity anomaly. Thus, the gravity effects of
144 Moho/Conrad undulations can be isolated, and finally, the Moho/Conrad geometries can be mapped based on
145 this residual anomaly. The initial Moho and Conrad depths, which are necessary inputs for density-contrast
146 interface inversion, are derived from seismic profiles. Seismic profiles are also taken as references for
147 estimating gravity inversion uncertainties since the seismic method has higher accuracy than the gravity
148 method. Thus, the present upper and lower crustal thicknesses (T_p) can be derived based on the Conrad,
149 Moho, sediment thickness and seafloor topography.

150 The initial thickness (T_i) of the northern margin is assumed to be 32 km, which is the mean thickness of the
151 present South China Block according to geophysical studies ([Hayes and Nissen, 2005](#); [Li et al., 2006](#); [Hu et al.,](#)
152 [2009](#); [Luo et al., 2018](#)). The initial thickness of the southern margin is set to 25 km because this value provides
153 the most accurate full-fit reconstruction model among the potential values ([Bai et al., 2015](#)). Our crustal
154 thickness inversion results show that 47.2% of the continental crust along the unstretched continental crust
155 limit (UCCL) is upper crust, and the remainder is lower crust. The initial thicknesses of the upper and lower
156 crust for the northern and southern margins are set to the values listed in Table 1 according to the estimated
157 proportions and the total crustal thickness. The stretching factors (β) of the upper and lower crust can be
158 mapped via the stretching factor definition ($\beta = T_p / T_i$). Finally, the crustal stretching style can be analyzed
159 according to the contrast between the upper and lower crustal stretching factors. Please note that the crustal
160 stretching style estimated based on this method represents the crustal configuration after deformation during
161 margin rifting, drifting and collision.

3.3 Total extensions restoration

The total average extension rate can be defined as the ratio between the increase in margin width and the duration of extension. The exact rifting initiation time is still unclear ([Lin et al., 2003](#); [Yang et al., 2004](#); [Braitenberg et al., 2006](#)), and the ages of the SCS oceanic basin remain controversial ([Briais et al., 1993](#); [Müller et al., 2008](#); [Li et al., 2014](#)); thus, defining the exact times of initiation and cessation of continental extension is difficult. Therefore, instead of the extension rate, the total extension is taken as a parameter to analyze the margin evolution in this paper. The thickening and shortening effects on the southern margin induced by collision modified the original total extension ([Zahirovic et al., 2014](#); [Bai et al., 2015](#)). Here, we do not try to restore the shortened margin width, and the “total extension” in the following sections refers to the apparent total extension, whose value is the final result of long-lasting rifting at the beginning and short-term collision at the end.

The present stretched northern margin of the SCS is located between the UCCL to the north and the northern continent-ocean boundary (COB) line of the SCS basin to the south (Fig. 3). The UCCL follows the basement thickness contour of 32 km (assumed to be the initial crustal thickness of the northern margin). The northern and southern COB lines of the SCS basin follow the 9 km basement thickness contour according to seismic interpretations (Fig. 4a). The southern end of the southern margin (SESM) has been traced to the fossil subduction belt ([Hutchison, 1996](#); [Clift et al., 2008](#); [Capitanio et al., 2010](#); [Metcalf, 2011](#); [Zahirovic et al., 2014](#)).

The present width of each margin is the distance between the northern and southern boundaries along a small circle path. The small circle paths of the conjugate margins (Fig. 4a) are derived via the GPlates software ([Müller et al., 2018](#)) based on the full-fit rotation poles by [Bai et al. \(2015\)](#) after [Lee and Lawver \(1994\)](#). The

183 pre-rifting width of the northern margin can be restored as

$$184 \quad W_n = \int_{COB}^{UCCL} dT_p / T_i . \quad (0)$$

185 where dT_p is the present whole crustal thickness of the integrating element, T_i is the initial whole crustal
186 thickness of the northern margin, and the integration path is the small circle line between the UCCL and the
187 COB. The pre-rifting width of the southern margin can also be derived in this way. The total extension is the
188 difference between the present and pre-rifting margin widths.

189 4. Employed data sets

190 The free-air gravity anomaly (Fig. 1b) in marine areas is based on the altimetry data from [Sandwell et al.](#)
191 [\(2014\)](#), whereas that in land areas is derived from the Earth Gravitational Model 2008 (EGM2008). Data on the
192 bathymetry, topography and sediment thickness are necessary for seawater and sediment density modeling.
193 The bathymetric and topographic data (Fig. 1a) are extracted from the global relief map of ETOPO1, which is
194 based on comprehensive geophysical methods ([Amante and Eakins, 2009](#)). The newest data on marine
195 sediment thickness ([Straume et al., 2019](#)) are used here. The lithospheric age used for lithospheric mantle
196 density modeling is determined based on magnetic lineations ([Müller et al., 2008](#)). The seismic wave velocity
197 structure used for modeling mantle density variations beneath the lithosphere is imaged based on a global
198 tomographic study ([Schaeffer and Lebedev, 2015](#)). Some deep seismic profiles are collected to calculate initial
199 Moho and Conrad depths for gravity inversion, constrain NE-trending fault delineation and estimate gravity
200 inversion uncertainties; these profiles are mapped in Fig. 1a, and their sources are listed in Table 2.

5. Results

5.1 Computed interface depths, stretching factors, and margin widths

Combined with seismic interpretations, the gravity anomalies in the dataset produced by [Sandwell et al. \(2014\)](#) (version 27) delineate several major faults with NE trends on the conjugate margins, as shown in Fig. 1b. The mapped geometries of the Conrad discontinuities have trends similar to those of the Moho (Fig. 3), mainly shallowing oceanward and deepening below sedimentary basins on both conjugate margins. The main difference is that the amplitude of the Moho depth undulations is larger. The stretching factor variations for the upper and lower crust can be mapped based on the geometries of the Conrad and Moho, the topography and bathymetry of the ocean floor, the sediment thickness and the assumed upper and lower crustal thicknesses. Fig. 4b shows the stretching factor differences ($\Delta\beta$) between the upper and lower crust. Sedimentary basins and the distal margin of the southern margin show $\Delta\beta$ distributions that are similar to those of the northern margin. However, on the southern margin, the predominantly lower crustal stretching region is not limited to the narrow distal bend on the western side of Reed Bank as in the northern margin, and this relatively broad region is located on the northern side of the Borneo-Palawan Trough (Fig. 4b).

Breakup line restoration results for the conjugate margins are shown in Fig. 4a. The total extensions are estimated based on these restoration results (Fig. 5). The total extension of the whole southern margin increases almost linearly from east to west. That of the northern margin has different trends in the eastern and western sections: it decreases from east to west in the eastern section but mainly increases from east to west in the western section (Fig. 5). The increased widths of the conjugate margins are perturbed by rigid blocks. For example, the rigid ZhongSha Island block on the northern margin corresponds to an oceanward convex COB, and at the conjugate southern margin, it has an oceanward concave COB (Fig. 4a).

5.2 Uncertainties and sensitivity

The accuracy of gravity inversion depends largely on density modeling ([Parker, 1973](#); [Oldenburg, 1974](#)). Heterogeneity in each Earth layer makes it impossible to model density variations accurately via numerical methods ([Chappell and Kusznir, 2008](#); [Wang et al., 2011](#)), and our density modeling methods aim to obtain a general picture of the density variations. Therefore, the gravity inversion results for the Conrad and Moho discontinuity depths (Fig. 3) present long wavelength trends. Many independent studies have shown that the density modeling method used here performs well for large-scale gravity inversion ([Bai et al., 2014](#); [Luo et al., 2018](#); [Tan et al., 2018](#); [Lebedeva-Ivanova et al., 2019](#)). The root mean square values of the Conrad and Moho depths between gravity inversion and seismic interpretations along the 11 deep seismic profiles on the SCS conjugate margins (Fig. 1a) are 1.9 km and 2.2 km, respectively, which are satisfactory for our margin-scale discussion. Please note that the seismic interpretations themselves also contain uncertainties sourced from data collection, velocity modeling and some other factors. For example, the discrepancy in the Moho depth from OBS2011 and OBS2013-3 at their intersection point is 1.6 km.

One basic assumption in mapping the crustal stretching factor is the uniformity of the initial upper and lower crust thicknesses in each margin. Although different initial upper and lower crust thickness values are set for the conjugate margins in this paper, the initial thickness of either margin could not have been entirely uniform. Thus, the differences between the assumed initial thickness and the real pre-rifting thickness would influence the stretching factor estimates. In addition, the uncertainty in the initial thickness could impact the breakup line restoration results ([Bai et al., 2015](#)). In our model, the initial thickness of the northern margin is ~1.3 times that of the southern margin (Table 1). These different initial thickness values do not form an obvious gradient in the stretching factor differences ($\Delta\beta$) between the upper and lower crust on the boundary (solid pink line in Fig.

243 4b) between the northern and southern margins. This result means that stretching factor differences are not
244 sensitive to our assumed initial thickness differences between the northern and southern margins.

245 Our restoration model assumes that there are no crustal volume increases or decreases except for the
246 high-velocity layer underplating on the NE margin ([Bai et al., 2015](#)). However, one of the mechanisms for lower
247 crustal thinning is lower crustal flow ([Hopper and Buck, 1996](#); [Clift et al., 2015](#)), which is also used to analyze
248 the stretching style variation of the SCS conjugate margins in the following sections. If the volume of outflow is
249 offset by the volume of inflow, then the influence of lower crustal flow on the restoration can be ignored.
250 However, defining the exact inflow and outflow volumes is difficult. Since this changeable volume is limited
251 compared with the volume of the whole margin, we do not try to explore this uncertainty further.

252 6. Symmetry evolution in a geodynamic context

253 When assessing the symmetry of the SCS margins, the pre-rifting crustal thickness, crustal rheology and
254 structures should be taken into consideration. End-member modeling indicates that the pre-rifting crustal
255 thickness cannot vary dramatically in the east-west direction ([Hayes and Nissen, 2005](#)), which is further
256 confirmed by a recent study ([Dong et al., 2020](#)). Subduction of the Izanagi plate under the South China Block
257 induced magma upwelling, which heated the lithosphere and thereby reduced the crustal viscosity ([Clift et al.,](#)
258 [2002](#); [Brune et al., 2017](#)). The pre-rift lithospheric thermal structure behavior along the east-west direction was
259 similar to that of the pre-rifting crustal thickness ([Dong et al., 2020](#)). A series of Mesozoic NE-trending sinistral
260 faults has been described on the South China Block ([Gilder et al., 1996](#)). These pre-existing faults are thought
261 to have formed much earlier than the initiation of the Izanagi subduction ([Fletcher et al., 2004](#); [Wang and Shu,](#)
262 [2012](#)). Therefore, the eastern and western margins should have featured similar pre-rifting crustal thickness
263 and crustal rheology, and the South China Block contained NE-trending faults before rift initiation.

Diverse studies infer that the conjugate margins of the SCS were subjected to pure shear deformation during the initial rifting stage ([Wu et al., 2012](#); [Chen et al., 2013](#); [Ding and Li, 2016](#); [Brune et al., 2017](#)) and during the formation of seaward-dipping faults on the main parts of the SCS conjugate margins (Fig. 6). However, the northward-dipping listric faults within narrow bands of conjugate distal margins imaged by seismic profiles indicate that simple shear deformation occurred around continental breakup ([Pichot et al., 2014](#); [Franke et al., 2014](#)). Since the stretching mode of the main conjugate margins was pure shear and the simple shear stretching was limited to narrow regions of distal margins before seafloor spreading in the SCS, the total extensions of the conjugate margins must have been predominantly symmetric. Continental crust was thinned substantially when simple shear occurred near breakup, and the lower crust of the conjugate distal margins was embrittled considerably at this stage ([Pérez-Gussinyé and Reston, 2001](#)). Therefore, the lower crust of both the upper and lower plates was thinned more than the upper crust, which means that the crustal stretching styles of the conjugate distal margins indicate bulk symmetry.

The SCS oceanic basin is divided into the East Subbasin and the Southwest Subbasin by the ZhongNan Fault ([Barckhausen et al., 2014](#); [Li et al., 2015](#)) (Fig. 1). In addition, both the stretching style and total extension exhibit differences between the western and eastern sides of the ZhongNan Fault (Fig. 4a and Fig. 5). Therefore, the conjugate margins are divided into eastern and western parts, and we discuss the N-S symmetry evolution of each part separately.

6.1 N-S symmetry in the western part

(1) Symmetry of the total extensions

The increased width of the NW margin linearly increases westward. Initially, the rifting center was along the pre-existing NE-trending fault, the paleo-Xisha Trough (Fig. 7a-b). The topographic gradient between

Indochina and the western rift domain induced compressive stress on the rift, which could have prevented continental breakup along the Xisha Trough ([Bird et al., 2006](#); [Stamps et al., 2010](#)). Since compression by the topographic gradient decreases southward and vanishes at the southern end of Indochina's topographically high region, the later rifting center abandoned the pre-existing NE-trending faults and oriented to the non-compressional region ([Le Pourhiet et al., 2018](#)). This reorientation has been suggested to have caused a southward ridge jump of approximately 20 km (Fig. 7c), while continental breakup gradually occurred from east to west, forming the V-shaped SCS oceanic basin ([Li et al., 2014](#); [Le Pourhiet et al., 2018](#)). Therefore, the pre-rifting NE-trending faults on the South China Block and the topographic gradient between Indochina and the western rifting domain resulted in a westward increase in margin extension (Fig. 5) ([Briais et al., 1993](#); [Hayes and Nissen, 2005](#)).

The increased width of the SW margin should have a similar trend due to pure shear rifting for the main parts of the conjugate margins, which can be seen in our estimate (Fig. 5). The linear trend of the total extension is perturbed by a relatively large rigid block known as the ZhongSha Islands (Fig. 5). The resistance to continental breakup imposed by the ZhongSha Islands localized extensional strain on the two sides of this rigid block before continental breakup. Pre-breakup strain dispersion would have produced more continental extension than strain concentration because narrow and highly thinned strain-loaded crust tends to break without further extension in the latter case. In addition, continental breakup occurred south of the rigid ZhongSha Block. Therefore, in the region affected by the ZhongSha Islands, the increased widths of the NW and SW margins are complementary: the increased NW width is larger than the average value, whereas the increased SW width is smaller than the average value.

(2) Symmetry of the crustal stretching styles

306 We find that the crustal stretching styles of the proximal sedimentary basins and the distal parts of the
307 conjugate margins are the same. The upper crust is stretched more than the lower crust in sedimentary basins
308 when the viscosity of the lower crust is low enough to cause lower crustal flow because of the local pressure
309 deficit at the Conrad discontinuity within basins (Fig. 7c and e). Shear stress on the lower crust imposed by
310 diverging asthenosphere along with crustal embrittlement causes the lower crust to thin more than the upper
311 crust at the distal margin during seafloor spreading ([Luo et al., 2018](#)) (Fig. 7d-f).

312 The lower crust of the southern margin presumably had a viscosity that was low enough to allow flow
313 because it was located between the active SCS oceanic basin and the young Proto-SCS basin during seafloor
314 spreading (Fig. 7d-f). The southern margin loaded southward-directed slab-pull stress during seafloor
315 spreading so that the low-viscosity lower crust flowed southward between the continent breakup and the
316 cessation of SCS spreading (Fig. 7d-f). This process would have thinned the lower crust more than the upper
317 crust. Therefore, at this stage, the region with mainly lower crust stretching on the southern margin would have
318 been much broader than that on the northern margin. Hence, the stretching styles at this stage were
319 asymmetric.

320 The collision between the southern margin and Borneo also modified the crustal stretching style of the
321 southern end, as has been indicated by seismic profiles CC' and DD' shown in Fig. 6 ([Hutchison, 1996](#); [Franke](#)
322 [et al., 2014](#)). This collision induced overthrust faulting in the upper crust and northward flow in the lower crust,
323 eventually thickening both the upper and lower crust (Fig. 7g-h). According to the maps of bathymetry (Fig. 1)
324 and stretching factor differences (Fig. 4b), we suggest that the northern boundary of the region modified by
325 collision is the Borneo-Palawan Trough, which is the same as the conclusion reached by [Hutchison \(2010\)](#).
326 Therefore, the present wide margin exhibits predominantly lower crustal stretching to the SW, and the
327 magnitude of collision-induced shortening is low relative to the magnitude of the total extension.

In summary, (1) the total extensions are symmetric and increase westward, which is probably the result of the pre-rifting faults on the South China Block and the topographic gradient between Indochina and the South China Block, and (2) the stretching styles are asymmetric because of southward lower crustal flow in the southern margin between continental breakup and seafloor spreading cessation (Table 3).

6.2 N-S symmetry in the eastern part

(1) Symmetry of the total extensions

The trend of the increased NE margin width can be divided into two sections: the region affected by the rigid Reed Bank and the eastern end portion (Fig. 5). Similar to the influence of the rigid ZhongSha Islands on the total extension, the rigid Reed Bank induced a greater increased width at its location on the southern margin and reduced the increased width on the conjugate northern margin (Fig. 5). However, the increase in the southern margin width by rifting was probably offset considerably by the subsequent collision, so there is almost no perturbation in the increased southern margin width associated with the Reed Bank. For the eastern end portion, the increased NE margin width is almost constant, ranging between 264 and 286 km, with a variation of only 22 km. This result probably appears because the continental breakup occurred almost simultaneously along one pre-rifting fault at ~32 Ma.

According to pure shear rifting for the predominant margins, the increased width of the eastern end portion of the SE margin should remain approximately constant. However, it decreases from west to east. The crustal thickness distributions indicate that the influence of the collision increases eastward on the southern margin (Fig. 4a), which can offset the total extension. Therefore, the increased widths of the NE and SE margins shifted from symmetric to asymmetric because of the collision between the southern margin and Borneo.

(2) Symmetry of the crustal stretching styles

349 The lower crust of the relatively narrow SE margin has been thickened by collision ([Hutchison, 1996](#);
350 [Franke et al., 2014](#)), so the present crust seems to have been uniformly stretched even though the lower crust
351 had been stretched more than the upper crust of the main SE margin before collision. In addition, due to the
352 rigidity of the Reed Bank, the stretching style of the uniformly stretched rigid Reed Bank was not modified
353 greatly by the collision. Therefore, a very narrow bend along the SE distal margin exhibits proximal lower
354 crustal stretching, and the stretching styles in the east are generally symmetric.

355 In summary, (1) the total extensions of the NE and SE margins shifted from symmetric to asymmetric in
356 response to the collision, and (2) the crustal stretching styles of the NE and SE margins shifted from symmetric
357 to asymmetric in response to slab-pull force during seafloor spreading and then shifted back to approximately
358 symmetric again in response to the collision (Table 3).

359 **7. Conclusions**

360 We obtained an overview of the symmetry of the marginal basin rifting in the SCS within the context of the
361 combined effects of rifting, drifting and collision processes on a continental-margin scale. This research is
362 based on delineating lateral fault distributions, mapping crustal stretching styles, and estimating total
363 extensions. Many previous studies indicate that the main portion of the conjugate margin has undergone pure
364 shear extension during rifting and that only a limited narrow band on each margin was deformed by simple
365 shear near breakup. These results mean that both the total extensions and the stretching styles of the
366 conjugate margins were symmetric on the whole before breakup. However, the complex post-breakup margin
367 evolution generated considerable differences between the conjugate margins (Table 3).

368 (1) Symmetry of total extensions. The total extensions were symmetric during continental breakup.
369 However, the symmetry was modified by the later collision between the southern margin and Borneo. The total

370 extensions in the western part retained their symmetry because the collision-induced modification in this area
371 was limited, but the total extension in the eastern part transformed to asymmetric because of the considerable
372 collision effect in this region.

373 (2) Symmetry of crustal stretching styles. Similar to the total extensions, the crustal stretching styles of the
374 conjugate margins were also symmetric before continental breakup. The southern margin with a low-viscosity
375 lower crust experienced southward pulling stress induced by Proto-SCS subduction, but the northern margin
376 did not. Therefore, southward lower crustal flow occurred during seafloor spreading, which transformed the
377 crustal stretching style from symmetric to asymmetric. Modification by later collision in the west was also
378 limited, so the stretching style remained asymmetric after collision; the obvious modification by collision in the
379 east transformed the crustal stretching style from asymmetric to generally symmetric.

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Fig. 1. (a) Bathymetry and topography from the ETOPO1 model (Amante and Eakins, 2009); solid green lines show seismic profile locations, and detailed information about each profile is provided in Table 2. (b) Free-air gravity anomaly (V27) based on altimetry data in marine areas and the Earth Gravitational Model 2008 (EGM2008) on land (Sandwell et al., 2014); main NE-trending faults are delineated according to gravity lineations under seismic constraints. Abbreviations in each figure are as follows: TXNB, TaiXiNan Basin; NWSB, Northwest Subbasin; ZSU, ZhongSha Uplift; ZSI, ZhongSha Islands; PRMB, Pearl River Mouth Basin; QDNB, QiongDongNan Basin; LDB, LeiDong Basin; BBGB, BeiBu Gulf Basin; YGHB, YingGeHai Basin; ZJNB,

667 ZhongJianNan Basin; RBB, Reed Bank Basin; BSB, Brunei-Sabah Basin; KB, Kutei Basin; ZMB, ZengMu
668 Basin; ENB, East Natuna Basin; WNB, West Natuna Basin; WAB, WanAn Basin; MB, Mekong Basin.

669

670 Fig. 2. Snapshots of plate tectonics at different stages after [Bai et al. \(2015\)](#), [Zahirovic et al. \(2014\)](#) and [Seton](#)

671 [et al. \(2012\)](#). (a) There were some NE-trending faults on the South China Block before rifting initiation, and the
672 fault near the margin center became active due to the slab pull of the Proto-SCS and the extrusion of the
673 Indochina Block. (b) During the opening of the NW Subbasin, the forces produced by Indochina extrusion and
674 the topographic gradient between the Indochina and South China margins resulted in the abandonment of the
675 initial main extensional fault, and a fault farther south became the main active fault. (c) During the opening of
676 the SW Subbasin, the topographic gradient produced a breakup line oriented to the region with a small
677 topographic gradient and formed a V-shaped oceanic basin. (d) The closure of the Proto-SCS shortened and
678 thickened the southern end of the southern margin.

679

(a) Conrad Depth

(b) Moho Depth

Fig. 3. Depths of the (a) Conrad and (b) Moho discontinuities in the SCS continental margins based on gravity inversion constrained by 11 deep seismic profiles. Thin gray lines show sediment thickness variations labeled with units of km; thick black lines show NE-trending and other main faults, as shown in Fig. 1b. The abbreviations are the same as those in Fig. 1.

(a) Breakup Line Restoration

(b) Stretching Factor Differences

Fig. 4. (a) Parameters and results of breakup line restoration. Small circle paths (thin green lines) are based on the full-fit reconstruction models by [Bai et al. \(2015\)](#) after [Lee and Lawver \(1994\)](#). The thick dashed red lines represent our restored breakup lines. UCCL, unstretched continental crust limit; COB, continent-ocean boundary; SESM, southern end of the southern margin; the other abbreviations are the same as those in Fig. 1. (b) Stretching factor differences ($\Delta\beta$) for the SCS conjugate margins. $\Delta\beta = \beta_u - \beta_l$, where β_u and β_l represent the stretching factors of the upper crust and lower crust, respectively. The purple line shows the boundary between the northern and southern margins according to gravity features. Please note that Luzon, Borneo, and the Indochina Block do not belong to the SCS margins. The initial crust thickness of each layer is listed in Table 1. Crustal structures along profiles AA', BB', CC' and DD' are shown in Fig. 6.

696

697 Fig. 5. Total extensions of the conjugate margins represent the difference between the present margin width
 698 and the pre-rifting margin width, which is the distance between the UCCL/SESM and the restored breakup line
 699 (Fig. 4a). The horizontal axis represents the distance from the restored breakup line to its western end (Fig. 4a).

700 NWSB, NW Subbasin.

701

Fig. 6 Crustal structures along four profiles after [Franke et al. \(2014\)](#); profile locations are shown in Fig. 4b.

Except in sedimentary basins, the faults on the SCS conjugate margins are mainly seaward-dipping. The collision between the southern margin and Borneo shortened and thickened the southern end of the southern margin.

Fig. 7. Schematic sections of the western and eastern margins, demonstrating the evolutionary processes at different stages. Profile locations are shown in Fig. 2. Before continental breakup at ~40 Ma (a and b), strain was mainly localized along the Xisha Trough on the western margin and at the center of the eastern margin. During the opening of the NW Subbasin (NWSB) at ~30 Ma (c and d), the rifting center migrated southward on the western margin, where the continental crust was not yet broken; the eastern margin had already broken, and seafloor spreading had initiated. There was no further stretching on the NE margin, but the lower crust flowed southward on the SE margin due to the low viscosity and southward slab-pull force. During the opening of the SW Subbasin (SWSB) at ~20 Ma (e and f), both the northern and southern margins in the west had extended more than those in the east, and seafloor spreading in the SWSB initiated; the northern margin was mainly quiet, and the lower crust still flowed southward on the southern margin. After the cessation of the SCS opening at ~10 Ma (g and h), the southern margin collided with Borneo, and the southern end of the margin was shortened and thickened. Different types of lower crust flow occurred during these processes: (1) the lower crust flowed into sedimentary basins after the upper crust was highly thinned, (2) the lower crust flowed toward the continent from the distal margin due to diverging asthenosphere, (3) southward lower crustal flow on the southern margin during seafloor spreading was driven by strain stress by slab pull from the Proto-SCS, and (4) northward lower crustal flow on the southern end of the southern margin was caused by the compressive stress induced by collision.

20 **Tables**

21 Table 1 Initial total, upper and lower crustal thicknesses (km) of the SCS conjugate margins.

Margin	Total Crustal	Upper Crustal	Lower Crustal
	Thickness	Thickness	Thickness
Northern	32.0	15.1	16.9
Southern	25.0	11.8	13.2

22

23

24 Table 2 Parameters of the deep seismic profiles on the SCS conjugate margins used in this paper. Profile
 25 locations are mapped in Fig. 1a.

Index	Name	Length	Conrad interpreted?	Moho interpreted?	Reference
1	ESP1985-2	395	No	Yes	Hayes and Nissen (2005)
2	OBH1996-4	220	Yes	Yes	Qiu et al. (2001)
3	OBS1993	410	Yes	Yes	Yan et al. (2001)
4	OBS2001	350	Yes	Yes	Wang et al. (2006)
5	OBS2006-1	480	Yes	Yes	Li (2011)
6	OBS2006-2	380	Yes	Yes	Ao et al. (2012)
7	OBS2006-3	320	No	Yes	Wei et al. (2011)
8	OBS2009-2	360	Yes	Yes	Li (2011)
9	OBS2009-1	250	Yes	Yes	Hao et al. (2011)
10	OBS2011	450	Yes	Yes	Huang et al. (2011)
11	OBS2013-3	240	Yes	Yes	Guo et al. (2016)

26

27

28 Table 3 Present symmetry between the SCS conjugate margins of the western and eastern parts from the view
 29 of total extensions and crustal stretching styles.

Compared aspect	Western part	Eastern part
Total extensions	Symmetric	Asymmetric
Stretching styles	Asymmetric	Approximately symmetric

30